Sediment yield from disturbed earth systems

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ABSTRACT

Changes of sediment-yield rates through time reflect evolutionary changes within a landscape. When a drainage basin is perturbed significantly by base-level, climatic, or tectonic change, sediment yields increase dramatically, but with no further disturbance they decline rapidly. These sediment-yield changes have been documented at all scales, from small experimental studies, to incised channels, to the Colorado River basin, and to the Himalaya Mountains. Thus, the shape of the sediment-yield curve can be used to estimate future sediment yields and to interpret past tectonic events.

INTRODUCTION

Change at Earth's surface occurs at all scales, from minute, when a small rill forms on a road cut or hillslope, to huge, when a plateau or mountain range is uplifted and subjected to erosional processes. When there is base-level lowering or tectonic uplift, landforms are modified by erosion, a process that follows an evolutionary development controlled by the nature of the materials affected and the energy of the system. For example, Graf (1977) demonstrated that the formation of an incised channel (gully, arroyo) follows a rate law in the form of a negative exponential function similar to that used to describe radioactive decay and chemical reactions. That is, the rate of growth of the channel decreases with time as it extends headward into smaller areas that provide less and less runoff. This was documented experimentally for the headward growth of a small drainage network (Fig. 1) in a 9.1-m-wide, 15.2-m-long rainfall-erosion facility in which sediment was placed and to which precipitation could be applied.

The type of change described above can be determined in the field only for relatively small, rapidly adjusting landforms. For example, incised channels such as gullies and arroyos follow a pattern of adjustment as illustrated in Figure 2. The quantity of sediment delivered from such an incising and adjusting channel changes markedly, and it is possible to track these changes by using sediment-yield data (Fig. 3). Sediment yield is the quantity of sediment delivered per unit time from the incising channel or expand-

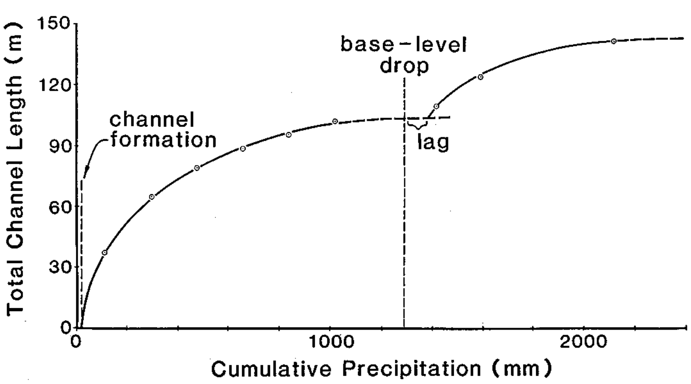


Figure 1. Increase of channel length with time as precipitation was applied to surface of experimental drainage basin and as base level was lowered. Time is expressed as total quantity of precipitation applied (from McLane, 1978; Schumm et al., 1987).

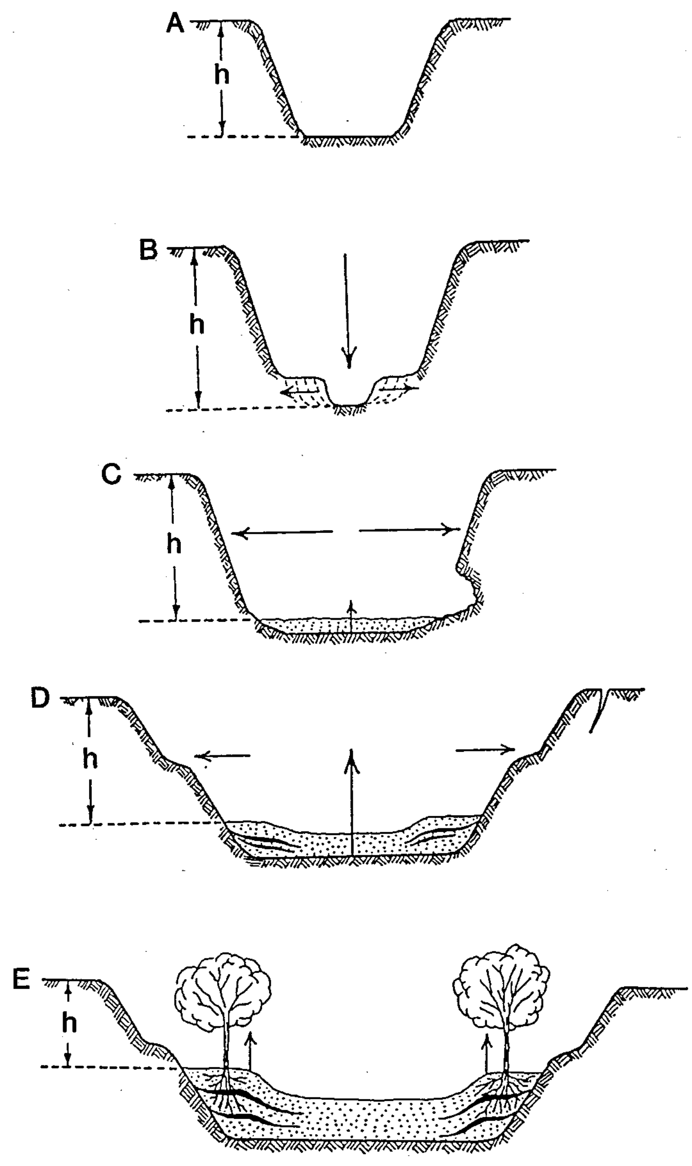


Figure 2. Evolution of incised channel from initial incision (A, B) and widening (C, D) to aggradation (D, E) and eventual relative stability (after Schumm et al., 1984); h is bank height.

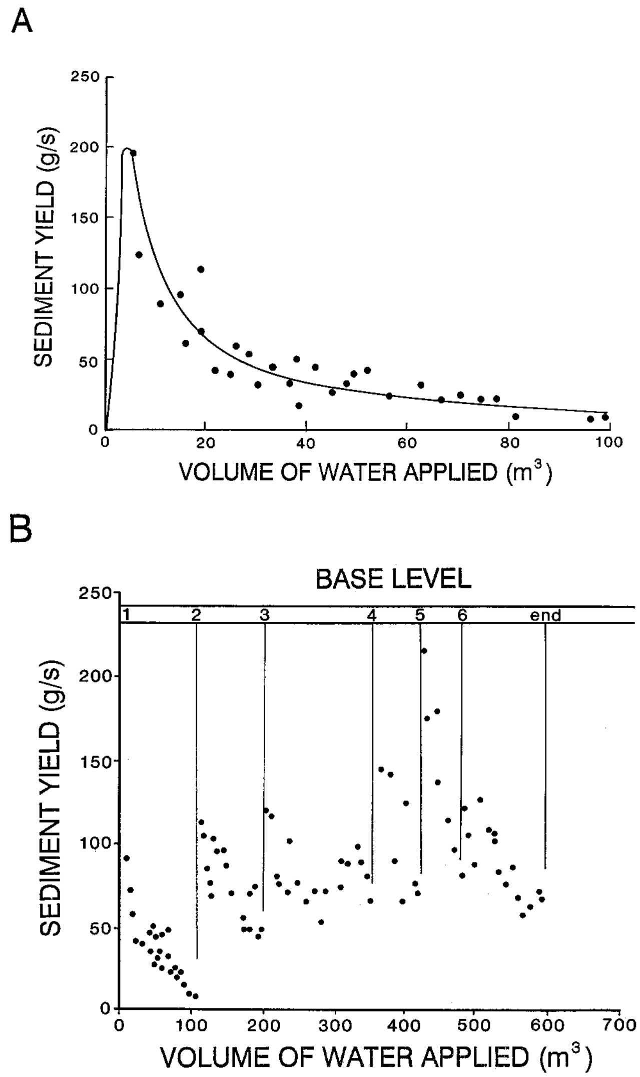
ing drainage network. In summary, a disturbed fluvial landform will evolve and produce sediment in a predictable manner, and it will eventually achieve a new steady-state condition following either a natural or human-induced perturbation.

Our objective is to demonstrate that the shape of the sediment-yield curve resulting from a disturbance will be similar for experimental studies, for incised channels in the southeastern United States and the upper Colorado River basin, and for mountain ranges. If so, predictions of future sediment yields and interpretations of past tectonic events can be made based upon the shape of the curve.

EXPERIMENTS

To investigate drainage network development, artificial precipitation was applied to sediment in the rainfall-erosion facility (Schumm et al., 1987). Sediment samples were collected at the outlet, during the initial development of the drainage network and during its modification (Fig. 3A). During one experiment, base level was lowered six times (Fig. 3B) by removing boards at the outlet of the rainfall-erosion facility. This caused channel incision and expansion of the drainage network (Fig. 1). The result of all of the experiments was a sediment-yield curve that was characterized by a rapid rise to a peak and then a relatively rapid fall to a new but higher level of sediment yield. Even in the controlled experiments (no change of precipitation intensity or duration), the variability of sediment yield was large. Nevertheless, similar sediment-yield patterns emerged during experimental studies of alluvial fan growth (Schumm et al., 1987, p. 70–71) and incised channel behavior (Begin et al., 1980; Schumm et al., 1987, p. 209), but in these cases the decrease was logarithmic. A more careful examination of the temporal variability showed a pattern of secondary peaks following the rapid decrease of sediment yield (Fig. 3C). These highs and lows reflect storage and flushing of sediment from the widening valleys (Fig. 2), as the morphologically complex drainage basin adjusted to a lower base level. This complex response of a drainage basin is characteristic of a relatively rapidly adjusting fluvial system of relatively high relief (Schumm, 1977). For example, during the experiments, the complex response was not obvious when relief was 0.3 m (Fig. 3A), but it was obvious when relief was 0.78 m (Fig. 3C).

The very rapid increase of sediment yield (Fig. 3) in response to base-level lowering is a result of taking sediment samples at the outlet of the rainfall-erosion facility, which was at the point of base-level lowering. If the sediment samples had been taken at some distance downstream from this location, the increase of sediment yield would have been less rapid, and the peak would have been broader, as the sediment was transported downstream and the initial pulse was attenuated. Therefore, the experiments produced results (Fig. 3) that were more analogous to the effects of uplift along a fault rather than sea-level lowering.



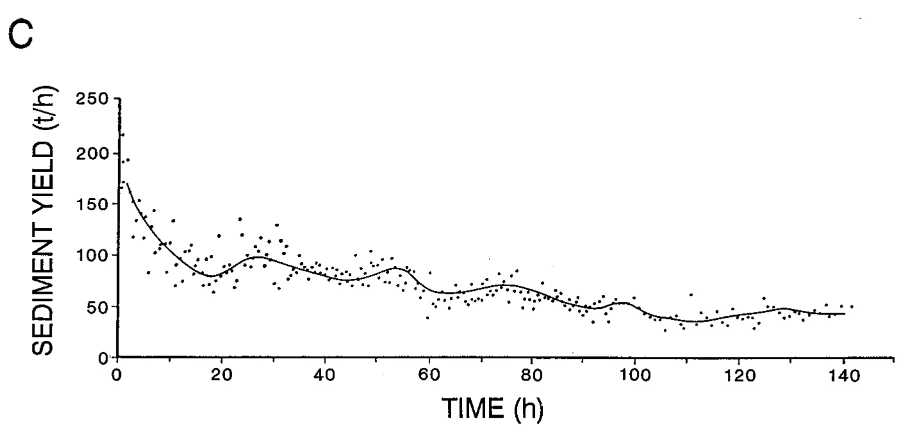


Figure 3. Sediment yield following base-level lowering. A: Changes of sediment yield with time following base-level lowering of 0.3 m at time 0. Time is expressed as volume of water applied to experimental soil surface; total time of application was 1 h (from Parker, 1977; Schumm et al., 1987). B: Sediment yield variations as result of six lowerings of base level (total lowering 0.94 m) showing rapid decrease from initial peak and increased variability with increasing relief in each case (from Parker, 1977; Schumm et al., 1987). Time is expressed as total volume of precipitation applied; total time of application was 78.5 h. C: Sediment yield variations following base-level lowering of 0.25 m at time 0, during 140 h of precipitation application to surface of rainfall-runoff facility. Total relief was 0.78 m; each point represents sediment sample, and moving mean line shows secondary peaks of about 25, 55, 75, and 100 h, as stored sediment is flushed from drainage network (from Parker, 1977; Schumm et al., 1987).

Incised Channels

When rivers are straightened and steepened (channelized) to reduce flooding, they respond as if base level were lowered. They incise, widen, and achieve a new condition of relative stability in about 100 yr in the southwestern United States and in about 40 yr in the humid southeastern United States (Schumm et al., 1984). Simon (1989) obtained data on the sediment loads transported through such channels in Tennessee (Fig. 4A). The curve is similar to those obtained during the experimental studies (Fig. 3), and it reflects the channel changes illustrated in Figure 2, plus an apparent flushing of stored sediment at stage E as in Figure 3C.

Field investigations in the upper Colorado River basin have revealed that the large arroyos formed by incision of valley-floor alluvium in the latter part of the nineteenth century (Cooke and Reeves, 1976) are at present storing sediment in newly developed flood plains (Gellis et al., 1991). These incised channels are also behaving as illustrated in Figure 2. At the later stages of adjustment, they are eroding less sediment and storing large amounts of sediment. As a result, sediment loads at the Grand Canyon gaging station have decreased, during the period of record, prior to closure of Glen Canyon Dam and other upstream dams in 1963 (Fig. 4B). In addition, sediment deposition in Lake Powell between 1963 and 1986 is only 43% of that estimated prior to dam construction (Ferrari, 1988), which indicates that the channel adjustment process is occurring throughout the upper Colorado River basin, in a manner similar to that in the runoff-erosion facility and in incised channels (Fig. 2).

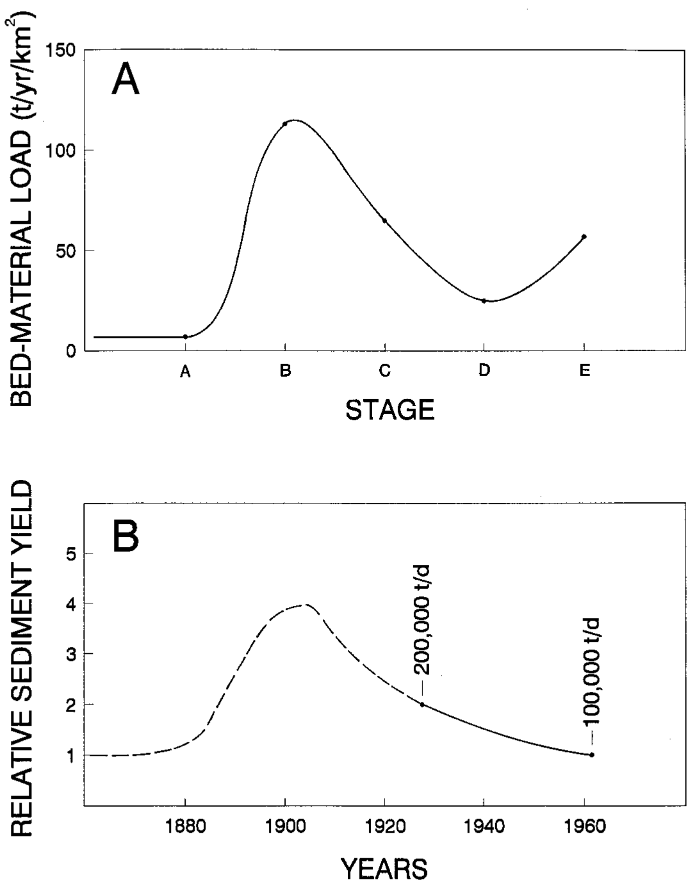


Figure 4. Sediment loads following channel incision. A: Bed-material load transported by incised Tennessee streams for each stage of incised-channel evolution (Fig. 2) (from Simon, 1989). B: Hypothetical (dashed line) and measured (solid line) sediment volumes transported through Grand Canyon. Arroyo incision commenced in 1880s. Daily sediment-load data were collected starting in 1930. For annual means from 1930 to 1963, see Gellis et al. (1991). In 1963, upstream dams trapped much of sediment and post-1963 record was not used.

Mountains

Rea (1992) examined the data from every Indian Ocean Deep Sea Drilling Project or Ocean Drilling Program drill site that contained a useful record of Himalaya-derived sediment deposition. The biostratigraphy from each of the 11 sites was recast onto a common geologic time scale, and linear sedimentation rates (LSR, cm/ka) were determined for every biostratigraphic zone. These LSR values were then multiplied by the dry bulk density (DBD, g/cm^3) and the weight percent of the mineral land-derived sediment component to give the mass accumulation rate (MAR, g[cm$^2 \cdot$ ka]$^{-1}$) of terrigenous sediment in the northern Indian Ocean, which in turn is an indication of mean sediment yield or flux.

In order to determine if there is a regional deposition-rate pattern, the MAR data were interpolated to a standardized time interval, normalized, and stacked and averaged. The time intervals selected are 0.5 m.y. for sediment younger than 15 Ma and 1.0 m.y. for older sediments. This averaging procedure serves to reduce noise and enhance signal by a factor equal to the square root of the number of data sets averaged, in this case between 8 and 11. Details of the stratigraphy and rate calculations were given by Rea (1992).

Results are shown in Figure 5. Little Himalayan material entered the Indian Ocean before about 12 m.y. ago and there are two

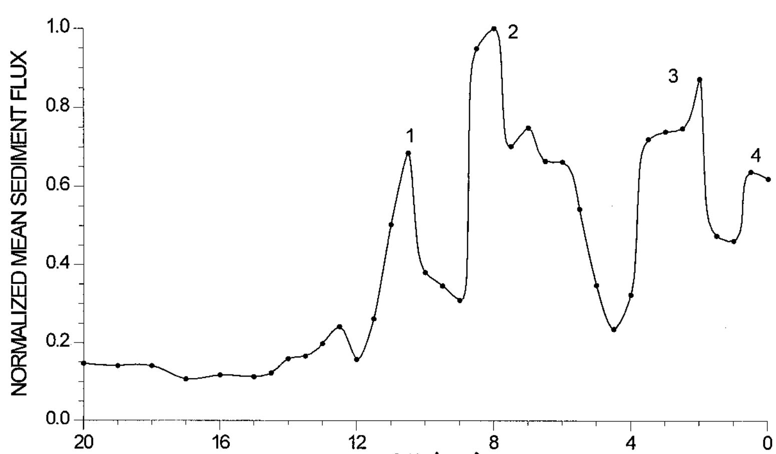


Figure 5. Normalized average sediment flux from Himalayas to northern Indian Ocean (from Rea, 1992). Rea described sedimentation as mass accumulation rate, which is quantification of true mass per unit area and unit time. It is product of linear sedimentation rate and bulk density. Mass accumulation rate was normalized such that highest value at any site has relative value of one. Peaks 1–4 are explained in text.

main episodes of terrigenous sediment flux, between 9 and 6 Ma and 4 and 2 Ma. Himalayan sediment flux data show little or no correspondence with the temporal variations in either the $\delta^{18}O$ global record of ice volume and temperature or to estimations of past sea level. Thus, these data have been interpreted as a record of the uplift and physical erosion of the Himalayas (Rea, 1992).

The first two major peaks (~10.5 and 8 Ma) resemble closely the curves of Figures 3 and 4. The third peak at ~2–4 m.y. is less similar to the experimental results, but the rapid rise of the third peak and the fourth minor peak is an indication of a significant change in this major Earth system. The right side of peak 2 shows variability characteristics of complex response, and the overall rising trend of the plot resembles the effect of the multiple base-level lowering shown in Figure 3B.

DISCUSSION

If sediment-yield-rate and sediment-deposition-rate curves always resemble the experimental, field, and marine results, then prediction for the near future and interpretation of past events is possible. That is, sediment loads in the Colorado River should continue to decline, but at a slower rate (Fig. 4B), assuming no major climatic or human influences. This ability to predict sediment yields should be of considerable value to land managers, conservationists, and reservoir engineers.

By using the shape of the curve of Figure 5, one can propose the following sequence of tectonic events for the Himalayas: (1) at ~14 Ma, slow uplift began and then increased rapidly to form the first peak; (2) between 10.5 and 9 Ma, the decrease indicates no uplift or only minor uplift; (3) between 9 and 8 Ma, substantial uplift produced the second maximum; (4) between 8 and 7.5 Ma, the decrease suggests no uplift; (5) between 7.5 and ~6 Ma, the slope of the curve suggests slow uplift or normal sediment yield variability (Fig. 5); (6) between 6 and 4.5 Ma, no uplift; (7) between 4.5 and 2 Ma, uplift to form peak 3; between 2 and 1 Ma, no uplift; and (9) uplift after 1 Ma to form peak 4.

Additional data are required to support the above scheme, but at least Figure 5 supports the conclusion that uplift of the Himalayas was and is episodic (Copeland and Harrison, 1990). For example, Amano and Taira (1992) recognized two pulses of uplift, the first from 7.5 to 11 Ma and the most recent after 1.0 Ma. These pulses coincide with the first two peaks and the final peak of Figure 5.

There is no question that climatic and sea-level changes can affect sediment delivery to depositional sites, but the effect of sea-level change extends only a relatively short distance upvalley (Schumm, 1993), and a given climate change can increase, decrease, or maintain sediment yields (Schumm, 1965). It is possible to conclude that the general shape of the sediment-yield curve applies throughout the range of fluvial landscapes, from small experimental drainage basins to mountain ranges; therefore, a valuable scale-independent tool is available to aid in prediction and interpretation of both short- and long-term geologic phenomena.

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