Published online in 2010 as part of U.S. Geological Survey Scientific Investigations Report 2010-5091.

Essential Ancillary Data Requirements for the Validation of Surrogate Measurements of Bedload: Non-invasive Bed Material Grain Size and Definitive Measurements of Bedload Flux

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Abstract

Achieving a significant advance in understanding the sedimentary dynamics of rivers, especially those with coarse-grained beds, depends upon the acquisition of data that adequately reflect sediment flux. In a similar vein, the successful development of a functional relation between bedload flux and contemporary hydraulics that is transferable from river to river requires an understanding of relations between the immediate source of bedload – the river bed – and the flow. This would benefit from deployment of a quick but efficient method of assessing the grain-size distribution of river-bed material, since this is one of several determinants of bedload flux and is a property that can be readily established in a previously ungauged channel. This paper reminds hydraulic engineers and geomorphologists of the need to deploy a method of data capture that allows the performance of surrogate measures of bedload to be assessed adequately. In particular, it highlights the performance and short-comings of the Birkbeck Sampler. This is an automatic slot sampler that provides a continuous, direct and sensitive measure of bedload flux that is as definitive as is feasible in the complex confusion of a river in spate. It has been deployed in a wide range of river environments and has proved to be both reliable and durable, having provided bedload records on ephemeral channels for more than a decade in one case. The paper also indicates a need for the use of a method that facilitates rapid and frequent surveys of river-bed materials in order to understand bedload dynamics that are measured by any means, not least those that detect bedload surrogates. The Digital Gravelometer is described, along with its advantages and limitations. Time-savings alone make this a valuable addition to the river scientist's tool-kit.

Introduction

The development of a technique for the surrogate measurement of bedload flux under field conditions has remained stubbornly elusive for more than half a century. The deployment of a hydrophone by Ivicsics (1956) gave promising results. However, subsequent instrumental development has been spasmodic despite the fact that advances have been facilitated by rapid developments in electronic signal capture and data processing (e.g. Downing et al., 2003). The challenge has been to produce an instrument that yields a signal that can be translated as an unequivocal representation of bedload flux. A further challenge has been the capture of information that provides an adequate indication of the grain-size distribution of the mobile material (Rickenmann and McArdell, 2007). In this context, there has been a pressing need for simultaneous deployment of a means by which bedload can be sampled as definitively as is practicable in order to yield data against which the results of surrogate measures of flux and mobile grain size-distribution can be rated.

Such validation is essential, but has almost always been lacking. The availability of large flow channel facilities as test-beds in which direct observations of bedload can be made and where mobile material can be captured has helped. However, the replication of field conditions has always been uncertain and, of course, there are limits to the size of grains that can be mobilized in flumes, so reducing the range of conditions over which the surrogate technique is tested and, consequently, the level of confidence in field data where the bed material and load involve larger grains. There is, therefore, a continued need to provide and improve methods of definitive bedload data capture that can be used for rating surrogate measurements.

In a similar vein, there has been a pressing need to develop a non-invasive method of establishing the grain-size distribution of the bed materials that act as the chief reservoir feeding the bedload process. Such a method needs to provide accurate information, be transferable from channel to channel with no need for re-parameterizing the procedure, involve minimal time for data capture in the field, and provide a means of achieving comprehensive coverage of the channel bed. These attributes would facilitate the repeat surveys needed to document the sedimentary changes brought by flood events. In addition, if the method minimized or eliminated disturbance of a site, this would ensure that the bedload sediment reservoir were not affected by the process of obtaining the data. Such a method has now been developed and will be presented, together with its limitations.

Definitive Measurement of Bedload Flux

Bedload samplers with horizontal slots are expensive to install and even more expensive to maintain. Installation may be problematic (e.g. where the channel-bed is not alluvial) and a significant consideration is that the infrastructure required commits the monitoring to a predetermined location. If the location turns out to be sub-optimal, relocation is expensive and the new site may be equally sub-optimal. Both the cost and the cumbersome nature of the installation usually preclude establishment of multiple sampling locations on the same river. If the slot sampler is more than just a passive sediment collector and is intended to provide values of bedload flux over short intervals, as would be required of a system against which to rate indirect measurements, the level of investment rises dramatically.

All these factors have encouraged the development and use of portable samplers that present to the flow a vertical slot and which are deployed manually over short intervals (e.g. Helley and Smith, 1971). A variant, which is semi-permanently installed, attempts to overcome some of the problems associated with repeated introduction of the sampler (Bunte, et al., 2004). Whilst acknowledging the attraction of cheap, portable measuring devices, their shortcomings have always been acknowledged, either in determining bedload flux or in representing adequately all the grain sizes mobilized (Bunte et al., 2004; Childers, 1999; Emmett, 1980; Novak, 1957; Ryan and Porth, 1999; Sterling and Church, 2002; Vericat et al., 2006). Because of the popularity of using portable samplers, despite their shortcomings, and because of the small number of fixed field installations (pit samplers), it could be argued that one of the most significant stumbling-blocks for evaluating any instrument that purports to provide a surrogate of bedload flux is not development of the instrument itself, but rather the validation of its signal against bedload flux measurements that can be considered definitive.

The Birkbeck Bedload Sampler

Horizontal slots have the advantage of being hydraulically ‘invisible’ i.e. they do not intrude on the flow and do not, therefore, increase local flow resistance or encourage back-watering. Poreh et al. (1970) have shown that the efficiency of slots in sampling passing bedload is virtually 100 percent under a range of flow conditions, providing the ratio of streamwise slot length to mobile grain size is between 10 and 20. Habersack et al. (1998) assessed flow structure within the collecting box of a large Birkbeck Sampler and found the velocities associated with vortices to be insignificant in the context of disturbing entrapped sediment up to a fill-stage in excess of 60 percent. Even at a fill-stage of 80 percent, velocities that might disturb sediment were confined to the centre of the pit, causing redistribution of entrapped sediment within the collecting box rather than ejection.

Of the slot samplers, the Birkbeck Sampler (Reid et al. 1980; Laronne et al. 1992, 2003; Fig. 1) has one advantage over others of the type (e.g. vortex tubes, Milhous, 1973; slot and conveyor-belt, Leopold and Emmett, 1997): it operates automatically. This has at least two benefits: it cuts the cost of data acquisition dramatically; and, where flood flows are discrete and rain-fed, it ensures the capture of data even if operatives are unable to be on-site.

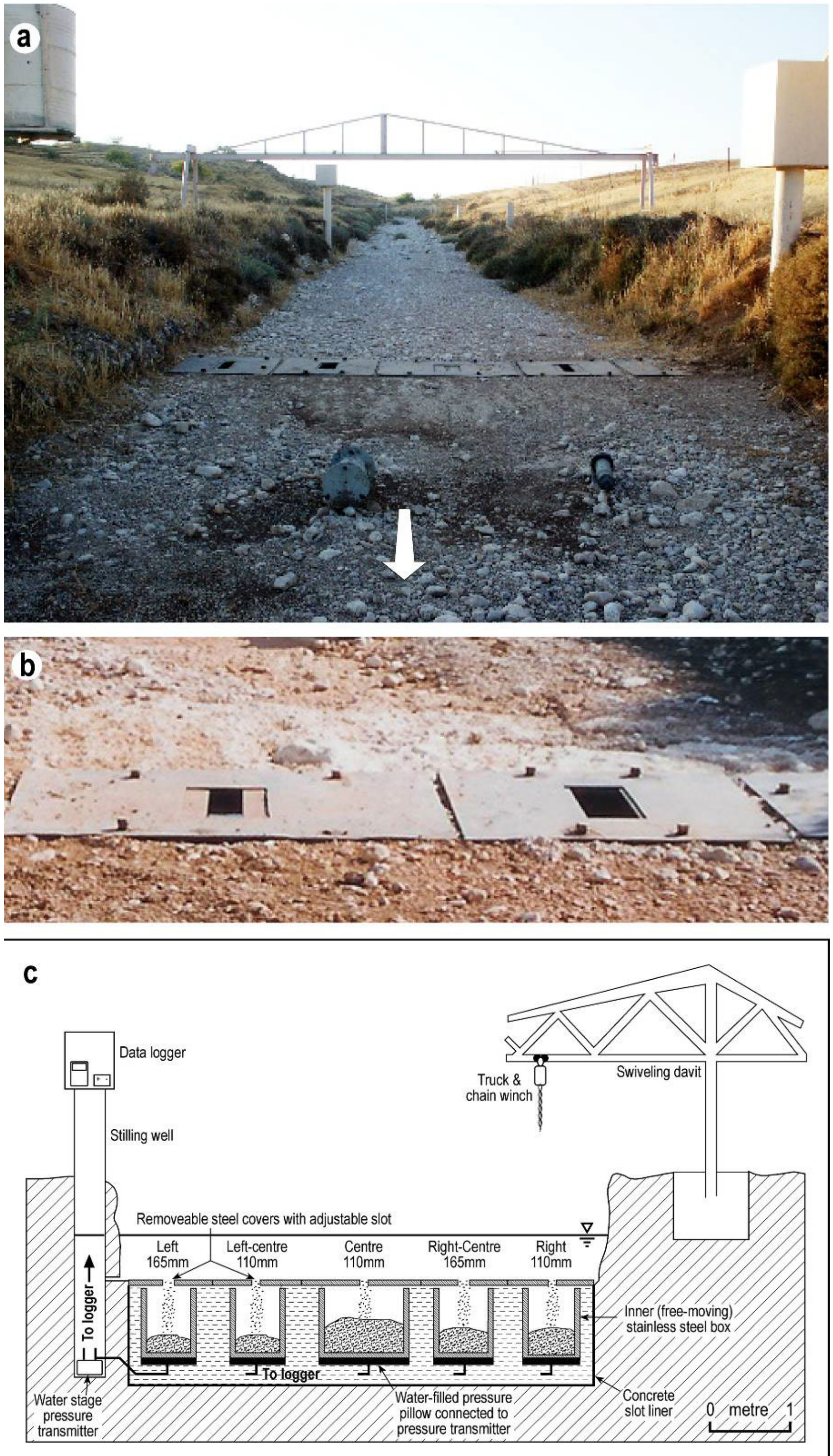

Figure 1. (a) View of Nahal Eshtemoa upstream through the bedload monitoring station. (b) Close-up of two of the Birkbeck slot samplers showing slot width adjustment. (c) Schematic of the five independent Birkbeck Bedload Samplers installed in the Nahal Eshtemoa.

Another significant advantage of the Birkbeck Sampler is that it provides a continuous record of bedload (Fig. 2).

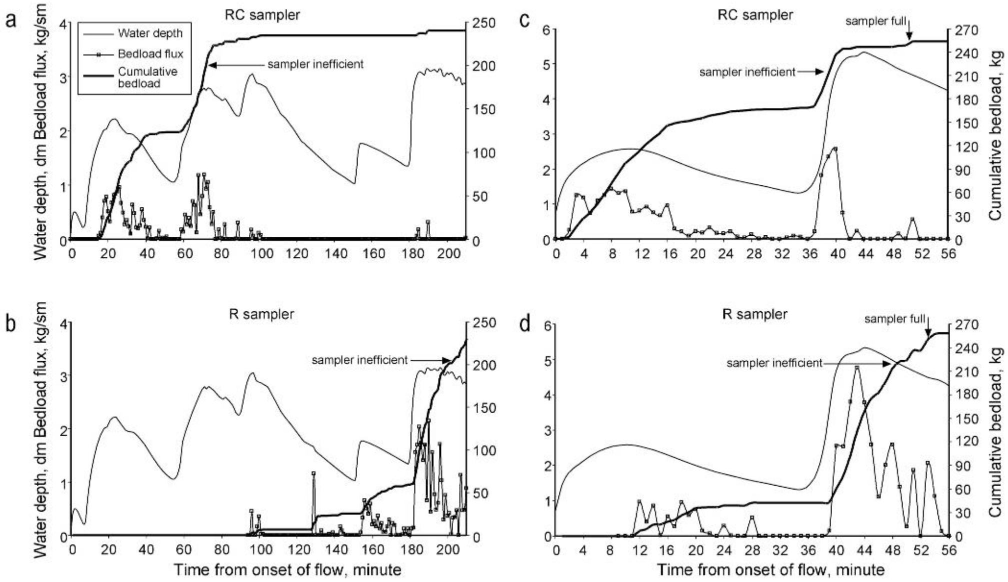

Figure 2. Water depth (thin line), bedload flux (line with symbols) and cumulative bedload mass (thick line) during flash-floods in the Nahal Eshtemoa: (a,b) 9 December 2000 (c,d) 26 October 2000. Note that the cover on Sampler R was removed at minute 94 during the 9 December 2000 event and at minute 9 during the 26 October 2000 event, so delaying the measurement of bedload relative to the RC Sampler, which accepted bedload from the onset of each event.

Its disadvantage is that it has a finite capacity. Without the use of devices such as a sludge pump to empty the accumulating sediment (Lewis, 1991), the sampler fills and eventually ceases to yield data. In an attempt to extend the bedload record, we have deployed a removable cover that initially masks the slot, preventing ingress of sediment until the cover is removed (Bergman et al., 2007). Used in conjunction with other samplers that receive sediment from the inception of bedload movement during passage of a flood, the bedload record is thereby extended (Fig. 2). But the value of this is tempered by the fact that the extended record is composed of measurements collected at different points in the channel cross-section. This could be remedied by installing a second sampler immediately down-channel along the same streamline as the sampler with the removable cover and allowing this to entrap sediment during the period after initial entrainment. The upstream sampler cover would be removed at some predetermined time in order to capture later phases of bedload along the same downstream flow path.

Alternatively, in the absence of using a sludge pump to empty the sampler during spate, a larger collecting box can be used (see Mizuyama et al., this volume). However, one complication of also deploying a longer slot is that the hydraulic 'invisibility' of the sampler decreases with increasing slot length because, with increased length, flow instability is induced by the interaction of the within-sampler vortices and the channel freestream (Ethembabaoglu, 1978). This will impact on sampler efficiency by encouraging winnowing of the entrapped sediment at high fill-stage.

Sampler capacity is a particular problem in ephemeral channels such as the Nahal Eshtemoa, where bedload flux is several orders of magnitude higher than in armoured perennial channels (Reid and

Laronne, 1995). Capacity problems were also sometimes experienced in the armoured perennial Turkey Brook (Reid et al., 1985). However, here, the receiving boxes were small (c. 0.24 m^3). Of the samplers deployed on the Nahal Eshtemoa, that with the largest capacity (0.4 m^3) would provide, *ceteris paribus*, 94 h of continuous record at fluxes typical of armoured perennials such as Turkey Brook (0.01 kg m^{-1} s^{-1}) and 9.4 h at extraordinary (for armoured perennials), short-lived fluxes of 0.1 kg m^{-1} s^{-1}. The large Birkbeck Sampler, deployed on the Drau River, Austria, with a capacity of 0.75 m^3 (Habersack et al., 2001), could provide a record of 177 and 17.7 h at the same fluxes. Considerably larger Birkbeck Samplers are being deployed in Japan. The largest, on the Uonogawa River (see Mizuyama et al., this volume), has a capacity of 6 m^3 and this would give a record of 1410 h and 141 h at fluxes such as those typically measured in Turkey Brook.

The cost of installing a single Birkbeck Sampler will vary by country (because of differences in labour or machinery hire charges) and with site and channel characteristics. In perennial rivers, there is the logistical challenge of creating a permanent pit-lining in the channel bed. In small channels with marked seasonal low flow, a coffer, or stream diversion, or damming and pumping might suffice to allow subaerial excavation of the bed and installation of the lining, whether from pre-cast components or by casting concrete on site (e.g. Turkey Brook, Reid et al., 1980). In the larger Drau River (width = 40 m; mean annual discharge = 64 m^{-3} s^{-1}; bankfull discharge = 250 m^{-3} s^{-1}; Habersack et al., 2001), a large-diameter pre-cast sewer pipe acted as the liner and was inserted in a submerged hole made by a large mechanical excavator able to enter the river. Ephemeral channels such as the Nahal Yatir (Reid et al., 1995) and Nahal Eshtemoa (Powell et al., 2001) present less of a challenge, since they are dry for 98 percent of time.

In addition to the pit-liner, the other components of a Birkbeck Sampler are: a pressure pillow attached to a pressure transducer (or, better if the logger is distant, a pressure transmitter), or a load cell (although, an array of three provides better stability) for establishing the changing pressure head of both the overlying water column and the accumulating sediment; a pressure transducer and stilling-well for measuring water-stage; a removable sediment-collection box, commonly of stainless steel or marine ply, equipped with rings for hauling; a pit cover made of steel or ply that incorporates the slot (preferably adjustable); and a data logger and instrument housing. In addition, a means of hauling the inner box is crucial to servicing the sampler and sampling the accumulated sediment systematically for grain-size. At its simplest, this might include a portable sheer-legs and winch that can be removed from the channel after servicing. In the Rio Tordera (Garcia et al., 2000), a truck and winch are slung from a fixed I-beam spanning the channel. In Turkey Brook, the Nahal Yatir and Nahal Eshtemoa, swivelling davits mounted on the river bank carry a truck and winch (Fig. 1). Here, once hauled from the pit, each inner box is swung downstream of the samplers so that the likelihood of accidentally knocking sediment into the pits and onto the pressure pillows is minimised. Where water depths preclude in-channel servicing, an I-beam or davit can be arranged such that the inner boxes are transferred to the river bank, where sediment sampling can take place.

Non-Intrusive Determination of Bed Material Grain Size

An understanding of sedimentary dynamics (e.g. entrainment thresholds and selective sorting by grain size) as part of a bedload monitoring programme requires an assessment of the channel-bed source material. The same is required in the predictive modelling of sediment flux. These and other purposes (which include ecological monitoring) benefit from frequent, non-invasive and comprehensive monitoring of the grain-size distribution of the channel bed. The problem is arguably more complex in gravel-bed rivers and it is for these channels that a method for the rapid acquisition of field data and the production of grain-size distributions of surface sediments has been developed (Graham et al., 2005a and b).

The Digital Gravelometer

The Digital Gravelometer – an automatic grain sizer - uses large-scale digital imagery and a user-friendly computerized algorithm that identifies and quantifies individual grains above a given size threshold. Compared with standard grid-by-number sampling (Wolman, 1954), the automatic grain sizer takes between one-sixth and one-twentieth of the time to yield a grain-size distribution.

Graham et al. (2005b) were not the first to develop an automated method using digital imagery and others have been published recently (e.g. Butler et al., 2001; Sime and Ferguson, 2003). What The Digital Gravelometer offers is a procedure that has been thoroughly tested on a wide (though not comprehensive) range of natural river gravels that have different grain shape, roundness and *in situ* fabric (Fig. 3).

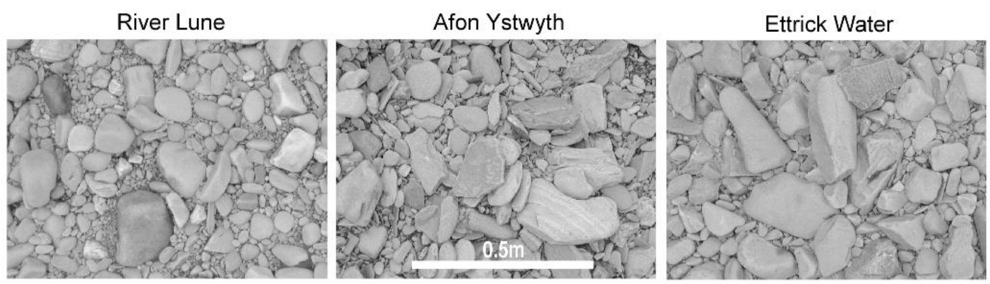

Figure 3. Typical bar sediments used to assess the performance of The Digital Gravelometer: equant, rounded, pale limestone and occasional dark sandstone clasts of the River Lune, England; platy, dark, fine-grained gritstone clasts of the Afon Ystwyth, Wales; equant, sub-angular to sub-rounded, speckled, pale, gritstone and shale clasts of the Ettrick Water, Scotland.

The field operation requires a digital camera (preferably having a CCD array that gives an image of at least 6 Megapixels) with flash (preferably separate from that often built into the camera) and, for scaling, a means of identifying points of known relative location in an image. For this, Graham et al. (2005b) use a wooden quadrat, 1.5 x 1 m that can be assembled on-site. In order to ensure good grain separation on the imagery acquired, shading of the target from direct sunlight is essential in all but overcast conditions. It is advisable, therefore, to carry some sort of parasol. For this, a bed sheet attached to a frame with outside dimensions 2 x 2 m, assembled on site, is convenient in all conditions except high winds. With the quadrat in position and (as needed) the parasol used to shade the target, the camera is held at shoulder height (lower or higher, depending on the resolution required; Fig. 4). A two-person team (one operating the camera and quadrat, the other the parasol) can move on from a single target in about 30 seconds, covering a whole river bar in a short time. If required, the centroid of each target area can be surveyed subsequently if a suitable marker is left at each. This allows registration of the images in a coordinate system that is tied to a known origin.

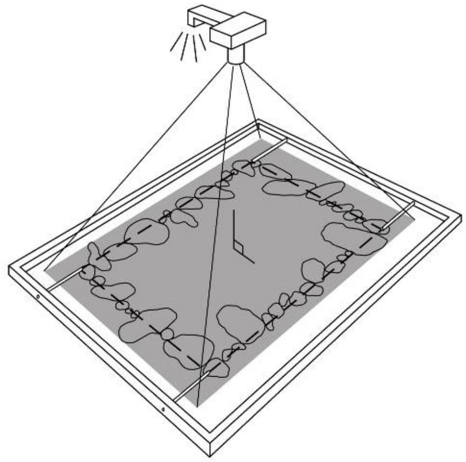

Figure 4. Schematic of procedure for digital image capture, showing handheld camera and quadrat with registration pins for rectification of the image. Note: unless the sky is overcast, the target area must be shaded from direct sunlight. The target should be illuminated by flashlight.

Using The Digital Gravelometer, the geometry of the image is corrected to account for any non-verticality of the camera axis using the known points in the image. Optionally, the effects of radial lens distortion may be corrected. The automated grain sizing procedure involves the application, in turn, of a grey-scale filter and a morphological bottom-hat transform. Object (i.e. grain) segmentation is achieved by applying, first, an adaptive double-threshold to the image-intensity and, second, a watershed segmentation with minima suppression (Fig. 5; Graham et al., 2005a and b).

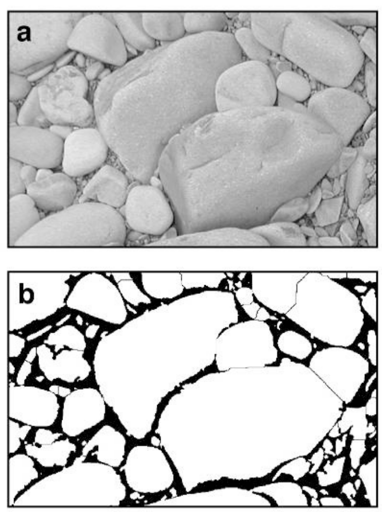

Figure 5. An example of the results of the image-processing procedure developed for The Digital Gravelometer: (a) extract from the digital image of the limestone clasts of the River Lune; (b) the same extract after segmentation by the image-processing procedure.

At this point, the image should be checked to ensure segmentation has been successful – this is the only time that operator intervention is required and then only for quick visual quality control. The b-axis of each grain is then defined using an ellipse-fitting routine and a correction is applied to make the results directly comparable with data derived from grading using square-hole sieves, if desired. With or without the correction, a cumulative grain-size curve is produced in a number of elected forms - area-by-number, grid-by-number equivalent – and grain sizes at standard percentiles are derived. The entire procedure is complex but, apart from image capture, fully automated. Further details are given in Graham et al. (2005a and b), as well as at *http://www.lboro.ac.uk/research/phys-geog/* where comprehensive information about The Digital Gravelometer can be found.

The Digital Gravelometer has been tested on a large number of *in situ* river gravels, the D_{50} of which ranges from 4 to 6.5 ψ (32 to 91 mm) and the D_{100} from 6.5 to 8.5 ψ (91 to 362 mm). The performance is impressive and comparable to that of a 100-grain Wolman sample. The mean square error at all percentiles of the size distribution except those of the upper decile is 0.05 ψ, while in the upper decile the error is 0.1 ψ (Fig. 6).

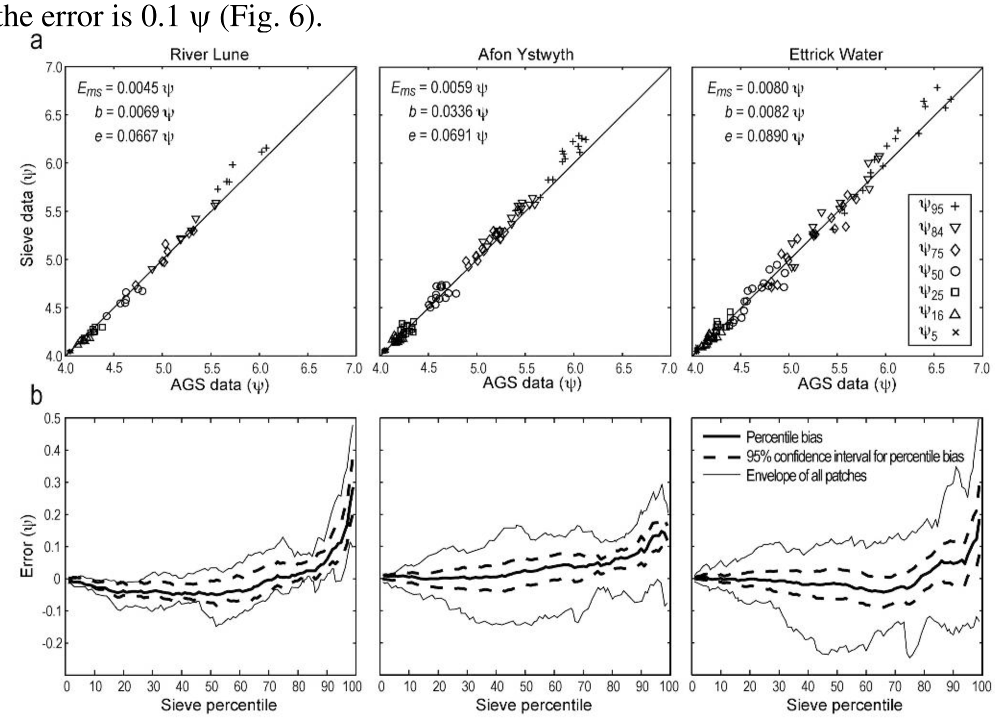

Fig. 6 – Performance of automatic grain sizer (AGS) - The Digital Gravelometer - when rated against sieve data for patches on the River Lune, Afon Ystwyth and Ettrick Water: (a) grain-size at specified percentiles (b) error at each percentile of the size distribution – bold and pecked lines are the bias and 95% confidence interval; the thin lines delineate the envelope for all samples. E_{ms} = mean sq. error; b = bias; e = irreducible random error.

The principal benefit of The Digital Gravelometer is the speed with which data are acquired and analysis is carried out. The software undoubtedly pays its way within the time it takes to acquire only a few samples. However, it has other significant benefits. Amongst these are: (i) that the ease of data capture facilitates multi-epoch assessment without disturbing the channel bed; (ii) surface facies can be distinguished and separately sampled in the field or subsequently and differently by aggregating selected images; (iii) the full inventory of grains is kept in digital form for later interpretation of e.g. grain shape, attitude etc; (iv) rapid data collection facilitates greater areal coverage for the same field effort, thereby making it feasible, for the first time, to capture data over large areas and, assuming an appropriate sampling design, thereby characterise bed material heterogeneity in bedload source areas with an unprecedented degree of accuracy; and (v) automation removes the operator variance associated with Wolman sampling (Wohl et al., 1996).

Disadvantages are: (i) that the procedure can currently be applied only to exposed sediments and a supplementary method of underwater sampling needs perfecting; and (ii) sand-sized material may lie below individual grain resolution and, as such, patches of sand may be delimited as large grains. However, current deployments using larger scale imagery (close-up focus) and the increasing affordability of cameras with large CCD arrays mean that resolution of grain size can lie in the sand fraction, if so desired.

Conclusions

Alongside the desirability of developing instruments that provide surrogates of bedload flux is a need to ensure the development and availability of methods to interpret the output signal. Because of the difficulties of contriving a water-lain alluvium in a laboratory flow channel and mobilizing it, these developments may most usefully be carried out in the field, despite all the logistical difficulties that this entails. This would help prevent the river sediment-transport community diverting down cul-de-sacs, misled by the limited realism of flume sediment dynamics, and expedite understanding of bedload transport phenomena.

We offer here two methods that are ancillary but vital to the development of surrogate bedload monitors. The Birkbeck Bedload Sampler provides a continuous measure of bedload flux against which surrogates can be rated. The Digital Gravelometer provides a means of encouraging multi-epoch sampling across large areas of the channel bed, so facilitating a fuller interpretation of the bedload record.

Acknowledgements

Numerous people have helped in the field and the laboratory. We are particularly indebted to: Yulia Alexandrov, Nati Bergman, Andrew Brayshaw, Tom Buffin-Bélanger, Hai Cohen, Lynne Frostick, Celso Garcia, Helmut Habersack, John Layman, Mark Powell, Natasha Todd-Burley, and Yitshak Yitshak. Funding for initial development of the Birkbeck Bedload Sampler (while IR was employed at Birkbeck College, London) came from the University of London Central Research Fund. The monitoring station on the Nahal Eshtemoa was funded by the Natural Environment Research Council of the UK, the Israel Academy of Sciences, the Israel Ministry of Agriculture, the Jewish National Fund and the Israel Water Authority. Funding for development of The Digital Gravelometer came from The Leverhulme Trust, The Gatsby Foundation and Loughborough University. Field and laboratory assistance was provided by Ian Dennis, Georgina Endfield, Julian Green, Helen Greenwood, Barry Kenny, Phillippa Noble and Alistair Rennie. We are grateful for the constructive reviews by Bill Emmett and Judy Haschenburger, which have helped us improve the paper.

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