BEDLOAD MOVEMENT IN MOUNTAIN CHANNELS: INSIGHTS GAINED FROM THE USE OF PORTABLE BEDLOAD TRAPS

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Abstract: The USDA Forest Service and Colorado State University cooperatively developed a portable bedload sampler designed to collect representative samples of gravel and cobble-bedload in wadeable mountain streams. Sampling results obtained from bedload traps are generally different from those obtained from Helley–Smith samplers. Bedload trap rating curves and competence curves are significantly steeper and have higher exponents than similar curves derived from Helley-Smith data. The observed differences have implications for computations of annual load, effective discharge, and critical flows for incipient motion and refine our understanding of coarse bedload transport in mountain streams.

INTRODUCTION

The USDA Forest Service (FS) Stream Systems Technology Center and Colorado State University (CSU) Engineering Research Center cooperatively developed a portable bedload sampler specifically designed to collect representative samples of gravel and cobble-bedload in wadeable mountain streams. The initial motivation for the development of the CSU/FS bedload traps was to identify the initiation of bedload movement for channel maintenance studies in coarse-bedded mountain streams. Flows necessary to begin to move the coarse surface layer making up the channel materials and higher flows are necessary to maintain the form and dimensions of stream channels (Schmidt and Potyondy 2004). A sampler was needed that could measure the critical flow for the onset of noticeable amounts of coarse gravel movement at multiple sites avoiding the need for costly sampling during the entire spring runoff period. The use of a small number of observations of bedload transport rates at low flows to calibrate a transport formula as proposed by Wilcock (2001), would provide important logistical and safety advantages provided the sampling included the wide spectrum of particle sizes and transport rates that naturally occur in these rivers and was of sufficiently long duration to support calibration.

The CSU/FS bedload traps are the result of 10 years of development work and include measurements from ten field studies at nine sites in gravel- and cobble-bed mountain streams. The study sites all have snowmelt runoff regimes and are located primarily in the northern and central Rocky Mountains (Figure 1, Table 1). A major constraint on the use of bedload traps is their limitation to wadeable conditions and the measurement of particles larger than sand (>4 mm). We have found that streams with plane-bed morphology can be waded at flows up to about 200 cfs (6.2 m^3/s), and we have successfully deployed the traps at flows up to 150% of bankfull discharge, watersheds as large as 23.5 mi^2 (61 km) and bankfull channel widths of almost 50 ft (15 m) (Bunte et al. 2007). The ability to operate the traps at flows up to 150% of bankfull makes it possible to use the data not only for the determination of incipient motion but also to develop sediment rating curves for a full range of discharges.

In all of our testing, we compared bedload trap results to data measured using a standard 3-inch Helley-Smith sampler (Helley and Smith 1971; Emmett 1980). The Helley-Smith sampler is commonly used for bedload measurements in coarse channels due to availability and ease of use. Unexpectedly, the bedload transport rates collected from the two samplers differed to a greater degree than we originally anticipated. As a consequence, we expended considerable effort over the years to understand the differences in the quantity and size of bedload collected by bedload traps and Helley-Smith samplers as the findings have important ramifications for understanding bedload transport processes in mountain channels. We are convinced that the bedload traps provide accurate samples of bedload transport rates and mobilized particle sizes, better reflecting the true nature of sediment transport in coarse gravel-beds streams than hand-held bedload samplers.

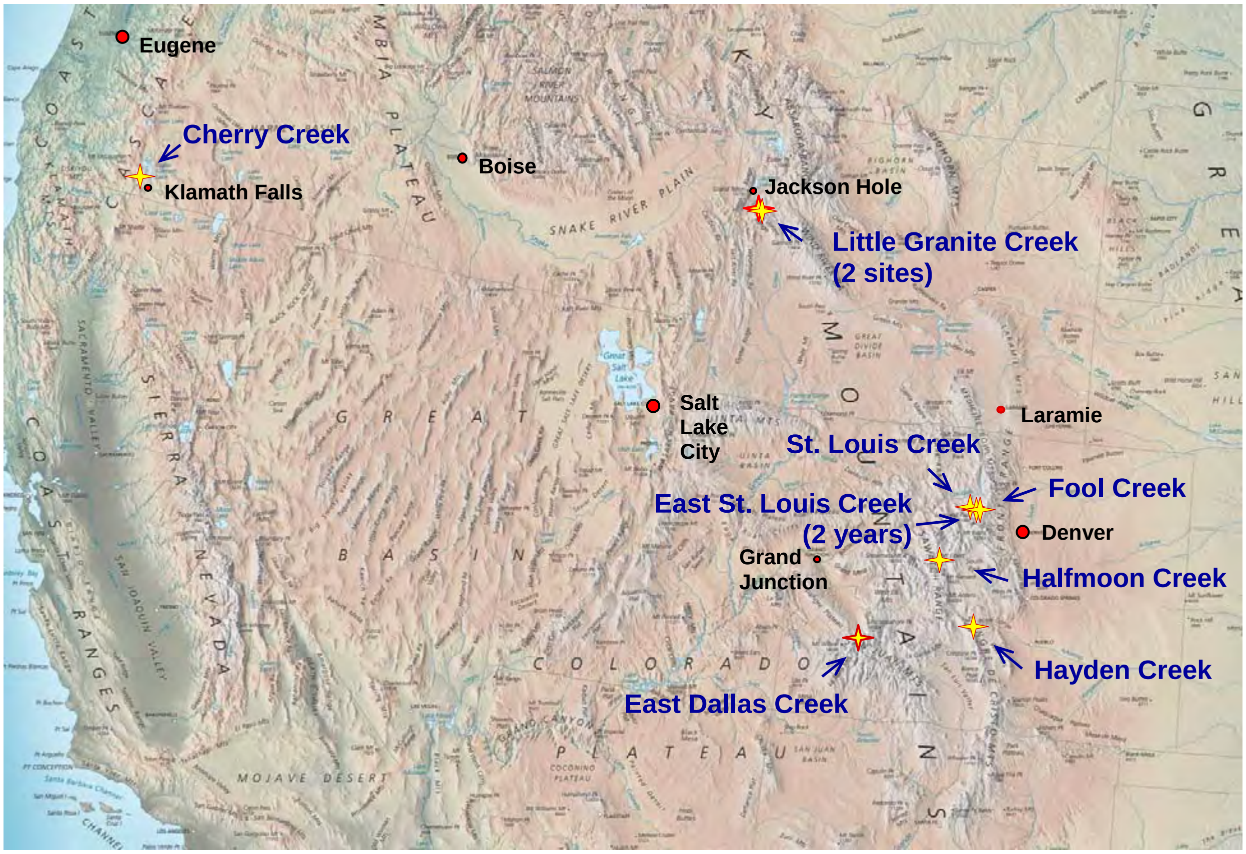

Figure 1 Location of study sites in the western United States.

THE SAMPLING PROBLEM AND NECESSARY SAMPLER CHARACTERISTICS

Accurate measurement of gravel and cobble transport rates is difficult due to a number of factors including the stochastic nature of the transport process, the wide range of particles sizes that are in transport (2 to 256 mm), the infrequent movement of the larger particles, the irregularity of the stream bed, and the logistics of obtaining samples under often dangerous high flow conditions. A variety of different sampling devices and strategies have been employed over the years in attempts to overcome these challenges including pit traps (Hassan and Church 2001; Sterling and Church 2002), net-frame samplers (Bunte 1996; Whitaker, 1997; Whitaker and Potts 1996), basket samplers (Nanson 1974; Engel and Lau 1981; Wilcock 2001), and larger versions of the Helley-Smith sampler such as the Toutle River and Elwha samplers (Childers 1991; Vericat et al. 2006).

For our objective of obtaining representative samples of gravel and cobble bedload in coarse-bedded wadeable streams, we needed a device that met the following criteria (Bunte et al. 2007):

- A large opening that permits large cobbles to enter the sampler,
- A deployment technique that permits long sampling times and thus integration over fluctuating transport rates,
- A large capacity that permits collection of large volumes of gravel and cobble bedload,
- Satisfactory hydraulic efficiency (good through-flow rate with little retardation or acceleration of flow),
- Satisfactory sampler efficiency (neither involuntary particle pick-up nor hindrance of particle entry), and
- Coverage of a large percentage of the stream width.

Additional desirable characteristics from a management perspective included a device that is relatively low cost, technologically simple, portable for use at remote sites, easy to install, and usable by a two-person team in wadeable flow.

Table 1: Characteristics of study streams.

Parameters / Stream; Year sampled	Predominant lithology	Basin area (km²)	Bank-full flow (m^3/s)	Bank-full width (m)	Meas'd range of flow (%Q_{bkf})	Water surface slope (m/m)	Surface		Subsurface % fines		Sub-surface D_{50} (mm)	Predominant stream type
							D_{50} (mm)	D_{84} (mm)	< 2 mm	< 8 mm		
St. Louis Cr., 1998	Granite	34	3.99	6.5	26 - 65	0.017	76	163	9	24	41	plane-bed, forced pool-riffle
Little Granite Cr., near. Confluence, 1999	Sediment-ary	55	5.66	14.3	61 - 131	0.017	59	133	8	16	42	plane-bed, forced pool-riffle
Cherry Cr., 1999	Volcanic	41	3.09	9.5	49 - 145	0.025	49	140	11	27	30	plane-bed, forced pool-riffle
E. St. Louis Cr., 2001	Granite	8	0.76	3.7	26 - 71	0.093	108	258	6	17	54	step-pool
Little Granite Cr., above. Boulder Cr., 2002	Sediment-ary	19	2.83	6.3	37 - 102	0.012	67	138	10	25	34	plane-bed, forced pool-riffle
E. St. Louis Cr., 2003	Granite	8	0.76	3.7	44 - 144	0.093	108	258	6	17	54	step-pool
Halfmoon Cr., 2004	Granite	61	6.23	8.6	17 - 77	0.014	49	119	13	29	26	plane-bed, forced pool-riffle
Hayden Cr., 2005	Sediment-ary	39	1.92	6.5	28 - 149	0.038	63	164	13	26	36	step-pool, plane-bed, mixed
East Dallas Cr., 2007	Volcanic	34	3.7	8.0	10 - 113	0.017	58	128	12	31	21	plane-bed, forced pool-riffle

DESCRIPTION AND OPERATION OF BEDLOAD TRAPS

After an initial failed attempt to use pit traps, we gradually refined the sampler design to the specifications shown in Figure 2. We use the term "bedload trap" rather than sampler because the traps collect all gravel particles >4 mm supplied to them over a one-hour sampling period until filled to capacity.

Bedload traps consist of an aluminum frame with a 12 by 8 in (0.3 by 0.2 m) non-flared opening to which a 3.0 to 5.5-ft (0.90 to 1.65 m) long sturdy nylon net is attached. The frame opening is large enough to collect 4 to 180 mm diameter gravel and cobble bedload particles.

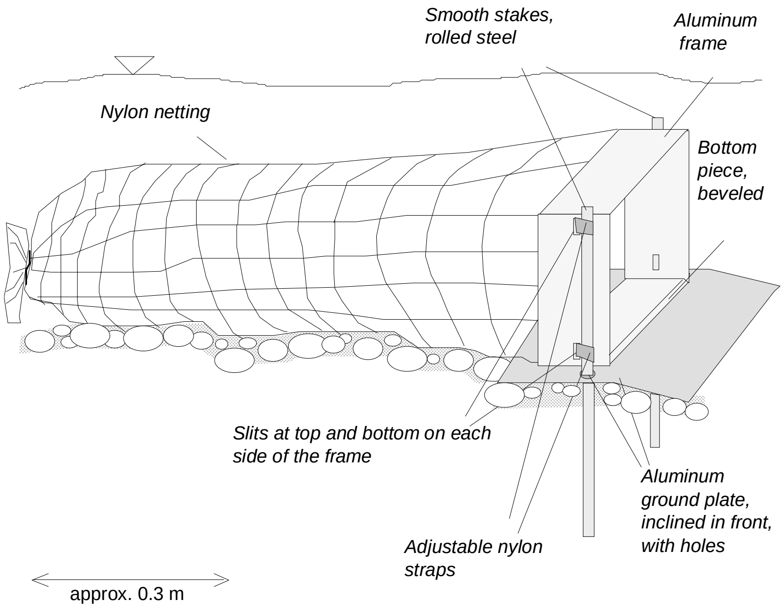

Figure 2 Schematic diagram of the CSU/FS bedload trap and its parts (from Bunte et al. 2007).

Bedload traps are installed on ground plates set flush with the average height of the stream bed and anchored to the bottom with metal stakes. Because of this, the traps do not have to be hand-held while sampling. This minimizes disturbance of the streambed, prevents involuntary particle entrainment, and means that they can be left in place for long time periods, typically up to one hour. The ground plates also increase near-bed flow velocities ensuring that all particles that move onto the entry of the plates enter the trap unobstructed.

The long trailing net which has a 3.6 mm mesh opening to allow for unobstructed water flow, provides capacity for the accumulation of a large volumetric sediment sample (up to 20 kg for a 3 ft net) and large amounts of organic debris that frequently occurs during the rising limb of high flow events. The nets need to be at least 3 ft long so that they do not fill and reduce hydraulic efficiency. The long nets allows the traps to be emptied by lifting the net's end from the water, untying it, and collecting the captured sediment while the traps remain in place on the ground plates (Figure 3).

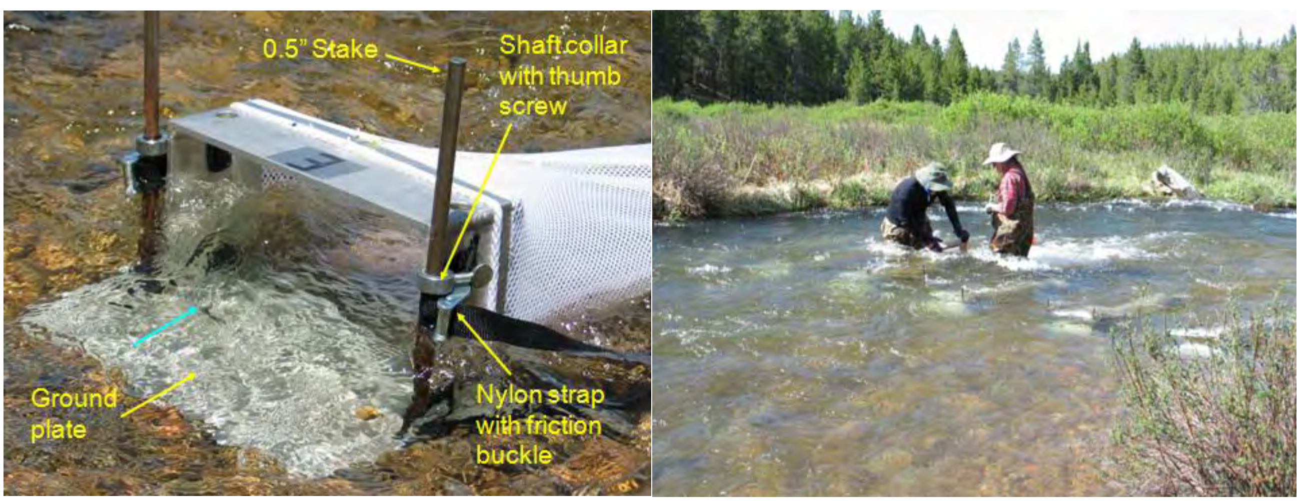

Figure 3 Close-up of a bedload trap installed on a ground plate at low flow and a typical deployment of six bedload traps installed across a stream channel flowing at 80% of bankfull flow. The two-person crew is emptying sediment from the nets.

Typically 4 to 6 nets are deployed across a stream channel spaced 1 to 2 m apart at a cross-section that is wadeable at flows up to bankfull discharge (Figure 3). The use of portable footbridges (Martinez and Ryan 2000) is recommended whenever possible since it reduces the amount of streambed disturbance during sampling and is a safe platform for servicing the traps at high flows. We have found that the traps work well on relatively stable coarse gravel beds provided the flows remain wadeable, transport rates are less than 10 g/m·s, and the channel lacks pronounced bedload waves that scour or aggrade the bed during the measurement period.

Detailed guidelines for bedload trap construction and operation are available from the Forest Service (Bunte et al 2007). A bedload trap can generally be constructed for less than $250.

SUMMARY OF RESULTS

Sampling results obtained from bedload traps are generally different from those obtained from Helley–Smith samplers with respect to bedload transport rating curves and flow competence curves (Bunte et al. 2004; Bunte et al. 2008). Both curves are well defined and the relationships are steeper than those obtained from Helley-Smith data (Figures 4 and 6).

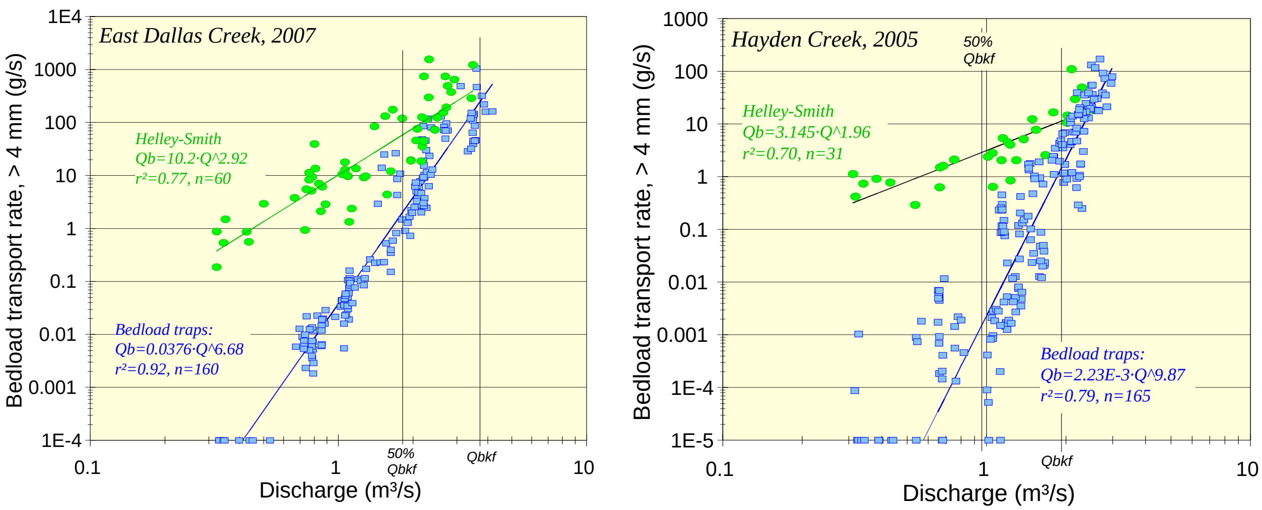

Figure 4 Sampling results from bedload traps (blue squares) and the Helley-Smith sampler deployed directly on the bed (green circles) for East Dallas Creek (left) and Hayden Creek, Colorado (right).

<u>Bedload Rating Curves.</u> Gravel transport rates obtained from bedload traps increase steeply with flow resulting in consistently steep, well-defined power curves with exponents of 7 to 16 for the suite of streams sampled (Figure 5). In contrast, gravel transport rates measured by the Helley-Smith sampler tend to have higher transport rates during low flows, more data scatter, and increase less steeply, having exponents ranging from 2 to 4. Transport rates measured with both samplers tend to converge as they approach bankfull flow, however, at 50 % of bankfull, transport rates from the Helley-Smith sampler are typically 1-4 orders of magnitude higher than those obtained from bedload traps.

<u>Flow Competence Curves.</u> Similar trends are evident with respect to flow competence curves which are used to estimate the critical flows for the transport of specific particle sizes (Bunte et al. 2004; Bunte et al. 2008). Flow competence power curves obtained from bedload traps are consistently steep, well-defined, and have exponents of 1.3 to 3.5 for the suite of streams sampled (Figure 6). In contrast, the maximum particle size transported as measured by the Helley-Smith sampler tend to show larger sizes moved during low flows, more data scatter, and to be less steep with exponents ranging from 0.5 to 1.1. The competence curves differ most at low flows and tend to converge as they approach bankfull flow, however, the convergence is less well defined than for the bedload transport curves; the bedload traps tended to collect coarser sizes at higher flows than the Helley Smith sampler.

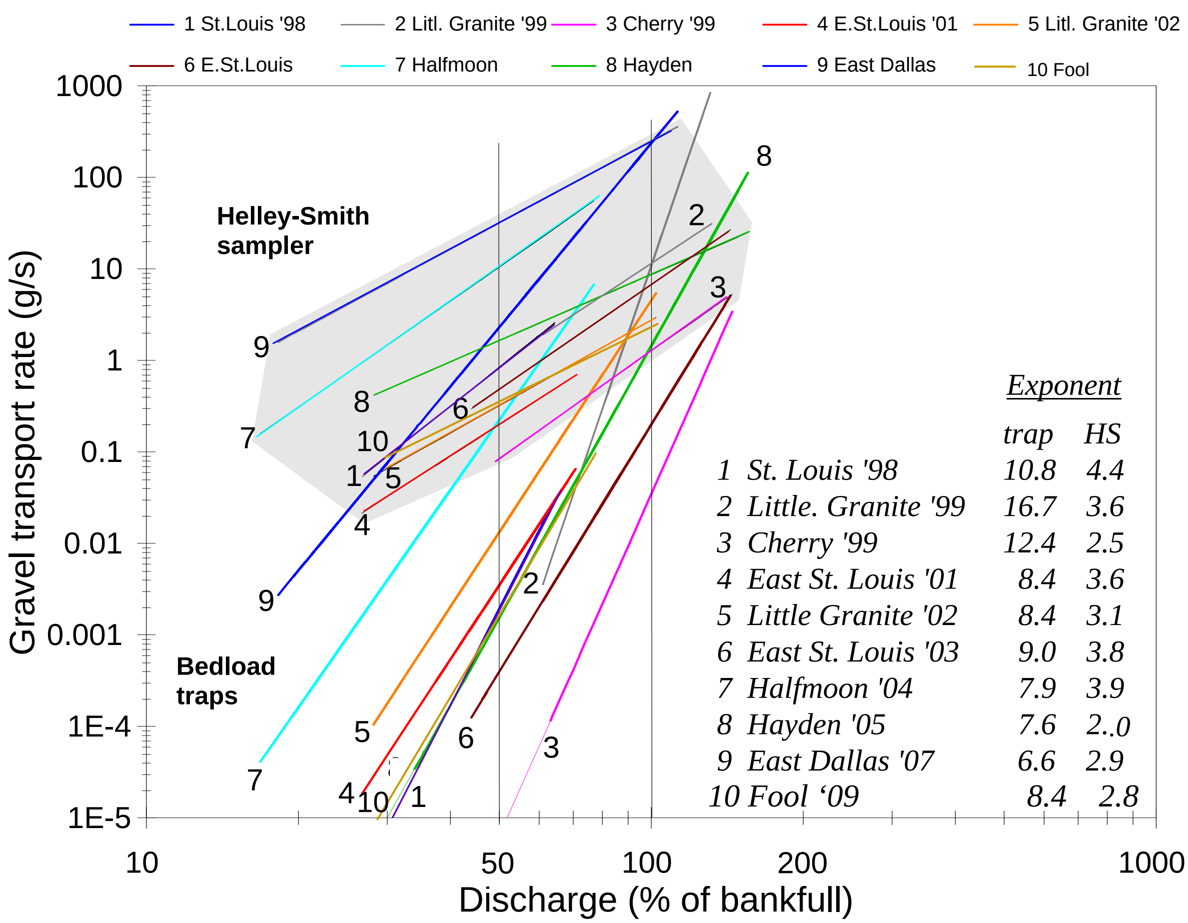

Figure 5 Gravel transport rates plotted versus percent of bankfull flow for bedload traps and the Helley-Smith sampler (plotted within gray-shaded area)at all study streams.

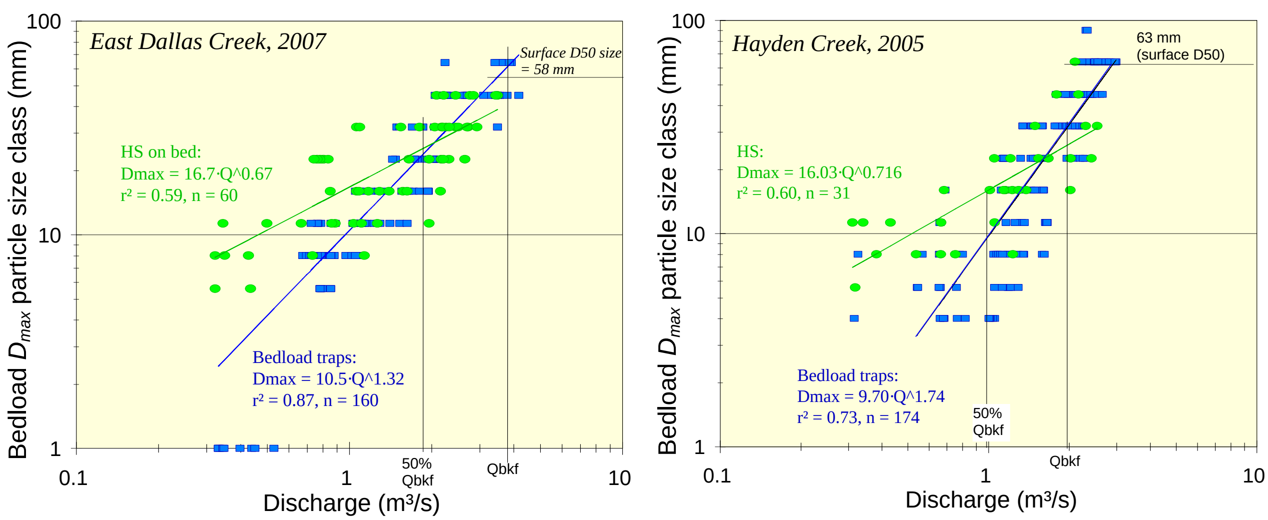

Figure 6 Sampling results from bedload traps (blue squares) and the Helley-Smith samplers deployed directly on the bed (green circles) showing the differences in flow competence curves for East Dallas Creek (left) and Hayden Creek, Colorado (right).

DISCUSSION

The discrepancy between transport rates and the maximum sizes moved from the two samplers are attributed to several factors including: (1) differences in sampling intensity and sampling time; (2) hydraulic and sampling efficiency of the bedload traps; (3) occasional inadvertent entrainment of particles during the sampling process; and (4) sampling time for representative sampling. We evaluated each of these factors and came to the conclusion that the characteristics and method of deployment of the bedload traps results in representative and accurate sampling of coarse sediment transport.

Admittedly, true transport rates are unknown at all of our study sites and all we have are comparative measurements and observations. One strong supporting piece of evidence can be inferred from studies in mountain gravel-bed stream that used similar devices with wide openings, long sampling times, and large mesh openings. These studies evaluated pit traps (Garcia et al. 2000; Hassan and Church 2001); wire basket samplers (Nanson 1974; Wilcock 2001), and net-frame samplers (Bunte 1996; Whitaker and Potts 1996; Whitaker 1997). Similar to bedload traps, the exponent of power function relationships between bedload transport rates and discharge from these studies had high exponents ranging from 7 to 18. Recall that our bedload trap field studies show ranges from 7 to 16. Finally, from a theoretical perspective, steep power function sediment transport exponents are similar to bedload transport equations for gravel-bed rivers, for example, the exponent of 14.5 in the Parker (1990) bedload transport model.

We examined the effect of sampling time on the observed differences by deploying bedload traps for 2, 10, and 60 minutes in a coarse-bedded stream (Bunte and Abt 2005a). Rating curve transport rates from 2 min sampling, the typical deployment time for a vertical measured with a Helley-Smith sampler, were significantly less steep than those for longer deployment times, however, sampling time explains only a small degree of the large difference between rating curves from bed load traps and a Helley-Smith sampler.

The sampling time required for representative sampling of a wide range of particles sizes also has a bearing on the discrepancy between bedload trap samples and Helley-Smith samples. Because of their long sampling time, typically 1 hour, bedload traps have a sampling intensity (defined as a function of sampler width, number of verticals, and time in contact with the bed) that is about 50 times higher than a typical Helley-Smith sample (Bunte et al. 2004). For example, deploying five bedload traps for 1 h each in a stream 6.5 m wide yields a sampling intensity of 0.235, or 23.5%. Deploying a Helley–Smith sampler at 2 minutes per vertical in 0.5 m increments in a stream 6.5 m wide yields a sampling intensity of only 0.005, or 0.5%. We know that short sampling times result in high variability due to the irregularity of particle movement and its fluctuation over time. Dietrich and Whiting (1989) proposed a method for estimating the minimum sampling time for specific particle sizes based on the criterion that sampling time should be long enough such that ‘‘the mass of a single large grain is equal to its proportion in the expected grain-size distribution.’’ Based on this criterion, the 1-hour sampling time used for bedload traps suffices for collecting representative samples at all measured transport rates, whereas the Helley–Smith samples provided representative gravel samples only during high transport rates. Consequently, from a theoretical basis, the bedload traps have distinct advantages over Helley-Smith samplers with respect to sampling duration and their ability to obtain representative samples of a broad range of particle sizes.

We also examined the hydraulic properties of the bedload traps (Bunte and Swingle 2004). Helley-Smith samplers have a hydraulic efficiency of 1.54 meaning that water velocities are increased due to the flared opening. In contrast, the unflared opening of the bedload traps likely results in a hydraulic efficiency less than 100 % but this is offset by the ground plate on which the trap rests. Near bottom flow velocities measured at various distances in front of the bedload traps found that velocities were 30-50 % faster compared to the velocity measured on the bed upstream. Flow acceleration is attributed to the smoothness of the ground plate. On the other hand, flow velocities decreased 10-20% near the middle of the trap opening due to the presence of the sampling net. Field observations indicate that as gravel particles approach the front of the ground plate they tend to be entrained into the sampler but particles do not appear to be pulled in from the sides as had been observed with Helley-Smith samplers (Hubbell et al. 1985; Bunte et al. 2008). The slight deceleration of flow in the trap center does not appear to appreciably affect the sampler performance for gravel particles, but more detailed studies are necessary. We further evaluated the sampling efficiency of bedload traps by comparing seasonal gravel load computed from bedload trap samples with the gravel mass excavated from a debris basin on East St. Louis Creek at the Fraser Experimental Forest. Bedload traps matched the sediment mass accumulated in the debris basin to within 56 – 117% (Bunte and Abt 2005b).

The ground plates are extremely important to the successful operation of the bedload traps in that they eliminate the need to repeatedly place the sampler on the stream bed and remain in place for extended sampling time; hourly, daily, or for the entire field season. This minimizes disturbance of the stream bed and prevents unintentional movement of particles. We have observed inadvertent dislocation of a bed particle when operating the Helley-Smith sampler and the subsequent entrainment of particles into the opening due to the sampler's high hydraulic efficiency. Because of the numerous verticals measured during a typical Helley-Smith measurement, up to 20 times when sampling a cross-section and up to 40 times when two traverses are done, opportunities for involuntary particle pick-up occur each time the sampler is placed on the bed. This is important because, for example, the inadvertent collection of only one 4-mm gravel particle in the Helley-Smith sampler during very low transport, when gravel movement begins, artificially inflates the transport rate. The amount typically exceeds that measured with bedload traps at the same flow by an order of magnitude (Bunte et al. 2004). Inadvertent collection of one or two additional particles using a hand-held bedload sampler during low transport rates can inflate the transport rate by several orders of magnitude when compared to the bedload trap measurement.

To evaluate the significance of the ground plates and the role of inadvertent entrainment, we conducted several studies where we deployed bedload traps along with measurements of the Helley-Smith sampler placed directly on the bed and then conducted a second set of measurements where the Helley-Smith was placed on the ground plates previously used for the bedload traps. Bedload transport rates collected by the Helley-Smith sampler set onto the ground plates were approximately the same as the range of values measured with bedload traps (Figure 7). However, data from the Helley-Smith placed directly onto the bed were considerably higher as previously explained, having the typical 2.5 orders of magnitude difference at 50% of bankfull flow (Bunte et al. 2008). The fact that Helley-Smith data from samples placed on ground plates are essentially similar to those derived from bedload traps clearly demonstrates the role inadvertent entrainment plays in the observed differences and supports the conclusion that bedload traps properly characterize the nature of coarse sediment transport in these systems.

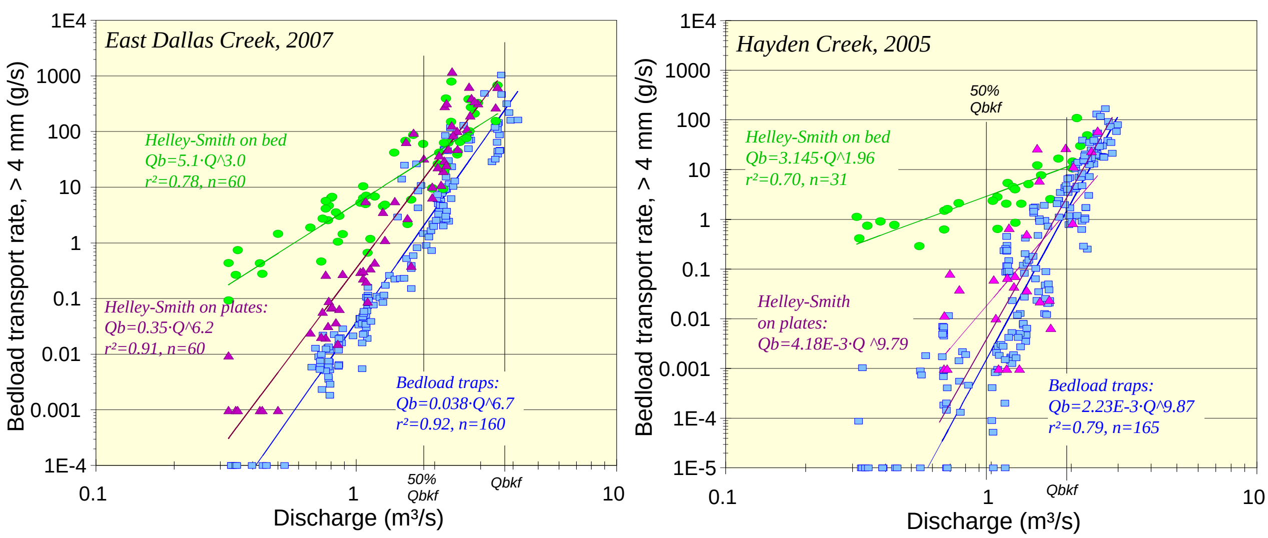

Figure 7 Sampling results from bedload traps (blue squares) and the HS sampler deployed directly on the bed (green circles) and on ground plates (magenta triangles). The examples are from East Dallas Creek (left) and Hayden Creek, Colorado (right).

CONCLUSION AND RECOMMENDATIONS

The observed differences have implications for computations derived from bedload data, as well as our understanding of how gravel-bed streams function. In general, the bedload trap data with their steeper transport curves suggests that a higher percentage of sediment moves at higher discharges than one would conclude from Helley-Smith based data.

Estimates of annual gravel bedload, for example, will be substantially higher when based on a bedload rating curve from a Helley-Smith sampler in years of generally low flows compared to bedload traps. Due to its steeper slope, bedload trap data will yield substantially higher annual gravel load estimate during high flow years compared to using Helley-Smith transport curves. In general, annual variability will increase with bedload trap data with smaller values in low flow years and higher values in high flow years.

Effective discharge, computed from the magnitude-frequency analysis (Wolman and Miller 1960) commonly occurs near bankfull flow based on the relatively flat Helley-Smith bedload rating curves (Figure 8). However, computed effective discharge will shift towards the highest flows recorded for a stream when a rating curve with a high exponent is used for the computation (Bunte 2002).

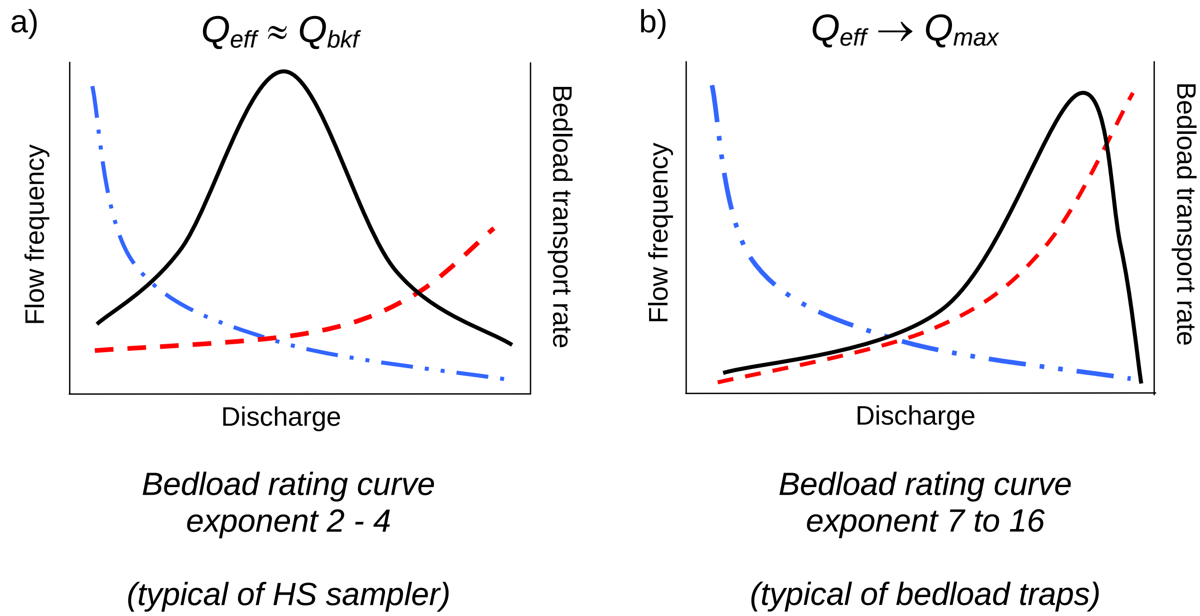

Figure 8 The effect of bedload rating curve slope on magnitude frequency analysis when using a Helley-Smith sampler (a) and bedload traps (b).

The computation of critical flows at incipient motion also depends on the sampler used. Bedload traps indicate a higher critical flow for small gravel particles and a lower critical flow for large gravel and cobbles compared to Helley-Smith data. These differences can influence conclusion drawn about bed mobility and channel maintenance flows requirements suggesting higher thresholds.

The CSU/FS bedload traps were recently approved by the Federal Interagency Sedimentation Project (FISP) as an appropriate sampler for coarse channels (FISP 2009) and bedload traps may be available for purchase in the future from FISP. Adjustment factors are being developed so that rating curves between the two samplers can be adjusted relative to each other (Bunte and Abt 2009, Bunte et al., this volume). While we believe that bedload traps yield representative samples of gravel and small cobble bedload, the Helley-Smith sampler fulfills an important role in coarse systems by providing a way to measure fine gravel (less than 4 mm) and sand that the bedload trap is unable to measure and by being deployable in unwadeably deep flows.

The FISP technical memorandum lists the following optimum conditions for the use of bedload traps. They are listed here to provide potential users with a clear description and guidance for appropriate uses of bedload traps and to encourage use of this technology.

1. The bed should be a stable, gravel or cobble bed suitable for the placement of the 12 x 16 in ground plates.
2. The bedload should consist of sizes ranging from 4 – 180 mm. The bedload trap has a bag with a 4 mm mesh.

3. Bedload transport rates should be such that the sampler can be left in place for 1 hour with the bag filling no more than 40 percent.
4. The stream needs to be wadeable at the time of measurement. The practical limit of wadeability corresponds to products of flow depth (ft) and mean flow velocity of 8 – 12 (ft/s). This equals unit discharges of 0.8 – 1.2 $m^3/s \cdot m$. In mountain gravel-bed streams with a snowmelt regime, the upper limits of wadeablility occur at flows of approximately 80-140 percent of bankfull.
5. Streams should be low in organic material transport at the time of sampling. Organic material especially during the rising limb of the hydrograph can be a problem.
6. Field sites should be suitable for the placement of a portable footbridge to serve as a platform for bedload measurements and other field data collection.
7. Sampled streams will generally need to be less than 50 ft wide.

The technical memorandum lists the following operational considerations for use of bedload traps:

1. Desirable field site properties include: a locally wide cross-section to ensure wadeability at high flow, vehicle accessibility to within a short walking distance, sufficient dry work space on the banks to process samples and store gear, the absence of boulders from the sampling cross-section, and suitability for the placement of a footbridge (if one is to be used).
2. Bedload traps need to be placed on ground plates. Ground plates need to be carefully installed at the general height of the bed, typically during low flows and at least one day prior to sampling so that the bed around the plates can re-equilibrate after installation. Ground plates should be installed 3-6 ft apart to cover the lateral variability of transport rates.
3. Bedload traps require as a minimum a two-person field team: one person to hold the end of the net and the receiving bucket when the sampler is emptied, and one person to untie the net, shake the sample into a bucket, and retie the net. Operators need to be prepared for physically demanding and strenuous work. Safety considerations for working in remote areas during high-flow conditions also speak strongly in favor of using teams of two or more people for this type of field work.

Acknowledgements Dan Cenderelli, Chester Watson, and Ted Geier provided helpful manuscripts reviews.

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