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Sediment availability and the prediction of storm-period sediment yields

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ABSTRACT The form of the suspended sediment concentration/discharge relationship or rating curve for a drainage basin reflects the overall pattern of erosion and sediment delivery operating in the upstream area. As such it may prove useful in the development of a realistic model of storm-period sediment yield. Several workers have highlighted the existence of 'exhaustion effects' in the form of the relationship and an attempt has been made to evaluate the evidence for temporal variations in sediment availability. Detailed records of suspended sediment concentration provided by continuous recording turbidity sensors installed in several basins in Devon, UK, have been used to study this feature of basin response. The implications for the development of sediment yield models are discussed.

INTRODUCTION

Reviews of scientific methodology have frequently highlighted the contrasting approaches of deductive and inductive reasoning (e.g. Kuhn, 1962; Popper, 1975). Whilst not wishing to enter the debate concerning their relative merits or precise definition, it would appear useful to consider developments in the modelling and prediction of suspended sediment yields in this context. Because of the general lack of detailed data on suspended sediment transport as a basis for model development, most attempts to construct storm-period sediment yield models have been essentially deductive. The large body of empirical and theoretical information associated with plot studies of soil erosion has been used as a basis for establishing equations and relationships to describe the detachment and movement of soil particles from the slopes of a drainage basin and the parameterization of sediment delivery and conveyance processes has commonly involved the application of theoretical hydraulic concepts. In this way Fleming (1975) was able to develop a conceptual model of the erosion-transport-deposition system within a drainage basin and workers such as Negev (1967), Simons *et al.* (1975), Alonso *et al.* (1978), Leytham & Johanson (1979), Smith (1976), Fleming & Fahmy (1973), Onstad & Bowie (1977) and Williams (1975, 1978) have described numerical models of varying degrees of sophistication capable of predicting storm-period sediment yields at the outlet of a drainage basin. Although many of the concepts employed in representing the erosion processes have been empirically verified at the plot scale, the extension of these concepts to the scale of a heterogeneous drainage basin and the representation of conveyance and delivery processes relies heavily on deductive reasoning.

Examples of the inductive approach are less numerous but could include the work of Guy (1964) and Walling (1974) in establishing the influence of various hydrological and meteorological variables on sediment yields, the conceptualization of sediment yield processes produced by Carson *et al.* (1973), the event-based models described by Rendon-Herrero (1974) and Nippes (1971), and the attempts at dynamic stochastic modelling described by Becchi *et al.* (1980) and Sharma *et al.* (1979). To some extent the paucity of work of this type reflects firstly, the perceived greater scientific and practical merit of the former approach, particularly in terms of model transfer, and, secondly, an associated progression from observation to theory, but it is also a response to the lack of the necessary detailed sediment yield data. Equally, this lack of data has precluded the rigorous testing of many of the deductive models referred to above.

As with many philosophical arguments, it could be suggested that these two apparently contrasting approaches are not mutually exclusive and should be integrated to facilitate further advances. More particularly, there appears to be a need to study existing sediment yield records with a view to isolating significant features of the suspended sediment response and to evaluating the extent to which these are recognized or reflected in available models which are essentially deductive in origin. It must, for example, be accepted that the conveyance and delivery components of many of these models have little or no empirical basis and may not adequately represent the processes actually operating in the drainage basin (cf. Walling, 1982).

THE SUSPENDED SEDIMENT CONCENTRATION/DISCHARGE RELATIONSHIP

The suspended sediment concentration/discharge relationship or rating curve for a drainage basin reflects the overall pattern of erosion and sediment delivery operating in the upstream area and provides a useful and readily accessible starting point for isolating and interpreting salient features of basin sediment response. For example, several workers have isolated a seasonal effect whereby sediment concentrations are higher or lower during a particular season (e.g. Hall, 1967; Guy, 1964; Walling, 1974; Temple & Sundborg, 1972). Hysteresis or exhaustion effects operating during individual events (e.g. Arnborg *et al.*, 1967; Walling, 1974; Wood, 1977; Beschta, 1981) and during a sequence of events (Negev, 1969; Walling, 1974; Wood, 1977; Beschta, 1981) have also been described and attributed to temporal variations in sediment availability. It is, however, significant that little or no explicit attempt has apparently been made to incorporate such seasonal, hysteretic and availability effects within existing numerical models.

The availability of detailed records of suspended sediment concentration provided by continuous turbidity monitoring on several Devon rivers (e.g. Walling, 1977) has allowed the authors to study the pattern of storm-period suspended sediment yield reflected in the sediment concentration/discharge relationship and to isolate significant features of the sediment response which should be incorporated in any attempt at model development. Results obtained from an analysis of 5 years of record (1974-1979) from the River Dart (46.0 km^2) will be presented here.

The form of the sediment concentration/discharge relationship

Traditionally, the suspended sediment concentration/discharge relationship has been plotted on logarithmic coordinates, and various authors have proposed that the slope or exponent of the associated regression line will lie between 1.0 and 2.0. This straight line trend is commonly associated with a considerable degree of scatter related to the seasonal, hysteretic and exhaustion effects referred to above and evidencing the complex controls of suspended sediment generation and delivery. Concentrations recorded for a given level of discharge will frequently range over several orders of magnitude and attempts have been made to reduce this scatter by subdividing the rating relationship according to season or rising and falling stage conditions (e.g. Walling, 1977; Loughran, 1977). Overall, however, the rating relationship will rarely provide the means of obtaining precise estimates of storm-period sediment yields, or a framework for developing an appropriate physically-based model.

It is suggested, however, that the apparent complexity of the sediment concentration/discharge relationship may be reduced by transforming it into a form more directly related to the dynamics of suspended sediment production. More specifically, it is proposed that it is more realistic to view suspended sediment transport in many rivers in terms of a simple mixing model. Suspended sediment generation is essentially limited to storm events and in a situation where sheet or rill erosion is the dominant source, sediment will be transported to the stream by surface runoff. The magnitude of the suspended sediment concentrations recorded in a stream during a storm event would therefore reflect the mixing of sediment-laden storm runoff with the prevailing baseflow. If the latter is high, the storm runoff concentrations could be considerably diluted, and, conversely, little dilution will occur if baseflow levels are low. Similar arguments could apply to situations where channel and gully erosion provide the dominant source of sediment since the sediment will largely be generated by the flow increment associated with storm runoff and will again be diluted by the existing baseflow.

A stormflow concentration/stormflow discharge relationship

Any attempt to apply a simple mixing model of this nature to the records of suspended sediment yield from a drainage basin faces a number of uncertainties in terms of estimating the sediment-generating storm runoff component of the total discharge, and of making allowance for the sediment concentration, albeit relatively low, which may be associated with baseflow. The former introduces the general problem of the exact mechanisms of storm runoff production and the relative importance of surface and subsurface flow (cf. Kirkby, 1978). However, by making a number of assumptions, a mixing model has been applied to the records of suspended sediment

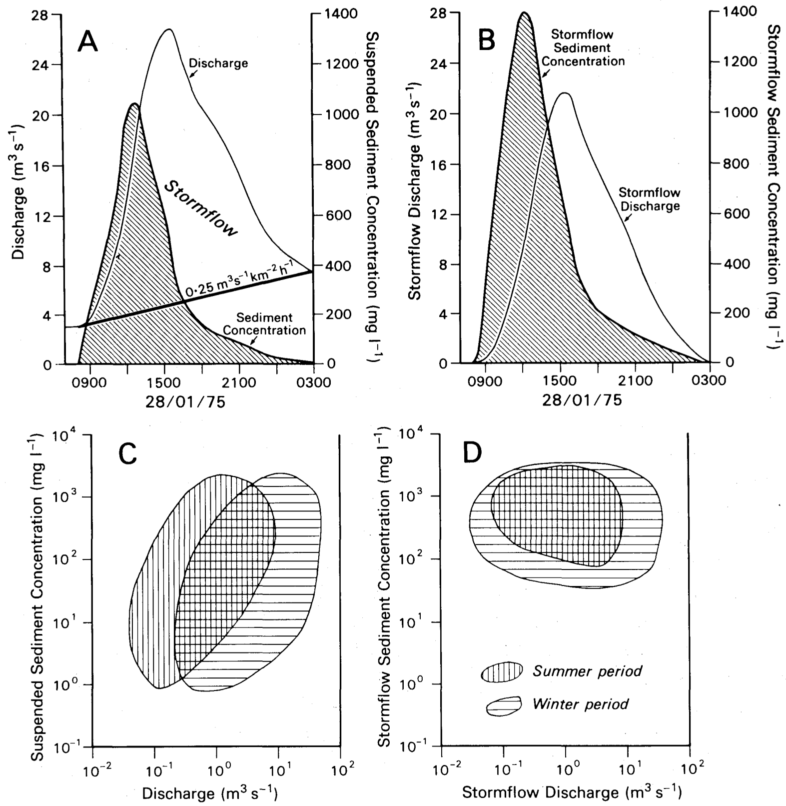

FIG.1 The stormflow suspended sediment concentration/ stormflow discharge relationship for the River Dart, showing the procedure for separating the stormflow discharge component (A), an example of the resultant data on stormflow concentration and discharge for individual events (B) and a comparison of the traditional sediment concentration/discharge relationship (C) with the stormflow relationship (D).

concentration from the River Dart in order to study the form of the stormflow concentration/stormflow discharge relationship. The rationale employed is illustrated in Fig.1A & B. The stormflow component of individual storm runoff events has been separated from the baseflow by constructing a straight line with a upward slope of 0.25 $m^3s^{-1}km^{-2}h^{-1}$, from the beginning of the storm hydrograph to intersect the falling limb. This separation procedure is similar to that advocated by Hibbert & Cunningham (1967), and has the advantage that it can be readily automated by computer processing. However, a steeper line has been employed in order to ensure that the cessation of stormflow generally corresponds with the appearance of low sediment concentrations. Stormflow sediment concentrations (C_s) have been calculated by applying the following simple mixing model:

$$C_s = (C_tQ_t - C_bQ_b)/Q_s \qquad (1)$$

where:
C_t, Q_t = concentration and discharge recorded for total flow;
C_b, Q_b = concentration and discharge associated with baseflow;
Q_s = stormflow discharge.
Baseflow concentrations have been estimated by linear interpolation between the levels occurring in the stream immediately prior to the storm hydrograph and those existing at the time of cessation of stormflow.

Data of the form shown in Fig.1B have been produced for 98 storm events on the River Dart and hourly values of streamflow discharge and stormflow sediment concentration have been used to construct the equivalent rating relationship depicted in Fig.1D. For convenience, the dominant field produced by the data plot rather than the individual data points is shown and a distinction has been made between the values for the summer (April-September) and for the winter (October-March) periods. This stormflow relationship may be compared with the more traditional plot of suspended sediment concentration versus discharge shown in Fig.1C. Two contrasts are immediately apparent. Firstly, there is no evidence of a positive relationship between concentration and discharge in the stormflow plot, and, secondly, the clear distinction between summer and winter data on Fig.1C is absent from Fig.1D. It would appear that the seasonal contrast in sediment production suggested by Fig.1C and noted in many other studies is essentially a dilution effect, with storm sediment being diluted by greater volumes of baseflow during the winter period, and may not represent any fundamental contrast in sediment generation processes.

The stormflow discharges and sediment concentrations used to construct Fig.1D together account for 90% of the total suspended yield of the River Dart during the period of record and it is suggested that this relationship provides a more meaningful basis for any attempt to decipher the processes of sediment production that Fig.1C.

Interpretation of the form of the stormflow sediment concentration/stormflow discharge relationship

The lack of any clear positive relationship between sediment concentration and discharge in Fig.1D implies that it may be equally realistic to think in terms of an essentially constant sediment concentration in stormflow runoff, a conclusion that would find support in the work of others such as Piest *et al.* (1975). Inspection of the relationships traced by individual storm events (Fig.2) suggests that the fields depicted in Fig.1D are composed of a number of hysteretic loops, with an essentially horizontal trend and evidencing considerably lower concentrations on the falling limb of the stormflow hydrograph. This distinction between the rising and falling limb could be interpreted in terms of the reduced detachment or transport of soil particles after the cessation of rainfall (cf. Novotny, 1980) or as the event proceeds (cf. Ellison, 1945; Emmett, 1970). It is also possible to interpret the relative position of the individual loops with respect to their vertical position in terms of sediment availability, and in view of the considerable emphasis placed on availability and exhaustion

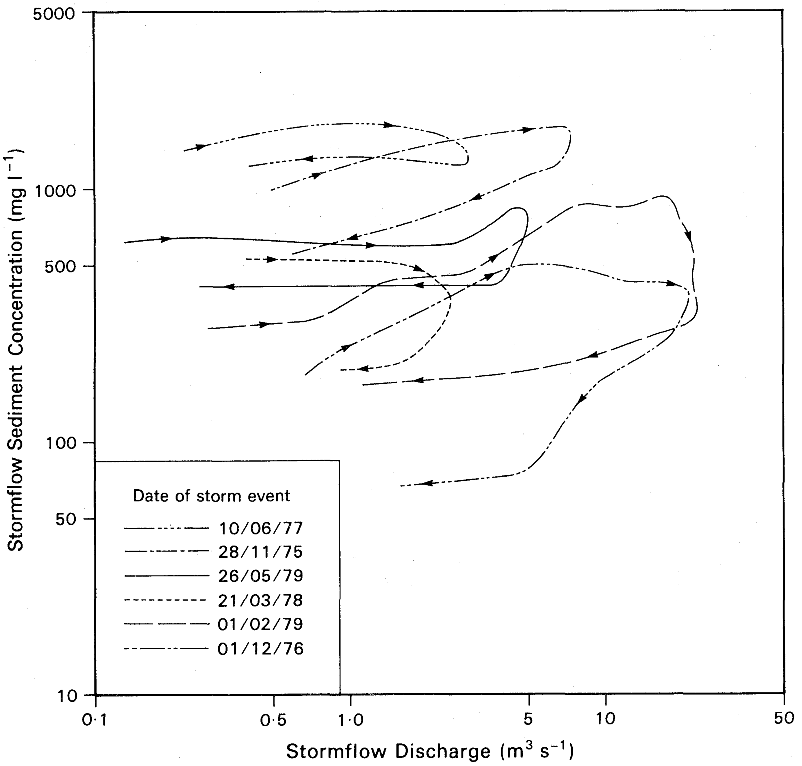

FIG.2 Hysteretic loops showing the trend of the stormflow sediment concentration/discharge relationship for individual events.

considerations in existing interpretations of sediment concentration/ discharge relationships further attention will be given to this phenomenon.

AVAILABILITY CONSIDERATIONS

Fig.3A depicts a sequence of storm runoff events on the River Dart which apparently exhibits an exhaustion of sediment supply over a period of 4 days. The traditional concentration/discharge relationship shown in Fig.3B demonstrates a parallel shift of the rating loops towards lower concentrations between peaks 1 and 2, partial recovery between peaks 2 and 3, but further rightwards shift between peaks 3 and 5. It is, however, clear that a considerable proportion of the apparent exhaustion could be simply a reflection of the increasing importance of baseflow dilution through the sequence. Fig.3C presents the stormflow concentration/discharge relationship for the same events and a somewhat different pattern emerges. This suggests that there is little contrast in sediment availability between peaks 1 and 3, but emphasises the exhaustion of sediment during peaks 2, 4 and 5, although interestingly, peak 5 shows no evidence of excessive exhaustion when compared to peaks 2 and 4.

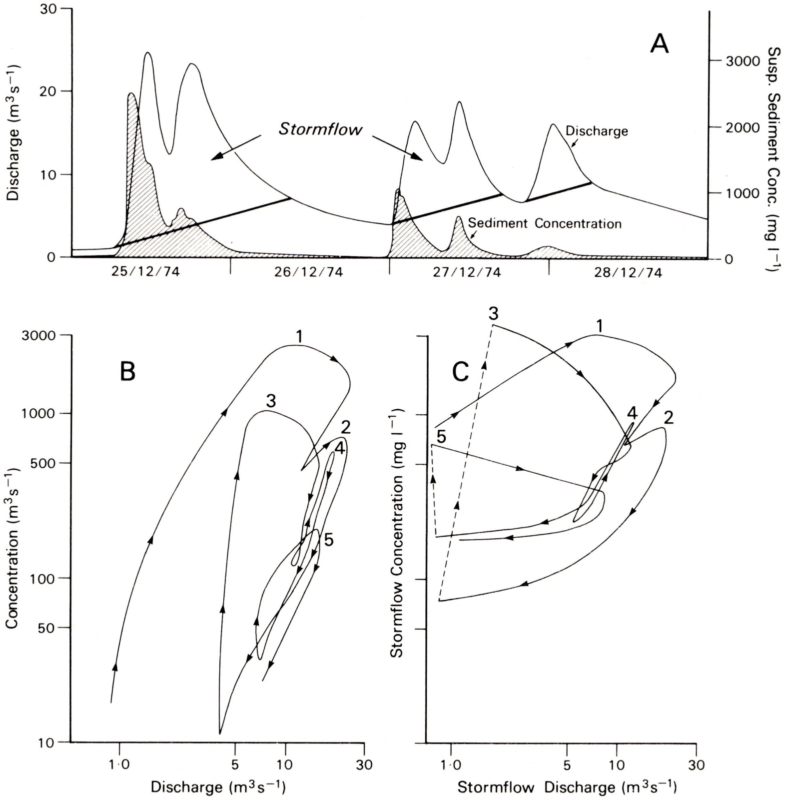

FIG.3 A sequence of storm hydrographs from the River Dart showing evidence of sediment exhaustion (A). The trends of the traditional sediment concentration/ discharge relationship and the stormflow relationship for the sequence are compared in B and C.

Fig.3C suggests that a reduction of sediment availability may occur during a compound event. This could be related to progressive wetting of the soil, armouring, or the exhaustion of readily available material and therefore lends some support to the concept of a vertical shift in the position of the rating loop according to sediment availability. The data presented in Fig.3C, however, provide little evidence of any reduction in sediment availability when comparing peak 1 with peak 3.

In order to consider in more detail the evidence for interstorm variations in sediment availability in response to variable "preparation" or "recovery" times, Fig.4 presents a relationship between peak stormflow concentration and peak stormflow discharge for the 98 discrete stormflow events during the period of record, on which the points have been differentiated according to recovery period. This is defined as the length of time elapsed since a preceding storm and during which physical and biological processes operate to increase the store of available sediment (e.g. Imeson, 1977). The relationship between peak concentration and discharge could be expected to exhibit a considerable degree of scatter in response to the influence of storm rainfall characteristics, changes in land use and other controls on sediment generation, but a consistent pattern emerges. It is again possible to suggest that stormflow events of varying magnitude are characterized by an effectively constant peak sediment concentration, although the level of that concentration varies according to the length of the preceding recovery period and therefore reflects sediment availability. Thus storms which occur at least 30 days after a preceding event are characterized by peak concentrations of about 2000 mg l^{-1}, whereas this value reduces to about 400 mg l^{-1} for events occurring less than 7 days after a preceding event.

In addition, the data for the second peaks of multi-peaked stormflow events have also been plotted on Fig.4. In this case, the recovery period is zero, and, as would be expected, the points generally fall below the field of the main data set. Although it has been suggested that events with a given recovery period will

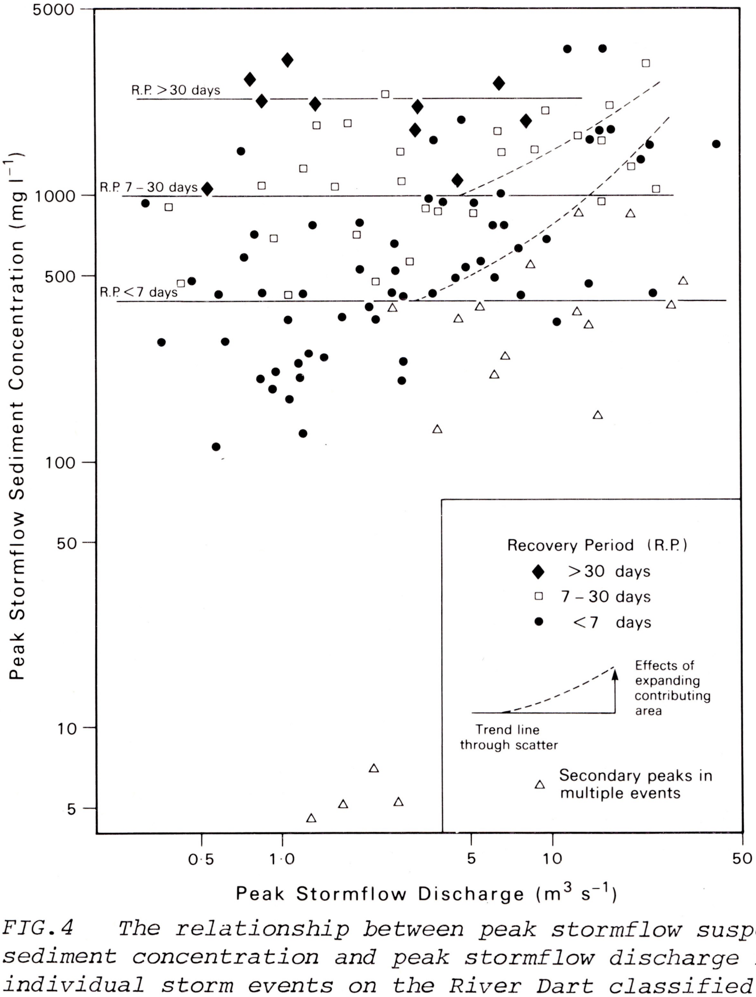

FIG.4 The relationship between peak stormflow suspended sediment concentration and peak stormflow discharge for individual storm events on the River Dart classified according to recovery period.

exhibit a constant peak sediment concentration, irrespective of the magnitude of the peak stormflow discharge, there is some evidence in Fig.4 of a tendency for increased concentrations at high peak discharges. This phenomenon is not unexpected and may be linked to the variable contributing area concept of storm runoff production. With high peak discharges there is an increased probability of the contributing area expanding into zones of the basin with a greater recovery period and therefore greater sediment availability. Such events could therefore exhibit a higher peak concentration than might be expected on the basis of the recovery period calculated from timing in relation to preceding storms. The greatest increase in peak concentration will occur when a high magnitude event follows a storm with a relatively low peak discharge, and when the zone into which the contributing area expands has not produced storm runoff for a considerable period of time. This increase will be less pronounced for events with relatively long recovery periods since sediment availability will be more uniform throughout the catchment.

SOME IMPLICATIONS

The results presented above relate specifically to a humid temperate environment with relatively low annual suspended sediment yields (ca. 70 $t\,km^{-2}year^{-1}$). These conditions differ from those for which many sediment yield models have been developed. Nevertheless, it is suggested that a number of important features of the sediment response can be isolated from analysis of the stormflow sediment concentration/discharge relationship and that any attempt to develop a meaningful sediment yield model should:

(a) Acknowledge the overriding importance of the surface runoff component of total discharge in sediment generation and attempt to incorporate a realistic representation of storm runoff production. There may be scope for treating sediment concentration as essentially constant over a range of stormflow discharge.

(b) Attempt to reproduce the typical hysteretic behaviour of sediment concentration during individual events by considering potential contrasts in detachment and transport capacities during the rising and falling limbs of the hydrograph.

(c) Incorporate a time-variant measure of sediment availability to take account of exhaustion effects operating both within multiple events and during a sequence of events. This will involve parameterization of the recovery process.

(d) Recognize that a realistic representation of sediment availability, exhaustion and recovery will necessitate consideration of the partial/variable source area concept of storm runoff production. With the exception of the work of Wall *et al.* (1980) there has been little attempt to integrate this concept of runoff production into sediment yield models.

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