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Recording bedload discharge in a semiarid channel, Nahal Yatir, Israel

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ABSTRACT An automatic Birkbeck-type recording bedload monitoring station has been established on the ephemeral Nahal Yatir, a gravel-bed stream that drains part of the semiarid northern Negev Desert. Bedload discharge is determined independently, synchronously and continuously by three slot samplers that are set at intervals across the channel and lie flush with the stream bed. Water-stage and water-surface slope are also measured continuously, all data being stored conveniently in digital format on a solid-state logger. Bedload has so far been recorded for four flash floods, revealing a peak flux-rate in excess of 10 kg m^{-1} s^{-1}, which is more than threefold the highest rates recorded in any river to date, and gives a glimpse of the reasons why bedload sedimentation is a particular nuisance in the world's drylands.

INTRODUCTION

Sediment yields are acknowledged to reach peak values in semiarid environments largely because the poor ground protection offered by sparce vegetation and the diminutive activity of soil fauna conspire to reduce infiltration rates and encourage overland flow (Langbein & Schumm,1958; Scoging,1989). However, the availability of slope material ranging widely in calibre and its transfer to the stream channel by erosion mean that the proportion of sediment leaving a semiarid drainage basin as *bedload* is commonly believed to be at least 10-fold, but often as much as 100-fold, that which is carried out of equivalent basins in humid environments. Evidence for this is largely inferential, if only because of the paucity of measurements of bedload. It comes from analyses of reservoir or lake deposits and a presumption that the relatively coarse (usually sand-sized) sediment that is present has been carried down the fluvial feeder as bedload (Laronne,1987), a presumption that is, in any case, questionable in the light of studies which show that even coarse sand can form a significant fraction of the *suspended* load of flash floods (Reid & Frostick,1987). In effect, there are no studies of bedload dynamics for ephemeral flood regimes despite the relative importance of bedload as a component of sediment yield in semiarid environments.

The reasons for the lack of information are identical with those that form a rationale for the development and deployment of automatic monitoring technology. Firstly, the incidence of desert rainfall is notoriously unpredictable both in time and space. Renard & Keppel (1966) have demonstrated the extreme spottiness of individual convective rain storms while Sharon (1972; 1974) has shown, in a number of semiarid settings, that the probability of receiving a similar longer-term pattern of rainfall diminishes dramatically over distances as small as a few kilometres. There is, therefore, considerable uncertainty attached to the acquisition of runoff and sediment load data, especially if monitoring were to be carried out at temporary monitoring stations and over short periods.

Secondly, the flashy nature of desert floods reduces the likelihood of acquiring adequate data using non-automatic, portable equipment. Hydrograph rise-times are commonly much less than 30 minutes and flood recession may be complete within a few hours (Reid & Frostick, 1989). This means that hydraulic conditions change rapidly, and implies that the sampling interval has to be extremely short. The protracted, channel cross-sectional, manual sampling strategy recommended for perennial and snowmelt regimes in streams of temperate humid regions, where flow may remain essentially steady for tens of minutes if not for hours (Emmett, 1980), cannot be deployed in desert flash floods. In addition, the turbid nature of the flow that arises from very high concentrations of suspended sediment reduces the level of confidence that can be attached to each repositioning of a portable bedload sampler since the stream bed cannot be seen, and this inevitably reduces the speed of operation.

Rapid changes in flow also create safety hazards, especially if manual sampling techniques involve wading. However, besides this, experience shows that the adverse hillslope conditions which arise soon after rainfall sets in and the bare soil becomes plastic, together with the fact that some streams in the dense channel networks which are characteristic of semiarid areas may already be running, can make a sampling station inaccessible if rainfall occurs unexpectedly and the site is remote.

All of these factors commend the development of a permanent monitoring station that deploys a fully-automated bedload sampling technique.

BEDLOAD SAMPLING METHOD AND EXPERIMENTAL SITE

Automatic monitoring techniques have given considerable insight of the complex processes that cause and regulate bedload transport. However, so far, they have only been applied to perennial or seasonal streams in which flow is more predictable than is the case with ephemeral rivers. Furthermore, the expense of both the installation and the upkeep of

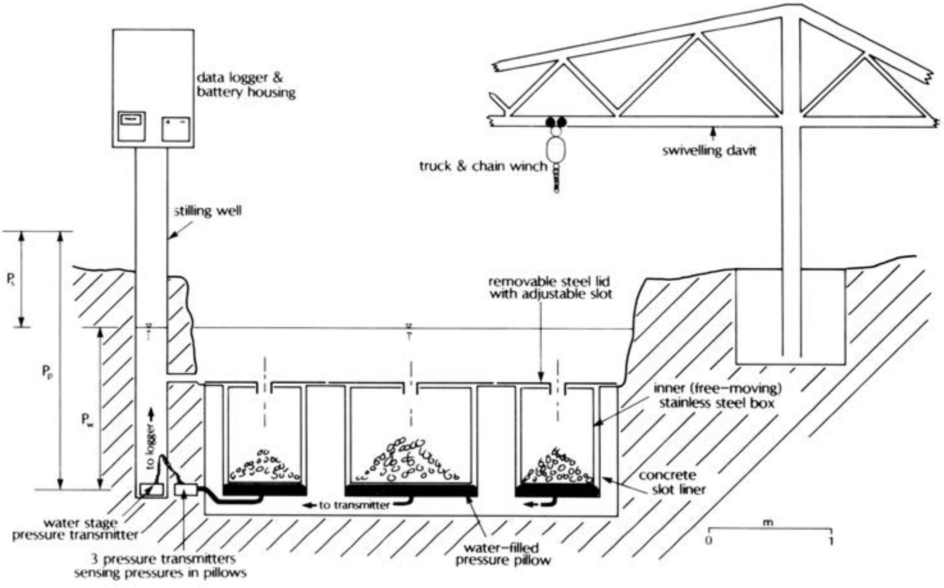

FIG. 1 Scale drawing of recording Birkbeck-type bedload slot-samplers installed on the Nahal Yatir, Negev Desert, Israel.

such equipment means that the quality of data that comes from continuous recording is only available for six streams worldwide, although at least three others are currently under investigation. All three techniques that have proved successful under field conditions employ a streambed slot designed to accept and trap bedload while offering minimal interference with the flow. However, two of the techniques - the conveyor-belt system on

FIG. 2 View of the Nahal Yatir during the flash flood on 8 February 1991, showing swivelling davit, sampling bridge and instrument housing at the sediment transport monitoring station.

FIG. 3 Sediment transport monitoring station on the Nahal Yatir after a flash flood showing the approach reach and the sampler slots.

the East Fork River (Leopold & Emmett,1976), and the vortex-tube system deployed on Oak Creek (Milhous,1973), the Torlesse Stream (Hayward,1979) and Virginio Creek (Taconni & Billi,1987) - are only semi-automatic. While this has certain advantages, such as manual control over the timing and selection of sediment for size analysis and no *machine*-limitation on the length of the transport record, it requires manning, and is therefore best suited to comparatively predictable flow regimes, especially those regulated by seasonal snowmelt. This, in itself, makes the use of such techniques impracticable in a desert setting where rainfall, let alone runoff, is unpredictable.

The other technique available is the Birkbeck-type pressure-pillow system (Reid et al., 1980). Although it has drawbacks, particularly the finite quantity of bedload that can be sampled during each flood event, it has the overriding advantage of fully automatic operation. It was first deployed on Turkey Brook, England, a perennial stream, but results have now also been published for Goodwin Greek, Mississippi, which has a seasonal regime (Kuhnle et al.,1988). Both generate rain-fed floods. In choosing a technique suitable for an ephemeral channel that would sustain unknown but high transport rates, it was the uncertain incidence of flash floods and the need for unmanned operation as much as any other factor which dictated the choice of the Birkbeck-type slot sampler.

Channel and catchment character

The Nahal Yatir is a gravel-bed stream that drains a water catchment of 19 km^2 which lies on the southwestern flank of the Hebron Mountains in the northern Negev Desert, 18 km NE of Beer Sheva. Bedrock consists largely of Late Cretaceous limestones that dip shallowly southeastward. However, over much of the catchment there is a veneer of Holocene loess that ranges in thickness from a few centimetres up to several metres. The area receives 230 mm of rainfall a year, mainly in winter between November and March, but potential evaporation is 2000 mm. The semi-natural vegetation consists, therefore, of sparse thorny scrub and seasonal herbs, but the upper part of the catchment lies within the Yatir forest - a low density pine plantation, while the Bedouin sow parts of the lower catchment with cereal crops on an irregular basis.

The reasons for choosing this site were, among others, its proximity to Beer Sheva and its accessibility at times of probable rainfall, and an expectation that, on average, at least 5 floods could be expected each year, so giving good prospect of useful data (Laronne, 1990).

The channel of the Yatir at the site chosen for installation of the bedload monitoring station is straight. The channel-bed is planar and has a width of 3.5 m. The banks are near-vertical and bankfull water-stage is *c.* 0.9 m. The bed material immediately above the bedload samplers has a median diameter (D_{50}) of 15 mm (surface and subsurface alike). Twenty-five metres above the samplers is a bar of coarser material where D_{50} of the surface and subsurface layers is, respectively, 49 and 28 mm. Such bars punctuate the long profile, establishing an alternating pattern of bars and 'flats' which is fairly typical of gravel-bed channels in the region (*e.g.* Hassan,1990).

The sediment transport monitoring station

The configuration of the monitoring station on the Yatir is shown in Fig. 1. What is not shown are the banks of scour-chains installed to check on the vertical exchanges of sediment that might take place, and, importantly, a second water-stage sensor set in a stilling-well 60.65 m upstream. This, together with the stage sensor at the sampler site, allows a continuous record of water-surface slope that is synchronized with the output record of the bedload samplers. Besides the monitoring equipment, a bridge was installed 7 m upstream from the slot samplers. This was designed to allow manual deployment of both a vertical array of current meters and, if appropriate, a portable bedload sampler. The installation can be seen in operation during a flash flood in Fig. 2, and after a transport event in Fig. 3.

The Yatir samplers differ from those on Turkey Brook in several respects. The capacity of the inner sediment collecting boxes is greater - the centre channel sampler has a capacity of 0.4 m^3, while those towards the right and left banks each have a capacity of 0.24 m^3. The cross-channel slot width, although adjustable, has been set at 0.11 m - half of that adopted at Turkey Brook. Both of these dimensional characteristics were chosen in anticipation of much higher sediment flux-rates on Nahal Yatir. But perhaps the most significant design improvement lies in the use of electrical pressure transmitters and a solid-state logger for data capture. With a sampling interval that can be as low as 0.25 s, the digital record is virtually continuous, and can be analysed quickly and efficiently after down-loading onto a suitable computer (a lap-top p.c. taken to the field site, in the case of the Yatir).

BEDLOAD SAMPLER OPERATION

Sediment moves into the sampler slot and collects in the inner, free-moving box which rides on a water-filled rubber pillow. Pressure in the pillow arises from the combined load of the stage-dependent water column and the box and its contents (p_p), and this is sensed and transmitted to a data logger at predetermined intervals. An independent pressure transmitter provides a simultaneous measurement of water-stage (p_w). After allowing for changes in p_w between one record and the next, and since the mass of the box can be ignored because it is constant, the change in p_p is functionally related to change in the submerged mass of accumulated sediment (Δp_s):

$$\Delta p_s = (p_{p2} - p_{w2}) - (p_{p1} - p_{w1}) \qquad (1)$$

By defining a coefficient, c, that relates pressure registered by the pillow to submerged mass of sediment, and allowing for the cross-channel width of the slot, W_{sl}, unit bedload discharge, q_b, for the interval between time t_1 and t_2 is derived from:

$$q_b = c\Delta p_s/W_{sl}(t_2 - t_1) \qquad (2)$$

The coefficient, c, is derived empirically, so allowing for any differences in the operational efficiency between individual samplers. An example of the results obtained from a load test is shown in Fig. 4. Objects ranging in weight from 0.3 to 80 kg were added and subtracted incrementally and the transducer output was recorded. The response is gratifyingly linear over the range tested, and there is negligible hysteresis between loading and unloading.

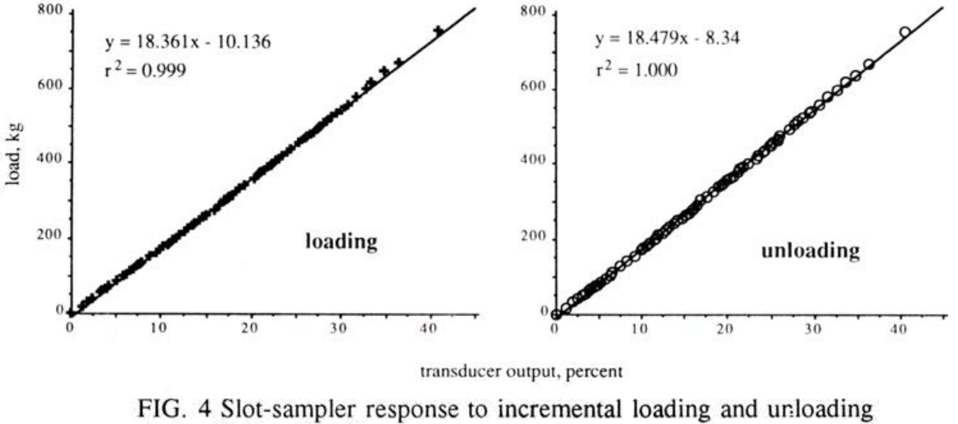

FIG. 4 Slot-sampler response to incremental loading and unloading during field calibration.

CONTINUOUS MEASUREMENT OF BEDLOAD DURING FLASH FLOODS

The bedload monitoring station on the Yatir was installed in 1990 and was operational during the 1990-91 flood season. After insetting the concrete slot liners but before finalizing the detailed configuration of the sensors and performing an *in situ* calibration, the passage of several flash floods had brought complete restoration of the channel.

The first continuous record of bedload on an ephemeral stream occurred on the Yatir on 8 January 1991. This is given as a pressure record in Fig. 5 in order to show the detailed nature of the information that is provided automatically by the four sensors (three bedload slot samplers and local water-stage). After applying Equation 2, the results can be expressed as unit bedload discharge. This is shown in Fig. 6 for the centre-channel sampler where the 0.25 s interval interrogation of the pressure transmitters by the logger has been averaged to give bedload flux rates on a minute by minute basis. Mass has been converted to subaerial values using a multiplier of 1.6 in order to facilitate comparison with the results of some other bedload studies and despite the fact that Birkbeck-type samplers directly provide the submerged mass values required for physical explanation of bedload flux.

Immediately apparent are the high unit transport rates. The peak value of just over 10 kg m^{-1} s^{-1} is more than threefold the previously reported highest unit rate, in this case for a braided proglacial outwash stream (Ashworth & Ferguson, 1986). It is more than a hundredfold and fourfold those reported for the perennial single-thread Turkey Brook and the seasonal single-thread Goodwin Creek, respectively - streams which deploy the same type of sampler. Also interesting is the degree of divergence between the stage-hydrograph and the bedload flux-rate curve.

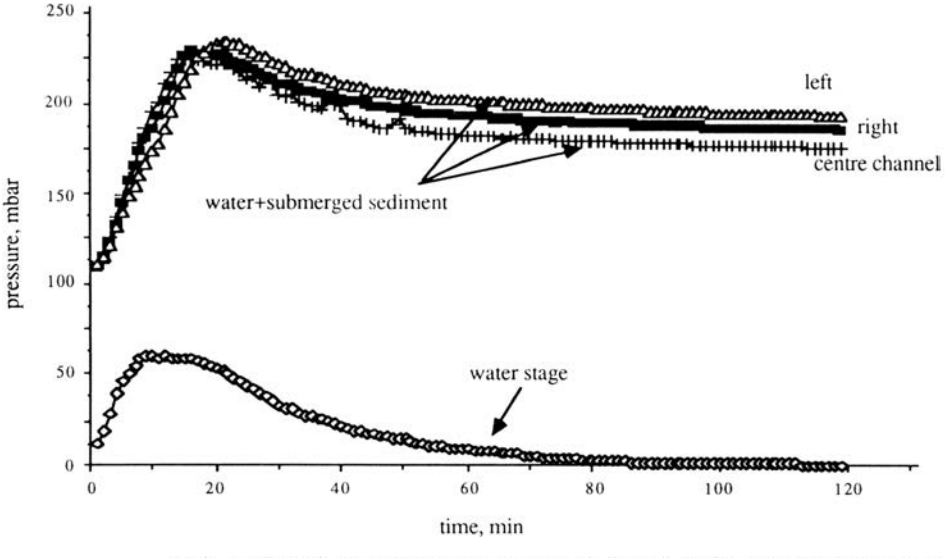

FIG. 5 Output from the pressure transmitters during the flash flood of 8 January 1991 on the Nahal Yatir.

CONCLUSIONS

The uncertain nature of runoff generation in desert environments together with the flashiness of floods makes automatic monitoring of bedload essential if data is to be gathered that will allow a full understanding of sediment transfer in the world's drylands

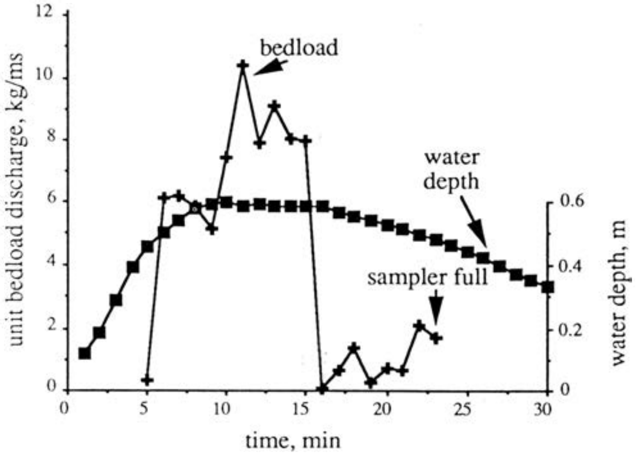

FIG. 6 Hydrograph of 8 January flash flood on the Nahal Yatir and unit bedload discharge (subaerial mass) along the channel centre-line averaged over 1-minute intervals from the virtually contiguous digital record.

where sedimentation problems are most acute but least welcome. The installation of a set of Birkbeck-type samplers on the Nahal Yatir and its operation during the 1990-91 flood season has demonstrated that automation is feasible even in such a harsh hydraulic flood regime. It has also given a glimpse of the record levels of unit bedload discharge that have hitherto only been *suspected* as characteristic of ephemeral streams.

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