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THE SEDIMENT DELIVERY PROBLEM

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ABSTRACT

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The linking of on-site rates of erosion and soil loss within a drainage basin to the sediment yield at the basin outlet, and improved knowledge and representation of the associated processes of sediment delivery, represent a major research need within the field of erosion and sedimentation and also an important scale problem in drainage basin studies. This paper reviews the limitations of the sediment delivery ratio concept by considering the problems of temporal and spatial lumping and its blackbox nature. Some recent advances in our understanding of the sediment delivery system and its modelling are described and the lack of detailed empirical investigations is highlighted. The significance of recent concern for the role of sediments in the transport of nutrients and contaminants to sediment delivery studies is introduced, and the need for further work in this field is emphasised.

THE CONTEXT

In any review of research needs in the field of erosion and sedimentation, it is likely that attention will be directed towards the problems and uncertainties that surround attempts to link on-site rates of erosion and soil loss within a drainage basin to the sediment yield at the basin outlet. A knowledge of this linkage is important for predicting sediment yields from a knowledge of local erosion rates, for evaluating the impact of particular land use scenarios on sediment yields, for investigating the movement of sediment-associated nutrients and contaminants from agricultural land and, conversely, for utilizing sediment load data to provide estimates of on-site rates of erosion or soil degradation. Thus, for example, Wolman (1977) highlighted this theme as meriting further study in an overview of changing needs and opportunities in the sediment field when he stated that:

> "A major effort is needed to understand the linkages between erosion from the land surface and transport in channels . . . What then are the appropriate paths and time constants for sediment movement?"

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and similarly that:

> ". . . when the system is looked at as a whole, it can be seen that a clearer tie is needed between phenomena of erosion from sources, storage and transport in channel systems."

Likewise, a review of water pollution from cropland and associated research needs produced by the U.S.D.A. (1976) emphasised that:

> "Development of a better understanding of the basic sedimentation and erosion processes involved between the time when runoff leaves a field area and when it reaches a continuous stream system is one of the greatest erosion and sediment research needs."

It would therefore seem appropriate to include a consideration of this theme within a Symposium on the Understanding of Hydrologic Processes at the Basin Scale, since it directly relates to the problems of understanding processes of erosion and sedimentation at this scale and it necessarily involves integration of both hydrological and geomorphological factors.

THE SEDIMENT DELIVERY RATIO AND ITS LIMITATIONS

It is well known that only a fraction, and perhaps rather a small fraction, of the sediment eroded within a drainage basin will find its way to the basin outlet and be represented in the sediment yield. Deposition and temporary or permanent storage may occur on the slope, particularly where gradients decline downslope, at the base of the slope, in swales, on the flood plain, or in the channel itself. The relative magnitude of this loss tends to increase with increasing basin size. Hadley and Shown (1976) have, for example, indicated that only ~ 30% of the sediment eroded in many of the small tributary basins (0.5—5.2 km^2) of the Ryan Gulch Basin in northwest Colorado, U.S.A., finds its way to the main valley, and in turn that only 30% of this sediment is transported to the mouth of the 124.8-km^2 basin. Similarly, a countrywide study of 105 agricultural production areas in the U.S.A. undertaken by Wade and Heady (1978) documented a range of sediment output between 0.1% and 37.8% of the gross erosion.

Less is known about the relative importance of the various losses within the hillslope—stream network system, but an investigation in the Oka Basin, central European U.S.S.R., reported by Golubev (1982) provides estimates for that region. These indicate that only 10% of the gross soil loss is transported to the larger rivers and that 60% is deposited on the lower parts of the slopes, 20% in ephemeral channels and 10% in the minor streams of the network. Studies of sediment loads transported downstream past a series of gauging stations on a major river may equally sometimes exhibit a decline in absolute load, again reflecting conveyance losses (Table I).

The term *sediment delivery* has been widely used to represent the resultant of the various processes involved between on-site erosion and

TABLE I

Sediment losses in major river systems

River	Station	Area (km^2)	Total suspended sediment load ($t\ yr.^{-1}$)	Loss between stations (%)
Nile	Kajnarty	1,850,000	133,700,000	17
(Sudan—Egypt)	Cairo	3,000,000	111,000,000	
Wisla	Zawichost	50,543	1,990,000	41
(Poland)	Plock	168,857	1,180,000	
Lech	Füssen	1,422	329,433	42
(Federal Republic of Germany)	Feldheim	2,124	192,489	
Po	Becca	30,170	4,374,650	13.3
(Italy)	Piacenza	35,430	3,791,010	
MeNan	Tha Pla	12,790	4,999,355	35
(Thailand)	Pitsannloke	25,491	3,252,201	
Atrak	Shirrin-Darrah	1,500	92,510	66
(Iran)	Reza-Abad	5,430	31,406	
Nazus	El Palmito	18,321	2,451,129	25
(Mexico)	Canon Fernad	33,468	1,813,094	

downstream sediment yield and the concept of a *sediment delivery ratio*, defined as the ratio of sediment delivered at the catchment outlet ($t\ km^{-2}\ yr.^{-1}$) to gross erosion within the basin ($t\ km^{-2}\ yr.^{-1}$), has been introduced as a means of quantifying this effect (e.g., Glymph, 1954; Maner, 1958; Roehl, 1962).

The magnitude of the sediment delivery ratio for a particular basin will be influenced by a wide range of geomorphological and environmental factors including the nature, extent and location of the sediment sources, relief and slope characteristics, the drainage pattern and channel conditions, vegetation cover, land use and soil texture. Several studies have attempted to produce empirical prediction equations for this variable, stimulated by recognition that a reliable assessment of the sediment delivery ratio would afford a ready means of estimating the sediment yield of a basin from estimates of soil loss obtained using established procedures such as the Musgrave (1947) equation and the universal soil loss equation (USLE) (Wischmeier and Smith, 1958). Basin area has frequently been isolated as a dominant control (e.g., A.S.C.E., 1975) and the U.S. Soil Conservation Service has developed a generalised relationship between delivery ratio and drainage basin area (Fig. 1) which has been widely applied in central and eastern U.S.A. (e.g., Robinson, 1977), often with little regard for the potential influence of local conditions. The inverse relationship between delivery ratio and area has been explained in

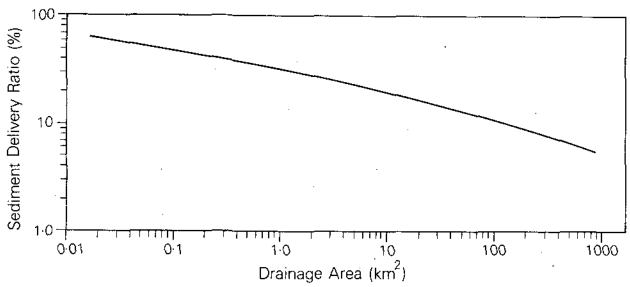

Fig. 1. Relationship between sediment delivery ratio and drainage basin area developed by the U.S. Department of Agriculture Soil Conservation Service for central and eastern U.S.A.

TABLE II

Examples of proposed relationships between sediment delivery ratio and catchment characteristics

Author	Region	Equation
Maner (1958)	Kansas, U.S.A.	$\log \mathrm{DR} = 2.962 + 0.869 \log R - 0.854 \log L$
Roehl (1962)	southeastern U.S.A.	$\log \mathrm{DR} = 4.5 - 0.23 \log 10 A - 0.510 \times \operatorname{colog} R/L - 2.786 \log \mathrm{BR}$
Williams and Berndt (1972)	Brushy Creek, Texas, U.S.A.	$\mathrm{DR} = 0.627\ \mathrm{SLP}^{0.403}$
Williams (1977)	Texas, U.S.A.	$\mathrm{DR} = 1.366 \cdot 10^{-11}\ A^{-0.100}\ R/L^{0.363}\ \mathrm{CN}^{5.444}$
Mutchler and Bowie (1975)	Pigeon Roost Creek, Mississippi, U.S.A.	$\mathrm{DR} = 0.488 - 0.006 A + 0.010\ \mathrm{RO}$
Mou and Meng (1980)	Dali River Basin, Shaanxi, China	$\mathrm{DR} = 1.29 + 1.37 \ln \mathrm{Rc} - 0.025 \ln A$

DR = sediment delivery ratio; R = basin relief; L = basin length; A = basin area; R/L = relief/length ratio; BR = bifurcation ratio; SLP = % slope of main stem channel; CN = S.C.S. curve number; RO = annual runoff; Rc = gully density.
Note: Units vary between equations.

terms of the decreasing slope and channel gradients and increasing opportunities for deposition associated with increasing basin size. Other attempts to develop prediction equations have included such variables as relief ratio and main channel slope (Table II).

The failure to produce a generally-applicable prediction equation is partly due to the complexity of sediment delivery processes and their interaction with catchment characteristics, and partly to a lack of definitive assessments of the dependent variable. Assessments that have been undertaken are themselves primarily based on a comparison of measured sediment yield with an *estimate* of gross erosion. The latter are generally derived from an estimate of sheet erosion based on a soil loss equation, corrected to take account of additional contributions from channel and gully erosion, and are

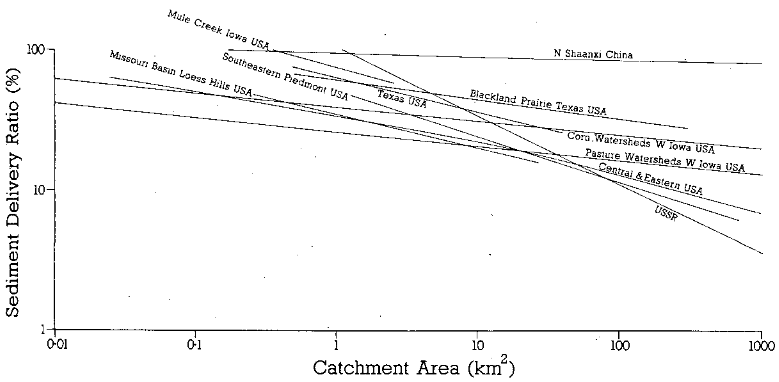

Fig. 2. Relationships between sediment delivery ratio and drainage basin area proposed for different regions. (Based on data presented in Roehl, 1962; Sokolovskii, 1968; Piest et al., 1975; Renfro, 1975; A.S.C.E., 1975; Williams, 1977; Mou and Meng, 1980.)

therefore open to considerable uncertainty. The various relationships between delivery ratio and basin area developed for particular areas presented in Fig. 2 emphasise the considerable diversity of values associated with basins of a given size. The delivery characteristics of basins in the southeastern Piedmont, U.S.A., contrast markedly with those of watersheds in the loess region of China where delivery ratios close to 100% occur over a wide range of basin size. Some consistency in the slope of the delivery ratio—area relationship for several regions in the U.S.A. is apparent, lending support to the view of A.S.C.E. (1975) than an exponent of −0.125 is typical, but even here a wide range of intercept values exists. The relationship ascribed to the U.S.S.R. is not strictly comparable with the other lines, in that it is derived from a generalised relation between a reduction factor for average turbidity and basin area presented by Sokolovskii (1968), and it has been ascribed an arbitrary intercept of 100% at 1.0 km^2. Nevertheless, the contrast in slope with the −0.125 referred to above again points to a diversity in the form of the relationship. This is further demonstrated in Fig. 3, which presents a number of relationships between sediment yield and catchment area reported in the literature. A.S.C.E. (1975) have proposed that the slope of this relationship is directly analogous to that of delivery ratio vs. basin area and Fig. 3 can therefore be seen as providing additional evidence of regional variations.

The uncertainties surrounding the wide range of delivery ratios reported by individual studies, and the lack of a generally-applicable predictive technique are paralleled by fundamental problems associated with the concept of a simple relationship between gross erosion and sediment yield. These problems relate in particular to the temporal and spatial lumping inherent in the concept and to its blackbox nature. These problems can be reviewed.

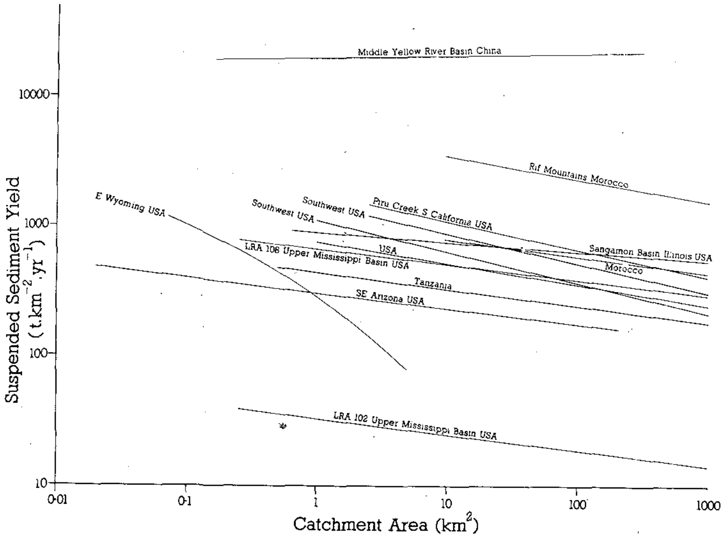

Fig. 3. Relationships between sediment yield and drainage basin area described in various studies. (Based on data presented in Brune, 1950; Scott et al., 1968; Rapp et al., 1972; Livesey, 1975; Strand, 1975; Dendy and Bolton, 1976; Hadley and Shown, 1976; Renard, 1977; Lahlou, 1981; and unpublished sources.)

Problems of temporal lumping

Problems of temporal lumping or aggregation can be viewed at a number of levels of resolution, ranging from the individual storm through to a long-term perspective of the erosion–delivery–yield system. At the level of the individual storm the work of Piest et al. (1975) has clearly demonstrated the considerable range of delivery ratios that may exist for particular events. Studies of a small 30-ha basin near Treynor, Iowa, U.S.A., over the period 1965–1971 documented the gross erosion and sediment yield for 55 events and showed the lack of a clear relationship between storm sediment yield and estimates of gross erosion. Delivery ratios ranged between 1% and 554% (Fig. 4) and were shown to be significantly influenced by antecedent soil moisture status and season. On an annual basis, delivery ratios in the same basin ranged from 6% to 72% with a 7-yr. mean of 46% and were related to the magnitude of annual precipitation and to the seasonal distribution of precipitation. The authors recognised that this variability in sediment delivery at the annual and storm-period level could simply reflect errors in estimating gross erosion, but it is impossible to gauge the potential magnitude of such errors. They preferred to account for the variations in terms of a watershed delivery or conveyance function, analogous to the Manning equation, in which:

$$D \propto RS/n \qquad (1)$$

where D = the conveyance factor; R = an expression of flow geometry; S = a watershed slope factor; and n = a watershed roughness factor, and which will vary from season to season and from year to year, according to land use and crop conditions. Equally, however, values of delivery ratio in excess of 100% could be interpreted as reflecting short-term storage and remobilisation during the delivery process, so that the sediment yield could exceed the estimate of gross erosion for a particular event. Analogous data suggesting annual variation in delivery ratios have been presented by Mutchler and Bowie (1976).

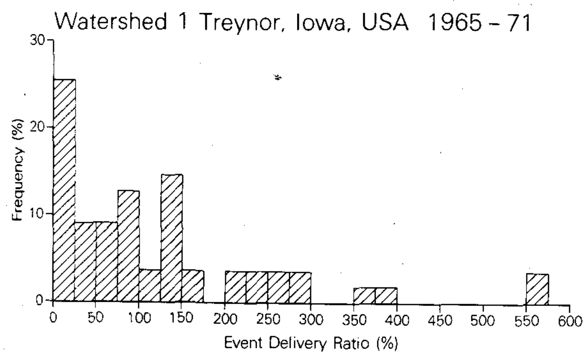

Fig. 4. Frequency distribution of event delivery ratios calculated for Watershed *1*, Treynor, Iowa, by Piest et al. (1975).

Similar temporal attenuation within the delivery process as a result of storage and remobilisation could be indicated by the lack of correspondence between annual patterns of sediment yield measured in large basins and those representing small constituent basins (e.g., McGuinness et al., 1971; Ketcheson et al., 1973; Dickinson and Wall, 1978). Dickinson and Wall (1977) have termed this a "temporal paradox" when reviewing a number of problems associated with sediment delivery, and the classic example cited by McGuinness et al. (1971) is illustrated in Fig. 5. This compares the typical sediment yield regime of small agricultural (0.5–1 ha) basins at the North Appalachian Experimental Watershed research station with the regime of the 15,500-km^2 basin of the Muskingum River gauged at Dresden, Ohio, U.S.A. The former represents the pattern of sediment movement from fields to first-order channels and closely reflects the annual distribution of the product of the rainfall energy and cover factor terms in the USLE, whilst the latter mirrors the annual runoff regime.

The existence of attenuation by storage and remobilisation within the sediment delivery process over a much longer time scale has been well documented by Trimble (1969, 1974, 1975, 1976) in his studies of culturally accelerated erosion in the Piedmont of Georgia and in Coon Creek,

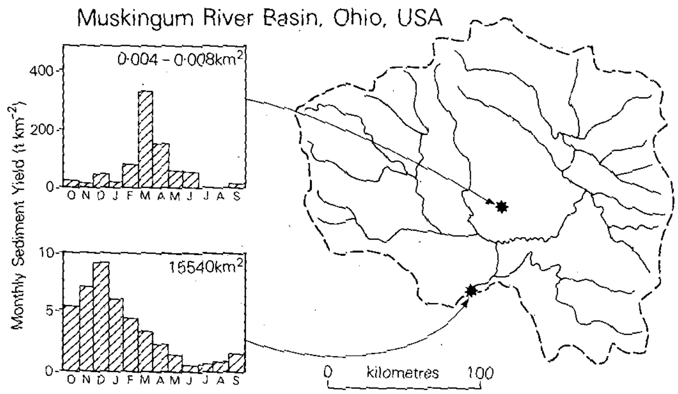

Fig. 5. Contrasts in annual patterns of sediment yield between small basins and a large river system. (Based on McGuinness et al., 1971.)

Wisconsin, U.S.A. By making use of historical documents, existing survey records and gauging data, and field surveys he was able to demonstrate that only a small proportion of the sediment eroded from these areas during the period of severe soil erosion in the latter part of the nineteenth century and the early twentieth century was transported out of the area by the rivers. Most accumulated as alluvium in the valley systems. However, when improved land-use practices were introduced, sediment yields did not decline to the extent that might have been expected, since these alluvial deposits were remobilised and transported out of the system. This response represents a considerable temporal discontinuity in the erosion—sediment yield relationship when viewed at this time scale. A typical pattern of valley aggradation and subsequent degradation and its relation to the pattern of sediment yield, as documented by Trimble (1969) in the Georgia Piedmont, is shown in Fig. 6C. Further details concerning the precise interaction of aggradation and degradation are presented in Fig. 6A and B which illustrate Trimble's findings in Coon Creek, Wisconsin, U.S.A. (Trimble, 1976). This shows the depth of overbank deposition within this 200-km^2 basin during the period 1850—1938 and the extent of subsequent channel degradation during the period 1938—1974. In the latter context, considerable degradation is apparent in the upstream reaches, but aggradation, and therefore storage, is still continuing in the downstream reaches. Sediment now being remobilised from the upstream valley deposits may be trapped in the lower valley perhaps to be remobilised yet again by the process of lateral channel shifting.

Other workers such as Costa (1975) have reported similar patterns of storage and remobilisation of sediment within the landscape as a result of changing land-use practices and it is important to recognise the associated temporal discontinuities in sediment delivery. Even under more natural or

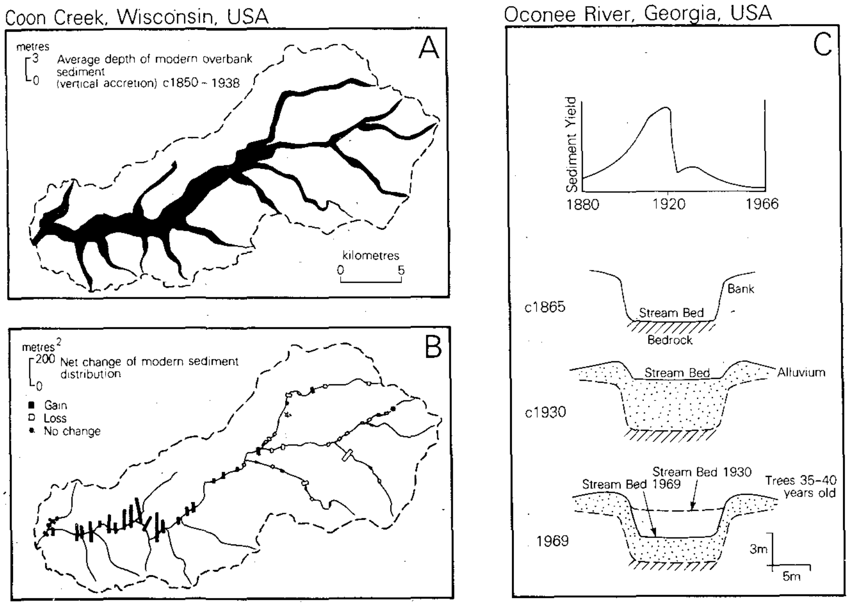

Fig. 6. Temporal discontinuities in sediment delivery as described by Trimble (1969, 1976). A illustrates the extent and depth of overbank deposition in the valley system of Coon Creek, Wisconsin, consequent upon accelerated soil loss from the watershed and B depicts the extent of more recent degradation and aggradation during the period 1938—1974. C demonstrates the typical pattern of valley aggradation and degradation in the Georgia Piedmont and its relationship to trends in the pattern of sediment yield.

undisturbed conditions, storage and remobilisation may occur in the delivery process and Schick (1977) has emphasised that such storage must itself be viewed in terms of magnitude—frequency relationships. The concept of geomorphic thresholds advanced by Schumm (1977) also has important implications in this context.

Problems of spatial lumping

Problems of spatial aggregation or lumping have been referred to as the spatial paradox by Dickinson and Wall (1977) and relate to the problems of attempting to represent the sediment delivery characteristics of a watershed with a single number. Spatial diversity of topographic, land use and soil conditions within a basin could be expected to produce considerable local variations in sediment delivery response. Burns (1979) has, for example, suggested that each sediment source should be viewed as possessing a unique delivery potential and that the probability of sediment being exported from a particular source should be related to its relative position with respect to the stream and the basin divide.

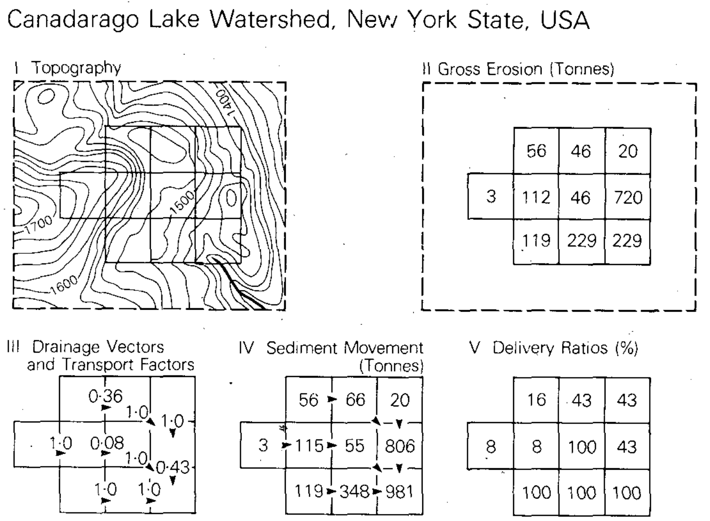

Fig. 7. The cell approach to modelling erosion and sediment yields proposed by Kling (1974) in his study of Canadarago Lake. Only a small portion of the overall grid of 10-acre (~ 4-ha) cells is illustrated.

Such problems have inevitably led to attempts to apply the delivery ratio concept on a distributed basis and a grid-square approach has been employed by a number of workers for this purpose. For example, Kling (1974) describes a study of sediment movement within the Canadarago Lake drainage basin in New York, U.S.A. which represented the basin by a series of 10-acre (~ 4-ha) cells. Gross erosion was calculated for each of these cells using the USLE and sediment was routed downslope towards the channel networks through a sequential arrangement of cells (Fig. 7). Sediment delivery from *within* an individual cell into the next cell was assumed to be 100%, but the proportion of the sediment delivered from an adjacent cell that was transported *across* a given cell was evaluated using a simple transport factor estimated from the ratio of the average slope of the given cell to that of the adjacent cell. If the adjacent cell was steeper than the receiving cell, deposition was assumed to occur, whereas if the adjacent cell was less steep, a transport factor of unity was employed. The failure to include a delivery term in the routing of sediment from within individual cells to adjacent cells could be questioned and, although the distributed approach inevitably possesses certain merits, there are major uncertainties surrounding the designation of delivery terms for individual cells, to the extent that the approach may in practice possess little advantage over a conventional lumped procedure. Some of this uncertainty is emphasised by Boyce (1975) when he attempts to reconcile the sediment delivery ratio of a 60-mi.^{2} (155-km^2) basin with the ratios applicable to constituent 6-mi.^{2}

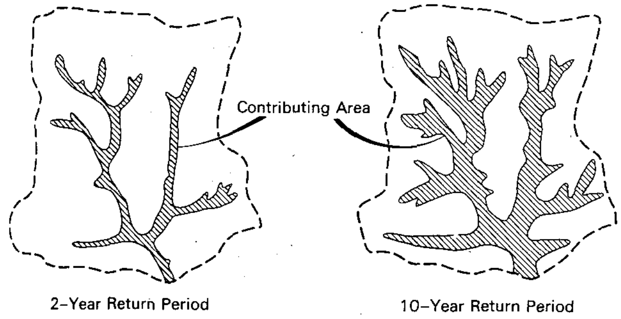

Fig. 8. A hypothetical example of the variation of the storm runoff contributing area and the stream network within a drainage basin for flood events of different magnitude.

(15.5-km^2) cells, bearing in mind the inverse relationship between sediment delivery ratio and basin area.

The problems of spatial lumping may be further highlighted by reference to the partial area and variable source area models of storm runoff generation (e.g., Kirkby, 1978). If, as now seems generally accepted in humid areas, storm runoff is produced from only a small proportion of the basin, and this contributing area varies according to antecedent moisture conditions (e.g., Walling, 1971; Moore et al., 1976) the magnitude of the sediment delivery ratio should be related to the relative extent and characteristics of this zone rather than the characteristics of the entire watershed (Fig. 8). Furthermore, the delivery ratio of both the overall basin and the contributing area could be expected to vary through time in response to changes in its extent. With an expanding contributing area, the former would increase, but the latter could either increase or decrease according to the dynamics of the expansion. If the growth was primarily in terms of a widening saturated zone bordering the streams, then, following the argument of Burns (1979) outlined above that the probability of sediment being exported is inversely proportional to the distance of the sediment source from the stream, delivery ratios for the contributing area might be expected to decline. If, however, growth was accompanied by a major increase in the density of the drainage net, the reverse situation could exist. Moreover, the dynamics of a variable contributing area might also be expected to embrace the remobilisation of sediment deposited within secondary source areas, which remain unconnected to the stream network under normal conditions, but contribute to the network during extreme storm events.

Problems of a blackbox concept

The sediment delivery ratio is effectively a blackbox concept, and many of the resultant limitations have already been highlighted when considering the problems of spatial and temporal lumping. Because it subsumes a variety of processes, it is difficult to assess the precise influence of various controlling factors and to forecast changes that might result from changes in catchment conditions. Different process assemblages will characterise different morphoclimatic zones. Thus the local nature of runoff-producing events, the process of channel infiltration with associated reduction in streamflow and sediment transport capacity, and the occurrence of discordant stream junctions with alluvial fan deposits may provide a dominant control over sediment delivery ratios in semi-arid regions (Hadley and Shown, 1976; Thornes, 1977; Wolman and Gerson, 1978), whilst they may be of little or no significance in humid terrains. Similarly, the sediment delivery ratios of drainage basins where the dominant sediment sources are mass movements such as earthflows and mudslides (e.g., I.A.H.S., 1981) will reflect different controls to those operating in areas of agricultural sheet erosion. The near 100% delivery ratios reported by Gong and Xiong (1980) and Mou and Meng (1980) for the gullied loess region of the Yellow River Basin in China are a particular response to the local conditions and may be attributed to the dominance of active gully erosion as the sediment source, to the morphology of the gully systems and to the occurrence of hyperconcentrations of suspended sediment ($> 500\,\mathrm{kg\,m^{-3}}$) which drastically reduce settling velocities and therefore the opportunities for deposition.

Even within a particular catchment, it is important to recognise that sediment delivery represents the resultant of a number of processes, each related to environmental variables in a specific manner. Thus in an attempt to produce meaningful guidelines for estimating sediment yields in the Piceance Basin in northwestern Colorado, Frickel et al. (1975) found it necessary to distinguish the processes of sediment delivery from the slopes to the channel and through low-order tributaries (i.e. basin areas of 1.3—13 km^2), from the processes operating in the higher-order segments of the channel network. Sediment yields from the former areas, designated source areas, were estimated using the P.S.I.A.C. (1968) method, which implicitly accounts for sediment delivery by taking account of such variables as relief and channel characteristics. Sediment yields from the larger basin were estimated as the product of the area-weighted average source area sediment yield and a sediment transport ratio. The latter was evaluated by assigning values (Table III) to individual channel reaches (> third order) and calculating the length-weighted average.

It seems clear that a more detailed representation of the various processes subsumed in the sediment delivery ratio is required if an effective understanding of the linkage between source-area erosion and downstream yield is to be obtained. The simple sediment delivery ratio must be replaced by a model which recognises the various processes involved in the movement of sediment from the source area through the basin system to the outlet, and which can take account of spatial variability within the system and the various time constants involved. As Wolman (1977) indicated, we are still some way from attaining such a goal, but it is now possible to specify

TABLE III

Guidelines for evaluating sediment-transport ratios in the Piceance Basin, Colorado

Sediment transport ratio	Channel conditions
1.0	(1) main channel(s) and most tributaries exist as raw gullies (2) channel is main stem of perennial stream
0.75	(1) main channel(s) and about one-half of the tributaries exist as raw gullies
0.5	(1) main channel(s) gullied but tributaries ungullied (2) most gullied channels are healed with vegetation indicating shallow flows
0.3—0.5	(1) discontinuous gullies
0—0.4	(1) most channels ungullied with evidence of deposition such as active fans, particularly at the mouths of tributaries (2) deposition in evidence on bottomlands where flows spread naturally or are used for irrigation

Based on Frickel et al. (1975).

processes that must be included and some progress is being made in modelling them.

ILLUMINATING THE BLACKBOX

Development of improved models of the sediment delivery process must depend to a considerable extent on the availability of detailed empirical investigations capable of elucidating the mechanisms involved. Unfortunately, few such studies are available and it has to be accepted that any investigation must face considerable, if not intractable, practical problems. Storages and residence times, in particular, may prove extremely difficult to document. For example, Wolman (1977) has indicated from his studies in a 2.6-km^2 basin in the eastern U.S.A. that a sediment yield of several years can be stored within the channel and be virtually undiscernible in the system. Similarly, Schick (1977) describes the very great problems involved in relating measurements of sediment input and output for an alluvial fan with estimates of storage within the fan.

Several theoretical sediment routing models for small drainage basins have been developed in recent years (e.g., Simons et al., 1975; Smith, 1976a, b; Li et al., 1976; Alonso et al., 1978; Li, 1979) and these have attempted to provide an improved representation of sediment transport across basin slopes. Smith (1976a, b) employed a kinematic equation to represent flow routing from a watershed and the stream power concept of

Yang (1972) was used to compute local transport capacity. The model proposed by Li et al. (1976) used a similar kinematic wave approximation for flow routing linked to a finite-difference procedure to route surface runoff to the channels, and sediment movement was simulated using the Einstein (1950) suspended load procedure and the Meyer-Peter, Müller bed load equation (U.S.B.R., 1960).

Similarly, developments in soil erosion modelling have included improved representation of sediment movement across the watershed slopes. Meyer and Wischmeier (1969) distinguished the processes of detachment and transport and developed a simple conceptual model of the soil erosion process in which sediment movement was limited either by the availability of material for transport or the capacity of rainfall and runoff to transport the detached soil. This has been further developed by other workers (e.g., Foster et al., 1980). Meaningful approximation of the transport capacity provides the key to effective simulation of the sediment delivery process, since the model can be evaluated for individual slope segments. However, herein lies a problem. The accurate assessment of transport capacity, and thus the opportunities for deposition, at the field scale still presents major difficulties, and the conveyance components of many soil loss models are based on optimized parametric functions rather than physically-based equations (e.g., Bruce et al., 1975). Neibling and Foster (1980) emphasise that whereas extensive literature exists on sediment transport by streamflow, little information is available on sediment transport by shallow overland flow. No widely accepted transport equations have been developed for overland flow. Streamflow sediment transport equations are often used, but these authors suggest that they may seriously over- or under-estimate sediment transport by overland flow. The Yalin (1963) equation is suggested to possess fewest drawbacks and has been adopted in the CREAMS model recently developed by the U.S. Department of Agriculture (Knisel, 1980).

More work is needed to improve the conceptual and mathematical representation of the surface delivery process, particularly in terms of representation of surface roughness characteristics, the depositional environment, the response of cohesive sediments (e.g., Partheniades, 1971), and the incidence and behaviour of soil aggregates as distinct from primary particles. Recent investigations (e.g., Swanson and Dedrick, 1967; Foster et al., 1980; Young, 1980) have, for example, demonstrated how aggregates may constitute a considerable proportion of the eroded sediment, and it is clear that they may behave rather differently from the primary particles frequently assumed on the basis of traditional laboratory analysis. Moreover, Shen and Li (1973) and Moss (1980) have pointed to the important influence of raindrop impact on sediment transport by sheet flow and Novotny (1980) has argued that the transport capacity of shallow overland flow may be considerably reduced during the falling stage of a hydrograph due to the cessation of energy inputs from rain which are important for keeping particles in suspension.

TABLE IV

Suggested effect of sediment particle size on the sediment yield of Elm Creek, Texas, U.S.A. (432 km^2)

Median particle size D_{50} (mm)	Average annual sediment yield ($t\,km^{-2}\,yr.^{-1}$)	Delivery ratio (%)
0.001	1,203	37.0
0.01	675	21.0
0.1	190	6.1
0.4	82	2.5

Based on Williams (1975).

Although available knowledge of sediment transport in channels is more complete, similar uncertainties exist as to the potential for depositional losses. In the WEST (Watershed Erosion and Sediment Transport) model described by Leytham and Johanson (1979), deposition within individual reaches is calculated using a kinematic wave streamflow routing technique and a consideration of particle settling velocities in relation to ambient shear velocities. At a simpler level Williams (1975, 1977, 1978) has proposed a number of channel routing functions, equivalent to sediment delivery ratios, to account for the movement of sediment through a channel network from small sub-basins (< 65 km^2) to the outlet of a large basin (< 2590 km^2), e.g.:

$$\text{(sub-basin channel routing factor) or (delivery ratio)} = \exp(-\beta T D_{50}^{1/2}) \qquad (2)$$

$$\text{(reach delivery ratio)} = \sum_{i=1}^{m} W_i \exp(-\beta D_i^{1/2}) \qquad (3)$$

where β = a routing coefficient for the overall basin (eq. 2) or the individual reach (eq. 3); T = travel time from sub-basin to basin outlet; D_{50} = median particle diameter of sediment; W_i = proportion of particle size D_i contained in sediment, and D_i = particle size. A similar approach has been proposed by Onstad and Bowie (1977).

However, these functions are primarily a means of apportioning estimated sediment losses amongst individual sub-basins (eq. 2) or amongst particle size classes (eq. 3). No guidelines are given for estimating β from basin or channel characteristics and, although Williams (1975) suggests that it is possible to demonstrate the effects of sediment particle size by varying the value of D_{50} in eq. 2 (Table IV), the dependence of deposition on travel time and a settling velocity proportional to the square root of particle diameter is not verified empirically. The physical basis of the assumed depositional process is in fact questioned by Novotny (1980) who queries the assumption that appreciable deposition of fine material will occur within the channel system and suggests that the necessary flow shear stress values will only

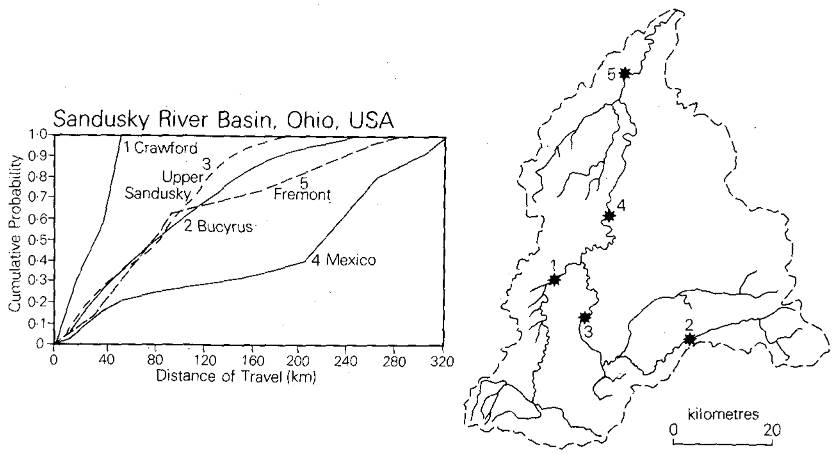

Fig. 9. Probability distributions of suspended sediment travel distances presented by Verhoff et al. (1979) for various gauging sites in the Sandusky River Basin, Ohio.

occur under very shallow flow conditions or in impoundments.

If deposition does occur, it is neccessary to consider the likelihood of re-entrainment and the typical travel distances of particles of a particular size during individual events. The use of radioactive tracers has provided a ready means of estimating the probability distribution of travel distances of bed load particles (e.g., Tazioli, 1981) but very little is known about the behaviour of suspended sediment. The study reported by Verhoff and Melfi (1978) and Verhoff et al. (1979) provides a notable exception to this dearth of empirical evidence. Working on the Sandusky River in Ohio, U.S.A., they suggest that suspended sediment is moved through the channel system by a series of storm events. Each storm event entrains sediment from the stream bed, banks and flood plain, transports it some distance downstream, and deposits it in the stream again. Average travel distances have been calculated from an analysis of the relative timing of the discharge hydrographs and the total phosphorus chemographs recorded at individual gauging sites, based on the assumption that the water is moving as a kinematic wave. Total phosphorus concentrations are considered to be closely related to suspended sediment concentrations and Fig. 9, which illustrates the cumulative probability distributions of travel distances at various stations in the Sandusky River Basin obtained by these workers, can equally be viewed as representing suspended sediment travel distances. In the upper reaches of one of the tributaries at Crawford (Fig. 9) the median travel distance is ~ 30 km and this value increases at the other sites. Further studies are required to verify the conclusions drawn from analysis of the chemograph timing and to determine if similar processes operate in other rivers.

This and other work on sediment movement through the landscape has helped very considerably to illuminate the blackbox of the sediment delivery ratio, but much more work is required. Lack of detailed empirical studies has necessitated numerous assumptions concerning the physical principles involved and, more particularly, recourse to theoretical hydraulic relationships developed for unrepresentative conditions. Uncertainties surround the precise behaviour of shallow overland flow and its interaction with rainfall energy, the roughness characteristics of natural slopes and their depositional environments, the incidence and behaviour of aggregates, the occurrence of intermittent movement, and the residence times or time constants involved in the various storages. Equally, acceptance of the spatial and temporal complexity of the sediment delivery system highlights the need for sophisticated distributed models to adequately represent the processes involved. Such models and the simple lumped delivery ratio concept could be viewed as lying at opposing ends of a spectrum of approaches to the sediment delivery problem. Perhaps the greatest need is for the development of approaches in the middle of this spectrum which can combine the operational simplicity of the delivery ratio concept with the physically-based perspective of the mathematical models which because of their data and computational requirements remain essentially a research tool.

THE QUALITY DIMENSION

The sediment delivery ratio concept and, to a large extent, existing sediment yield models provide information on the *magnitude* of the sediment yield from a basin and its relation to gross erosion. Recent interest in the role of sediment in the transport of nutrients and contaminants (e.g., U.S.D.A., 1976; Shear and Watson, 1977; Ongley et al., 1981) emphasises the need for information on the properties of that sediment and more particularly the relationship of these properties to those of the sediment source (e.g., Walling and Peart, 1980). Considerable enrichment of the fine and organic matter fractions is frequently associated with the erosion and conveyance process. These fractions are in turn the most chemically active and play a major role in the transport of nutrients, pesticides and other contaminants. Sediment delivery considerations should therefore also embrace information on the preferential delivery of certain fractions of the eroded sediment and, equally, the preferential loss of other fractions.

A considerable body of information exists on the relationship of the particle size characteristics and organic matter content of soil eroded from erosion plots to that of the original soil (e.g., Table V). This indicates that the clay fraction may be enriched by up to 1.5 times and the organic fraction by more than twice. Analysis of plot data from individual storms has also indicated that enrichment ratios tend to decrease markedly in response to increasing soil loss (e.g., Massey and Jackson, 1952), and Menzel (1980) has proposed a generalised relationship between enrichment ratio,

TABLE V

Plot studies of the relationship between the particle size characteristics and organic matter content of eroded sediment and the parent soil

Study	Location	Enrichment of eroded sediment
Slater and Carleton (1942)	New York, U.S.A.	organic matter enrichment ratio*1 1.12—1.9 (annual mean)
Miller (1977)	Guelph, Ontario, Canada	organic carbon enrichment ratio 1.39—1.42 (average of nine runoff events, 1973—1975)
Lal (1976)	Ibadan, Nigeria	mean erosion ratios*2 of 2.06—2.29; organic carbon enrichment ratio 2.21—2.75 (1972—1974)
Massey and Jackson (1952)	Wisconsin, U.S.A.	average enrichment ratio for organic matter of 2.1 (1949—1951)
Young and Onstad (1978)	Laboratory (Barnes Loam)	clay enrichment ratios 1.47 for rill erosion, 0.79 for interrill erosion

*1 Enrichment ratio = ratio of content of eroded sediment to that of parent soil.
*2 Erosion ratio = ratio (silt + clay)/(gravel + sand) of eroded sediment to (silt + clay)/(gravel + sand) of field soil.

ER, of nitrogen and phosphorus and soil loss, Sed (kg ha^{-1}), for individual events at the field scale which takes the form:

$$\ln(\mathrm{ER}) = 2 - 0.2 \ln(\mathrm{Sed}) \quad (4)$$

The enrichment associated with sediment yield from small plots is essentially the product of selective erosion, but it is difficult to separate the effects of in situ selectivity of the erosion process from preferential deposition during the conveyance or delivery process. This latter effect could be expected to become increasingly important at the basin scale. Less information is available on the relationship between the properties of transported sediment and source material at this scale, but again there is clear evidence of enrichment. Rhoton et al. (1979) report considerable enrichment in total clay and fine clay content of the sediment yield from five small watersheds (0.3—3.2 ha) in Defiance and Wood counties, Ohio, U.S.A., and also significant changes in cation-exchange capacity and clay mineralogy (Table VI). In terms of mineralogy, suspended sediments contained higher concentrations of illite and expandables and lower concentrations of vermiculite and quartz, relative to watershed soils.

Fig. 10 provides a further example of the potential contrasts in the particle size characteristics of suspended sediment and source material (chemically dispersed mineral fraction) by comparing the proportions of clay, silt and

TABLE VI

Comparison of suspended sediment and soil properties for five small drainage basins in Ohio, U.S.A.

Basin	Property													
	total clay (%)		fine clay (%)		CEC (meq/100 g clay)		expandables (%)		vermiculite (%)		illite (%)		quartz (%)	
	soil	sediment	soil	sediment	soil	sediment	soil	sediment	soil	sediment	soil	sediment	soil	sediment
Roselms *1*	52.8	63.8	39.1	51.3	37	40	13	14	20	17	56	60	11	9
Roselms *2*	34.6	55.8	34.3	45.5	39	52	11	16	22	18	44	53	23	13
Blount	27.0	58.2	38.6	50.8	41	43	14	25	31	22	41	41	14	12
Paulding	52.7	70.0	38.1	53.0	41	46	8	19	22	16	53	60	17	5
Hoytville	42.3	53.3	56.6	56.2	46	47	23	21	21	11	45	59	11	9
Mean	$\overline{41.8}$	$\overline{60.2}$	$\overline{41.3}$	$\overline{51.4}$	$\overline{41}$	$\overline{46}$	$\overline{14}$	$\overline{19}$	$\overline{23}$	$\overline{17}$	$\overline{48}$	$\overline{54}$	$\overline{15}$	$\overline{10}$

Based on Rhoton et al. (1979).

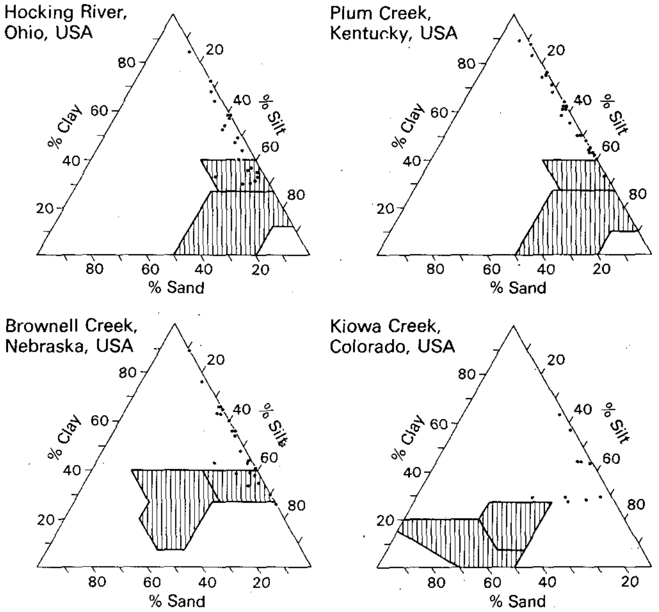

Fig. 10. Comparison of the particle size composition of suspended sediment and soils for four drainage basins in the U.S.A. The textural classes of the dominant soils are denoted by *shaded zones*. (Based on data contained in Mundorff, 1964a, b; Anttila, 1970; Flint, 1972.)

TABLE VII

Characteristics of the four drainage basins cited in Fig. 10

Basin	Area (km^2)	Mean annual sediment yield ($t\ km^{-2}\ yr.^{-1}$)
Hocking River subwatershed *1* (Ohio, U.S.A.)	2.66	467
Plum Creek subwatershed *4* (north-central Kentucky, U.S.A.)	ca. 1.80	1,250
Brownell Creek subwatershed *1* (Nebraska, U.S.A.)	ca. 0.32	ca. 976
Kiowa Creek subwatershed K79 (Colorado, U.S.A.)	ca. 2.56	ca. 200

sand in suspended sediment samples collected from four small basins in the U.S.A. with equivalent information on the soils derived from their textural classification. The data have been obtained from sediment yield studies undertaken by the U.S. Geological Survey. This simple comparison involves a number of limitations related to the comparison of plotted points for the sediment with generalised fields for the soils; to the assumption that the soil data are representative of the actual sediment sources; and to 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. 10 evidences 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.

All four basins illustrated in Fig. 10 exhibit relatively high suspended sediment yields (Table VII) and certain tentative conclusions about the sediment delivery characteristics of the basins may be drawn from the particle-size information. If the effects of selective erosion in increasing the clay content of eroded sediment are ignored, and it is assumed that all clay-sized particles move through the conveyance system without deposition, then what is effectively a 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.:

$$\text{DR}\ (\%) = C_{\text{soil}}\ (\%)/C_{\text{sed}}\ (\%) \qquad (5)$$

Taking a mean clay content for the soils in each catchment, the values of delivery ratio calculated in this way 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 could mean that these values are underestimates, but, equally, the likelihood of clay being deposited within natural aggregates during the conveyance process would mean that the values are overestimates. 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.

Taking account of the lack of precision in the estimates of the clay content of the soils and the other problems associated with the data presented on Fig. 10, the contrasts in delivery ratio values between the catchments may be more apparent than real. However, the differences could reflect contrasts in catchment characteristics. Thus the low values obtained for Kiowa Creek and Brownell Creek could be ascribed to the greater proportion 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 other drainage basin characteristics.

Further information on contrasts in particle-size distribution between source material and sediment yield at the basin outlet can be introduced by considering some results from a study undertaken by the author on two intermediate-sized drainage basins in Devon, Great Britain (Fig. 11). The basin of the Jackmoor Brook (9.8 km^2) is largely developed on relatively soft Permian marls and sandstones and exhibits less marked relief and lower slope angles than the nearby River Dart basin developed on more resistant Carboniferous shales. Mean annual suspended sediment yield from the River

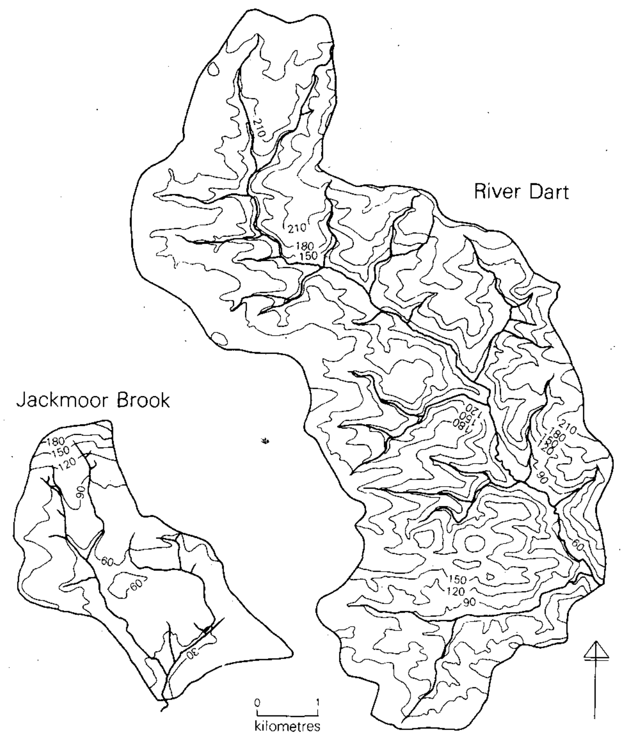

Fig. 11. Relief and drainage of the Jackmoor Brook and River Dart drainage basins, Devon, Great Britain.

Dart is estimated to be $80\,t\,km^{-2}\,yr.^{-1}$, whilst that from the Jackmoor Brook is $\sim 50\,t\,km^{-2}\,yr.^{-1}$. The contrasts in relief between the two basins might be expected to produce contrasts in sediment delivery response and this is supported by an analysis of particle size data.

Fig. 12 presents typical particle size distributions for source material and for suspended sediment yields from the two basins, and enrichment (or depletion) ratios for individual particle size classes have been calculated by considering the ratio of the proportion of a particular size class in the suspended sediment to that in the source material. Enrichment ratios show much greater variation in the case of the Jackmoor Brook and evidence values approaching 1.5 for particles $< 2\,\mu m$ in diameter and nearly 0.5 for particles $> 20\,\mu m$ in diameter. If it is assumed that the influence of selective erosion mechanisms differs little between the basins, the contrasts in enrichment ratios may be ascribed to contrasts in sediment delivery response with its associated preferential deposition of coarse material. The lack of any marked enrichment or depletion in the case of the River Dart may be related to the steeper slopes and channel gradients and therefore a more efficient delivery system.

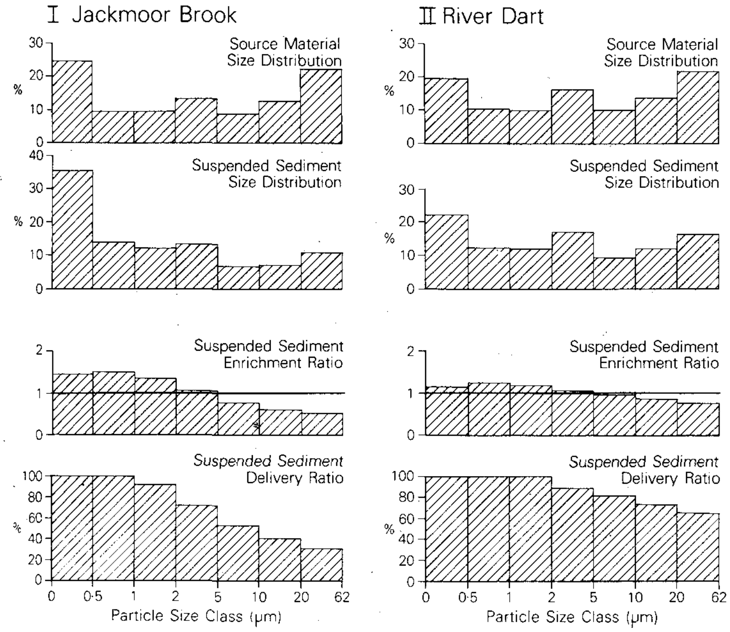

Fig. 12. Relationships between the particle size distributions of suspended sediment and source material for the Jackmoor Brook and River Dart basins.

If it is assumed that the < 0.5-μm fraction of the sediment eroded within the basin is conveyed or delivered to the basin outlet without loss (i.e. 100% delivery ratio), it is again possible to compare the proportions of the other particle-size classes in the suspended sediment with those of source material, and to calculate the loss or deposition necessary to account for the former values. The values of sediment delivery ratio for the Dart and Jackmoor Brook calculated in this manner from the data presented in Fig. 12 are 85% and 70%, respectively. Values for individual particle size classes have also been evaluated (Fig. 12) and these demonstrate the expected inverse relationship between sediment delivery and particle size. The clear contrasts between the values for the Jackmoor Brook and those for the River Dart again emphasise the more efficient delivery system of the Dart Basin.

The particle-size selectivity of the erosion and sediment delivery process within the Dart and Jackmoor Brook basins evident in Fig. 12 is paralleled by similar contrasts between source material and sediment yield for other properties as outlined in Fig. 13. The organic carbon content of suspended sediment is over 60% higher than that of typical source material, and similar enrichment values apply to both nitrogen and total phosphorus because of their close dependence on organic matter content. The lack of any significant contrast between the two basins in the enrichment of these properties suggests that the differences in erosion and sediment delivery dynamics

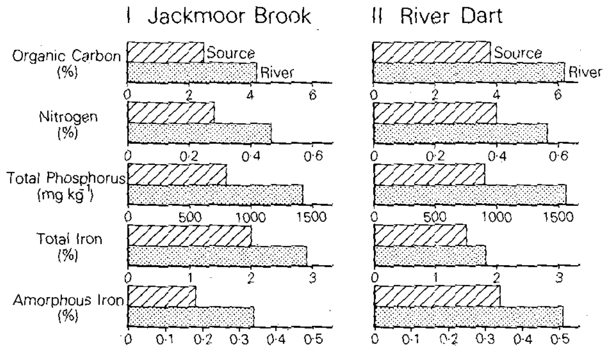

Fig. 13. The enrichment of several sediment properties evident in suspended sediment transported by the Jackmoor Brook and the River Dart.

apparent in Fig. 12 from the particle-size characteristics of source material and sediment are of less importance for the organic fraction. This may be tentatively related to the lower specific gravity of organic material as compared to mineral sediment. However, both measures of iron content show greater enrichment in Jackmoor Brook sediment (45—90%) than in that from the River Dart (20—40%) and would appear to be more closely related to the contrasts in erosion and sediment delivery dynamics outlined above and therefore to the mineral fraction.

The need to consider sediment properties introduces an additional dimension to sediment delivery studies and further complexity to the topic. Thus, for example, it is apparent from the results outlined above that mineral sediment may respond to delivery processes in a different manner to the organic fraction and that different sediment quality parameters will therefore exhibit contrasting conveyance behaviour. Knowledge of the nature and location of major sinks within the delivery system could also be of considerable importance in evaluating environmental hazards associated with certain sediment-associated contaminants. Moreover, attempts to control non-point pollution from agricultural land must involve an understanding of sediment delivery processes so that the application of fertilizers and pesticides likely to move in sediment-associated form can take into account the probability of movement to the stream system.

THE PROSPECT

Appreciation of the wider environmental significance of erosion and sediment delivery processes in the context of material transfer through terrestrial and aquatic ecosystems provides a further need for improved understanding of sediment delivery processes. Although attractive for its simplicity, the sediment delivery ratio concept involves numerous problems and there is a need for a more refined approach. The lack of empirical studies of the processes, pathways, sinks and time constants involved in the delivery process must hamper progress in this direction and detailed field investigations should be encouraged. The need to embrace the quality dimension of sediment delivery may assist such studies by focussing attention on additional facets of the conveyance process and by providing supplementary evidence (e.g., Logan, 1978). Recent developments in distributed modelling of erosion and sediment yield clearly represent a significant advance, but a simpler approach embodying the improved knowledge associated with these developments is required for operational application. The quest for improved understanding and representation of the sediment delivery process must remain an important research need in the field of erosion and sedimentation and of drainage basin studies.

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