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Channel sediment behaviour as a basis for modelling delivery processes

W. A. RIEGER, L. J. OLIVE & C. J. GIPPEL
Department of Geography and Oceanography, Australian Defence Force Academy, University of New South Wales, Campbell, ACT, Australia 2600

Abstract The response of sediment concentration to discharge during storm events is used to differentiate possible factors which may be contributing to the delivery of sediment from the slopes to the channel. The behaviour of the variable source area model for surface runoff may be responsible for the temporal and spatial variations in sediment response. The wetted behaviour of clay particles and the effects of pH on sediment movement may explain sediment depletion in storm events.

Comportement des sédiments dans les chenaux des rivières utilisé comme base pour la mise en modèle des processus de fourniture de sédiments à ces cours d'eau

Résumé L'effet sur la concentration en transports solides des apports en sédiments qui se produisent lors d'une averse orageuse est utilisé pour déterminer les facteurs potentiels qui contribuent au apports en sédiments des pentes vers les cours d'eau. Le ruisellement superficiel des différents types de sols, variable selon les régions, peut être à l'origine de certaines variations qui se produisent, dans le temps comme dans l'espace, dans les apports en sédiments. La réaction des particules de sol argileux une fois humidifiées et les effets du pH sur les mouvements de sédiments, peuvent expliquer la décroissance de transport solide au cours des averses.

INTRODUCTION

Past research on erosion within river basins can be divided into two broad categories. In the first category, researchers have concentrated on the actual processes operating on the basin slopes and examined factors which might possibly control these processes (Kirkby, 1980). The notable aspect of this type of research is that it is based on the sub-basin level, where individual slopes or small plots are the basis for determining the behaviour of the variables governing erosion processes. In the second category, researchers have concentrated on sediment yield, or the eroded slope material which is removed from a basin via the stream channel. In this case, sediment delivery is the key factor and can be looked upon as the resultant of all the erosional processes operating on the basin slopes (Walling, 1984).

Thus the two approaches differ according to the scale, or level, at which slope erosion processes are operating. Slope and plot research involve micro-level processes, while sediment yield research involves a basin level process in the form of the sediment delivery mechanism which is the aggregate of the micro-erosional processes operating on the slopes. With these scales forming the basis for analysis, it is not surprising that different rates of erosion are cited in the literature. Small scale studies have indicated large sediment loads from parts of the slopes and at the same time, total sediment yields at the basin scale are small in comparison.

The two approaches also differ in the area of modelling erosion processes. By far, the bulk of model development has taken place in the context of micro-scale processes (Kirkby, 1980). In comparison, researchers involved with basin-scale processes have, for the most part, been content with estimating sediment yields from empirical data and made few attempts at modelling. One of the possible exceptions is Moore (1984).

This paper is an attempt to isolate some factors which may form the basis for model development in the area of sediment delivery. The time based data used to generate yield estimates contain important information concerning the behaviour of the delivery processes and thus can form the basis for modelling. In effect, the approach used here works backwards from the stream channel to the slopes. The storm event behaviour of sediment within the channel is first examined, then this behaviour forms the framework for differentiating which factors are possibly involved in the delivery process.

CHANNEL SEDIMENT BEHAVIOUR

The nature of sediment yield data

To obtain a measure of sediment yield from a particular basin, measures of discharge Q and sediment concentration C are required. The yield for a given time interval is simply:

$$\int_0^t Q(t)\ C(t)\mathrm{d}t \tag{1}$$

The important aspect concerning yield is that it is time based and the phase variations in Q and C are taken into consideration in its calculation.

In most field studies of sediment yield, time based observations of discharge are relatively easy to obtain and can be generated from stage data. However, time based observations of sediment concentration are another matter and, at present, there is no single method which will easily measure total sediment concentration in a stream. One approach used by researchers to overcome (or avoid) this difficulty, is to measure suspended sediment concentration S. Where soil types in the basin are dominated by fines, the use of S can be rationalized and time based values of S can be obtained using automatic water samplers or turbidity monitors. S is then substituted for C in equation (1) and yield is in terms of suspended sediment.

Suspended sediment response

The data used in yield analysis can also form the basis for examination of suspended sediment responses, or the relationship between S and some form of Q during storm events. As the sediment delivery process is storm event based, the behaviour of sediment response may give some indication of the nature of the delivery process.

In the past, most researchers have used relatively simple, linear models to relate suspended sediment to discharge. These models take the general form of:

$$S = a\,Q^{b} \tag{2}$$

where a and b are regression coefficients.

The main shortcoming of equation (2) is that it does not consider the inherent temporal variation in concentration and discharge during a storm event. As such, phase is ignored and it is assumed that S responds instantaneously to Q. Response studies using this type of framework shed little light on the nature of the delivery process, except at the trivial level.

A more realistic approach to sediment response is provided by hysteresis plots. The plots are formed by generating a scatter diagram, then joining adjacent points in time by straight lines. They have the advantage of indicating both the spread of the observations and the temporal variations between S and Q during a storm event. Usually, the high frequency components in the raw data make the plots difficult to interpret, but smoothing of the two series before plot generation, overcomes this problem (Olive & Rieger, 1985). Where smoothing is used, the resulting hysteresis plots given an indication of the broad behaviour of sediment response (see Fig. 1).

Response patterns

The authors examined response patterns in five small, adjacent basins in the southeast of New South Wales (Olive & Rieger, 1985). Yellow duplex soils, with high clay content, dominate the lower slopes of the basins. Suspended sediment concentration was therefore an appropriate variable to use in the response studies. The actual sediment responses were based on hysteresis plots for hourly observations during storm events in the basins over a two-year period.

The storm event sediment responses fell into seven distinct types, as shown in Fig. 1, and have the following implications concerning the sediment delivery process:

(a) There was spatial variation in response for individual storm events, with the type of sediment response varying between basins.
(b) Individual basins showed temporal variation in response and had up to five different response types in the two-year study period.
(c) The unrecognisable response type dominated the study period and

occurred in 40% of the storm events analysed.

(d) Response type was unrelated to pre-storm soil moisture conditions or to a single storm characteristic other than at the obvious level where multiple-rise responses were related to large storms and single-rise responses were related to moderate storms.

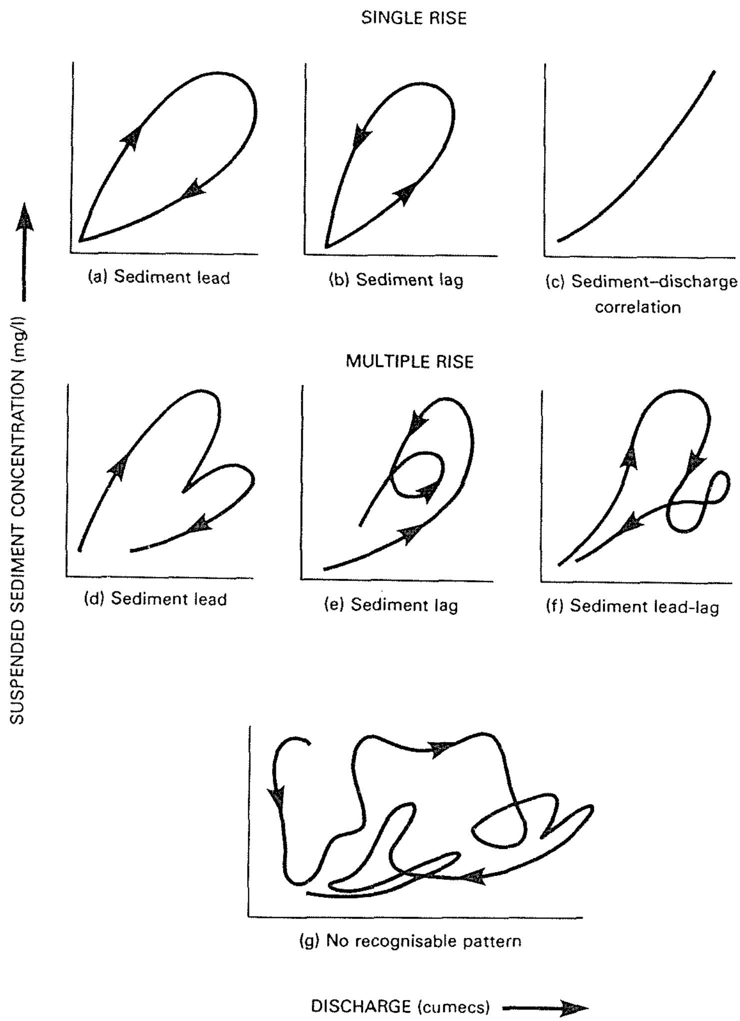

Fig. 1 Storm sediment response types.

(e) Sediment depletion is evident in most responses, with high concentrations at the beginning of a storm and concentration decreasing throughout the storm.

Sediment response was also examined in the context of stormflow (quickflow) which has been postulated as a possible delivery mechanism. Stormflow was obtained by baseflow separation using a low pass recursive filter (Lyne, 1979) on the original discharge series. The sediment response patterns showed the same characteristics as before, the only difference being a reduction of the unrecognizable patterns from 40% to 20% of the responses analysed (Rieger & Olive, 1984).

MODELLING SEDIMENT DELIVERY

Sediment responses provide both a start and end point for modelling the sediment delivery process. They act as a starting point in that they provide information concerning the possible nature of the delivery process, as shown above. They also act as an end point since any model must replicate the responses know to exist in basins. Given the complexity of response type and the spatial-temporal variation of response, modelling the delivery process would, at first, seem a daunting task. However, some of this complexity is reduced if the delivery process is couched in terms of discharge source areas and sediment factors. Considered together, they begin to supply some explanation of the five observations discussed in the previous section.

Discharge source areas

Runoff has been considered to be the major mechanism for sediment delivery from the slopes to the channel (Moore, 1984). While runoff can take various forms and paths on a basin slope, the most important in terms of sediment transport capacity are surface runoff and rapid preferential subsurface flow. Natural piping can double the contributing area (Jones, 1987), but pipeflow is generally characterized by low to very low sediment concentration (Hadley *et al.*, 1985). The assumed importance of macropore flow to storm runoff generation in responsive, forested basins (e.g. Mosley, 1979) has recently been challenged by Pearce *et al.* (1986). Their isotope study found storm runoff to be dominated by stored water generated by near-stream saturation overland flow.

Direct measurements of sediment transport via preferential subsurface pathways is virtually impossible due to the difficulty in eliminating unnatural boundary conditions. However, particulate transport by this mechanism is theoretically possible (White, 1985; McDowell-Boyer *et al.*, 1986) and should not be entirely discounted. Given these problems of measurement, the geomorphologist has to be content with surface runoff as the major mechanism for sediment delivery.

The most realistic approach to surface runoff is based on the variable source area model (Dunne, 1978). Basically, this model has surface runoff generated from saturated areas within a basin. The major factors contributing to flow from these saturated areas are direct precipitation falling on them and return flow, which is subsurface flow re-emerging at the soil surface.

The importance of this model to sediment delivery is that it explains the spatial and temporal variations in surface runoff. During a storm event, the saturated areas tend to expand outwards from the stream channel, depending on the nature of precipitation inputs. Temporal variations in rainfall intensity will cause expansion or contraction of the source areas for overland flow. The actual spatial variations in source areas can be mapped using a technique developed by O'Loughlin (1981, 1986). This technique uses topographic features and soil properties of a basin and defines the saturated areas for varying rainfall intensities.

The variable source area model, then, gives a key to some of the behaviour shown in sediment response. As the actual location of saturated areas within a basin is a function of topography and soil properties, a single storm can be expected to result in differing patterns of saturated areas for adjacent basins. Also, the temporal variations in rainfall intensity during a storm event will cause variations in the size and distribution of source areas for surface runoff.

Sediment supply factors

In most basins, there is an ample supply of fine material on the slopes which is available for transport to the stream channel. Also, during a storm event, there is sufficient energy for the transport of this material via overland flow from saturated areas. Yet, the sediment response functions indicate sediment depletion during storm events. There are high concentrations at the beginning of storms and successive peaks in the sedigraph have lower concentrations even though successive discharge peaks are of similar magnitude.

This contradiction can possible be explained by the behaviour of fine clay particles under differing conditions of wetting. When a soil is in a non-saturated state, little energy is required to mobilise and transport the fine material. However, when in a saturated state, molecular attraction between clay particles greatly increases and larger energies are needed for their mobilization.

Thus, during the initial part of a storm event, the saturated areas of a basin may be small, but most of the fine material within the saturated area is delivered to the channel. As the saturated areas expand, little of the fines are available for transport due to the wetted condition of the soil. In effect, sediment availability is not a function of the size of the saturated areas, but rather of the perimeter of the saturated areas, where soil moisture and energy conditions allow mobilization of the fine material.

It is surprising that most geomorphologists and hydrologists have sought to explain sediment entrainment in terms of physical processes, when the role of chemical processes in fine particle transport is well known to soil scientists.

Higher temperatures are associated with lower stability in cohesive soils due to the disruption of physico-chemical interparticle bonds (Kelly &

Gularte, 1981). Water temperature is a possible index of this effect (Irvine & Drake, 1987). High concentrations of fulvic acid are common in forested environments. When complexed with organic acid, clay particles have increased mobility (Melnikov & Kovenya, 1974; Tan, 1982). Clay dispersion is also affected by pH and the electrolyte level (Tan, 1982). The authors have observed that organic solutes become progressively diluted during storm event runoff, after initial high concentrations following rainfall (Gippel, 1987). This, no doubt, reflects changing soil water chemistry, which is possibly controlling sediment availability.

CONCLUSIONS

The modelling of sediment delivery processes has, for the most part, been ignored by researchers. A possible reason is that the delivery process involves a large scale, basin process which is the aggregate of a complex interaction of physical and chemical variables at the micro scale level. As such, it is difficult for any researcher to determine a suitable starting context in which to begin modelling. This paper has proposed the behaviour of sediment response within a stream channel as a possible starting point for the modelling process. Storm event sediment response patterns can be easily generated from existing data used to determine sediment yield and provide some important leads as to the nature of the delivery process. Analysis of the patterns showed both a spatial variation in response and sediment depletion throughout a storm. These could be explained by source areas of surface runoff within basins and the related effect of soil moisture conditions and pH of the transport medium on particle mobility. While the explanation of these factors was necessarily brief, it did indicate how channel behaviour can form the basis for determining specific areas of a basin which might be important to modelling the delivery process.

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