DEVELOPMENT OF AN IMPROVED BEDLOAD TRAP FOR SAMPLING GRAVEL AND COBBLE BEDLOAD IN COARSE MOUNTAIN STREAMS

Kristin Bunte[1], John P. Potyondy[2] and Steven R. Abt[3]

[1] Colorado State University, Fort Collins, Colorado, kbunte@engr.colostate.edu
[2] USDA Forest Service, Rocky Mountain Research Station, jpotyondy@fs.fed.us
[3] Colorado State University, Fort Collins, Colorado, sabt@engr.colostate.edu

Keywords: coarse bedload sampling, rating curve, flow competence, incipient motion,

ABSTRACT

Bedload traps are portable, cost-effective, and appropriate samplers for gravel bedload. They are easy to install and operable in wadable flow. Their long sampling time reduces variability in sampled transport rates and avoids sampling bias; sampling efficiency is generally satisfactory. Bedload rating curves for total and fractional gravel transport as well as flow competence curves obtained from bedload traps are generally steep and relatively well-defined. The ability to sample marginal transport rates permits direct measurement of incipient motion. Bedload traps also appear suitable as calibration tools for electronic devices.

INTRODUCTION

Gravel- and cobble-bed streams are formed by the transport of coarse bedload. However, accurate measurements of gravel and cobble transport rates and particle sizes are still difficult to obtain. Electronic devices are not (yet) advanced enough to provide a reliable conversion between recorded signals and the number and the size of particles moved. A physical sampler is therefore needed to provide accurate and sievable samples of coarse bedload that can be related to instantaneous flow and used for calibration of signals rates.

Vortex samplers (e.g., Milhous 1973, Hayward and Sutherland 1974, Tacconi and Billi 1987) and continuously weighing pit samplers (e.g., Lewis 1991; Powell et al. 1998; Sear et al. 2000; Reid et al. 2002) can provide representative measurements of instantaneous transport rates of gravel and cobble bedload in mountain streams. However, substantial streambed construction is involved in the installation, which makes these devices difficult, time-comsuming and costly to deploy and also unsuitable for remote sites.

Small non-recording pit trap samplers (e.g., Church et al. 1991; Wathen et al. 1995; Bunte 1997; Hassan and Church 2001; Sterling and Church 2003) can be installed in a streambed by a small field crew with shovels and buckets. However, trap operation is limited to flows in which an operator can reach down to the stream bottom to empty the traps. Pit traps also have highly variable sampling efficiency. During high flow, sand and fine gravel may travel in suspension, and given a sufficiently high energetic flow, even mid-sized gravel particles may skip over the trap opening. Together with the problem of resuspending particles already captured in the trap and losing them from the sample, both processes lead to diminishing trap efficiency and underprediction of transport rates at high flows. The sampling efficiency may vary spatially as well, because flow energy often increases at an uneven rate over a cross-section.

Net-frame bedload samplers have openings several square feet large and collect gravel and cobble particles in long and relatively coarse-meshed, trailing fishing nets. These large samplers have been successfully used to sample gravel and cobble bedload over a wide range of flows (Bunte 1996; Whitaker and Potts 1996; Whitaker 1997). However, applicability of net-frame samplers is limited because they require a bridge with sturdy vertical bars for support, a sill on the stream bottom for good ground contact, and the strength of several people to operate.

Bedload traps discussed in this paper overcome many of the deficiencies listed above and were developed under a cooperative agreement between the USDA Forest Service's Stream Systems Technology Center and the Engineering Research Center at Colorado State University. The primary motivating force behind development was a need by the Forest Service to accurately and easily measure the onset of gravel and cobble bedload transport in remote mountain streams for the purpose of quantifying channel maintenance instream flows on National Forest land. While the original intent was limited to the determination of incipient motion, subsequent analysis has demonstrated that data collected with the bedload traps in coarse-bedded streams can also be used to determine cross-sectional transport rates and establish bedload transport rating curves.

To achieve the objective of accurately measuring the onset of gravel and cobble bedload transport, bedload traps had to representatively collect all mobile gravel particle sizes, cause minimal stream bed disturbance, and be easy to operate in wadable flow.

A suitable bedload trap would therefore have to meet the following design criteria:

- Have a sufficiently large sampler entrance to allow cobbles to easily enter,
- Be stationary to allow for long sampling times to increase the probability of sampling infrequently moving particle sizes,
- Have a large bag to collect a large sample volume without reducing sampling efficiency,
- Have a comparatively large mesh width to keep flow resistance at a minimum,
- Be lightweight for portability,
- Be operable in flow depths and velocities as long as the stream remained wadable, and
- Require no more than two persons to operate in the field.

BEDLOAD TRAPS: DESIGN AND OPERATION

Given the above design criteria, a sampler was designed consisting of the following parts (Fig. 1):

- Sturdy aluminum sampler frame,
- Sampling bag made of fishing net,
- Nylon straps with friction buckles,
- Aluminum ground plate, and
- Two smooth iron holding stakes.

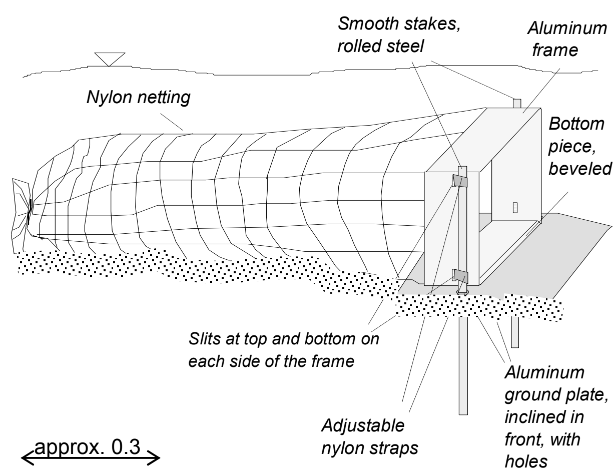


Fig. 1: Schematic Diagram of a Bedload Trap.

Bedload traps developed for collecting gravel (> 4 mm) and small cobble bedload consist of an aluminum frame, 0.3 by 0.2 by 0.1 m in size that is temporarily strapped onto a ground plate anchored into the stream bottom by metal stakes. Bedload is collected in a trailing net of approximately 25 liter volume (6.4 gal.), 0.9 m long and with a 3.5 mm mesh width (Figs. 1 and 2). Sampling capacity is estimated as 40% of the sampler volume (i.e., 10 liters or 20 kg of gravel). Several bedload traps are typically installed in roughly 1-m spacing across the stream on a riffle or a stream widening that will be wadable to flows of bankfull or more (Fig. 3). During the

Fig. 2: Detail of Bedload Trap with Ground Plate.

Fig. 3: Four Bedload Traps Installed at Little Granite Cr. at Low Flow (2002).

sampling period (which is usually one hour), the end of the net is tied shut with a piece of cotton covered rope. The net can be untied and emptied with the traps in place, or the traps can be removed from the ground plates and brought to the bank for emptying. Operation of the bedload traps is easy in wadable flow but becomes more difficult as flow reaches the limit of wadability (Fig. 4) (Abt et al. 1989) and may require a 3-person team and/or the use of safety devices (e.g., safety ropes, belaying, temporary footbridge).

Bedload trap samples may contain large amounts of coarse organic material, particularly when sampling in forested watersheds during the rising limb of snowmelt highflow (Fig. 5). These organics need to be separated from the gravel before bedload transport can be analyzed.

Fig. 4: Emptying Bedload Traps at Above Bankfull Flow at Cherry Cr., 1999.

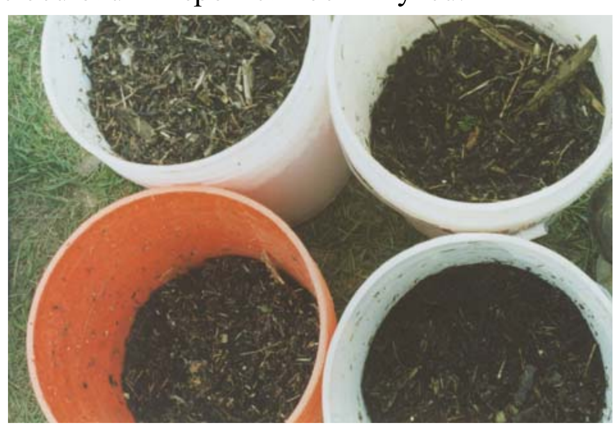
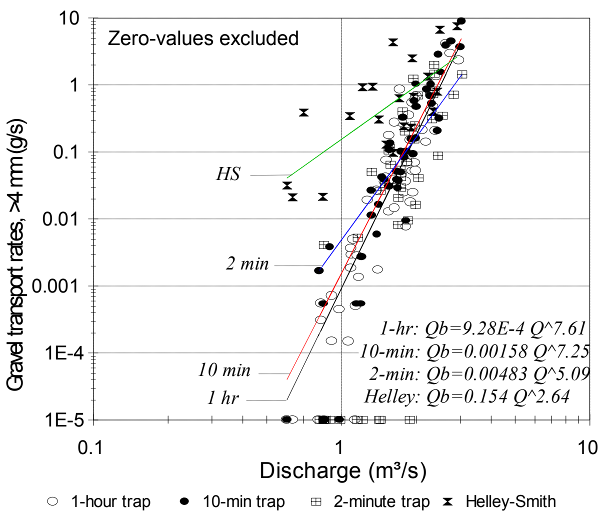


Fig. 5: Large Amounts of Organic Material may be Collected in the Bedload Traps.

Sampling time

Bedload traps are designed for sampling times of about one hour. A 1-hour sampling time is usually feasible up to moderately high flow but fast changing flow or high transport rates may necessitate shorter times. A long sampling time (or a large number of short-duration samples) is necessary for representative sampling of fluctuating transport rates for several reasons: (1) Long deployment averages transport rates and reduces the measured variability. (2) It decreases the undersampling bias that occurs when short (or only a few) samples are collected from lognormally- or Hamamori-distributed transport rates which are skewed towards large rates (i.e., mode and median rates are smaller than the mean). (3) When particles of the size classes just becoming mobile move infrequently (e.g., once per hour), a long sampling time prevents an overprediction of transport rates that occurs when an infrequently moving particle is collected by chance and allotted to a short sampling time (Bunte and Abt, submitted). Avoiding these sampling biases, bedload traps deployed for one hour provide steeper and more well-defined bedload rating curves than those obtained from a 2-minute deployment (Fig. 6a), even if legitimate zero-samples (i.e., those that occurred at flows larger than the smallest non-zero sample) are included in the power function regression analysis (Fig. 6b).



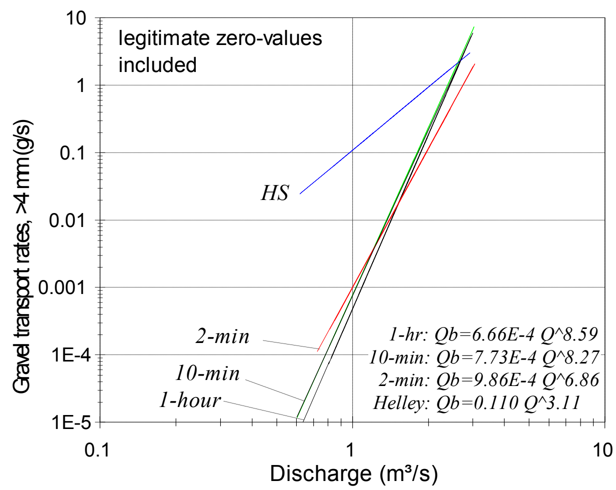


Fig. 6a: Bedload Rating Curves from Different Sampling Times with Bedload Traps and Helley-Smith sampler (HS) at Little Granite Cr., '02.

Fig. 6b: Rating Curves from Different Sampling Times: Zero-Values Included in the Regression Analysis.

Sampling efficiency

Bedload traps appear to have a satisfactory sampling efficiency within the limitations posed by the design. The presence of a ground plate under the sampler prevents inadvertent particle entrainment and thus oversampling. The long-duration deployment reduces positive and negative bias in samples at low and high flow typically associated with short collection times (see above). However, if the traps are allowed to fill beyond their capacity (which may happen during a 1-hour sample when large amounts of coarse organic material is transported or when gravel transport rates are high), transport may be underestimated. To prevent this bias, several shorter duration samples need to be collected. With the current size and mesh width of the bag, small cobbles are the largest particles that can be sampled representatively, although larger ones fit into the sampler opening. This limitation arises because transport rates are usually so high when cobbles start to become mobile that the bag fills beyond capacity before enough time has elapsed to permit infrequently moving medium and large cobbles to be properly sampled.

Detailed field measurements of velocity profiles at the trap entrance, along the ground plate, and on the bed upstream of the plates, showed that bedload traps do retard the mean flow velocity in the water column, particularly when the net is filled to capacity. However, this retardation is counteracted by an acceleration of the bottom flow velocity due to the smooth aluminum surface of the ground plates. Particles that moved onto the ground plate are usually transported immediately into the sampler. A delay in particle capture may occur if a small recirculating eddy develops at the transition between the bed and the ground plate. Small particles may swirl around in this eddy for a while before entering the trap. However, significant sediment build-up or a scour trough has not been observed in this location. Flume studies to fully evaluate the sampler's inflow velocity distributions and hydraulic efficiency are being planned.

RESULTS

These bedload traps have been used to collect gravel and small cobble bedload in several coarse-bedded Rocky Mountain streams. Study streams have gradients of 0.093 to 0.012, basin areas of 8 to 55 km^2, bankfull flows of 0.8 to 5.7 m^3/s (26-200 cfs), and surface D_{50} particle sizes of 49 to 108 mm. Some of the results obtained from these field measurements are summarized below.

Steep bedload transport rating curves

Transport rates computed from bedload trap samples can cover a wide range. The smallest measurable non-zero sample comprises one particle 4-5.6 mm in size in one of the traps during a 1-hour sampling time. This corresponds to a transport rate on the order of 0.0001 g/s. Conversely, samples may be as large as 20 kg in 6 minutes per trap and produce transport rates of 100 g/s or more. Transport rates that span up to 6 orders of magnitude over a 2- or 3-fold range of flow with relative little variability produce steep and relatively well-defined rating curves of total and fractional gravel bedload transport rates (Bunte et al. 2001; Bunte et al., in revision; Bunte and Abt, in press). Power function bedload rating curves fitted to measured transport rates yielded exponents between 8 and 16 in the five studied mountain streams (Fig. 7). Similarly high exponents were reported e.g., by Hassan and Church (2001) and Wilcock (2001) who also used long sampling times.

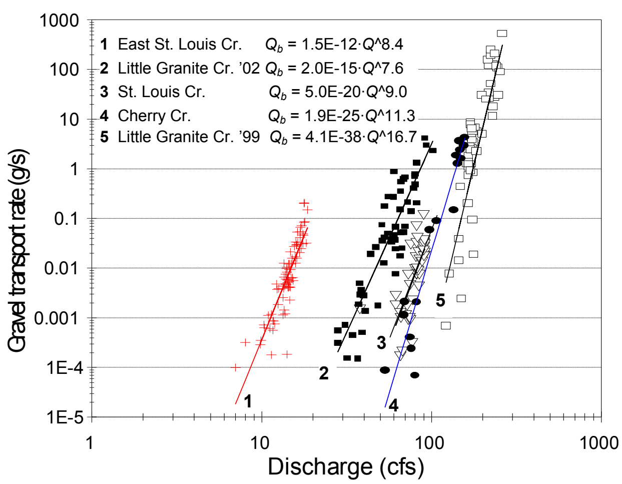


Fig. 7: Bedload Rating Curves from Bedload Trap Samples in Five Streams.

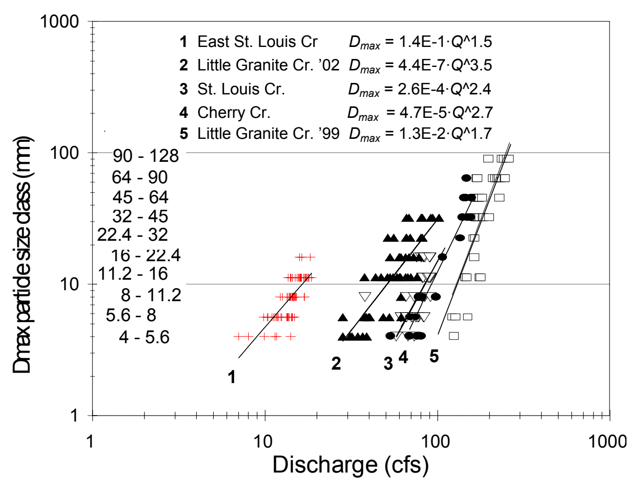


Fig. 8: Flow Competence Curves from Bedload Trap Samples in Five Streams.

Steep flow competence curves

Samples from the bedload traps also show a strong coarsening of the bedload particle-size distribution with increasing flow. The bedload D_{max} (size class of the largest particle size per sample) increases from 4 mm at flows 30-50% of bankfull to between 22 and 128 mm at flows 70-130% of bankfull. A 2- or 3-fold increase in flow thus also produces a strong increase in the largest bedload particle size, spanning up to 10 size classes of 0.5 phi. Power function regressions fitted to the relationships between D_{max} and flow (flow competence curves) are therefore comparatively steep and well-defined when based on bedload trap samples (Fig. 8, above).

Incipient motion

Incipient motion can be determined from the largest bedload particle-size per sample (flow competence method) or from the exceedence of a small preset fractional transport rate (small transport rate method). Measured field results are usually not compatible between the two methods which lead to the opinion that incipient motion is better calculated from flow and bed-material data than directly measured (Wilcock 1988). However, as bedload traps quite accurately sample infrequently moving particles, critical flow for incipient motion computed from the flow competence curve corresponds to the critical flow required for the transport of two particles/m·hr per size class (Fig. 9). This similarity suggests that bedload traps are suitable for direct measurements of incipient motion, an advantage that bypasses assumptions necessary in a computational approach (Bunte et al., in revision).

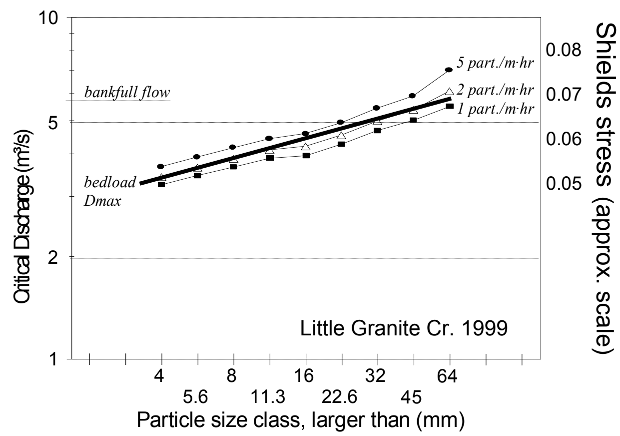


Fig. 9: Critical Discharge for Initial Motion: Largest Grain and Small Transport Rate Method.

Comparison of bedload trap sampling results ith results from a Helley-Smith sampler

At each of the streams sampled, bedload was also collected with a 3-inch Helley-Smith sampler for 2 minutes per vertical spaced 0.5-1 m apart. This sampler is not designed for collecting gravel > 10 mm but is frequently used in gravel/cobble beds due to its portability and ease of use. Bedload trap rating curves are considerably steeper and orders of magnitude lower at low flow than rating curves obtained for gravel > 4 mm from a Helley-Smith sampler (Bunte et al. 2001; Bunte and Abt, in press; Bunte et al., in revision). Transport rates from both samplers become similar at flows near or above bankfull. Bedload traps deployed for two-minutes (a sampling period similar to that often used for a Helley-Smith sampler) produced rating curves only moderately less steep than those obtained from bedload traps in a 1-hour deployment (Fig. 5a and b). Thus, sampling time contributes, but cannot explain, the large difference between rating curves from bedload traps and Helley-Smith samples at low flow.

Bedload traps as a calibration tool for electronic devices

To date, few if any electronic devices developed for measuring gravel and cobble transport produce signals from which the mass and the size of a bedload particle can be accurately determined. Bedload traps provide physical and sievable samples of gravel bedload transport that appear to be representative and measured transport results are in tune with theoretical knowledge of bedload transport mechanisms. This suggests that bedload traps are a suitable device with which to calibrate signals obtained from electronic devices that detect gravel transport. There is a calibration dilemma, though. While very close proximity of two sampling devices may cause disturbance in transport patterns around each of the two devices, the high spatial and temporal variability of gravel transport can cause unequal results if two devices are deployed further apart (Downing et al., in press). Multiple repetitions of a side-by-side comparison may be required to average out spatial and temporal variability and thereby overcome this calibration dilemma.

SUMMARY AND CONCLUSION

Bedload traps were designed for sampling gravel and small cobble transport in wadable coarse-bedded streams. Within the range of design conditions, bedload traps appear to provide accurate measurements of gravel transport. The long sampling time reduces variability in measured transport rates and largely eliminates sampling biases due to short-time sampling. Trap placement on ground plates avoids inadvertent particle pick-up. Obtaining representative samples of particles > 128 mm and of very high transport rates requires a larger net or larger mesh width to avoid overfilling the net. Bedload trap rating curves and flow competence curves are comparatively steep and well-defined and both have larger exponents than curves obtained from a Helley-Smith sampler. The ability to obtain representative samples during marginal transport rates for particle size fractions that are just becoming mobile permits direct measurements of incipient motion. Collection of representative samples of gravel and cobble bedload combined with portability and ease of use appear to make bedload traps suitable for calibration tools for electronic devices.

ACKNOWLEDGEMENTS

This research would not have been possible without the help of Kristin Bunte's husband Kurt Swingle and others in the field. Larry Schmidt supported this ongoing study in many ways. The study was funded by the Stream Systems Technology Center, Rocky Mountain Research Station, USDA Forest Service, Fort Collins, CO.

REFERENCES

Abt, S.R., R.J. Wittler, A. Taylor, and D.J. Love, 1989. Human stability in a high flood hazard zone: *Water Resources Bulletin* Vol. 25 (4): pp. 881-890.

Bunte, K., 1996. Analyses of the temporal variation of coarse bedload transport and its grain size distribution (Squaw Creek, Montana, USA): *U.S.D.A., Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report* RM-GTR-288, 123 pp.

Bunte, K., 1997. Development and field testing of a bedload trap for sand and fine gravel in mountain gravel-bed streams (South Fork Cache la Poudre Creek, CO): Report prepared for the Stream Systems Technology Center, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 53 pp.

Bunte, K. and Abt, S.R., (in press), Sampler size and sampling time affect measured bedload transport rates and particle sizes in gravel-bed streams. In: *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances*. IAHS-Publ.

Bunte, K. and Abt, S.R., (submitted), Bias in measured transport rates due to sampling time and implications for annual load computations. *Geomorphology*.

Bunte, K., Abt, S.R. and Potyondy, J.P., 2001, Portable bedload traps with high sampling intensity for representative sampling of gravel transport in wadable mountain streams: *Seventh Interagency Sedimentation Conf.*, Reno, Nevada, p. III-24 to III-31.

Bunte, K., Abt, S.R., Potyondy, J.P. and Ryan, S.E., (in revision), Measurement of coarse gravel and cobble transport using a portable bedload trap: *Journal of Hydraulic Engineering*.

Church, M., Wolcott, J.F. and Fletcher, W.K., 1991, A test of equal mobility in fluvial sediment transport: behavior of the sand fraction: *Water Resources Research* Vol. 27(11): pp. 2941-2951.

Downing, J.A., Fraley, P.J., Bunte, K., Swingle, K., Ryan S.E. and Dixon, M., in press. Acoustic gravel-transport sensor. In: *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances*. IAHS-Publ.

Hassan, M.A. and Church, M., 2001, Sensitivity of bedload transport in Harris Creek: Seasonal and spatial variation over a cobble-gravel bar: *Water Resources Research* 37 (3): 813-825.

Hayward, J.A. and Sutherland, A.J., 1974, The Torlesse stream vortex-tube sediment trap: *Journal of Hydrology* (N.Z.) Vol. 13(1): pp. 41-53.

Lewis, J., 1991. An improved bedload sampler: Proceedings of the Fifth Federal Interagency Sedimentation Conference, Las Vegas, Nev., Subcommittee of the Interagency Advisory Committee on Water Data, p. 6.1- 6.8.

Milhous, R., 1973. Sediment transport in a gravel-bottomed stream: Ph.D. thesis, Oregon State University, Corvallis, USA.

Powell, D.M., Reid, I., Laronne, J.B., and Frostick, L.E., 1998, Cross stream variability of bedload flux in narrow and wide ephemeral channels during desert flash floods. In: *Gravel-Bed Rivers in the Environment.* P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, eds., 177-196, Water Resources Publications LLC, Highlands Ranch, Colorado.

Reid, I., Laronne, J.B. and Powell, M., 2002, The Nahal Yatir bedload database: sediment dynamics in a gravel-bed ephemeral stream: *Earth Surface Processes and Landforms* Vol. 20: pp. 845-857.

Sear, D.A., Damon, W., Booker, D.J. and Anderson, D.G., 2000, A load cell based continuous recording bedload trap: *Earth Surface Processes and Landforms* Vol. 25: pp. 689-672.

Sterling, S.M. and Church, M., 2002, Sediment trapping characteristics of a pit trap and the Helley-Smith sampler in a cobble gravel-bed river: *Water Resources Research* 38(6), 10.1029/2000WR000052, 2002.

Tacconi, P. and Billi, P., 1987, Bed load transport measurement by a vortex-tube trap on Virginio Creek, Italy. In: *Sediment Transport in Gravel-Bed Rivers.* C.R. Thorne, J.C. Bathurst, and R.D. Hey (eds.), John Wiley, Chichester, pp. 583-615.

Wilcock, P.R., 1988, Methods for estimating the critical shear stress of individual fractions in mixed-sized sediment: *Water Resources Research* Vol. 24 (7): pp. 1127-1135.

Wilcock, P.R., 2001, Toward a practical method for estimating sediment transport rates in gravel-bed rivers: *Earth Surface Processes and Landforms* Vol. 26: pp.1395-1408.

Wathen, S.J., Hoey, T.B. and Werritty, A., 1995, Unequal mobility of gravel and sand in weakly bimodal river sediments: *Water Resources Research* Vol. 31 (8): pp. 2087-2096.

Whitaker, A.C. and Potts, D.F., 1996, Validation of two threshold models for bedload initiation in an upland gravel-bed stream. In: *Watershed Restoration Management - Physical, Chemical, and Biological Considerations*. American Water Resources Association, Proceedings of the Annual Symposium 1996, pp. 85-94.

Whitaker, A.C., 1997, *The initiation of coarse bed load transport in gravel bed streams*. Ph.D. Dissertation, University of Montana, Missoula, 148 pp.