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The continuous monitoring of bed load flux in various fluvial environments

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Abstract We present detailed advantages and limitations of an accurate, reliable, durable and relatively cheap means of continuously monitoring bed load flux and texture using Birkbeck-type slot samplers based on almost a quarter of a century of data. These have been derived from alpine, mid-latitude perennial, Mediterranean, semiarid, and arid fluvial settings in rivers 1–40 m wide that have characteristic surface bed materials in the sand-granule to cobble range. Methods of construction and principles of operation, calibration, data handling, ranges of flux rates and textural characteristics of bed load are discussed.

Key words bed load flux; cessation of motion; incipient motion; sampling; texture

INTRODUCTION

Slot (also termed pit) samplers do not affect the flow and are therefore usually considered to be more accurate than other bed load samplers, unless the latter can be shown to have hydraulic and sampling efficiencies of 100%. Slot samplers are of various types, utilizing either a vortex tube (Milhous, 1973; Hayward 1979; Tacconi & Billi, 1987), a continuous conveyor belt (Leopold & Emmett, 1976) or a local weighing device (Reid *et al.* 1980). The Birkbeck sampler has become the preferred method (Lewis, 1991; Kuhnle, 1992; Laronne *et al.*, 1992; Harris & Richards, 1995; Garcia *et al.*, 2000; Cohen & Laronne, 2000; Sear *et al.*, 2000; Habersack *et al.*, 2001). Several other methods have been used to sample bed load without unduly affecting the flow (Ashida *et al.*, 1976; Lenzi *et al.*, 1999), but these have not been widely used.

With a growing need for high quality, continuous bed load data sets from automatically activated samplers, we offer observations and provide operational principles of relevance to deploying the Birkbeck sampler in various environments (Table 1).

PRINCIPLE OF OPERATION

The Birkbeck bed load sampler operates on the principle of weighing the mass of bed load that enters a slot. Variations in water stage are accounted for by independently

Table 1 Characteristics of rivers monitored with Birkbeck bed load slot samplers by the authors and reported here. Bedforms are denoted, respectively, by R/P, F, B, AB as riffle/pool, flat, bar and alternate bar, and multiple and single thread as m and s. * denotes D90. Grain size is in millimetres.

	Yatir	Eshtemoa	Tordera	Drau	Rahaf	Qanna'im	Jornada	Walnut Gulch gully
Mean annual precip. (mm)	250	280	800–1310	800	90	70	245	324
Catchment area (km^2)	19	112	35	2561	79	10	1.8, 5.9	1.5 10^{-3}
Bed width (m)	3	6	5.5	40	27	13	~1	0.7
Longitudinal slope (%)	0.95	0.75	2	0.18	1.7	2.7	~2	2
Multiple or single thread	s	s	s	s/m	s/m	s	s	s
Surface D_{50} / D_{95}	6/17*	17/71*	54/228	66/120	7–170/ 70–350	12–100/ 90–200	medium sand	sand–medium gravel
Subsurface D_{50} / D_{95}	10/45*	18–25/83*	16/83	28/100	5–50/ 40–170	4–50/ 40–115	medium sand	sand–medium gravel
Bed forms	F, B	F, B	R/P, F, B	AB	braids, patches	patches, AB	none	clusters
Annual mean no. of bed load events (range)	5 1–12	4 0–6	3 0–6	summer–incessant	0–9 variable	0–5 variable	0–5 variable	0–6 variable
Bankfull discharge (m^3 s^{-1})	8	25	5	~250	41 (barfull)	7 (barfull)	?	?
Mean annual discharge (m^3 s^{-1})	data set too short	2.23	0.84	64	2.79 (min)	data set too short	data set too short	data set too short

monitoring water stage (Reid *et al.* 1980). The sampler has a hydraulic efficiency (Poreh *et al.*, 1970) of 100% when sediment fill is small. The efficiency decreases with increasing fill; for example, in the Drau at low flow, efficiency is 90% at a fill of 60%, decreasing to 66% at a fill of 80% (Habersack *et al.*, 2001). The extent of this decrease is expected to vary with both the length of the slot and the flow velocity field above the slot. The bed load sampling efficiency is likely to decrease considerably less because saltating, rolling and sliding grains, once inside the sampler, are unlikely to exit, even though there is slow circulation within the sampler. The decrease in hydraulic efficiency arises from the generation of recirculation flow cells within the sampler as it fills. At least four such cells, the velocity of which increases with extent of the fill, have been identified. The flow is typified by a general upwelling region at the centre of the sampler. When the sampler is almost full with sediment, the hydraulic efficiency is lowest over the centre of the sampler, where the sediment surface is most elevated (Habersack *et al.*, 2001). Due to the separation of the channel flow and the water column within the sampler, slot samplers are excellent separators of bed load and suspended sediment (Poreh *et al.*, 1970). The latter is deposited only at very low stage.

The mechanical efficiency of the weighing device is not 100%: there is some friction between the inner and outer boxes, the pillow may slightly deform, temperature effects may occur, falling sediment initiates fluctuations in pillow pressure that require time to be dampened, etc. When the transducers that monitor water stage and pillow pressure are located in different environments (e.g. on the river bank and in a stilling well), temperature corrections are required (Harris & Richards, 1995). Our transducers have required no temperature correction, because they are all in contact with the stream.

To ensure that the bed does not scour downstream of the samplers—the cover of which is smooth, thereby decreasing friction and causing the flow to accelerate—cement aprons have been installed in the Yatir, Eshtemoa and Qanna'im and also in the 27 m wide Rahaf. These aprons (i.e. sills) have been roughened by partially embedding local clasts in the cement. Because anabranches change their location and bed elevation in braided rivers, we have dealt with a rising bed elevation in the Rahaf by inserting an increasing number of "spacers" under the sampler cover, thereby raising it by as much as 40 cm and so ensuring it is flush with the sediment surface. Scour immediately upstream of slot samplers will also affect sampling efficiency. We have monitored for scour using tracer clasts, scour chain elbow deflection and post-flood changes in bed elevation. Our records indicate that it is rare where a channel-wide apron is constructed, because it serves as a local base level.

CONSTRUCTION

Slot orientation, width and length

Photographs of etch marks made by moving particles on the sampler cover indicate that the direction of movement is essentially downstream. This is expected of straight reaches in single thread and relatively narrow streams. In wider streams, at meander bends and especially in multi-thread systems, local near-bed flow direction may differ considerably from the downriver direction. Indirect evidence of the direction of movement in a narrow river is afforded by the symmetric cross sectional distribution of bed load flux in the Yatir, whereas in the wider Eshtemoa the pattern is slightly asymmetric at high flows, reflecting the effect of a 200 m distant upstream bend that induces a transverse bed load trajectory favouring the left bank (Powell *et al.*, 1999). If the slot is not aligned with local bed load trajectories, the width through which bed load enters the samplers is greater than that of the slot. When deployed in bends or in wider reaches, this needs to be taken into account as a source of sampling error. As a precaution, small vanes have been used elsewhere to ensure that bed load enters only from the upper slot entrance (Sear *et al.*, 2000).

The choice of an appropriate slot width depends on the grain size distribution (gsd) of the riverbed and expected flux of bed load in the context of sampler volume. In order to capture all clasts, it is axiomatic that slot width should be larger than the coarsest clasts (Hubbell *et al.*, 1981). Our samplers have slots that can be varied in width (0–180 mm) to suit individual river reaches and sampling objectives. In perennial streams, where bed load fluxes are typically very low (Reid & Laronne, 1995), slot width can be increased considerably, and values as high as 200 mm have been deployed. However, in ephemeral streams, with bed load flux several orders of magnitude larger over the same range of flow conditions (Laronne & Reid, 1993; but, see also Hayes *et al.* (2002) for similarly high fluxes in perennial rivers with large sediment supply), increasing the slot width considerably decreases the length of the record. Hence, planning an appropriate slot width depends on the local gsd, on the extent of armour development (Laronne *et al.*, 1994) and on expected bed load fluxes, which are themselves dependent on hydraulic and hydrological factors. In the Eshtemoa, we have used a slot width of 110 mm, though presently we are also deploying a slot width of 165 mm, 50% larger. This will allow us to determine more accurately when the coarser material of the channel bars is mobilized—i.e. when equal mobility is attained (Powell *et al.*, 2001).

Slot length should be larger than the maximum hop length of saltating particles. Because gsd is commonly truncated at a fixed size, the calculation of the slot length may be based on this grain size. The maximum hop length is calculated from the Shields parameter, a hiding factor and a ripple factor (Habersack *et al.*, 2001). At Jornada, slot length is 100 mm; in the Yatir, Eshtemoa, Rahaf and Qanna'im it is 400 mm; on the Tordera it is 480 mm, similar to that used at other locations (Sear *et al.*, 2000); on the alpine Drau, slot length is 1500 mm.

Inner box dimensions and box hauling

Sampler volumes are either 0.24 or 0.48 m^3 at many of our sites, except the Drau (0.75 m^3) where the sampler and logger remain underwater during the entire spring and summer freshet (Fig. 1). Other reported sampler volumes are similar, with the exceptions of those (0.15 m^3) used by Sear *et al.* (2000) and, more recently, by Powell (see below) at both Jornada and Walnut Gulch (0.018 m^3). Small sampler boxes may be lifted manually. Larger ones require either a fixed davit (Turkey Brook, Yatir and Eshtemoa), or a fixed I-beam (Tordera), or where channel width makes a fixture impractical (Rahaf) and where fixed installations are environmentally detrimental (Qanna'im), a portable beam may be used; in wide channels, hauling may be accomplished from a bridge if this is sited appropriately (Drau).

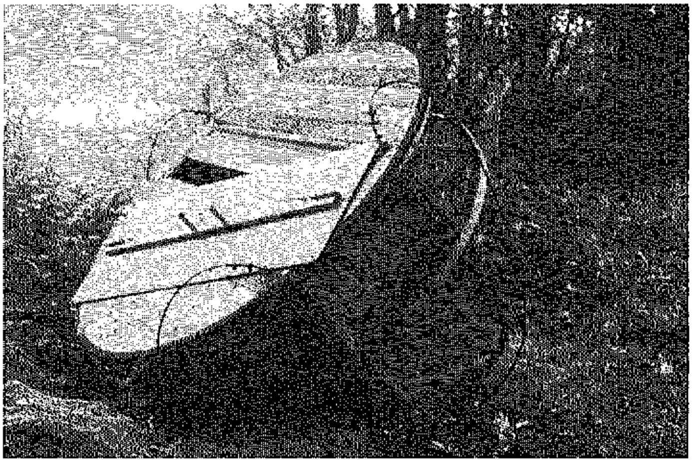

Fig. 1 The Drau slot sampler (inner box) is the largest Birkbeck sampler deployed to date. For scale, slot length is 1.5 m.

PRESSURE SENSING

Neoprene water-filled pillows have been used at the Eshtemoa continuously for over a decade. Pillows rarely puncture. Puncture repair is simple, although some have contended otherwise and provided a design modification (Harris & Richards, 1995). Pillows may be purchased from one of several companies, or they can be manufactured cheaply by vulcanizing at any local tyre repair service station. Pillow response is linear when the water fill does not contain much soluble gas. However, gas may evolve within the pillow and a bleeder should be attached to the top. In order to maximize sensitivity, the pressure transducer should be at the same elevation as the pillow. Standard errors of the mean estimate of bed load are typically ±0.3 kg for small (0.24 m^3) samplers and ±0.6 kg for those twice this capacity.

Load cells are another means of monitoring the sediment load accumulating in a Birkbeck-type bed load sampler (Lewis, 1991). Load cells are used in industrial weighing applications and are available in a wide range of sizes and configurations. In a typical load cell, multiple strain gauges are connected to form the four legs of a Wheatstone bridge circuit. When an input voltage is applied to the bridge, the output becomes a voltage proportional to the force acting on the cell, which can be amplified, processed and recorded using conventional electrical instrumentation and loggers. In a Birkbeck sampler, the load cell is mounted on the floor of the outer box and supports the inner box such that the weight of the accumulating load is transmitted entirely and directly to the cell's strain element. Load cells are less prone to temperature effects and simple ones cost as much as locally made pressure pillows (Sear *et al.*, 2000). Lewis (1991) used a single, centrally located load cell, whereas a more uniform distribution of pressure on a single load cell can be attained by utilizing a stainless steel "scissor" cradle (Sear *et al.*, 2000). Birkbeck-type samplers with load cells are currently being used by Powell to study sediment transport in small rills at the Jornada Long-term

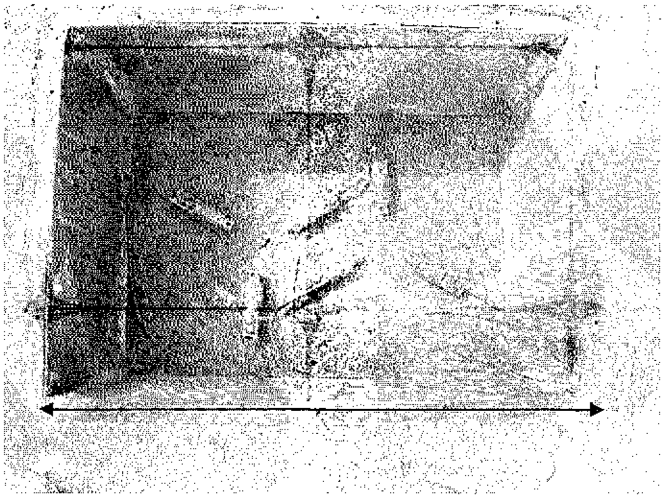

Fig. 2 View into the outer box of a Jornada bed load sampler. Length of cross stream arrow is 71 cm. Each of two sets of 3 load cells monitors the weight of one inner sampler box to ensure stability during uneven filling.

Ecological Research Station, New Mexico and in a first order gully at Walnut Gulch, the experimental watershed of the Agricultural Research Service, US Department of Agriculture in southeast Arizona. Due to the shallow depths (decimetres), limited sediment size (sand to medium gravel) and short flow duration (tens of minutes), the samplers are small and, at Jornada, can be serviced without the need for heavy duty lifting gear. Each inner box is supported by three load cells to ensure sampler stability in the event of uneven filling (Fig. 2). The load cells are connected in parallel to provide a single voltage output proportional to the accumulating load.

CALIBRATION

Loading and unloading calibration regression equations are identical, indicating that pillow response is linear and non-hysteretic (Laronne *et al.*, 1992; Harris & Richards, 1995). We have undertaken calibrations using individual weights ranging from 4 to 65 kg. In all instances, the coefficients of determination exceeded 0.99 and the response of the pressure transducer remained linear.

We have analysed the annual variation in the slope of pillow calibration regression equations. A change in pillow response may derive from a number of factors such as minor but variable air content within the water in the pillow, variable temperature during calibration, and a change in the response of the transducer. Sampler calibration varied, often by about 5% between years. In some instances (Qanna'im), sampler calibration remained essentially constant. That the calibration factors did not consistently increase with time indicates that the manufacture of pillows by rubber vulcanization is sufficient and that it is not essential to provide a metal frame, as suggested by Harris & Richards (1995). Indeed, most of the pillows we have employed are made with material used to raise equipment weighing as much as 50 t, reflecting their strength and durability. It is evident that some samplers changed their response more than others, but it is gratifying that in almost all instances the changes are small. Whatever the reasons for the changes may be, they indicate that long term use of pressure pillow-based Birkbeck type samplers requires periodic repeat calibration, a routine common to all scientific instruments.

DATA ANALYSIS

Record termination and time averaging

Record termination takes effect when sampling efficiency decreases, often occurring abruptly. For instance, it occurs at 744 min in the centre sampler during the 21 December 2000 event in Nahal Eshtemoa (Fig. 3(a)). The time when the record should be terminated lies between two adjacent data points and the choice between them is subjective. Terminating a record before the sampler is entirely full also implies that the sediment accumulated thereafter should not be incorporated in textural analyses.

The nature of the bed load record depends in part on the interval chosen to compute flux. The bed load record shown in Fig. 3(b) is based on 4-min averaging of a 0.5-min database. By comparing it with Fig. 3(a), it is evident that the record is

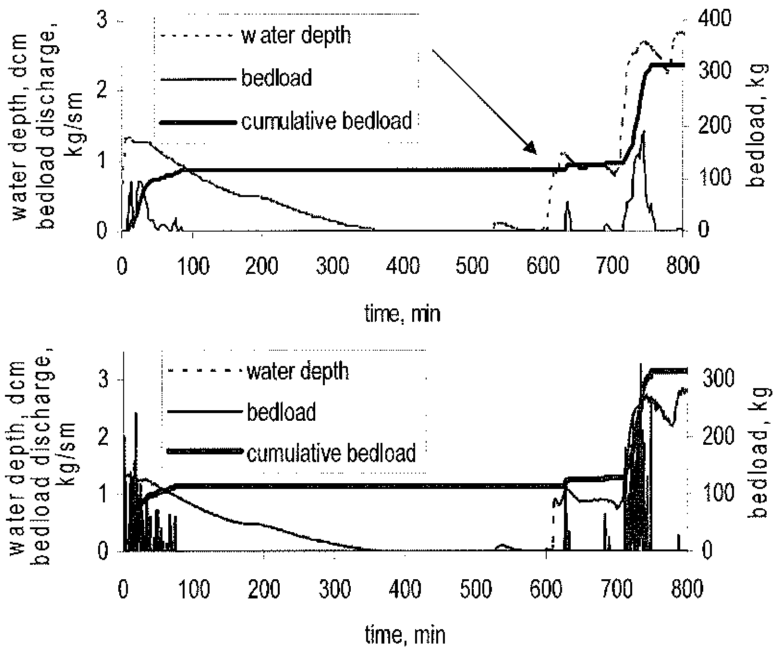

Fig. 3 (a) Stage hydrograph, bed load flux (4-min averaged) and cumulative bed load in the central sampler on the Eshtemoa, 21 December 2000. Sampler efficiency dropped at 744 min (see arrow). (b) Bed load flux (0.5-min averaged) and cumulative bed load in the central sampler at Eshtemoa, 21 December 2000. Spikiness increases as the interval of time averaging decreases.

dampened and lacks the high peaks and troughs that are characteristic of the smaller interval data. The spikiness of response is removed at progressively shorter time intervals as the average bed load flux increases.

Coping with small pressure fluctuations within the sampler

As sediment enters a sampler it falls and thereby causes a fluctuation in pillow pressure. This fluctuation dampens within a few to several dozen seconds (Harris & Richards, 1995). It is only at low transport rates that this noise manifests itself as an oscillation around a bed load flux of zero. Unless such fluctuations are dealt with, the bed load calculation procedure includes small but false values. The small oscillations are easily discerned from the untreated record. Over time, we have used two distinct methods to deal with these fluctuations. Initially, we disregarded all negative, admittedly small, values and assumed them to represent zero flux. However, the deletion of negative values does not eliminate each of the following small compensating positive values. When summing the mass of deposited bed load interval by interval, a larger value may be derived than the mass that can be stored within the box. A more sophisticated means of treating the fluctuations is to delete both the small negative values and the small succeeding positive values. All our bed load records are now subjected to this procedure. The fluctuations limit the ability of the Birkbeck sampler to determine threshold conditions under unsteady flow. But, for steady flow, the effect of these fluctuations can be eliminated by lengthening the interval over which bed load is calculated. In addition to the cautious treatment of flux values that are close to zero, only a continuous string of positive values of bed load should be used. When flux rates are very low, they should be calculated only for intervals over which the cumulative deposited sediment weighs more than the confidence limit of the calibration relation. We recommend that under no circumstances should a single positive bed load flux datum be considered.

Initiation and cessation of motion and hysteresis in bed load flux *vs* water depth relations

The record in Fig. 3(a) and (b) includes three individual hydrograph rises. A close-up view on the first rise (Fig. 4) reveals that initiation of motion occurred at considerably higher stage (and shear stress) than cessation of motion, as documented by earlier observations using Birkbeck samplers (Reid *et al.*, 1984). Indeed the Birkbeck system is sufficiently sensitive to determine these thresholds. However, incipient motion cannot be determined with this system when a flash flood bore runs over a dry bed, i.e. when the sampler is not primed. This is a common occurrence in arid-zone ephemerals (the Rahaf and Qanna'im).

The relation between bed load flux and water stage is at times hysteretic, as it is in Fig. 4. The Birkbeck sampler can determine whether hysteresis occurs, allowing a description of the direction of the relation, whether clockwise or anticlockwise.

Extending the bed load record

Continuous bed load records are notoriously short due to the limited volume of samplers. Record extension has been achieved by periodically pumping a slurry of

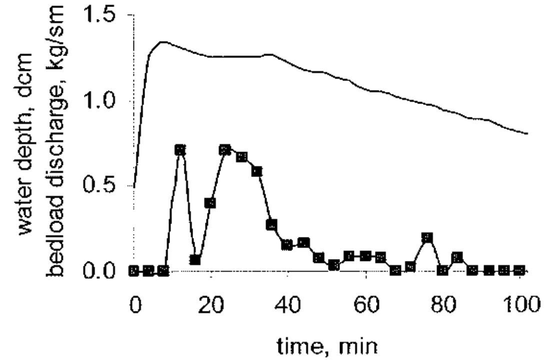

Fig. 4 Stage hydrograph (line) and record showing initiation and cessation of bed load (squares) during the first of three rises on 21 December 2000 (see Fig. 3(b) and text for details).

water and sediment from the sampler (Lewis, 1991), an ingenious solution which, however, requires attendance at the site. When flux rates are not too high, record length can be considerable if sampler volume is large. Indeed, the voluminous sampler employed in the Drau (Fig. 1) has allowed us to monitor bed load continuously for a period of up to a week (Habersack *et al.*, 2001). Bed load records may also be prolonged if one or more among a group of samplers deployed at a reach are uncovered after others have been filled. We have successfully used this method at the Eshtemoa. For instance, in one of the floods, a covered sampler was manually uncovered and began collecting bed load 7 min after the initiation of transport, by which time the four other samplers had variously accumulated 18–91 kg.

BED LOAD FLUX AND BED LOAD SAMPLING FOR TEXTURAL ANALYSES

Bed load flux

The Birkbeck system has been utilized to monitor a very wide range of bed load fluxes. This extends from a reported 0.0001 kg sm^{-1} in a perennial armoured lowland river (Sear *et al.*, 2000) to 60 kg sm^{-1} in the unarmoured, steep (2%) and braided Rahaf (Cohen & Laronne, 2000). That one relatively simple monitoring system can handle a five-fold order of magnitude range is exceptional. Self-evidently, the conditions in such diverse rivers are not only hydrologically and sedimentologically distinct (e.g. in the length of flood recession, thereby determining the extent of surface winnowing and armouring), but the monitoring and calculation steps also differ markedly. For instance, bed load flux in armoured, lowland British streams is logged every 10–30 min, whereas, in the Rahaf-Qanna'im, bed load is logged every 10 s (averaging five 2-s data). Longer logging intervals have enabled us to establish the conditions of incipient motion even when flux rates are low, such as in the Tordera, thereby determining the provenance of bed load in a sedimentologically patchy, armoured bed through a comparison of sympathetic changes in bed load and surface bed material textures (Garcia *et al.*, 1999; Laronne *et al.*, 2001).

Bed load texture

In small samplers the entire deposit can be sieved and otherwise studied. To give guidance on the suitability of a sampling strategy in larger (> 0.2 m^3) samplers, we have installed a door in the side of the inner box to view stratification (Fig. 5). This serves a similar function to the Perspex window of the inner box of the Birkbeck sampler on Goodwin Creek (Kuhnle, 1992). Assessing the accumulated material in this manner allows slicing of samples according to stratification, rather than by some arbitrary method. Stratification is best viewed after the deposit has been dewatered. To achieve a fresh, undisturbed view of stratification, it is necessary to incline the sampler away from the door before opening it. Once opened, the sediment may be lightly brushed to reveal any stratification.

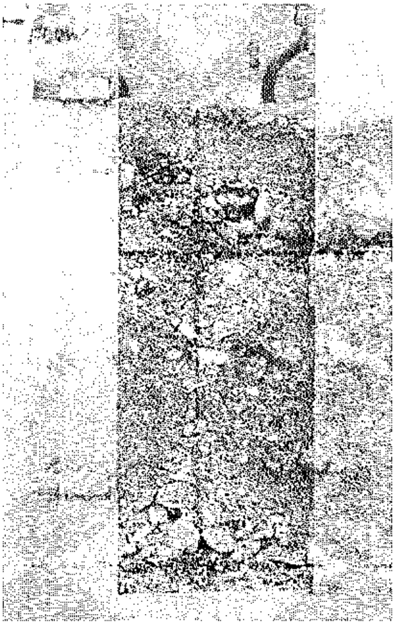

Fig. 5 Side view of Eshtemoa right-centre sampler showing accumulated, layered (arrows) bed load, (9 December 2000). Flow towards the left.

Morphology and texture of accumulating deposit: implications for sampling strategy

In the Drau, the median grain size and D_{90} of the trapped sediment remained constant throughout the bottom two thirds of accumulated sediment but decreased sideways symmetrically about the centre-line of the sampler in the upper one third (Habersack *et al.*, 2001). In contrast, in the Rahaf and Qanna'im we have observed and documented a distinct and large sideways increase in texture. This symmetric span-wise variation of texture requires that representative sediment layers be taken from the centre to either left or right wall of a sampler. The shape of the deposit is often cross-sectionally symmetric, attested by only a small difference in angle between the right and left side slopes (Figs 6 and 7). The manner of sediment accumulation implies that horizontally sliced samples represent a synchronous accumulation only for the bottom deposits—these reflect bed load at incipient motion. Horizontal slices of subsequent deposits are diachronous, the centre fraction arriving earlier than that toward the sides. Sediment within the centre third of a sampler is sub-horizontally stratified, albeit having a downstream dip of, typically, about 8 degrees. So in layer sampling the accumulated deposit, either allowance is made for the varying cross-stream angle of stratification or one accepts that the material cannot all be attributed to a single time-slice in each case.

FUTURE DEVELOPMENTS

The automatic, continuous-monitoring and direct-weighing Birkbeck-type bed load sampler will certainly undergo a variety of changes to suit future needs. These may

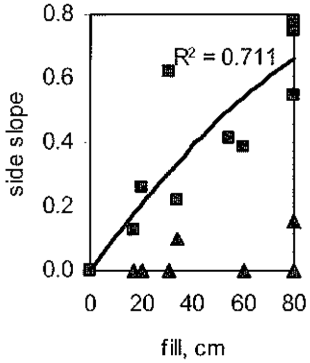

Fig. 6 Variation of sediment side-slope angle (squares) with extent of sampler fill (to which the regression line and coefficient of determination pertain). Triangles represent the difference in slope of the sediment surface between right and left sides of a sampler. Zero value refers to several instances where a thin veneer of sediment had an essentially horizontal surface.

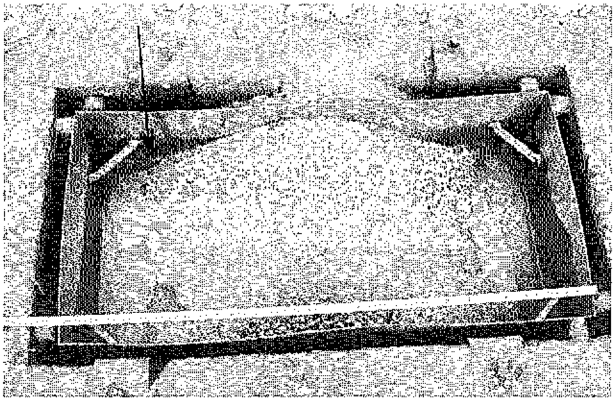

Fig. 7 Symmetrical heap of accumulated bed load. Arrow shows direction of flow.

include automatic opening of slot covers, construction of a spanwise multi-slot device, and its use for the definitive calibration of direct (e.g. Stirling & Church, 2002) and indirect (e.g. hydrophones and a variety of ultrasonic sensors) bed load monitoring systems.

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