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A Comparison of Coarse Bedload Transport Measured with Bedload Traps and Helley-Smith Samplers

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Abstract

Gravel bedload transport rates were measured at eight study sites in coarse-bedded Rocky Mountain streams using 4-6 bedload traps deployed across the stream width and a 76 by 76 mm opening Helley Smith sampler. Transport rates obtained from bedload traps increased steeply with flow which resulted in steep and well-defined transport rating curves with exponents of 8 to 16. Gravel transport rates measured by the Helley-Smith sampler started with much higher transport rates during low flows and increased less steeply, thus fitted bedload rating curves were less steep with exponents of 2 to 4. Transport rates measured with both samplers approached similar results near or above bankfull flow, but at 50 % of bankfull, transport rates from the bedload traps were 2-4 orders of magnitude lower than those obtained from the Helley-Smith sampler. The maximum bedload particle sizes also differed between the two samplers. They were smaller in the bedload traps than the Helley-Smith sampler at low flows, while at higher flows bedload trap collected larger particles than the Helley-Smith sampler. Differences in sampler opening size and sampling time contribute to the measured differences, but the biggest effect is likely attributable to the bedload traps being mounted onto ground plates thus avoiding direct contact between the sampler and the bed and preventing involuntary particle pick up.

Keywords: gravel bedload transport, bedload sampling, bedload traps, Helley-Smith sampler, flow competence

1. Introduction

Research about bedload transport in mountain gravel-bed streams can take two general approaches: either build a well-equipped research facility at a suitable stream location and use it for several years (e.g., 1-8 and, of course, 9-13 that are summarized in 14) or use mobile equipment that does not require permanent structures and take measurements that address local research questions in a variety of different streams. This study deals with the mobile approach.

By far, the most frequently used device for sampling bedload under transient field conditions is the Helley-Smith sampler. The 76 by 76 mm opening Helley-Smith sampler was designed for collecting small gravel of 2 – 10 mm [15]. However, the sampler was frequently used in coarse-bedded streams. Examples of large studies include [9, 10, 16-26], and this study.

Over the years, concerns have been raised about the efficiency of pressure difference samplers like the Helley-Smith. Investigations showed that the sampling efficiency varied with collector type and deployment. For example, [27-29] observed that bag size, mesh width and sampling duration affected the sampling efficiency, [30] found that the orientation of the sampler and its size had an effect, and [31,32]

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showed that thickness of the sampler wall mattered. Several studies revealed that different types of Helley-Smith samplers yielded different sampling results [32-41]. Others reported a satisfactory sampling efficiency for sand to medium gravel particles [9,42-44] (see [45] for a summary of this research). Thus, transport rates vary depending on the type of Helley-Smith sampler used and on deployment details.

Numerous problems arise when a 76 by 76 mm Helley-Smith sampler is deployed in high-energy, coarse-bedded streams. Being handheld and having a small sampler bag with a fine mesh width, the sampling time per vertical (i.e., the time of ground contact per sample) must typically be kept short (0.5 to 2 minutes). Short sampling times do not provide representative samples of particle sizes that are at the threshold of entrainment and move infrequently. Moving particles in the size class just at incipient motion are rare and may or may not be contained in a short-term sample (it is more likely they are not). This makes the 76 by 76 mm Helley-Smith sampler poorly suited for incipient motion studies. The suitability is worsened by the fact that placing the Helley-Smith sampler onto the bed can dislodge and entrain particles from the bed into the sampler. Even if this happened only occasionally, setting the sampler repeatedly onto the stream bed (up to 20 times per cross-sectional sample or up to 40 times when two traverses are done) provides ample opportunity. When samples are otherwise small and fine-grained, adding a gravel particle significantly increases the sampled transport rate and coarsens the particle-size distribution. Furthermore, with its small opening, the 76 by 76 Helley-Smith cannot representatively sample large gravels (32 – 64 mm) that roll over their *b*- and *c*-axes, while cobbles do not fit into the sampler entrance.

Larger Helley-Smith type samplers such as the 152 by 152 mm opening size Helley-Smith and the Toutle River 1 sampler, the Elwha sampler (102 by 203 mm), and the Toutle River 2 sampler (305 by 152 mm) were developed to overcome the size limitation posed by the smaller sampler [39, 40, 41, 46-51]. While large gravels and small cobbles do fit into the sampler entrance, the utility of handheld versions of these larger Helley-Smith samplers is much reduced by the difficulty experienced when holding them in fast flow, the poorer control of their placement on the bed surface, and their higher potential for involuntary particle pick-up [52,53]. Thus, large Helley-Smith samplers have their own set of deployment and sampling efficiency problems. Small Helley-Smith samplers remained the device most frequently used for handheld deployment, due to their relative ease of use, together with their portability and widespread availability.

A research question arose for coarse-bedded Rocky Mountain headwater streams regarding the flows required to move medium and coarse gravel and whether water diversion would affect gravel mobility and thus stream morphology. Given that neither the small nor the large handheld Helley-Smith sampler were well suited for measuring the particle sizes at incipient motion or the mobility of large gravel, a need developed for a bedload sampler that would give a reliable account of when gravel and cobbles start to move in gravel- and cobble-bed streams. Considering that measurements would have to be done in a variety of different headwater streams at high flows, the new device had to be portable, cost-effective, easy to operate at high flow, and have a sampling efficiency near 100 % to yield representative samples of gravel bedload. Based on sampler characteristics desirable for obtaining representative samples of gravel and cobble bedload in wadeable streams, bedload traps were developed as a sampling device. Their design was based on the fulfillment of several criteria. One criterion was that the sampler can collect a wide range of gravel and cobble particle sizes over transport rates ranging from one small gravel particle per hour to hundreds of gravel particles per minute. Due to the typically skewed distribution of short-term transport rates with frequent small and infrequent large rates (e.g., [36,37, 54-60]), bedload traps had to be capable of long sampling times to minimize oversampling at low and undersampling at high transport events [61]. Due to lateral variability of transport over a stream channel cross-section and its change over time, bedload traps had to be able to collect samples at several locations within the cross-section simultaneously. A gravel and cobble bed surface is typically irregular, so the sampler should neither protrude above the general height of the bed thereby allowing small particles to escape under the sampler nor should the sampler opening be below the general height of the bed where it would receive unduly large amounts of sediment. Finally, when being placed onto the bed, the sampler should not inadvertently dislocate and entrain easily mobilized surface particles. To overcome these problems, a base plate is an integral part of the bedload trap design.

Over the past eight years, we have used and tested our bedload trap design in eight field studies at seven different sites and found that they worked quite well as long as flows remained wadeable and the bed near the traps did not experience pronounced scour or aggradation. Because a handheld, 76 by 76 mm Helley-Smith sampler was and is still frequently used to collected bedload in coarse-bedded streams, it was important to also collect bedload samples using this sampler at each site in order to compare collected transport rates and particle sizes from the two devices. It is the objective of this study to show and discuses the differences in results obtained for bedload traps and the Helley-Smith sampler from intensive sampling during eight field studies.

2. Methods

2.1. A newly developed sampler for gravel and cobble bedload

Bedload traps consist of an aluminum frame 0.3 by 0.2 m (Fig. 1 a and b). This non-flared sampler opening is large enough to accommodate coarse gravel and small cobble particles. A sturdy nylon net 0.9 – 1.6 m long (or longer) is attached to the frame to receive the bedload. A 3.5 mm mesh opening allows water to flow through the net with little retardation of flow and collects particles larger than 4 mm in size. With a volume of 25 liters for a 0.9 m long net, the

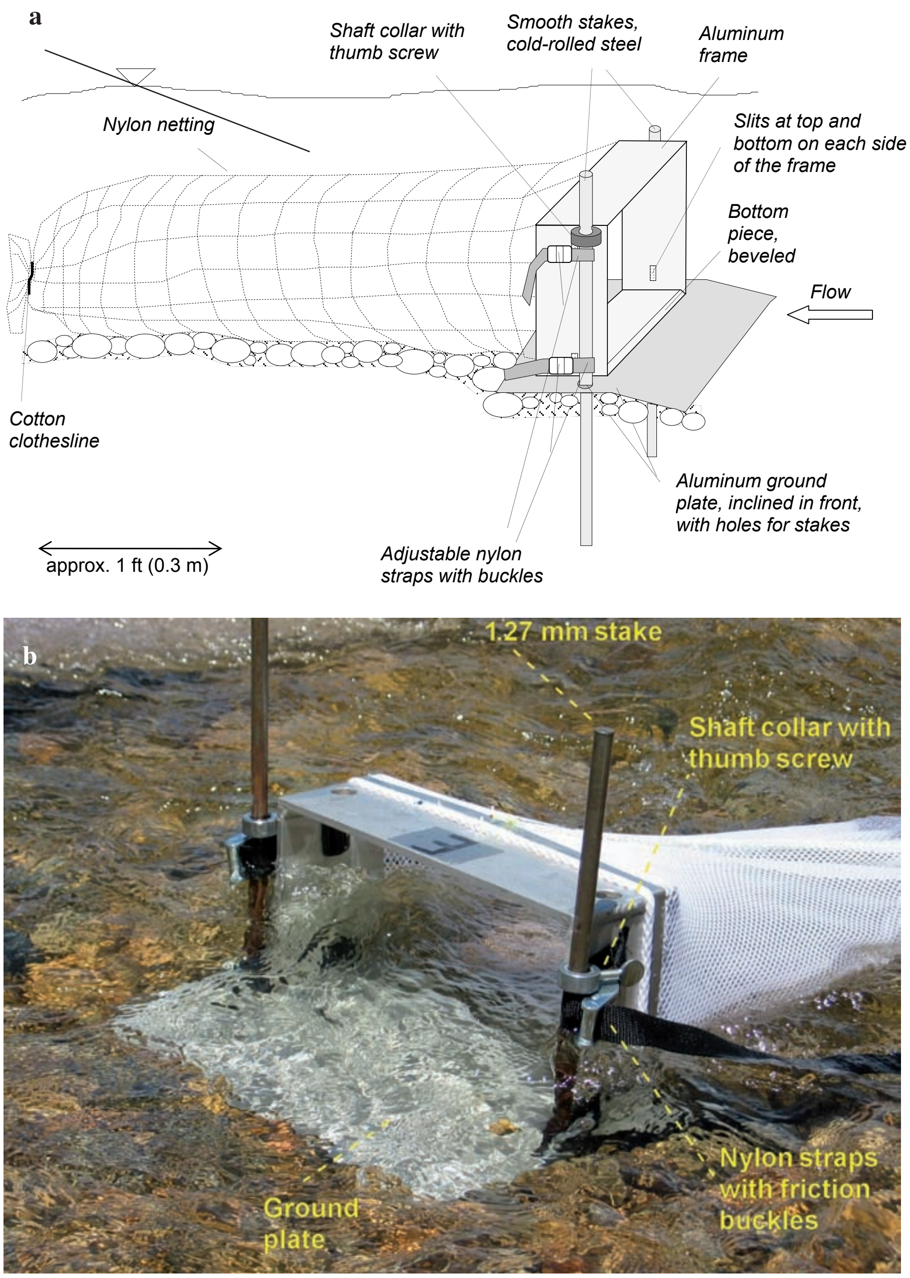

Fig. 1 a and b: Drawing of bedload trap **(a)**. Bedload trap installed on a ground plate at low flow **(b)**.

bedload trap capacity is approximately 10 liters or about 20 kg of gravel. This permits the collection of large samples. The capability for collecting a large sample volume is needed because mountain gravel-bed streams tend to carry a large amount of organic debris (pine needles, pine cones, bark, leaves, twigs and sticks – particularly during the first rising limb of flow) that get caught in the bedload traps. In order to avoid overfilling the traps, sampling time was reduced to 30 minutes at times when large amounts of bedload and/or organic material were in transport, and was a short as 5 minutes in extreme cases.

Bedload traps are mounted onto ground plates 0.28 by 0.41 m in size that are placed at the average height of the bed (non-protruding) and are anchored to the stream bottom with two metal stakes pounded into the bed. Placement of bedload traps onto ground plates avoids involuntary particle pick-up when deploying and retrieving the traps. Ground plates need to be repositioned to be on the bed surface if the bed scours or aggrades. Attachment of the bedload traps to the stakes with webbing straps permits long sampling times of about one hour during which operator attendance is not required. Bedload traps are comparatively cost effective (about $220 U.S. per trap) and portable for use at remote or undeveloped sites. Bedload traps can be operated by two people at flows up to the limit of wadeability (Fig. 2a) and are most conveniently operated from a foot bridge (Fig. 2b). Detailed information on how to construct and operate bedload traps is provided in a guideline document [62].

2.2. Typical sampler deployment

Four to six bedload traps were installed across a stream spaced 1-2 m apart, and they sampled simultaneously [63,64]. Sampling time was typically 1 hour per sample but was reduced to 30 or even 10 minutes when transport rates were high in order to avoid overfilling the sampler net. Four to nine samples of gravel bedload were collected almost every day over the snowmelt highflow seasons that lasted from 4 to 7 weeks. This amounted to 21-196 samples per site with an average number of 92. Sampled flows ranged from low flows of 16 % to highflows of 140 % of bankfull discharge (Q_{bkf}), but not all study streams exhibited this range.

At all study sites, bedload was also collected using a 76 by 76 mm Helley-Smith sampler (thinwalled, 3.22 opening ratio and a 0.25 mm mesh bag), sampling at 12 to 18 locations spaced in 0.4-1.0 m increments across the stream for 2 minutes per vertical and completing one traverse. The sampling verticals were either placed into spaces between the bedload traps or samples were collected in a cross-section a few m downstream while the bedload traps were removed from the ground plates. One or two samples were collected with the Helley-Smith sampler each day, amounting to 20-80 samples per site. Transport rates computed from Helley-Smith samples at the study sites usually fit well with those obtained from Helley-Smith samples collected by the USDA Forest Service at sites close to ours in earlier years.

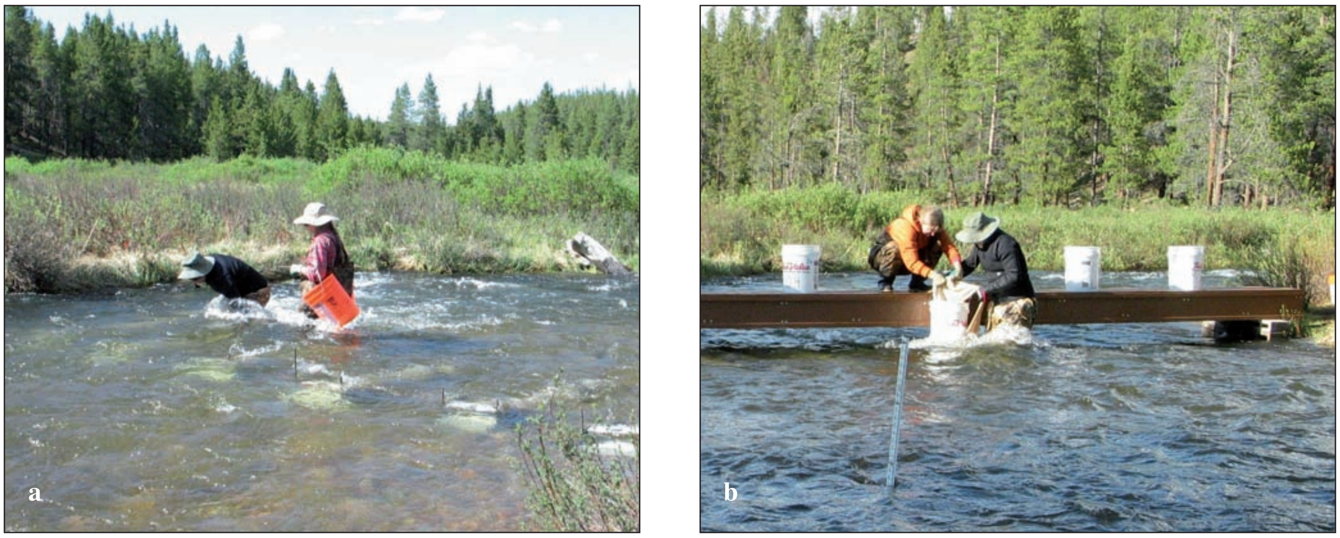

Fig. 2 a and b: Six bedload traps installed in the stream are emptied at 80% of bankfull flow (**a**). Emptying of bedload trap from a foot bridge (**b**).

2.3. Characteristics of the sampled streams

The study sites were located in steep, armored, mountain streams with coarse gravel and small cobble beds. Details of the stream characteristics are listed in Table 1. The measuring sites were located on National Forest Service land in the northern and central Rocky Mountains of Montana, Wyoming, Colorado and Oregon (USA) in subalpine and montane zones at altitudes between 2,000 to 3,000 m above sea level. The streams at the study sites are incised into glacial or glacio-fluvial deposits. Although most of the stream basins had experienced some logging, mining and road building several decades ago, today the basins are comparatively undisturbed and mostly forested (Engleman spruce (*Picea Englemannii*), lodgepole pine (*Pinus contorta*), Douglas fir (*Pinaceae Pseudotsuga menziesii*), with alder (*Alnus*), birch (*Betula*) and cottonwood (*Populus*) species interspersed in riparian areas. Open valley floors are vegetated by forest meadows or willow thickets (comprising willows (*Salix*), sage brush (*Artemisia*), shrubby cinquefoil (*Potentilla*), juniper (*Juniperus*) as well as grass and herbaceous plants).

All sampled streams have a snowmelt highflow regime in which runoff typically increases from 10-20 % of bankfull discharge (Q_{bkf}) in early to mid May to 80-140 % Q_{bkf} between late May and mid June, depending on the depth of the annual snowpack and weather conditions. Examples of snowmelt hydrographs for two of the eight study sites are shown in Fig. 3. Daily fluctuations of flow were pronounced; discharge between daily low flows around noon and daily peak flows in the early to late evening could vary by up to 50 %. Most sampled streams were slightly entrenched such that highflows of 140 % Q_{bkf} caused little overbank flooding.

Table 1: Characteristics of the streams near the study sites.

Parameter / Stream and year sampled	Area	Basin area (km²)	Bank-full flow (m³/s)	Bank-full width (m)	Water surface slope (m/m)	Surf. D_{50} (mm)	Subs. D_{50} (mm)	Predominant stream type [82]
St. Louis Cr., '98	North Ctr. Colorado	34	3.99	6.5	0.017	76	41	plane-bed
Little Granite Cr., nr. confluence '99	West Ctr. Wyoming	55	5.66	14.3	0.017	59	42	plane-bed
Cherry Cr., '99	South-Western Oregon	41	3.09	9.5	0.025	49	30	plane-bed, forced pool-riffle, cascade
E. St. Louis Cr., '01	North Ctr. Colorado	8	0.76	3.7	0.093	108	20-50 (est.)	step-pool
Little Granite Cr., abv. Boulder Cr. '02	West Ctr. Wyoming	19	2.83	6.3	0.012	67	34	plane-bed
E. St. Louis Cr., '03	North Ctr. Colorado	8	0.76	3.7	0.093	108	20-50 (est.)	step-pool
Halfmoon Cr., '04	Central Colorado	61	6.23	8.6	0.014	49	26	plane-bed, w/ pool-riffle
Hayden Cr., '05	South Ctr. Colorado	39	1.92	6.5	0.038	63	36	step-pool, plane-bed, mixed

2.4. Computation of transport rates

The collected bedload was bagged, dried, sieved in 0.5 phi increments and weighed. Transport rates were computed individually for each bedload trap (g/m·s), assigned to the fraction of stream width represented by the trap (g·m/m·s = g/s) and summed over all traps in the cross-section to obtain the total cross-sectional transport rate (g/s). Sediment collected in the Helley-Smith sampler was composited over all sampling verticals as is typically done. A cross-sectional unit transport rate was computed in g/m·s and multiplied by the total stream width to yield the cross-sectional transport rate in g/s. Because the Helley-Smith sampler collects particles smaller than 4 mm, the fine portion of the samples was truncated at 4 mm to compare similar particle sizes for both samplers. We did not truncate the upper portion of the size distributions.

2.4.1. Samples with zero-transport

The deployment of bedload traps in a highflow season often started at flows below the onset of gravel motion in order to identify the threshold flows at which small gravel particles start to be mobile. Consequently, samples collected at those low flows did not contain bedload particles. As flows increased, some samples contained one or a few particles in one of the traps per hour while other samples had none. As flows increased further, samples with zero particles no longer occurred. The sub-threshold zero samples collected before the onset of bedload motion do not define a transport-discharge relationship (an indefinitely large number of such samples could be collected over the months of low flow, for example) and therefore should not be used when defining a bedload rating curve. By contrast, the zero transport measurements that occur after bedload transport has just begun with very small transport rates (above-threshold zero-values) are part of the variability of bedload transport and should therefore be included when computing a bedload rating curve. The discharge at which the first positive transport rate occurred was taken as the threshold beyond which zero-values were included in the computation of rating curves.

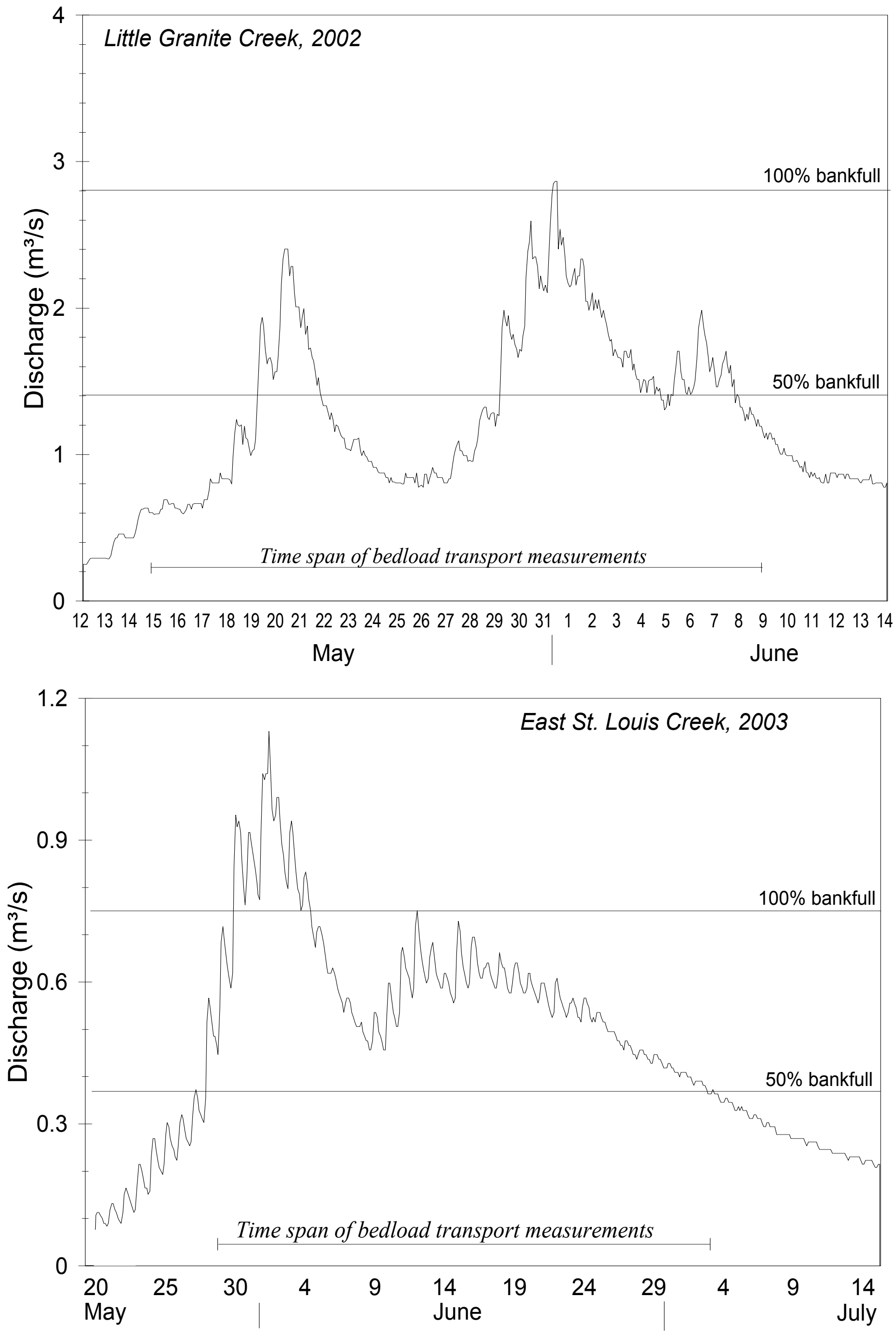

Fig. 3: Examples of snowmelt hydrographs for two of the eight study sites: Little Granite Creek, 2002 (top) and East St. Louis Creek, 2003 (bottom).

2.4.2. Fitting bedload transport rating curves and flow competence curves

Best fit linear functions were fitted to log-transformed data of gravel transport rates (Q_B) and discharge (Q) to yield power function regressions in the form of

$$Q_B = a \cdot Q^{b} \qquad (1)$$

where a is the power function coefficient and b the exponent. In order to include above-threshold zero transport values in the power function regressions, they were

Table 2: Exponents and coefficients obtained from fitted power function relationships between bedload transport (g/s) and discharge (m3/s) as well as the largest bedload particle size (mm) and discharge (m3/s) for samples from the bedload traps.

Stream	Bedload transport rating curves				Flow competence curves			
	Exponent b	Coefficient a	r^2	n	Exponent g	Coefficient f	r^2	n
St. Louis ‘98	10.8	1.06E-06	0.58	40	2.38	1.26	0.43	41
Little Granite ‘99	16.2	6.77E-12	0.76	58	3.49	0.110	0.67	58
Cherry ‘99	12.4	2.90E-08	0.84	21	2.71	0.739	0.90	21
E. St. Louis ‘01	8.39	13.9	0.78	79	1.52	32.0	0.60	91
Little Granite ‘02	8.43	7.02E-04	0.88	48	1.69	5.22	0.66	53
E. St. Louis ‘03	8.98	2.79	0.82	133	1.97	41.4	0.81	133
Halfmoon ‘04	7.89	2.83E-05	0.81	163	1.40	3.98	0.57	149
Hayden ‘05	7.55	0.0088	0.79	192	1.74	9.70	0.73	176

assigned a transport rate one order of magnitude lower than the smallest collected non-zero-value. This measure has the same effect as the standard practice of adding the value of 1 to log-transformed data before a regression analysis. Best fit linear functions were also fitted to log-transformed data of the largest collected bedload particle size per sample (D_{max}) and discharge (Q) to yield power function flow competence curves of the form

$$D_{max} = f \cdot Q^{g} \quad (2)$$

where f is the regression coefficient and g the exponent. For sites with a relatively small range of flows over which Helley-Smith samples were collected, and for sites with a relatively small number of samples, the data sets of Helley-Smith samples were supplemented with US Forest Service data (also truncated at 4 mm) from earlier studies collected at near-by sites using the same sampling protocol in order to better define the trend of the fitted bedload transport rating curve. These data are not included in the plots.

3. Results

Transport rates and maximum bedload particle sizes collected with bedload traps and the Helley-Smith sampler, as well as fitted bedload rating and flow competence curves are presented for all eight study sites. Measured bedload transport rates and particle sizes differed greatly between the two samplers, and the differences were remarkably consistent for all eight studies.

3.1. Bedload transport rating curves from bedload traps

At each study site, transport rates collected with the bedload traps over a highflow season spanned 4 – 6 orders of magnitude, and transport rates increased rapidly with flow (Fig. 4). Because bedload traps let particles < 4 mm pass, the lowest measurable transport rate is the collection of one 4-5.6 mm particle with an average weight of 0.1 g in one of the bedload traps over a 1 hour sampling time. Depending on stream width, trap spacing and sampling time, this catch results in a mass-based transport rate on the order of 0.00001 g/s. The highest collected rates exceeded 100 g/s. Power function rating curves were fitted to this wide range of measured transport rates and yielded exponents ranging from 8 to16 (Table 2). All rating curves were relatively well defined with r^2-values of 0.58 - 0.85. Steep bedload rating curves with comparably high exponents have also been obtained by other studies in coarse-bedded mountain streams that used sampling devices other than Helley-Smith samplers (Table 3). These devices were either installed in the bed (such as pit samplers), on the bed, or caught bedload across an overfall. Samplers set onto the bed were unflared, had relatively large mesh widths and long sampling times, such that an inadvertently dislodged small particle would either pass through the relatively large mesh width or become negligible in the otherwise large sample volume. It thus appears that in coarse-bedded mountain streams, samplers with wide openings, large sample storage capacities, large mesh width, long sampling times and little propensity for inadvertently picking up particles from the bed measure very small transport rates at low and large transport rates at high flow. The resulting wide range of transport rates provides steep rating curves with high exponents. The range of particle sizes collected in a sampler does not appear to affect the rating curve steepness in these streams: samplers in Table 3 that collected gravel only [65,3,4,66,67,68,69] have similarly steep bedload rating curves as those samplers that also collect sand and fine gravel [70,71]. If rating curve steepness is unaffected by truncation of the lower end of the sampled size distribution, then fractional rating curves (except for perhaps the largest one or two size classes) must be parallel to each other. This was the case for the stream measured by [64] as well as for all other studies in which bedload traps were deployed.

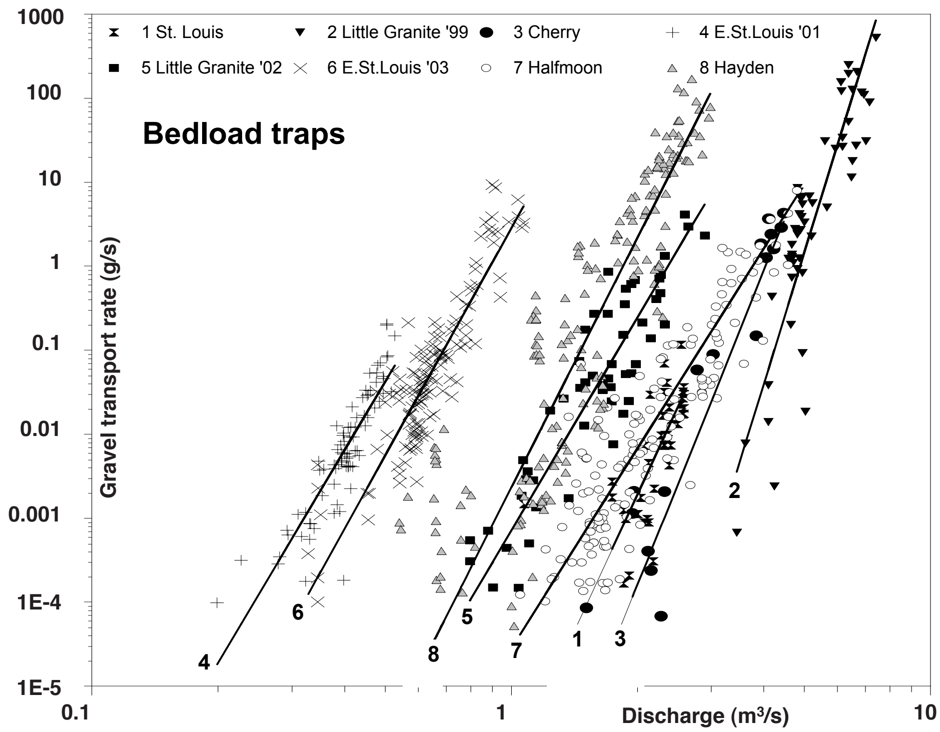

Fig. 4: Transport rates and fitted power function rating curves for bedload traps at the eight study sites.

At all bedload trap study sites, transport rates continued to increase at high flows with the same trend they exhibited during low and moderate flows. This was true even at the highest flows of 140 % Q_{bkf} (with 250 % Q_{bkf} typically being the highest flow recorded within 60 years). A flattening of the rating curve at high flows that has been reported in some studies, e.g., [2,60,66,71], did not occur in these slightly incised, steep, coarse-bedded, armored, and supply-limited mountain streams.

3.1.1. Comparison of transport rates from bedload traps to those of the Helley-Smith sampler

Gravel transport rates collected with the Helley-Smith sampler were generally higher than those collected with bedload traps, particularly during the lower flows. At the highest flows, transport rates from the Helley-Smith sampler and the bedload traps became similar. The range of transport rates obtained from the Helley-Smith sampler spanned only 2-4 orders of magnitude per site (due to the relatively high transport rates collected at low flows), whereas gravel bedload transport rates from the bedload traps spanned 4-6 orders of magnitude. The small range of transport rates measured with the Helley-Smith sampler produced rating curves that were considerably less steep than those from the bedload traps and yielded exponents between 2 and 4 (Table 4, Fig. 5), whereas bedload trap exponents were 8 to 16. Exponents between 2 and 4 are commonly obtained for bedload rating curves from Helley-Smith samples [72,51,73,74,41].Common trends in the gravel bedload transport rating curves computed from bedload traps and a Helley-Smith sampler for all study sites become more distinct when discharge is expressed in percent of bankfull flow (determined either from stream morphology or a long-term flood record) (Fig. 6). At all sites, rating curves from bedload traps were consistently and considerably steeper than those obtained from the Helley-Smith sampler. At 50 % Q_{bkf}, when gravel particles just started to move, bedload traps collected transport rates 1 - 4 orders of magnitude smaller than the Helley-Smith sampler. Near bankfull flows, when many particles were moving in almost all gravel size classes, transport rates measured with both samplers became similar. Computed intersection points of the rating curves obtained from both samplers were on average 131 % (90-194 %) Q_{bkf}.

3.2. Sampled bedload particle sizes

3.2.1. Flow competence curves for bedload trap samples

The largest collected bedload particle sizes (D_{max}) were plotted versus the flow at the time of sampling to yield flow competence curves. In flows exceeding bankfull, the D_{max} particle sizes collected in the bedload traps were cobbles 64-90 and 90-128 mm (Fig. 7). With transported maximum bedload particle sizes ranging from 4 mm at the lowest flows to cobbles at the highest flows, fitted power function flow competence curves had exponents of 1.4 to 3.5 and were relatively well defined (Table 2).

3.2.2. Comparison of flow competence curves between samplers

The largest bedload particles collected in the 76 by 76 mm Helley-Smith sampler at the highest flows were gravels of 45-64 mm, while cobbles 64-90 mm were almost never found in the sampler. The D_{max} bedload particle sizes in the Helley-Smith sampler were thus 0.5-1 phi size classes smaller than those collected with the bedload traps (Fig. 8). The collection of smaller particle sizes at high discharge is attributable to the small opening of the Helley-Smith sampler as well as the short (2-minute) sampling time that undersamples infrequently moving large particles [61]. Sampler placement on large rocks or blockage of the sampler opening [41] might have played a role, but that is not known. Collection of several 2-minute samples per vertical, or better a larger Helley-Smith net that permits 5-minute samples might have eased this problem, but

Table 3: Exponents of power function relationships between bedload transport rates and discharge curves obtained for samplers with wide opening, long sampling times and large mesh widths in mountain gravel-bed streams.

Study	Sampler type	Sampler opening (width · height · length or depth; m)	Sampling time	Exponent of gravel bedload rating curve
Nanson (1974) [65]	Wire basket sampler with 6.4 mm mesh	0.3 · 0.15 · 0.38	Several min.	6.7
Bunte (1991; 1996) [3,4]	Net sampler with 10 mm mesh	1.53 · 0.3 · 3.0	10 - 90 min.	16-18
Bunte (1997) [81]	Pit traps, with 12.7 mm top grid	0.3 ∅ · 0.26	1 hr. to 1 day	7.3
Whitaker (1997) [66]; Whitaker and Potts (1996) [67]	Net sampler, with 32 mm mesh	1.0 · 0.45 · 3.0	1 - 60 min.	6.6
Garcia et al. (2000) [70]	Automatically weighing pit trap	0.13 · 0.48	15 min.	11*
Wilcock (2000, 2001) [68,69]	Wire baskets with 25.4 mm mesh hanging from a log	1.2 · 0.6 · 0.3	Several hrs. to 1 day	9.6
Hassan & Church (2001) [71]	Pit traps	0.29 ∅ · 0.38	1 hr to 1 day	10-18

* est. after conversion of τ to Q

Table 4: Exponents and coefficients obtained from fitted power function relationships between bedload transport and discharge as well as the largest bedload particle size and discharge for samples from the Helley-Smith sampler.

Stream	Bedload transport rating curves				Flow competence curves			
	Exp. B	Coeff. a	r^2	n	Exp. g	Coeff. f	r^2	n
St. Louis '98	4.41	0.0396	0.64	229*	1.03	4.27	0.46	205*
Little Granite '99	3.64	0.0208	0.49	321*	0.868	4.94	0.46	247*
Cherry '99	2.52	0.0763	0.51	46#	0.670	5.70	0.57	36*
E. St. Louis '01	3.56	6.68	0.54	174*	1.01	18.8	0.27	81
Little Granite '02	3.10	0.109	0.51	22	0.532	6.91	0.32	66
E. St. Louis '03	3.81	20.7	0.86	40	1.07	25.0	0.50	40
Halfmoon '04	3.85	0.132	0.83	205*	0.970	7.94	0.73	204*
Hayden '05	2.40	1.81	0.64	104*	0.777	14.5	0.52	108*

* Sample size includes data set collected by S. Ryan and her crews. # Sample size includes data set collected by the Winema National Forest.

was not feasible at rapidly changing flow when the collection of one cross-sectional sample with 2-minutes per vertical already took about 45 minutes. At low flows, by contrast, when small gravel particles were just beginning to move, the Helley-Smith collected larger particles than the bedload traps. The larger particle sizes in the Helley-Smith samples at low transport rates were likely due to an inadvertent occasional dislodging of a mobile surface particle when setting the Helley-Smith sampler onto the bed and the subsequent entrainment of the dislodged particle into the sampler opening due to the sampler's high hydraulic efficiency of 154 % [46]. The authors observed this process on several occasions when the area around the sampler opening was viewed through a piece of plexi glass. Increasing the number of 2-minute samples per vertical and thus the number of times the sampler is placed onto the streambed would have exacerbated the problem. [75] who used a 76 by 76 mm Helley-Smith sampler within a leaden frame (i.e., the crane-version), set it next to a pit trap, and left it there for long sampling times (20 min. to 23 hours), found that the Helley-Smith collected less gravel than the pit traps. These findings confirm that repeated placement of a handheld Helley-Smith sampler and the resulting inadvertent particle pick-up are the probable causes for the relatively large gravels captured by the Helley-Smith sampler at low flows.

Because the Helley-Smith sampler collected larger bedload particle sizes than bedload traps at low transport and smaller ones at high transport, the fitted power function flow competence curves for the Helley-Smith sampler had exponents of 0.5 to 1.1 (Table 4). These were significantly lower than exponents obtained from bedload traps (1.4 to 3.5). The bankfull particle sizes collected with the Helley-Smith sampler reached, on average, 71 % of those collected in the bedload traps, whereas at 50 % Q_{bkf}, the D_{max} particles in the Helley-Smith sampler were 1.4 times larger than those collected with the bedload traps. Fitted flow competence curves for both samplers intersected at moderate flows between 46 and 88 % Q_{bkf}.

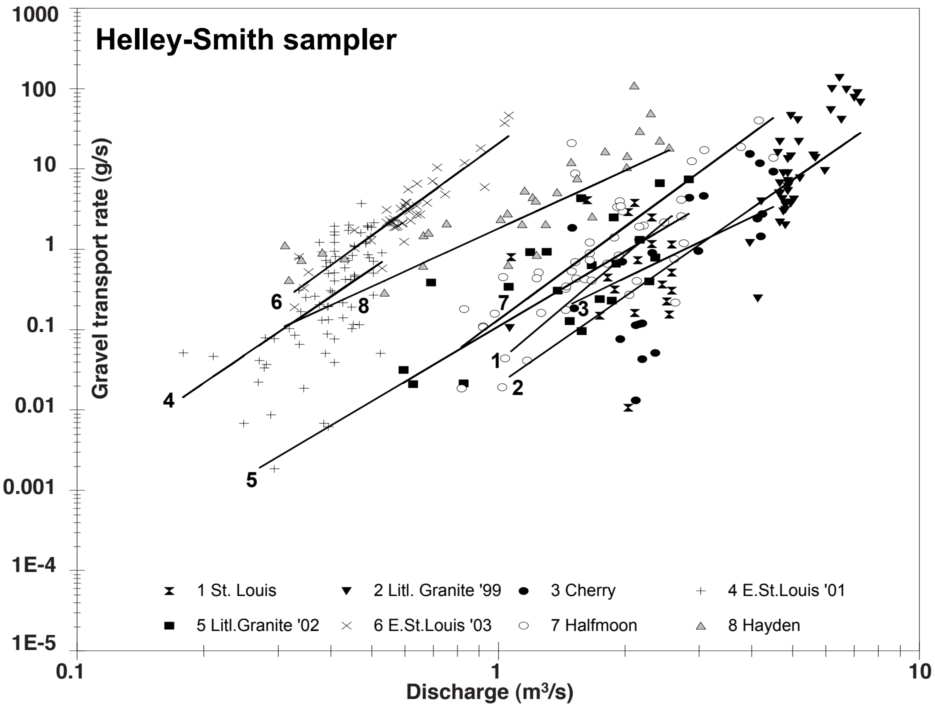

Fig. 5: Gravel transport rates for particles larger 4 mm computed from Helley-Smith samples at eight field sites. Helley-Smith samples from other studies used to supplement our data are not displayed.

4. Discussion

True transport rates were not known at our study sites. However, several factors suggest that transport rates and particles sizes collected with bedload traps are relatively accurate. For one thing, bedload traps were specifically designed for sampling gravel and cobble bedload, featuring a large and unflared opening, a large sampler bag with a wide mesh that, together with the mounting of bedload traps onto ground plates permit a long sampling time and avoids involuntary particle dislodgement and capture. The importance of these design features is underscored by the fact that results from other devices that have similar characteristics also yield steep bedload transport rating curves with high exponents when deployed in mountain streams (Table 3). Of these characteristics, sampling time and sampler opening size appear to have smaller effects on the observed differences in results between the two samplers than the use of ground plates.

The effects of sampling time on transport rates measured with bedload traps were quantified by [61] in a coarse-bedded mountain stream. Transport rates computed from 2-minute deployment at the lowest transporting flows were about 5 times larger than for 1-hour sampling. Near bankfull flow, transport rates from 2-minute deployment were about 5 times smaller than for 1-hour sampling. Although notable, compared to the observed 2-4 orders of magnitude difference in transport rates between the two samplers at 50 % Q_{bkf}, sampling duration explains only a small fraction of the observed difference in transport rates computed for bedload traps and the Helley-Smith sampler. Increased sampling time affects not only the total measured transport rates but also the largest sampled bedload particle sizes by providing a greater chance for infrequently moving large particles to enter the sampler. These particles are less likely to be collected if the sampling time is short. The sampler opening size affects collected particle sizes as well. The 0.3 by 0.2 m sampler opening of the bedload traps permits cobbles of the 128 mm size class (and larger) to enter the sampler, while cobbles (except for the smallest ones) do not fit into the 76 by 76 mm Helley-Smith sampler opening. As a result, transport rates and maximum particle sizes measured at the highest flows with the Helley-Smith sampler are smaller than those collected with the bedload traps. Several studies [33,40,41] show that the 152 by 152 mm Helley-Smith sampler collected larger D_{max} particle sizes than the smaller version. However, [52,53] attribute the larger sample mass collected by a 152 by 152 mm compared to a 76 by 76 mm Helley-Smith sampler to a larger propensity of the 152 by 152 sampler to dig into (mine) the bed.

The unflared sampler opening of the bedload traps causes a hydraulic efficiency that is likely less than 100 %. This inefficiency is compensated to some degree by the extension of the ground plates in front of the trap opening. Velocity profiles measured at various distances in front of the bedload traps in field and flume experiments [76] indicated that the near-bottom flow velocity on the ground plate about 1 cm above ground was faster by 30-50 % compared to the velocity measured on the bed upstream. This effect is attributed to the smoothness of the ground plate. In the middle of the trap opening, the presence of the sampling net decelerated flow velocities by 10-20 % compared to measurements on the bed upstream. However, compared to a hydraulic efficiency of 1.54 for the Helley-Smith

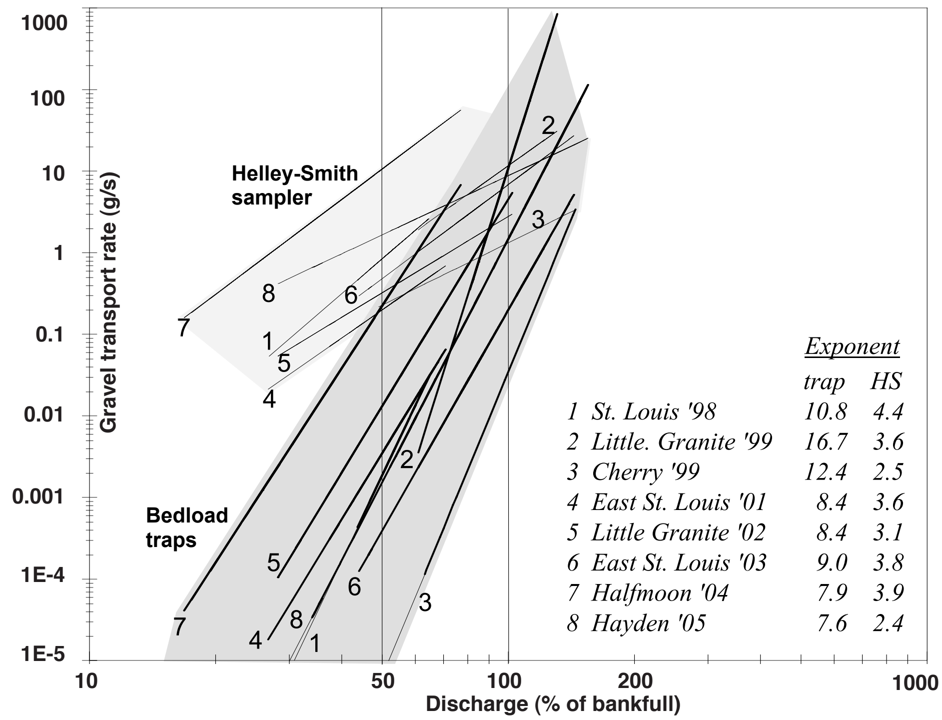

Fig. 6: Comparison of fitted rating curves for bedload traps (thick lines on a dark gray background) and the Helley-Smith sampler (thin lines on a light gray background). Discharge is normalized by bankfull flow

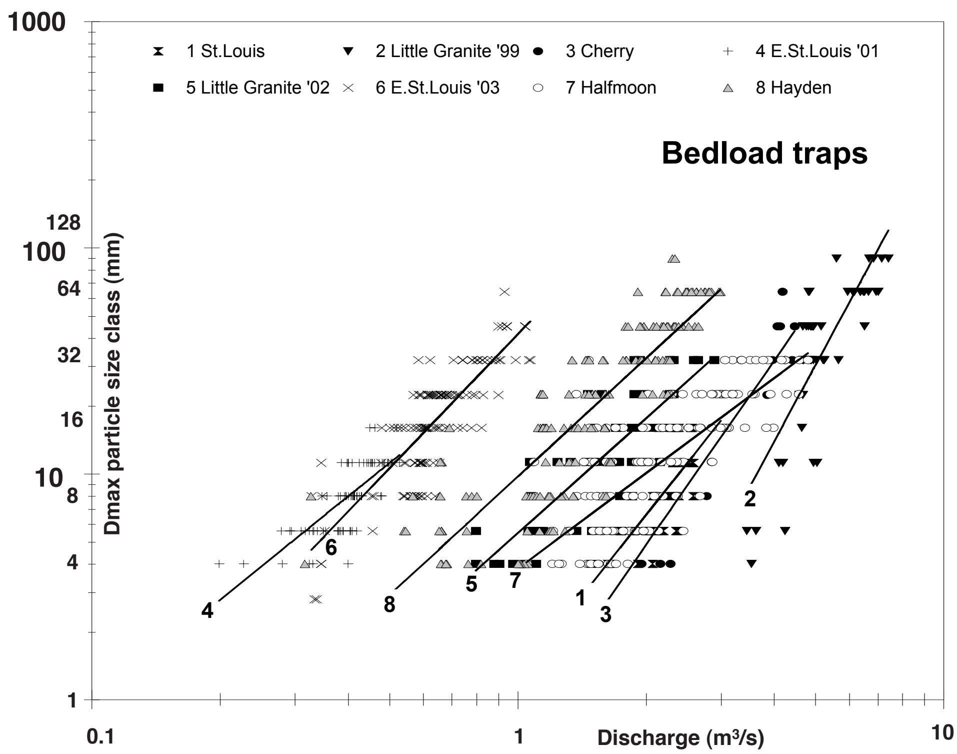

Fig. 7: Largest sampled bedload particle sizes (Dmax) collected in the bedload traps and fitted flow competence curves.

sampler over the entire intake area, a 30-50 % increase in the near-bottom velocity at the trap entrance and a 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.

The feature responsible for the largest difference in measured transport results between bedload traps and Helley-Smith are the ground plates. Deployment of bedload traps onto ground plates that remain in place during the entire field season eliminated unwanted particle pick-up. Inadvertent dislocation of a bed particle when setting the Helley-Smith onto the bottom of a gravel bed and subsequent entrainment into the opening due to the sampler's high hydraulic efficiency has been observed in our field studies. Opportunities for involuntary particle pick-up are multiple as the Helley-Smith sampler is set onto the bed up to 20 times when sampling a cross-section and up to 40 times when two traverses are done. When transport rates are very low at the beginning of gravel motion, and only one 4-mm particle is moving through a 7 m wide cross-section per hour, the resulting true transport rate is 0.000028 g/s. If this one gravel particle is collected in one of 6 bedload traps deployed over a 7 m wide cross-section, the measured transport rate is 0.000108 g/s. However, collecting one 4-mm particle in a 2-minute Helley-Smith sample with 15 sampling verticals results in a measured transport rate of 0.0051 g/s. Thus, the inadvertent collection of only one 4-mm gravel particle in the Helley-Smith sampler during very low transport produces an artificially inflated transport rate that exceeds the one measured with bedload traps by an order of magnitude [64]. Inadvertent collection of an additional 16 mm bed particle in a 76 by 76 mm Helley-Smith sampler (a very easy thing to do) increases the transport rate to 0.62 g/s and is several orders of magnitude over the bedload trap measurement.

A trial deployment of the Helley-Smith sampler onto the ground plates after the bedload traps were removed at one of the study sites demonstrated the effect that involuntary particle dislocation and entrainment into the sampler has on measured transport rates. Transport rates collected by the Helley-Smith sampler set onto the ground plates (using the same sampling intensity as that used for placement onto the bed) were within the same range as the bedload traps, while transport rates collected with the Helley-Smith placed directly onto the bed were considerably higher, reaching the typical 2.5 orders of magnitude difference at 50 % of bankfull flow [77]. These results are comparable to the study by [9] that showed similar transport rates between a conveyor belt sampler and a 76 mm opening Helley-Smith sampler that was deployed on a concrete sill.

Sampling results suggested that gravel transport rates obtained from bedload traps also provide a relatively accurate description of incipient motion conditions. Critical flow for incipient motion can be computed using either the largest grain or the small transport rate method [78]. Both methods are thought to be fully compatible only under ideal circumstances. Sampling results from the bedload traps showed that the two methods are more compatible than previously thought for field measurements [64]. There was no similarity of incipient motion results between the two methods for samples collected in the Helley-Smith sampler. Comparable results in both incipient motion methods makes bedload traps suited for direct measurements of incipient motion using either method.

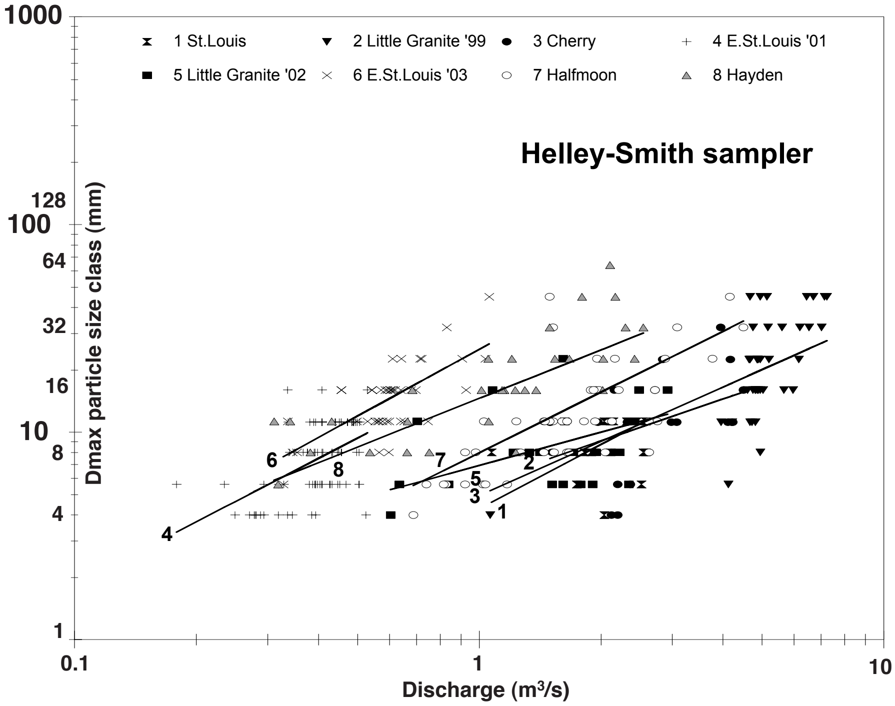

Fig. 8: Largest sampled bedload particle sizes collected in the Helley-Smith sampler and fitted flow competence curves.

The question arises whether bedload traps might undersample gravel transport when flow and transport rates are very low. The smoothness of the ground plates ensures that once a particle has entered the ground plate it is typically transported into the trap without delay. Sometimes, however, a particle rests on the plate for a while before proceeding into the sampler. This delay erroneously decreases the current measured transport rate and increases the rate for the next sample as the particle eventually moves off the plate and into the collection bag. Another process that might cause temporarily lowered transport rates is the occasional development of a small trough at the ground plate front edge. Small particles may swirl around in the trough for a while before entering the ground plate. Both these processes likely result in only minor under representation of transport rates. Significant undersampling using bedload traps can occur, however, if the ground plates are inappropriately installed at an elevation above the average local bed or if the ground plates become pedestalled. Pedestalling may happen if repeated wading behind the traps at high flows scours a trench, and headcuts start migrating upstream between the ground plates. Undersampling also occurs if the sampler net is allowed to overfill. This may happen when sampling time is not reduced sufficiently at times when large amounts of coarse organic material are transported during the first rising limb of a highflow season in a forested watershed. Overfilling the bedload trap net reduces its sampling efficiency [61].

Difference in bedload transport rating curves that stem from the deployment of different samplers have implications for subsequent computations. Annual load estimates, for example, will yield substantially higher values when based on a bedload rating curve from a Helley-Smith sampler in years of generally low flows compared to bedload traps, while years with high flows yield a higher annual load estimate when based on bedload trap samples. Effective discharge, computed from the magnitude-frequency analysis [79] commonly occurs near bankfull flow based on the relatively flat Helley-Smith bedload rating curves. However, the computed effective discharge will shift towards the highest flows recorded for the stream when a rating curve with a high exponent is used for the computation [80]. Similarly, the computation of critical flows at incipient motion (e.g., τ_c or Q_c) will vary depending on the sampler used. Compared to the Helley-Smith sampler, bedload traps indicate a higher critical flow for small gravel particles and a lower critical flow for large gravel and cobbles. These differences can lead to different conclusions regarding bed mobility or requirements for channel maintenance flows.

Exponents of the rating and flow competence curves are not correlated between the two samplers and therefore not predictable from one another. However, the difference in transport rates between the two samplers at 50 % of bankfull flow is predictable and increases with the steepness of the bedload trap rating curve, meaning that the high bedload trap exponents have the biggest influence in determining the magnitude of the difference.

5. Conclusion

This study developed bedload traps as a sampling device for gravel and cobble bedload in coarse-bedded mountain streams. Bedload traps were tested at eight study sites and their sampling results were compared to those obtained at the same sites from a 76 by 76 mm Helley-Smith sampler. Bedload rating and flow competence curves obtained from bedload traps were consistently and considerably steeper than those obtained from the Helley-Smith sampler at all eight study sites and typically better defined. At low flows, bedload traps measured smaller transport rates and collected smaller D_{max} bedload particle sizes than the Helley-Smith. At high flows, bedload traps collected more and coarser bedload than the Helley-Smith. These differences are attributable to the use of a ground plate with the bedload traps and the flared Helley-Smith's sampler body and that is repeatedly placed onto the bed surface. The larger opening and longer sampling time of the bedload traps also contribute to this result. The presence of a ground plate that eliminated unwanted particle pick-up seemed to have the largest effect on the observed difference in measured transport rates and particle sizes the two samplers. Differences in measured bedload transport rates and D_{max} bedload particle size have implications for all computations derived from the data, as well as our understanding of how gravel-bed streams function.

Bedload traps appear to yield fairly representative samples of gravel and small cobble bedload. The accuracy of transport results obtained from a Helley-Smith sampler can be improved by placing the sampler onto ground plates or any other surface that eliminates unwanted particle pick-up. The Helley-Smith sampler fulfills an important role in coarse systems by capturing the fine gravel (less than 4 mm) and sand that this type of bedload trap is unable to measure and by being deployable in unwadeably deep flows using a bridge or a boat.

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