The continuous monitoring of bedload 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 bedload 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 single and multi thread rivers 1 - 40 m wide that have a characteristic surface bed materials in the sand-granule to cobble-boulder range. Methods of construction and principles of operation, calibration, data handling as well as ranges of flux rates and textural characteristics of bedload are discussed.

KEY WORDS bedload flux, sampling, incipient motion, cessation of motion, texture

INTODUCTION

Slot (also termed pit) samplers do not affect the flow and are, therefore, more accurate than other bedload 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) 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; Sears *et al.,* 2000; Habersack *et al*., 2001; Powell *et al*., 2001). Several other methods have been used to sample bedload without unduly affecting the flow (Ashida *et al*., 1976; Lenzi *et al*., 1999), but these have not been used widely.

With a growing need for high quality, continuous bedload datasets from automatically activated samplers, we offer observations and provide operational principles of relevance to deploying the Birkbeck sampler in various environments. Further details will be included in the manuscript to be published in the IAHS red book series.

PRINCIPLE OF OPERATION

The Birkbeck bedload sampler operates on the principle of weighing the mass of bedload that enters a slot. Variations in water stage are accounted for by independently monitoring water stage *(*Reid *et al. 1980).* The sampler has a hydraulic efficiency of 100% when sediment fill is small, it is 90% at a fill of 60% and it decreases to 66% at a fill of 80% (Habersack *et al*., 2001). The bedload sampling efficiency is likely to decrease accordingly. The decrease in efficiency derives 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 fill, have been identified (Habersack *et al*., 2001). Due to the separation between the channel flow and the water column within the sampler, slot samplers are excellent separators of bedload and suspended sediment (Poreh *et a*l., 1970). The latter is deposited only at very low stage.

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 - a cement apron has been installed. Anabranches change location and bed elevation varies considerably in braided rivers. We have dealt with a rising bed elevation in the Rahaf anabranch by attaching an increasing number of 'spacers' to the sampler.

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 in straight reaches of 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. As a precaution, small vanes have been used to ensure that bedload enters only from the upper slot entrance (Sears *et al.*, 2000).

The choice of an appropriate slot width depends on the grain size distribution (gsd) of the riverbed and expected flux of bedload 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 perennials, where bedload 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 ephemerals, with bedload flux several orders of magnitude larger than in perennial counterparts over the same range of flow conditions (Laronne & Reid, 1993), increasing the slot width significantly 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 bedload fluxes, which are themselves dependent on hydraulic and hydrologic factors. In the Eshtemoa we have used a slot width of 110 mm and presently also 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 a*l., 2001).

Slot length should be larger than the maximum hop length of saltating particles. Because the truncation of gsd is commonly undertaken at a fixed size, the calculation of the slot length may be based on this a lower truncation. The maximum hop length is calculated from the Shields parameter, a hiding factor and a ripple factor (Habersack *et al.*, 2001).

Inner box dimensions and box hauling

Sampler volumes are either 0.24 or 0.48 m^3 at all our sites except the Drau (0.75 m^3), where the sampler and logger remain underwater during the entire spring and summer freshet. Other reported sampler volumes are similar except the smaller boxes used by Sears *et al.* (2000) and recently by Powell at Jornada and Walnut Gulch (see below). 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), a portable beam where channel width makes a fixture impractical (Rahaf) and where fixed installations are environmentally detrimental (Qana'im); in wide channels hauling may be accomplished from a bridge if this is sited appropriately (Drau).

PRESSURE SENSING

Neoprene pillows have been used at the Eshtemoa continuously for over a decade. Pillows rarely puncture. Puncture repair is simple, though some have contended otherwise and provided a design modification (Harris & Richards 1995). 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 at the same elevation as the pillow. Standard errors of estimates of bedload 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 pressure. In a Birkbeck sampler, the load cell is mounted on the floor of the outer box and supports the inner box in such a way 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, function independently of water stage and simple ones cost as much as locally made pressure pillows. Lewis (1991) used a single, centrally located load cell, whereas a more uniform distribution of pressure on a single load cell is attained by utilizing a stainless steel 'scissor' cradle (Sears *et al.*, 2000). Birkbeck-type samplers are currently being used by Mark Powell to study sediment transport in small rills at the Jornada, New Mexico and in a first order gully at Walnut Gulch, SE Arizona. At Jornada and Walnut Gulch, each inner box is supported by three load cells to ensure sampler stability in the event of uneven filling. 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 essentially identical, indicating that pillow response is linear and non-hysteretic (Laronne et al., 1992; Harris & Richards, 1995). Summarizing the annual variation in the slope of pillow calibration regressions, all the coefficients of determination exceeded 0.99 and response of the transducers remained linear.

Sampler calibration varied, often by about 5% between years. In some instances 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 (see Harris and Richards, 1995). 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. Whatever the reasons may be, the changes indicate that long term use of pressure pillow-based Birkbeck type samplers requires repeat calibration, a maintenance routine common to all scientific instruments.

DATA ANALYSIS

Record termination and time averaging

Record termination takes effect when sampling efficiency decreases, often occurring abruptly. 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 bedload record depends in part on the interval chosen to compute flux. As the averaging period increases, the response is dampened and lacks the high peaks and low fluxes that are characteristic of the smaller interval data. The spikiness of response is removed at progressively shorter time intervals as the average bedload flux increases.

Initiation, cessation of motion and hysteresis in bedload flux *vs* water depth relations

Close-up view of bedload records reveal that initiation of motion occurs at considerably higher stage (and shear stress) than cessation of motion, as documented by earlier observations using Birkbeck samplers. Indeed the Birkbeck system is sufficiently sensitive to determine these thresholds. However, incipient motion cannot be determined with this system in bores (sudden flash floods), particularly where the sampler is not primed. The Birkbeck can determine whether hysteresis occurs, allowing a description of the direction of the relation, whether clockwise or anticlockwise.

Extending the bedload record

Continuous bedload records are notoriously short due to the limited volume of samplers. Record extension has been achieved by periodically pumping a slurry of water and sediment from the sampler (Lewis, 1991). When flux rates are not too high, record length can be considerable if sampler volume is appropriately large. Indeed, the voluminous sampler employed in the Drau has allowed us to continuously monitor bedload for a period of up to an entire week (Habersack *et al.*, 2001). Bedload 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. During the Oct. 26, 2000 flood, a covered sampler began collecting bedload 7 min after others, at which time the other 4 samplers had variously accumulated 18-91 kg.

Coping with small pressure fluctuations within the sampler

As sediment accumulates inside a sampler, it falls and thereby creates a fluctuation in pillow pressure, which dampens within few to several dozen seconds (Harris & Richards, 1995). We have utilized two distinct methods to deal with these fluctuations. Initially we disregarded all negative, admittedly small values, and assumed them to represent zero flux. A more advanced means of treating the fluctuations is to delete the erroneous small negative values, as well as the small succeeding positive values. Moreover, only continuous traces of bedload are utilized. When flux rates are very low, they can be calculated only for intervals over which the cumulative deposited sediment weighs more than the confidence limit of the system.

BEDLOAD FLUX AND BEDLOAD SAMPLING FOR TEXTURAL ANALYSES

Bedload flux

The Birkbeck system has been utilized to monitor a very wide range of bedload fluxes. These have ranged from a reported 0.000 001 kg/sm in a perennial armoured lowland river (Sears *et al.* (2000) to 60 kg/sm in the unarmoured, steep (2%) and braided Rahaf (Cohen & Laronne, 2000). That one relatively simple monitoring system can handle a sevenfold order of magnitude range is exceptional. Self evidently, the monitoring conditions in such diversely distinctive rivers are not only hydrologically and sedimentologically distinct, but the monitoring and calculation steps also differ markedly. For instance, the Rahaf-Qana'im samplers are logged the average of five 2 s data. Longer logging time spans have enabled us to determine the conditions of incipient motion even when flux rates are low, such as in the Mediterranean Tordera, allowing us to determine the origin of the bedload from the patch-dominated, armoured bed (Garcia et al., 1999; Laronne *et al*., 2001). Birkbeck bedload flux records may also be used to evaluate bedload equations (Reid *et al.*, 1996).

Bedload texture

In small samplers the entire deposit can be sieved and otherwise studied. To sample the trapped bedload in larger (> 0.1 m^3) samplers, we have installed a door in the inner box to view stratification. This allows slicing of samples according to stratification, rather than 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.

Morphology and texture of accumulating deposit: implications for sampling strategy

Unlike in the Drau we have observed and documented in the Rahaf and Qana'im a distinct and large sideways increase in texture. The 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 was often cross-sectionally symmetric, attested by small difference in angle between the right and left side slopes. This implies that horizontally sliced samples represent a synchronous accumulation only for the bottom deposits. So in layer sampling the accumulated deposit, either allowance is made for the varying angle of stratification or one accepts that the material cannot all be attributed to a single time-slice.

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