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Event bed load yield measurement with load cell bed load traps and prediction of bed load yield from hydrograph shape

D. A. SEAR
Department of Geography, University of Southampton, Highfield, Southampton SO17 1BJ, UK
d.sear@soton.ac.uk

Abstract One of the goals of sediment transport research is to predict the bed load yield of ungauged catchments. However, what little field data exist are characterized by temporal fluctuations in the record of event yield. Attempts to model the process of transport typically involve the derivation of empirical relationships between commonly measured variables such as stream discharge and the rate of bed load transport. Such approaches fail to account for the effect of sediment supply on the process of transport, which is known to contribute to the variability in records. This paper sets out a conceptual model of sediment transport that establishes a link between the form of the stream hydrograph and the effectiveness of an event as indexed by sediment yield. The model is then tested against a dataset of 60 bed load transport events recorded using a new type of load-cell pit trap. Total event power is shown to be capable of explaining 70% of the variance in event yields for a small woodland stream.

Key words bed load yield; event duration; sediment supply; stream hydrograph

INTRODUCTION

One of the goals of sediment transport research is to be able to predict the volume or mass of bed load transported by floods. In turn, these may be aggregated over a year to produce annual estimates of bed load yield, both of which are useful for the prediction of reservoir sedimentation, and the design of gravel traps. However, bed load transport is known to be highly unpredictable (Gomez, 1991). At the fundamental level, bed load transport is a function of the entrainment and the movement of individual grains on a stream bed, itself an unpredictable and stochastic process (Hassan & Church, 1992). The supply of sediment available to be transported is known to be a function of both temporal and spatial variations in entrainment characteristics (cluster, armouring and patches) of the river bed. Stream beds dilate, or become more tightly packed under marginal transport conditions, affording higher resistance to entrainment. In supply limited rivers, the sudden availability of new sources of bed load from armour break-up, bar mobilization or bank collapse, may become locally important and result in order-of-magnitude changes in measured transport rate. Such variability is reflected in the high degree of scatter exhibited by bed load rating curves, although it seems particularly pronounced in supply limited humid-temperate streams (Reid & Larrone, 1995). Thus, an important factor in the process of bed load transport is the extent to which local (controlled by entrainment) *vs* remote (controlled by sediment transport) sources of supply interact with the sequence of flows to create temporal and spatial variability in transport at a section (Lane & Richards, 1997). We can hypothesize that

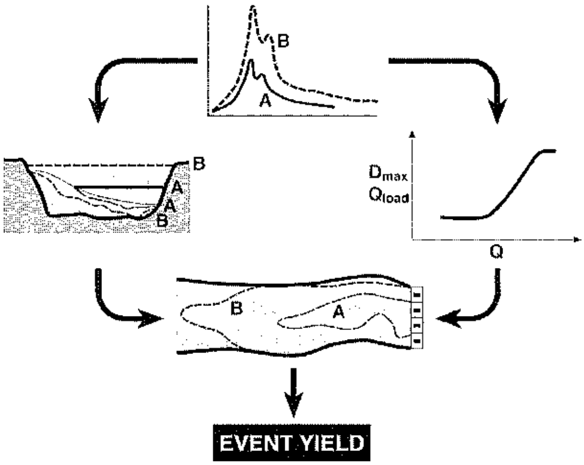

Fig. 1 Conceptual model of bed load transport and the role of event magnitude and duration in controlling sediment supply to traps.

sediment will be available at different times and in different locations during an event (Fig. 1). As flows rise, new sources are accessed, the significance of which will depend on the geomorphology of the channel; for example, channels with relatively high bar amplitude will only access sediment on the bar tops relatively infrequently. Similarly, wide shallow channels, may access most of the channel bed relatively rapidly. An additional factor influencing the temporal patterns of bed load recorded at a section, will be the distance that bed load can travel to supply material to the point of measurement during a flood event. Most tracer studies of particle movement indicate an average event travel distance of <4 channel widths, with maximum average values of <17 channel widths for high magnitude floods. An important factor affecting the connectivity of the measurement point with upstream sediment supply must therefore be the duration of flow over the critical threshold for transport, together with some consideration of where the sources of sediment are within the upstream reach. Set alongside this aspect of the flood hydrograph (the event duration) is the event magnitude, as this conditions the proximity to thresholds of entrainment, armour break up, and access to vertical sources of sediment (Fig. 1).

This paper takes a holistic approach to the interpretation of temporal variations in bed load transport yield measured at a gauging station using a dataset of 60 individual bed load events collected over the period 1998–2002. Consideration of the role of local *vs* remote sources of sediment is made.

STUDY SITE AND METHODS

Four bed load samplers were installed across a section in a straight reach of the Highland Water, a small gravel-bed channel located in a 12.5 km^2 semi-natural wooded catchment in southern England. The Highland Water Bed load Sampler (HWBS) is a load-cell based continuous recording pit-trap (Sear *et al.*, 2000). The HWBS consists of an aluminium outer box within which an aluminium inner box is inserted. The outer box has a hinged lid, fastened flat by nylon cable ties. Bed load enters the trap through a 0.2 m wide slot cut into a hinged plate on top of the trap. Low profile fences were fitted to the sides of the slot to prevent lateral ingress of sediment. The whole lid is raised slowly to afford access for emptying and to avoid scour. A series of 16 lithium-greased ball bearings reduces friction between the inner and outer box (Fig. 2). The whole structure is situated within an existing pre-cast concrete slot, together with three other identical traps. The design is intended to be independent of the need for an expensive permanent structure and can be placed in a hole dug within the gravel-bed and backfilled.

To overcome the problem of spatially variable loading, the inner box rests on a specially designed stainless steel "scissor" cradle (Fig. 2). The cradle design directs the load force through the vertical axis of a single button load cell across the longer (cross-stream) axis of the trap. For symmetrical boxes, the cradle could be designed so that the four points of contact accord with the four corners of the trap. Bench tests confirmed the design and these were supplemented by extensive field tests using calibrated weights (see Sear *et al.*, 2000 for details).

Annual re-calibration has proven the system to be stable, with some drift accounted for by accumulation of sediment around the load cell cradle. The traps have functioned without the need for significant maintenance for over 65 bed load events. Flows have varied up to floods of 1:50 year recurrence interval.

The estimate of bed load yield is based on the summation of 10-min measurements of bed load transport rate undertaken for each trap, and the resultant values integrated across the cross-section, assuming that transport rates at the channel margins are effectively zero. Only events where the traps were not filled completely have been used, reducing the overall number of usable events from 65 to 60.

Stream power was calculated according to the formula:

$$\omega = \rho g Q S / b \tag{1}$$

where ω is the stream power in W m^{-2}, ρ is the density of water taken to be 1000 kg m^{-3}, g is the acceleration due to gravity (9.81 m s^{-2}). Water surface slope (S) was directly

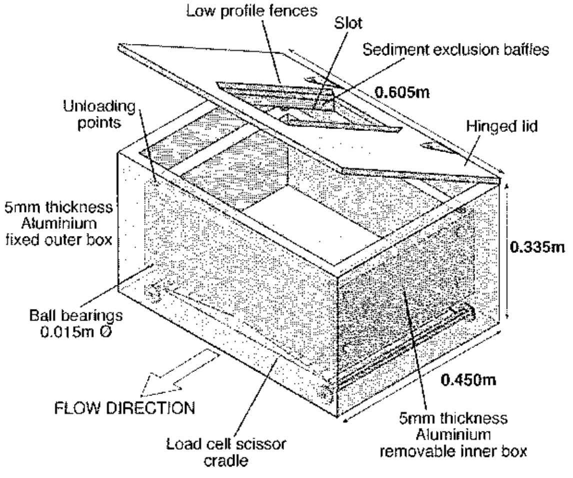

Fig. 2 Highland Water bed load sampler.

measured from the difference in elevation between two Druck pressure transducers located immediately upstream of the traps and on the first riffle crest, some 20 m upstream. Discharge (*Q*) is measured at the cross-section in which the traps are located and *b* (bed width) was fixed at the monitoring site by a gauging structure. Stage, discharge and water surface slopes are logged at 10-min intervals. The logged values represent averages derived from 10-s sampling within the intervening 10-min period. This results in a stable estimate of water surface elevation, that precludes the need for a stilling basin, which in these streams is prone to siltation.

RESULTS

Bed load transport is dominated by material in the coarse sand–medium gravel ranges (D_{16} 1.3 mm, D_{50} 3–7 mm, D_{84} 7–22 mm), that is similar in composition to the bulk grain size of upstream bar material, and somewhat finer than surface armour found on riffles and in pools. Transport rates are low compared to ephemeral channels during flash floods, but are of similar magnitude to those observed in the Turkey Brook, a stream with similar geology and sedimentological properties (Reid & Larrone, 1995). Bed load transport is characterized by counter-clockwise hysteresis, that is diagnostic of a delayed onset of bed load transport such is typical where upstream sources control the supply of bed load (Bathurst, 1987). Tracer experiments in the study reach have shown the significance of discrete upstream sediment sources (largely pools and point bars) in contributing to bed load transport measured at the traps.

A temporal sequence of event yield recorded at the traps is shown in Fig. 3. Four sources of variability in bed load yields may be considered: (a) variability in entrainment thresholds between events (Reid *et al.* (1985); (b) local increases in sediment supply from bank collapse; (c) variability in the sediment supply from upstream sources (bars and pools); and (d) variations in event magnitude. Evidence for the operation of all these factors is discussed.

In accounting for the scatter observed in measured transport rates, Reid *et al.* (1985) suggested that the thresholds of initiation of transport and cessation were often

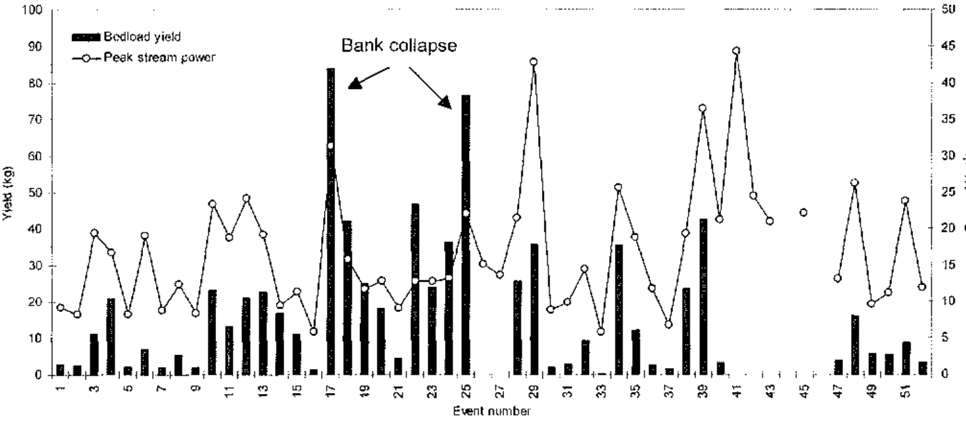

Fig. 3 Plotted sequence of event yield and maximum event power, illustrating the role of bank collapse on bed load transport.

different, with lower thresholds for final motion. A similar result is found in the Highland Water, but is interpreted not as representing the difference in static *vs* dynamic resistance to movement, but rather is due to the temporal variability in the supply of material from upstream sources. Similarly, Reid *et al.* (1985) observed a temporal variation in entrainment thresholds associated with prolonged periods of bed stability that they suggested was responsible for variations in measured transport rate and event yield. This was not observed in the Highland Water; rather as the period between bed load events increased subsequent entrainment thresholds tended to reduce (Fig. 4). This is again interpreted as representing the difference in dominant sediment sources; the Highland Water largely deriving bed load from upstream patches of fine material stored in bars and the margins of pools.

The role of local changes in sediment supply is shown in Fig. 3. During one of the largest events recorded, scour induced failure of the bank immediately upstream of the bed load traps resulted in a three-fold increase in event yield. Furthermore, the local morphological adjustment arising from the bank failure induced a change in bed load routing away from the left bank and towards the right bank. This is reflected in the sustained high levels of yield recorded from Trap 1 (right bank) and a reduction in yields over the same period in Trap 4 (left bank).

Grain size analysis shows that the bed load most closely approximates to that of the upstream bar and pool sediment. Riffle surface sediments are coarse and compacted, and have been shown from tracer studies to be stable over the flow range (Booker, 2001). The suggestion is that bed load transport in the Highland Water is not so much locally derived as influenced by the storage and exchange of sediments in the upstream reach; specifically bar and pool areas.

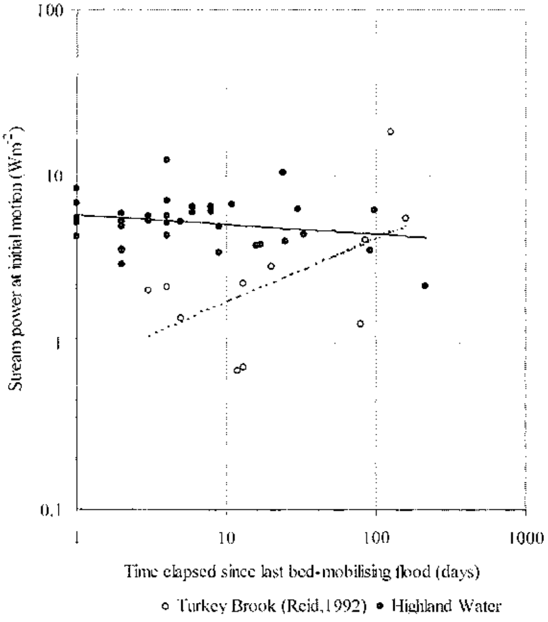

Fig. 4 Variations in the threshold of entrainment for bed load transport for the Highland Water and Turkey Brook, illustrating the contrasting response to time between bed load events.

DISCUSSION

The influence of event duration and magnitude on sediment transport rates has been previously suggested as a means of classifying the effectiveness of extreme floods (Costa & O'Connor, 1995). Three types of flood were discerned: (1) those that have high magnitudes, but short duration; (2) those that have long duration but are below or at the threshold of motion; and (3) those that are of high magnitude and duration. The latter were considered to be the most geomorphologically effective since these had the largest total available energy for sediment transport. Using the database of 60 floods covering events up to 1:50 year Recurrence Interval, it is possible for the first time to test this conceptual model (Fig. 5). In Fig. 5, the circles scale in proportion with total event yield (a measure of geomorphological effectiveness), but are positioned according to the peak (maximum) stream power of an event, and the total duration of the vent above the threshold of motion. Geomorphological effectiveness is maximized for events of high magnitude and long duration (B), but also for those of long duration and moderate magnitude (C). Short duration high magnitude events (A) owe much of their effectiveness to the collapse of the river banks, and break up of the armour layer, creating new "local" sources of bed load. Conversely, events that fail or are close to the threshold of transport of whatever duration (D) generate only limited bed load transport. The reason for the effectiveness of Type (B) events is that they not only access new sources through armour break-up and bank erosion, but they also establish

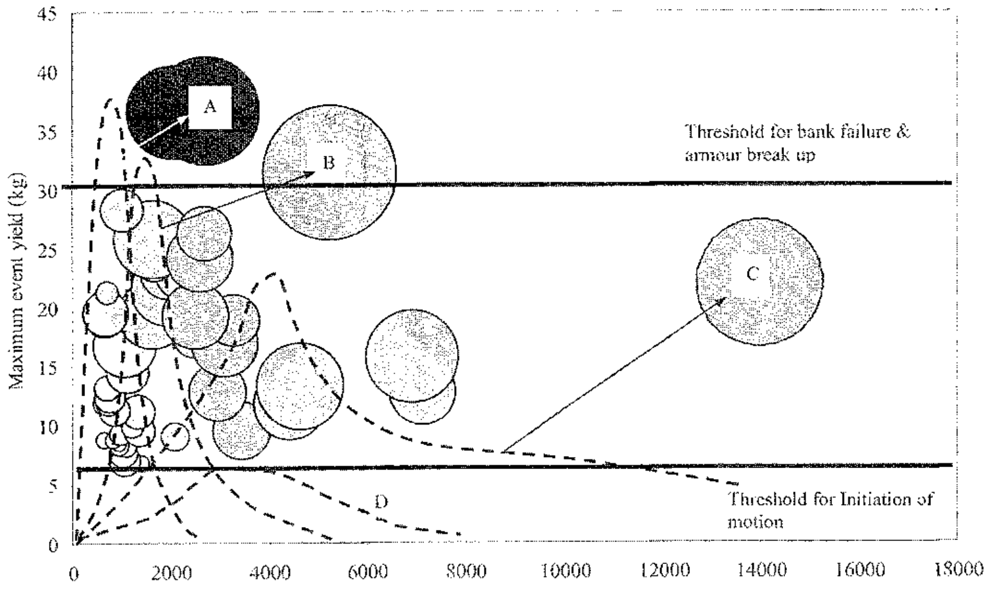

Fig. 5 Flood effectiveness and the role of event magnitude and duration, after Costa & O'Connor (1995). The stream power "hydrograph" represent different types of event. The shading of the circles represent: white, close to threshold sediment transport; light grey, moderate power, short duration events; medium grey, moderate power, longer duration events; black, high power, short duration events. Event B is a high power, long duration flood, whilst Event C is a long duration moderate power flood.

connectivity between sediment sources over much larger areas of the upstream river bed (see Fig. 1).

Given that event duration as well as magnitude seem to have an influence on bed load yield for a given flood event, it should be possible to derive a relationship between total event power and total bed load yield. Rickenmann (1997, 2001) has demonstrated the relationship between a similar measure based on flood runoff volume above the threshold for sediment transport and event bed load yield. Rickenmann (2001) demonstrates the essentially log-linear relationship between these measures of flood effectiveness for a range of rivers including those with similar slope and grain-size distributions to the Highland Water. Total event power used in this study, is calculated from the area under the curve defined by stream power (W m^{-1}) on the Y-axis and event duration (seconds) on the X-axis, with units in M jm^{-1}. The relationship between total event power and total event yield is given in Fig. 6. Over 70% of the variation in event yield is explained by this term, compared with 52% and 54% for maximum event power and event duration, respectively. Factors contributing to the unexplained variation are likely to include the presence of stochastic supply from bank collapse, the exhaustion of upstream sources particularly during longer duration events, and the influence of turbulence in conditioning marginal sediment transport rates.

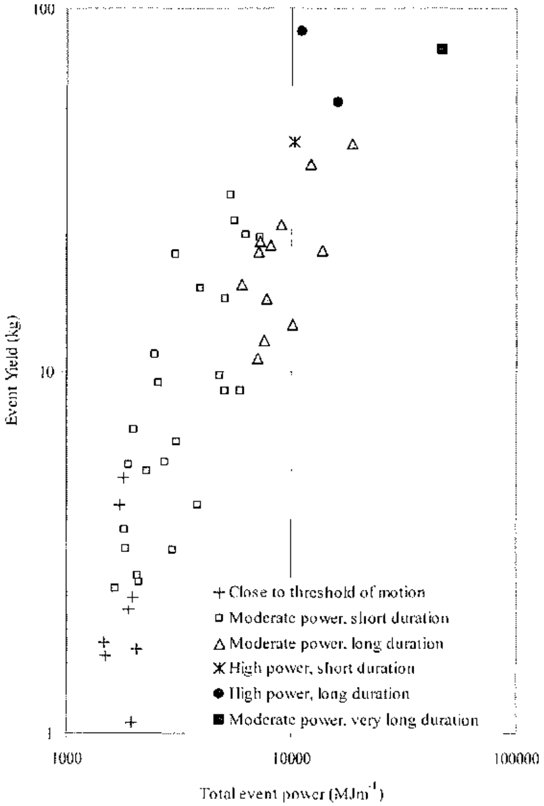

Fig. 6 The dependence of event yield on total event power, classified according to flood event type.

CONCLUSIONS

A new portable and cheap load-cell based continuos recording bed load trap has been successfully deployed and run for 4 years, over which time 65 bed load events have been recorded for flows up to 1:50 year recurrence interval. Sediment transport rates are of comparable magnitude to those reported in similar streams, but there are significant differences. Thresholds for initiation of bed load transport do not increase with time between events; rather these remain stable or reduce. Similarly, events are characterized by negative hysteresis. Both these factors point to the importance of upstream sources in controlling temporal variations in event yield. It is demonstrated that for predictive purposes, total event power, a variable that includes duration as well as magnitude, explains over 70% of the variability in event yield. A model of the effectiveness of different flood types is tested. Four types of event are identified in the Highland Water. Those of high magnitude and long duration are associated with maximum effectiveness because they not only access new sources through armour break-up and bank erosion, but they also establish connectivity between sediment sources over much longer reaches (and larger areas) of the upstream channel.

The identification of the significance of the form of the flood hydrograph on bed load yield has implications for interpreting the impacts of land management activity and climate change on channel morphology. Conditions that increase flood magnitude but reduce flood duration may be associated with sedimentation since transfer of material will occur over relatively short distances, such as is the case with many land drainage programmes (Robinson, 1990). Conversely, longer duration events of higher or similar magnitude to present, may result in much more channel activity as longer reaches of the river network (and associated sediment sources) become connected.

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