Measurement of Coarse Gravel and Cobble Transport Using Portable Bedload Traps

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Abstract: Portable bedload traps (0.3 by 0.2 m opening) were developed for sampling coarse bedload transport in mountain gravel-bed rivers during wadable high flows. The 0.9 m long trailing net can capture about 20 kg of gravel and cobbles. Traps are positioned on ground plates anchored in the streambed to minimize disturbance of the streambed during sampling. This design permits sampling times of up to 1 h, overcoming short-term temporal variability issues. Bedload traps were tested in two streams and appear to collect representative samples of gravel bedload transport. Bedload rating and flow competence curves are well-defined and steeper than those obtained by a Helley–Smith sampler. Rating curves from both samplers differ most at low flow but approach each other near bankfull flow. Critical flow determined from bedload traps is similar using the largest grain and the small transport rate method, suggesting suitability of bedload trap data for incipient motion studies.

DOI: 10.1061/(ASCE)0733-9429(2004)130:9(879)

CE Database subject headings: Bed loads; Gravel; Incipient motion; Sampling; Sediment transport; Transport rate; Measurement.

Introduction

Coarse bedload transport in mountain gravel- and cobble-bed rivers is characterized by several phenomena which make representative sampling difficult: (1) particles of the largest mobile size class for a given flow move infrequently; (2) bedload-transport rates can span up to several orders of magnitude; and (3) bedload-transport rates fluctuate considerably over time and space (e.g., Ehrenberger 1931; Hayward and Sutherland 1974; Church 1985; Hubbell et al. 1987; Gomez et al. 1989; Gomez 1991; Bunte 1996). Consecutively sampled transport rates may vary by orders of magnitude even during near constant flow, while 50–100% of the bedload transported may be concentrated within a small portion of the stream cross section. This temporal and spatial variability is attributable to a variety of processes [summarized in Bunte and MacDonald (1999)] which make bedload transport notoriously difficult to quantify.

The complexity of bedload transport processes in mountain gravel-bed streams needs to be better understood to support instream flow quantification and other management decisions. This necessitates using samplers that provide accurate measures of gravel and cobble bedload and that can be deployed quickly at remote sites. Accurate measurements of gravel transport rates in the largest mobile size class—when only a few particles of that size are in motion at a given time—are particularly important for incipient motion studies. Samplers suitable for this task should have the following properties: the ability to obtain a physical and sievable sample of bedload at specific flows, portability for use at remote sites, use without stream excavation or construction, and the ability to collect representative samples of gravel and cobble-sized bedload material. To achieve these objectives, the sampler must have an opening sufficiently large for coarse gravel and small cobble particles, and sampling should cover much of the width of the stream. The sampler needs to be hydraulically efficient and neither excessively accelerate nor retard flow. The sampler should also be mountable on a fixed surface on the stream bottom and accommodate a large sample volume, thus facilitating a long sampling duration. Sampling time should exceed the transport frequency of infrequently moving large particles, so that at least a few have a chance to enter the sampler during the sampling time. Long sampling times are desirable to average out short-term temporal variations in transport rates (Gomez et al. 1991) and are necessary to avoid bias in sampled transport rates, although sampling must be short enough to associate a bedload-transport rate with a discrete discharge value. None of the currently available bedload samplers combines *all* of these properties (Table 1).

Development and Operation of Bedload Traps

Bedload Trap Design

The prominent characteristics of the sampling device designed for this study are a large opening and a long sampling time (at low transport rates), attributes more typical of a “trap” than a “sampler.” The term “bedload trap” is therefore used to describe these devices, even though they are not installed below the bed surface. The traps designed for this study have a frame 0.3 m wide, 0.2 m

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Note. Discussion open until February 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 26, 2002; approved on March 2, 2004. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 130, No. 9, September 1, 2004. ©ASCE, ISSN 0733-9429/2004/9-879–893/$18.00.

Table 1. Attributes of Bedload Samplers Used for Gravel and Cobble Bedload. (+) Attribute is Present, (−) Attribute is Absent and (+/−) Presence of Attribute Depends on Configuration and Circumstances

Attribute	Vortex sampler[a]	Birkbeck sampler[b]	Unweighable pit traps[c]	Basket sampler[d]	Net-frame sampler[e]	0.076 m pressure-difference samplers[f]	Large pressure-difference samplers[g]
Physical sample for sieve analysis	+	−	+/−	+	+	+	+
At least 20–30% width sampled	+	+	+	−	+/−	−	−
Large sampler opening	+	+	+	+	+	−	+/−
Long sampling duration	+	+	+	+/−	+	−	−
Portability	−	−	+	+/−	+/−	+	+
Use without stream excavation or construction	−	−	−	+/−	+/−	+	+/−
Ease of use	+/−	+	+/−	+/−	−	+	−

[a] Milhous (1973); Hayward and Sutherland (1974); O'Leary and Beschta (1981); Tacconi and Billi (1987); and Atkinson (1994).

[b] Reid et al. (1980, 1985); Reid and Frostick (1986); Reid and Laronne (1995); Powell et al. (1998); Garcia et al. (2000); and Habersack et al. (2001).

[c] Church et al. (1991); Powell and Ashworth (1995); Bunte (1997); Hassan and Church (2001); and Sterling and Church (2002).

[d] Mühlhofer (1933); Hubbell (1964); Nanson (1974); Engel and Lau (1981); Gao (1991); Xiang and Zhou (1992); and Wilcock (2001).

[e] Bunte (1992, 1996); Whitaker and Potts (1996); and Whitaker (1997).

[f] Helley and Smith (1971); Druffle et al. (1976); Johnson et al. (1977); Beschta (1981); Emmett (1980, 1981); Childers (1991); Gaudet et al. (1994); Ryan and Troendle (1997); Ryan and Porth (1999); and Sterling and Church (2002).

[g] Hubbell et al. (1987); Dinehart (1992); Childers (1999); and Duizendstra (2001a,b).

high, and 0.1 m deep, fabricated of 6.4 mm thick aluminum (Bunte et al. 2001) (Fig. 1). Dimensions were selected to accommodate particles up to small cobble sizes (128 mm). The bottom part of the frame is beveled at an angle of 30° to provide a smooth entrance for bedload particles. The frame is placed onto a ground plate to ensure good contact with the stream bottom. Ground plates are made of 3.2 mm aluminum. The front edge of the ground plate is inclined 10° down in the upstream direction to provide a smooth transition between the streambed and the bedload trap entrance. The ground plates have holes on either side through which metal stakes are driven into the streambed to anchor the ground plates and the traps. Slits near the top and bottom on both sides of the frame serve to hold 25 mm wide nylon straps which are adjustable in length by heavy-duty friction buckles and slide over the stakes to hold the traps in place. A flexible connection is essential because the stakes can rarely be driven into the bed parallel to the bedload trap frame in coarse gravel-bed streams. The stakes are 12.7 mm in diameter, rolled steel, 0.9–1.2 m long, and have a sharpened tip. Their surfaces are smooth so that the nylon straps can easily slide up and down.

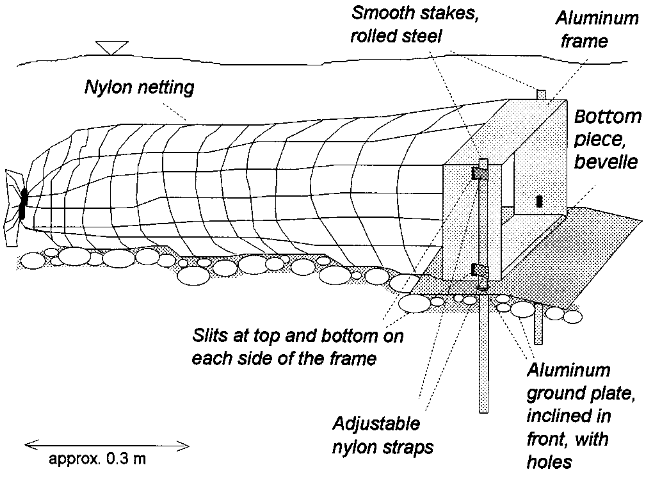

Fig. 1. Schematic diagram of the bedload trap

Sediment is collected in a trailing net that extends approximately 1 m downstream of the frame. The netting is sturdy, knotless, and abrasion-resistant, crocheted of thin nylon yarn and available from fishery aquaculture suppliers. The mesh opening of 3.5 mm combines the advantages of relatively unobstructed water flow with the ability to trap gravel particles as small as 4 mm. The downstream end of the net is tied shut with a short-length cotton rope (clothesline) that can easily be opened to remove collected sediment. The net has a fill volume of about 0.025 m^3, equivalent to about 50 kg of gravel. Assuming a 40% fill level is acceptable without compromising sampler efficiency (Emmett 1981), trap capacity is approximately 20 kg. This mass permits deployment of bedload traps for long time periods (one or more hours) during low and moderate transport events.

Trap Installation on Streambed

Trap installation is best done at relatively low flows and a few days prior to the onset of bedload transporting flows. A small area of the streambed is cleared of large surface particles to obtain a level space onto which a ground plate is positioned flush with the average height of the streambed. The inclined front edge of the plate should slightly penetrate the bed. Alternatively, the ground plates can be installed by pushing the angled front edge a few cm deep into the streambed. Particles are then removed from beneath the plate until the plate is positioned at the average height of the bed. Ground plates are anchored to the stream bottom by the stakes, driven 0.3–0.6 m into the streambed. Use of a stake driver helps to keep the stakes upright as they are pounded into the streambed and protects the stake tops. Pieces of garden hose inserted over the stake tops mark the location of the stakes in deep flow and assist with relocating the traps.

Once the ground plates are in place, a few midsized gravel particles may have to be placed over the beveled front edge to create a smooth transition between the streambed and ground plate. Coarse gravel particles are placed along the sides of the

Fig. 2. Traps installed at Little Granite Creek are submerged at bankfull flow. The black rectangles indicate the location of four of the six traps (view downstream).

Fig. 3. Untying the net before emptying the bedload traps at Little Granite Creek

plate to avoid streambed erosion along the plate margins. Plate installation is completed by scattering a few handfuls of finer gravel on top of the rearranged bed to partially fill voids. Bedload traps should be allowed to equilibrate with the channel bottom for at least several hours before sampling begins.

After the bedload trap frame is set onto the ground plates, the straps are adjusted in length to obtain the desired position and optimal ground contact. Fasteners (i.e., shaft collars with fitted thumb screws) are slid over the stakes and push the straps downward to secure the traps on the ground plates. Once installed, stakes and ground plates remain in place for the entire sampling season, unless local scour or deposition necessitates repositioning. Rechecking the frames for optimal ground plate contact is necessary during and between sample collection.

Trap Locations in Streambed

A wide riffle is the most wadable part of the stream and provides the best chances for reaching all traps during high flow. The combined widths of all traps installed across the stream should cover 20–40% of the active streambed, depending on the desired sampling intensity or accuracy with respect to lateral variability of bedload transport. Trap spacing can be regular, or, if known, cover positions with high transport rates more closely (Yang and Gao 1998). In this case, the computation of cross-sectional transport rates needs to reflect irregular trap spacing [e.g., Eq. (3)].

Emptying Bedload Traps

An important feature of bedload traps is that they can be emptied while the frame remains in place on the ground plate, avoiding disturbance of the stream bottom (Figs. 2 and 3). Bedload and organic debris accumulate at the downstream end of the net. For emptying, the net is held shut above the accumulated debris, and the end of the net is lifted out of the water. The cotton line is untied, and the content of the net is emptied into a bucket. The net may be left open in the flow until the next sample starts or can be immediately retied and dropped into the current for another sampling period. Wading must be restricted to the downstream side of the bedload traps to avoid dislodging bed-material that may enter the traps. Wading near the traps should generally be kept to a minimum as foot traffic can dislodge particles which may cause bed scour behind and beneath the ground plates and destabilize them. Bedload samples taken with the bedload traps in forest streams often contain large amounts of organic debris (up to 0.015 m^3 per trap per 1 h during the rising limb of snowmelt highflow). This material needs to be separated from the sample to obtain the inorganic portion, but its quantification may provide useful information for stream ecologists. No sample should be discarded without careful inspection because bedload particles may be concealed among the organic debris.

Field Testing

Stream Sites

Bedload traps have been field tested at several gravel- and cobble-bed Rocky Mountain streams during snowmelt runoff (Bunte and Abt 2003). This study describes field results obtained at St. Louis Creek in the Fraser Experimental Forest near Fraser, Colo., about 120 km NW of Denver (Bunte 1998) and at Little Granite Creek (Fig. 2), a tributary to Granite Creek in the Gros Ventre Range in NW Wyoming, about 50 km east of Jackson Hole, Wyo. (Bunte 1999). Characteristics of the two streams and their field sites are provided in Table 2 [for frequency distribution of subsurface material at Little Granite Creek see Fig. 5(b), for cumulative distribution of surface and subsurface material at Little Granite Creek and St. Louis see Figs. 6 and 11]. The streams differ mainly in basin area size, width and discharge, while gradient, stream morphology, and bed-material are similar. Characteristics of bedload-transport measurements are summarized in Table 3.

Measurements of Bedload Transport

At St. Louis Creek, five bedload traps were installed in a slightly diagonal pattern across a riffle about 1 m apart. Up to eight samples per day were collected between daily low flows and a few hours after daily peak flows, and sampling periods usually lasted for 1 h. At Little Granite Creek, six bedload traps were installed across a wider than average riffle. Spacing between the traps varied from 1.6 to 2.2 m due to the location of large rocks (Fig. 2). Up to five sets of bedload samples were taken per day between the falling limb of flow in the morning and the rising limb in the late afternoon. Maximum flow reached 133% of bankfull. At this flow, wading became difficult (Abt et al. 1989), and operating the traps required a 3-person team. Nevertheless, the traps operated satisfactorily, and none were dislodged by flow. On occasions, ground plates at locations with high transport were buried under 0.1–0.15 m of sediment and had to be repositioned to be flush with the stream surface. Sampling periods typically lasted for 1 h but occasionally had to be reduced to periods as

Table 2. Stream and Site Characteristics

Parameter	St. Louis Creek 0.5 km upstream of diversion dam	Little Granite Creek 1 km upstream of confluence with Granite Creek
Basin area (km^2)	35	55
Maximum basin elevation (m)	3,860	3,200
Site elevation (m)	2,900	1,980
Stream width (m)	6–8	8–12
Stream morphology	Plane-bed with occasional riffles and pools	
Cross-section geometry	Asymmetrical riffle	
Stream gradient (m/m)	0.017	0.017
Active stream width (m)	6.3	12.4[d]
Bankfull parameters at study site		
Width (m)	6.5	14.3[d]
Depth (m)	0.38	0.39
Velocity (m/s)	1.50	1.03
Discharge (m^3/s)	4.0[a]	5.7
Surface bed-material		
D_5; D_{16}; D_{50}; D_{84}; D_{95} (mm)[b]	4; 22; 76; 160; 208	~1; 17; 69; 166; 236
Subsurface bed-material		
D_5; D_{16}; D_{50}; D_{84}; D_{95} (mm)[c]	~1; 4; 41; 125; 179	~0.5; 5; 41; 141; 209

[a] Ryan and Troendle (1996).

[b] 400 particle pebble counts; particle sizes were measured with gravelometer graded in 0.5 ϕ size classes.

[c] 130 kg samples, using a barrel sampler (Milhous et al. 1995), sieved in 0.5 ϕ increments.

[d] Cross section at study site was purposefully selected to be wider than average.

Table 3. Characteristics of Bedload Measurement for Two Sites

Parameter	St. Louis Creek	Little Granite Creek
Bedload traps		
Number installed	5	6
Spacing (m)	1.0	1.6–2.2
Usual sampling time (h)	1	1
Number of samples collected	41	58
Flows sampled (%Q_{bkf})	28–65[a]	65–133[b]
Bedload $D_{\max}$ size class (mm)	16–22.4	90–128
Maximum sample size	0.2 kg/h	20 kg/6 min
Helley–Smith sampler (this study)		
Number of verticals	12 to 13	18
Average spacing (m)	0.50	0.74
Usual sampling time (s)	120	120
Number of samples collected	18	44
Flows sampled (%Q_{bkf})	28–65	65–133[b]
Bedload $D_{\max}$ size class (mm)	16–22	45–64
Helley–Smith sampler (previous studies)		
Data sets published by	Ryan (1998)	Ryan and Emmett (2002)
Number of verticals	16	20
Average spacing (m)	0.5	0.3 to 0.4
Usual sampling duration (s)	30–60	30–60
Number of samples collected	200	280
Flows sampled (%Q_{bkf})	23–128	10–185
Bedload $D_{\max}$ size class (mm)	32–64, few particles >64	

[a] One sample collected at 16% Q_{bkf}.

[b] Three consecutive samples collected at 19% Q_{bkf}.

short as 6 min when bedload sheets similar to those observed by Whiting et al. (1988) filled the net with 20 kg of gravel.

At both field sites, bedload samples were also collected with a 0.076 by 0.076 m opening, 3.22 expansion ratio, thin-walled sheet-metal Helley–Smith sampler (Ryan and Porth 1999). This device is often used to sample bedload in remote gravel-bed streams, although it was not designed for sampling large gravel and cobble particles nor for facilitating long sampling times of 30–60 min. Widespread usage is due to practical reasons such as portability and ease of use in handheld operation, properties not present in larger Helley–Smith type samples with an opening size more suitable for trapping coarse gravel and cobbles. Sampling duration for the Helley–Smith sampler was 2 min per vertical, and one traverse was completed per sample similar to methods used by Ryan and Troendle (1997). At St. Louis Creek, Helley–Smith samples were collected at a cross section a few meters downstream of the bedload traps at 12 to 13 evenly spaced verticals 0.5 m apart. Placement of the Helley–Smith directly behind bedload traps was avoided, nevertheless, transport rates may have been slightly diminished due to particles being caught in the bedload traps 2–5 m upstream. At Little Granite Creek, this potential for undersampling was avoided by fitting the 18 Helley–Smith sampling verticals into the spaces between the traps. This resulted in a somewhat irregular spacing of 0.5–0.85 m that averaged 0.74 m per vertical.

Samples from each of the bedload traps and the Helley–Smith samples composited over the cross section were bagged for laboratory analysis. Some trap samples were comprised of only one or a few small gravel particles. Their size was measured in the field using a gravelometer (Potyondy and Bunte 2002) and the number of particles per size class recorded. Similarly, the size class, number, and weight of particles larger than 32 mm were determined in the field to reduce the amount of sediment analyzed in the laboratory. To facilitate conversion between particle mass and particle number at each site, relations between the average particle weight $\overline{m_i}$ per size class (g) and the retaining sieve size D_i (mm) were established from large subsurface sediment samples. For samples sieved in 0.5 ϕ size classes, the least-squares regression analysis yielded the power functions

$$\overline{m_i}=0.00363D_i^{2.92} \quad \text{for St. Louis Creek and} \tag{1a}$$

$$\overline{m_i}=0.00270D_i^{3.05} \quad \text{for Little Granite Creek} \tag{1b}$$

Computation of Bedload-Transport Rates

At St. Louis Creek where bedload traps were evenly spaced, mass-based fractional unit transport rates q_{bi} for 0.5 ϕ size classes were computed from

$$q_{bi}=\frac{\Sigma m_i}{w_s \cdot n_s \cdot t_s} \tag{2}$$

where Σm_i=dry bedload mass per size class in all traps; w_s=trap width; n_s=number of traps used concurrently; and t_s=sampling time. Fractional transport rates are summed for all size classes i to obtain total transport rates per unit width q_b (g/m s). At Little Granite Creek, trap spacing was uneven. Fractional transport rates were computed for each trap, multiplied by the representative section of stream width assigned per trap, and summed over all stream sections.

$$Q_{bi}=\frac{m_{i1}\cdot w_{i1}}{w_s \cdot t_{s1}}+\frac{m_{i2}\cdot w_{i2}}{w_s \cdot t_{s2}}+\cdots+\frac{m_{i6}\cdot w_{i6}}{w_s \cdot t_{s6}} \tag{3}$$

where m_{i1} to m_{i6}=bedload mass collected in the ith size class for trap number 1 to 6; w_1 to w_6=representative sections of stream width for traps 1 to 6; w_s=width of a bedload trap; and t_{s1} to t_{s6}=sampling times for traps 1 to 6. Summing over all size fractions yields the total transport rate Q_b over the entire stream width. Dividing Q_b by the active stream width yields the unit transport rate q_b in units of g/m s. For the number of particles per size class, the term m_i (mass of all particles) in Eqs. (2) and (3) is substituted by n_i (number of particles). Particle numbers are either counted or computed from the average particle mass per size class [Eq. (1)].

Transport rates for Helley–Smith samples were computed using the equal-width increment method (Edwards and Glysson 1999), with no adjustment for unequal spacing (0.5–0.85 m) at Little Granite Creek. Nevertheless, transport rates computed from this study fit well with Helley–Smith transport rates obtained in previous (equal-width) studies at both sites.

This good fit permitted supplementing Helley–Smith data from this study with the larger Helley–Smith data sets collected previously. At St. Louis Creek, Ryan (1998) and Ryan et al. (2002) collected more than 200 samples at a site approximately 400 m upstream from the site of this study between 1992 and 1997. These samples span a range of flows between 23 and 128% of bankfull and were taken with a 0.076 by 0.076 m opening, thin-walled Helley–Smith sampler, 3.22 expansion ratio, at 0.5 m intervals across the stream and 2 min per vertical. At Little Granite Creek, Helley–Smith samples were supplemented with a set of 280 Helley–Smith data collected by W. W. Emmett in the years of 1982–1993, and by S. E. Ryan in 1997 (Ryan and Emmett 2002). Samples in the Emmett/Ryan study were taken with a 0.076 by 0.076 m thick-walled Helley–Smith sampler, 3.22 expansion ratio, at 20 verticals spaced 0.3 to 0.4 m across the stream and for 30–60 s per vertical. These data span a wide range of flows between 10 and 185% of bankfull. The measuring site for the Emmett/Ryan study is about 1 km downstream from the site used in this study. There are no significant tributaries or sediment storage areas between the two sites, so rates of flow and sediment transport should be comparable.

Results

Transport Rates and Particle Sizes from Bedload Trap Samples

A wide range of transport rates was sampled with the bedload traps at both sites. The smallest measurable nonzero transport rate is 1 particle/h in the size class 4–5.6 mm in one of the bedload traps. Resulting minimum transport rates depend on the number of traps deployed and the active stream width and are 5 particles/h at St. Louis and 7 particles/h at Little Granite Creek. Transport rates were generally low at St. Louis Creek where flow reached only 65% of bankfull. Despite this small range of measured flow between 1.6 and 2.6 m^3/s, mass-based transport rates sampled with the bedload traps extended over three orders of magnitude from 0.00018 to 0.12 g/s (0.00003–0.018 g/m s). The largest number of particles transported per hour at St. Louis Creek was 210 for the size class 4–5.6 mm and 3 for the size class 16–22.4 mm. At Little Granite Creek, mass-based transport rates for all size classes ranged from 0.00074 to 617 g/s (0.00006–50 g/m s), spanning six orders of magnitude over a twofold range of flow between 65 and 133% of bankfull (Fig. 4). As flow exceeded bankfull, bedload sheets 0.1–0.15 m thick and a few meters wide were observed and crept downstream with a velocity of approxi-

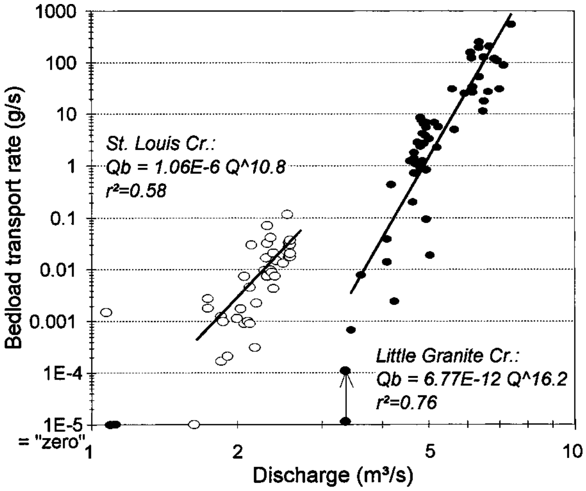

Fig. 4. Gravel transport rates (>4 mm) sampled with the bedload traps at St. Louis Creek and Little Granite Creek. Samples with zero transport rates are plotted along the *x* axis.

mately 0.01 m/s. This produced locally high transport that reached hourly rates of 20,000 particles in the size class 4–5.6 mm, 2,000 for 16–22.4 mm, and 8 for the size class 90–128 mm. The strong increase in transport rates measured with the bedload traps and flow yielded steep rating curves. The exponent for total unit transport rates is 10.8 for St. Louis Creek (excluding the two low flow data points that have high uncertainty but greatly affect the exponent) and reached 16.2 at Little Granite Creek. The zero-transport value at a discharge of 3.5 m^3/s at Little Granite Creek was assigned a transport rate of 0.0001 g/s and is included in the rating curve fit. The three samples with zero-transport rates collected at a flow of 1.1 m^3/s (19% Q_{bkf}) after the high flow season demonstrate the absence of gravel transport at low flow. They are below the threshold of gravel motion and therefore not included in a regression analysis of bedload transport rates.

Bedload rating curves fitted to fractional transport rates yielded lower exponents than those for total bedload. For neighboring size classes, fractional rating curves are close and almost parallel to each other [Fig. 5(a)], indicating similar transport rates for a specified flow, similar transport–discharge relationships, and similar subjection to sampling constraints. When scaled by the proportion that each particle-size class has in the bedmaterial subsurface distribution, fractional rating curves move closer to each other [Fig. 5(b)] and fall within a factor of 2 near bankfull flow. This suggests that gravel is transported approximately in proportion to its availability in the subsurface material. At moderate flow, fractional transport rates for coarse gravel (both scaled and nonscaled) are higher than those for fine gravel, while at higher flows, transport rates for both sizes become more similar. This results in rating curves being less steep for coarser particles. The flattening might be due to several factors: transport processes might be involved, or sampling time might be too short for infrequently moving large gravel (see discussion of effect of short sampling times). It may also be a computing artifact due to the small range of flow over which coarse gravel is transported (the exponent of a power regression fitted to scattered *x*-*y* data decreases if the *x*-data range is reduced).

A general coarsening of bedload for increasing flow is shown in Fig. 6. Samples obtained from the bedload traps at Little Granite were grouped into six classes of increasing discharge and group particle-size distributions were computed. Below bankfull flow, bedload particle-size distributions visibly coarsen as flow increases, but they do not appear to change much between 101 and 117% of bankfull flows and fail to coarsen to the subsurface particle-size distribution. This may be due to incomplete mobilization of the bed and/or exceedence of the trap sampling capacity for large cobbles.

Comparison of Transport Rates from Bedload Traps and Helley–Smith Sampler

Transport rates sampled with the bedload traps were compared to those obtained from Helley–Smith samples. The large data sets of Helley–Smith samples collected during previous studies by Ryan (1998); Emmett (1999); and Ryan and Emmett (2002) were used for this comparison because they span a wider range of flows and transport rates than Helley–Smith data obtained during this study and fit well with the smaller data sets collected in this study [Figs. 7(a and b)]. To account for the mesh size of 3.5 mm in the bedload traps, the bedload portion <4 mm was excluded from all Helley–Smith samples. At St. Louis Creek, the bedload rating curve for Helley–Smith samples has an exponent of 3.5 when zero values are excluded [dashed line in Fig. 7(a)]. Including the eight samples with zero-transport rates by assigning them a value of 0.001 g/s (one order of magnitude below the lowest measured values) increases the exponent to 4.4. A similar shift occurs at Little Granite Creek. Without zero values, the Helley–Smith rating curve has an exponent of 3.1 [dashed line in Fig. 7(b)] that increases to 3.8 when the 30 samples with zero-transport rates are assigned a value of 0.001 g/s and included in the analysis.

A striking difference exists between the bedload rating curves of the bedload traps and the Helley–Smith sampler for both streams. Rating curves for the bedload traps are considerably steeper than those for the Helley–Smith samples with exponents of 10.8 and 16.2, compared to exponents of approximately 4 for the Helley–Smith samples (zero values included) [Figs. 7(a and b)]. At flows 50% of bankfull, gravel transport rates from the bedload traps are three to four orders of magnitude less than gravel transport rates in the Helley–Smith data sets. This disparity decreases for higher flows until about bankfull flow is reached, and the bedload trap rating curve intersects the Helley–Smith rating curve at Little Granite Creek. At the highest measured flow of 133% of bankfull, measured transport rates are in the same order of magnitude for both samplers. The discrepancy between transport rates from the two samplers at low transport rates may be attributed to several factors that include: (1) differences in sampling intensity and sampling time; (2) hydraulic and sampling efficiency of the bedload traps; (3) occasional inadvertent entrainment of small to medium gravel particles during the sampling process; and (4) sampling time for representative sampling. These factors are discussed later.

Determination of Critical Flow

Knowledge of the critical flow needed to transport gravel and cobble (i.e., morphology-forming) bedload is important for instream flow analyses or channel restoration. Onset of particle motion can be defined by two methods: critical flow required for incipient motion of individual particles (largest grain method) or for exceedence of a small specified transport rate (small transport method) (Wilcock 1988). Computational determination of critical flow for either of the two methods is problematic, and availability of reliable and suitable measurements of incipient motion would overcome the dependence on computational methods. Bedload

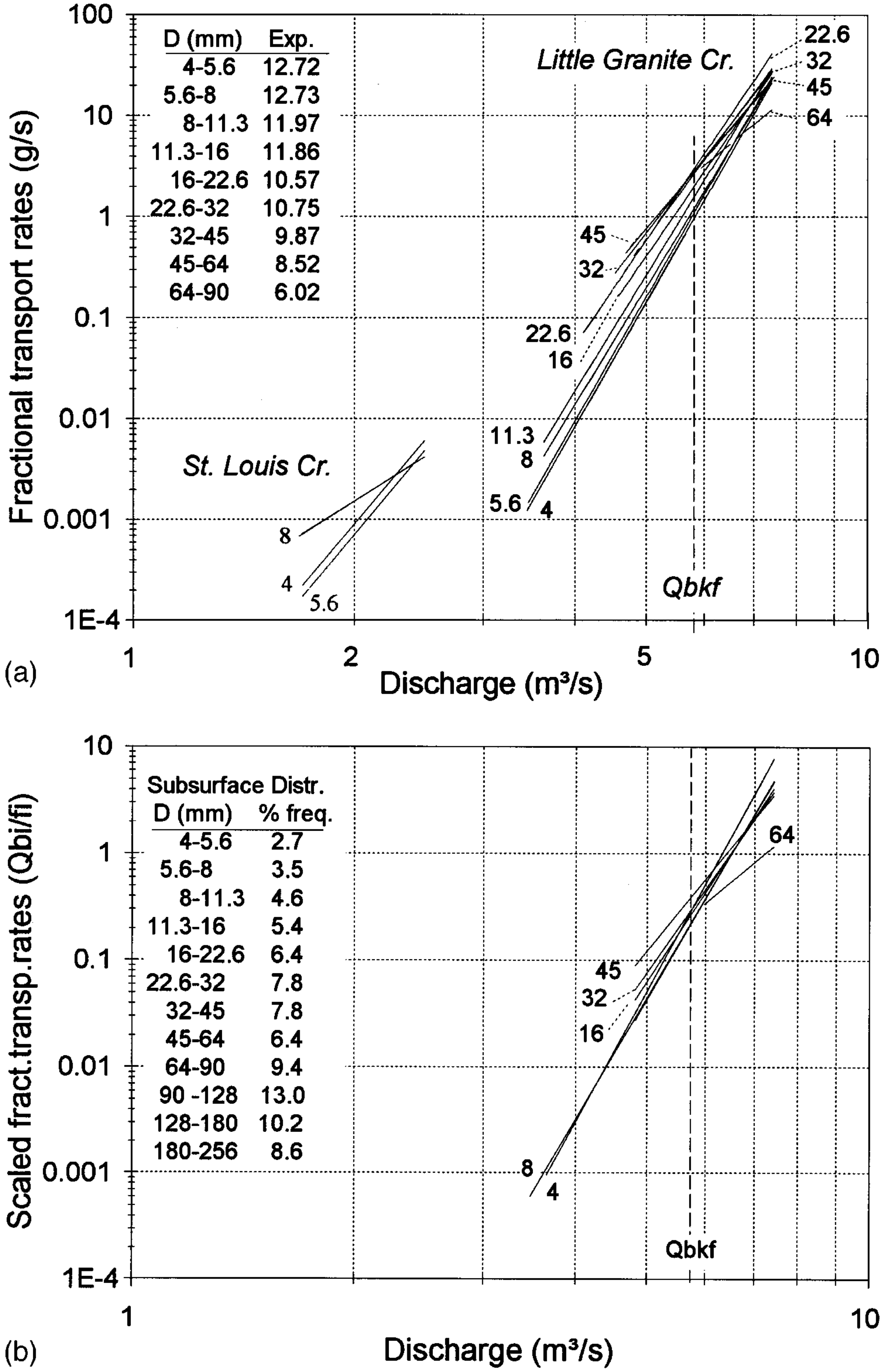

Fig. 5. (a) and (b) Fractional gravel transport rates for 0.5 ϕ size classes sampled with the bedload traps at St. Louis Creek and Little Granite Creek. Exponents of power-function rating curves fitted to data from Little Granite Creek are provided for each size class in the inset table (a). Fractional gravel transport rates scaled by the proportion of each size class in the subsurface bed material distribution (see inset table) for Little Granite Creek. For clarity, graphs are shown only for every other particle size class (b).

traps with their large opening, large sampling capacity, and long sampling duration offer the opportunity to directly measure incipient motion using either of the two approaches.

For the largest grain method, a regression function is fitted to the largest transported bedload particle size ($D_{\max}$) and discharge at the time of sampling. The resulting flow competence curves for both samplers are shown in Fig. 8 for Little Granite Creek. The curve for bedload traps is steeper and better defined than the curve from the Helley–Smith sampler which has considerable data scatter. Bedload traps collected no particles at low flow 0.6–2 m^3/s (11–35% Q_{bkf}), while the Helley–Smith sampler collected particles up to the 16–32 mm size class. During mod-

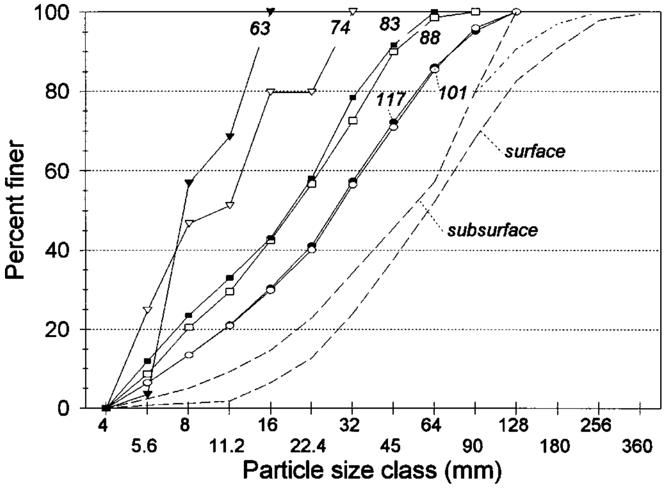

Fig. 6. Coarsening of bedload particle-size distributions for increasingly higher flows at Little Granite Creek. Numbers on curves indicate mean flow for a group of samples expressed as percent of bankfull. Subsurface and surface particle-size distributions are shown for comparison. The coarse part of the subsurface size distribution was adjusted upward to better represent the coarsest particles for which the 130 kg sample mass was too small.

erate flows 2–4 m^3/s (35–71% Q_{bkf}), bedload traps collected smaller $D_{\max}$ particle sizes than the Helley–Smith sampler; at high discharge, bedload traps collected larger $D_{\max}$ particles than the Helley–Smith sampler. The absence of gravel particles in the bedload traps at low flow and the small particle sizes at moderate flow are attributed to a largely immobile bed. The larger particles caught by the trap at high flow are attributed to a larger opening and the long sampling time which permits infrequently moving large gravel and small cobbles to be collected.

Critical flows determined from the flow competence curves differ greatly between the two samplers. According to the bedload trap curve, $D_{\max}$ particles in the size classes 4–5.6, 16–22.4, and 64–90 mm were entrained by flows of 2.8, 4.2, and 6.1 m^3/s, respectively (50, 74, and 108% of bankfull flow). Based on the Helley–Smith curve, particles in the size classes 4–8 and 16–32 mm were entrained at flows of 1.2 and 5.7 m^3/s (20 and 100% of bankfull flow). Thus sampler design and operation result in pronounced differences in flow competence estimates from the largest grain method.

For the small transport rate method, rating curves were fitted to measured fractional transport rates from which the critical flow for a specified low transport rate can be read or extrapolated. In this study, fractional transport rates were expressed in terms of the number of bedload particles per size class n_{bi} (particles/h). This number-based unit provides a visual and perceptible measure of bedload transport rates and is convertible to a mass rate [Eqs. (1*a*) and (1*b*)]. Fig. 9 shows fractional rating curves fitted to numbers of particles per size fraction in 1 ϕ (Helley–Smith) and 0.5 ϕ units (bedload traps) for Little Granite Creek. The minimum particle number transport rate at Little Granite Creek is 7 particles/h for bedload traps and 120 particles/h for the Helley–Smith sampler. Exponents of the number-based rating curves are almost identical to those obtained from mass-based fractional rating curves in Fig. 5(a) due to the fixed relation between particle size and mass. Thus fitted particle number transport rates for bedload traps are generally lower and have steeper rating curves than particle number transport rates obtained from Helley–Smith bedload samples, similar to total transport rates shown in Fig. 7(b).

Critical discharge for entrainment of specified fractional particle number transport rates can be estimated from Fig. 9 and varied substantially between the two samplers. Based on data from the bedload traps, particles of the size classes of 4–5.6, 16–22.4, and 64–90 mm require critical discharges of 3.1, 3.7, and 5.1 m^3/s for a minimum transport rate of 7 particles/h across the width of the stream, suggesting that earliest entrainment of gravel of 4–64 mm occurred at flows between about 54 and 89% of bankfull. Particle transport rates for the Helley–Smith sampler (with a minimum measurable particle number transport rate of 120 particles/h) were considerably higher. Extrapolation to a low transport rate of 7 particles/h suggests critical discharges of 0.14 and 0.6 m^3/s (2.5 and 8.8% of bankfull) for the size classes of 4–8 and 16–32 mm. Thus sampler design and operation also results in pronounced differences in estimates of critical flow from the small transport rate approach for incipient motion.

The critical flow for particles of specified size classes estimated from both approaches (largest grain, Fig. 8 and a small fractional particle number transport rate Fig. 9) is shown in Figs. 10(a and b). For bedload traps, critical flow from the small transport rate approach was about 10% larger than critical flow from the flow competence curve for 4–5.6 mm particles [Fig. 10(a)] and 20% smaller for 64–90 mm particles. In general, though, critical flow is comparable for both methods when bedload traps are used, as expected by Wilcock (1988) for ideal bed and sampling conditions. This is likely due to large opening, large capacity, and long sampling time associated with bedload traps. There is little similarity between the two methods of critical flow determination when a Helley–Smith sampler is used [Fig. 10(b)].

Critical flows computed with either of the two methods can be made comparable between streams by scaling the bedload $D_{\max}$ particle size by a characteristic size of the bed (e.g., the D_{50}), while critical discharge can be scaled by bankfull flow, or expressed as dimensionless shear stress.

Discussion

The large difference observed between transport rates sampled with bedload traps and the Helley–Smith sampler raises some interesting questions. Effects of sampling intensity and sampling time, hydraulic and sampling efficiency, inadvertent particle entrainment, and required period for representative sampling are considered below in an attempt to explain the reasons for the differences.

Sampling Intensity and Its Effect on Computed Transport Rates

Relative sampling intensity I_r may be defined as the dimensionless ratio

$$I_r = \frac{I_s}{I_{\text{pot}}} = \frac{w_s \cdot n_s \cdot t_s}{w_{\text{act}} \cdot t_{\text{tot}}} \tag{4}$$

where I_s=intensity with which samples are collected; w_s=width of the sampler; n_s=either the number of Helley–Smith sampling verticals across the stream (times two if two traverses are used) or the number of traps used concurrently in the stream; and t_s=sampling period. I_{pot}=maximum potential sampling intensity where w_{act}=active (bedload-transporting) stream width; and t_{tot}=time period allotted to one sample (e.g., 1 h) over which flow

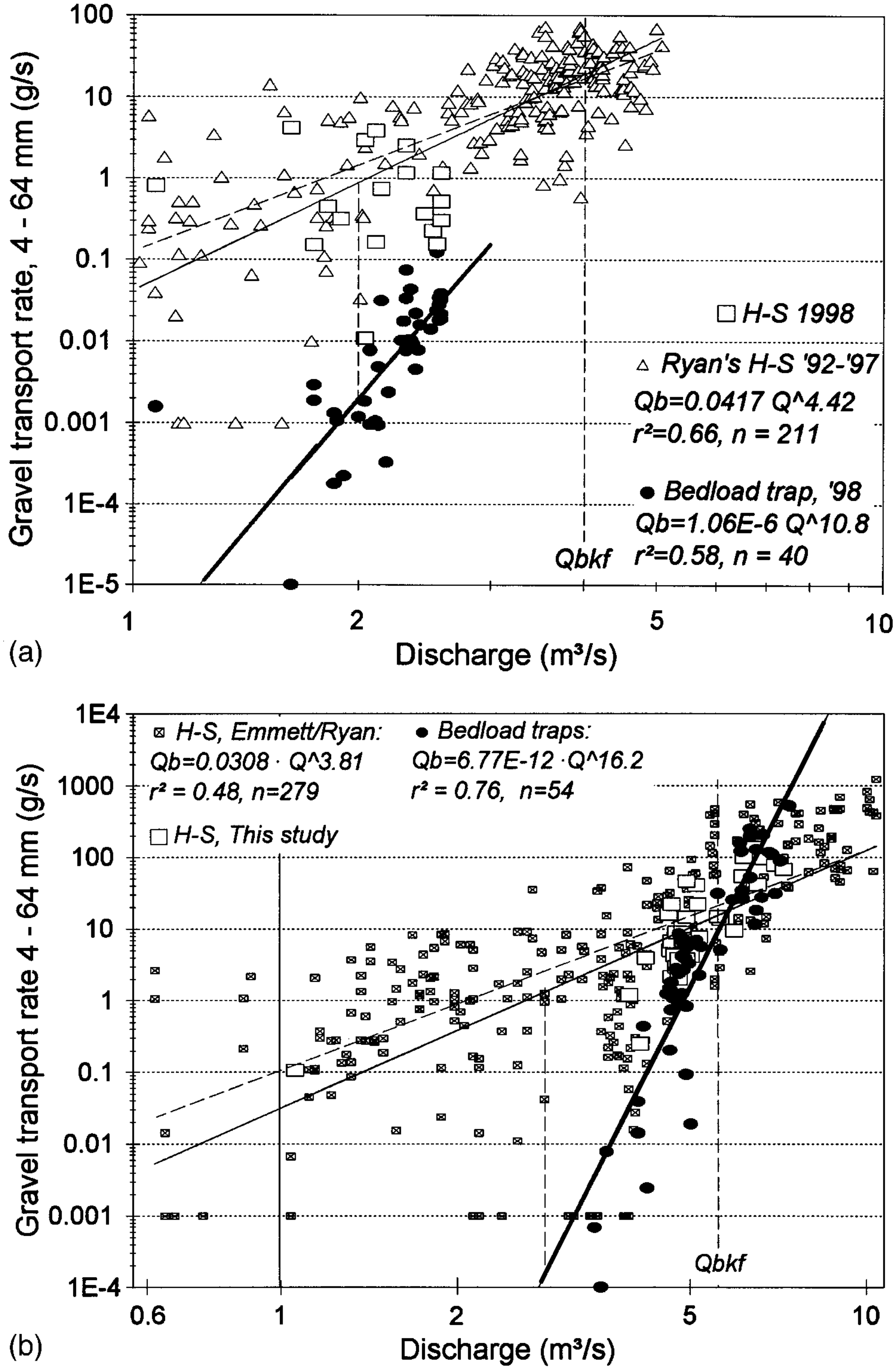

Fig. 7. (a) and (b) Comparison of gravel transport rates sampled with the bedload traps and the Helley–Smith sampler at St. Louis Creek (a) and Little Granite Creek (b). Helley–Smith data collected in this study are shown but not included in the rating curve analysis. Legitimate zero-transport rates measured with the bedload traps and the Helley–Smith sampler are assigned transport rates of 0.0001 and 0.001 g/s, respectively. Dashed line is rating curve for Helley–Smith sampler with 30 zero-transport samples excluded from the regression analysis.

may be considered constant. 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 for 2 min per vertical in 0.5 m increments in a stream 6.5 m wide yields a sampling intensity of 0.005, or 0.5% [Eq. (4)] which is about 50 times less than the sampling intensity for the bedload traps. Most of this difference is due to sampling time.

Short sampling times can largely overestimate gravel transport during periods of marginal transport when particles move infrequently. Assume, for example, a true transport rate of two particles of a given size class per hour over a 1 m width. A typical Helley–Smith sampling scheme with a sampling duration of 2 min per vertical spaced 0.5 m apart has a 1% chance [(2 part./60 min·1 m)·(2 min/1 part.)·0.076 m·2] of collecting one of those

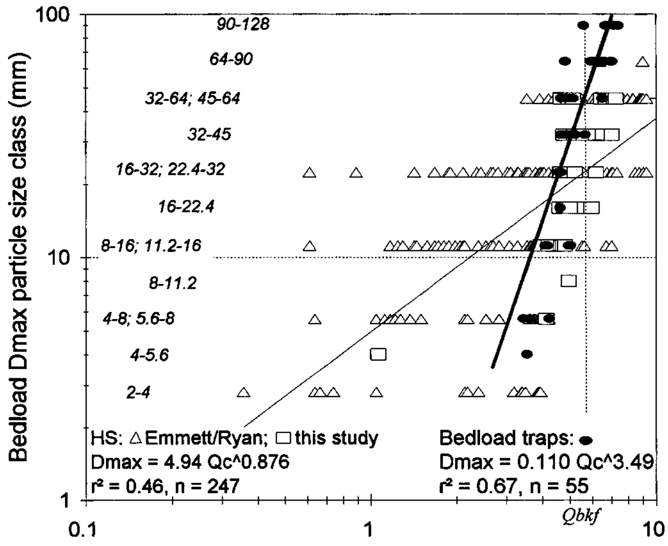

Fig. 8. Bedload $D_{\max}$ particle size versus discharge (flow competence curves) for bedload traps (thick line) and Helley–Smith sampler (thin line) at Little Granite Creek. Particle size classes are in 0.5 ϕ units for bedload traps and 1.0 ϕ units for Helley–Smith samples.

particles. However, if one infrequently passing particle is indeed collected within a 2 min sampling time, the computed transport rate is 1 particle/0.076 m·2·2 min, or 197 particles/m h. This exceeds the true transport rate of 2 particles/m h by a factor of 100. By contrast, if the 2 min sample contained no particle in that size class, the resulting transport rate is zero. The large difference in the computed hourly transport rate between collecting one particle per 2 min (=197 particle/m h) and none (=0 particle/m h) causes high variability in computed fractional transport rates. A rating curve fitted to such data is higher at low flows (approximately by a factor of 2 to 3) than a rating curve fitted to samples taken over a much longer duration. Including or excluding legitimate zero values from the rating curve has a relatively small effect on the rating curve steepness (see above) and accounts for only a small portion of the difference between bedload traps and Helley–Smith rating curves.

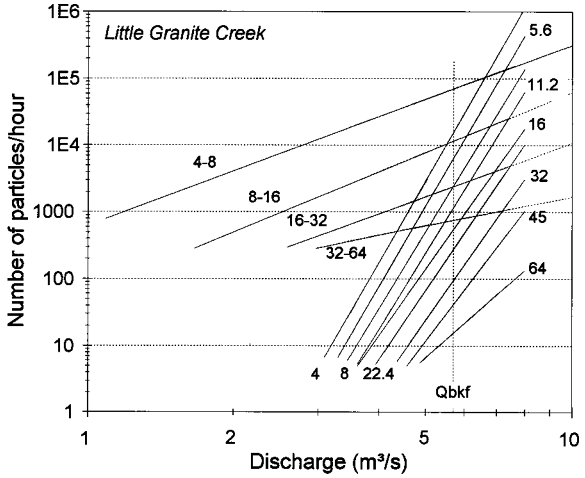

Fig. 9. Fractional particle-number transport rates versus discharge for bedload traps (steep lines, 0.5 ϕ size classes) and Helley–Smith samplers (flatter lines, 1 ϕ size classes) at Little Granite Creek

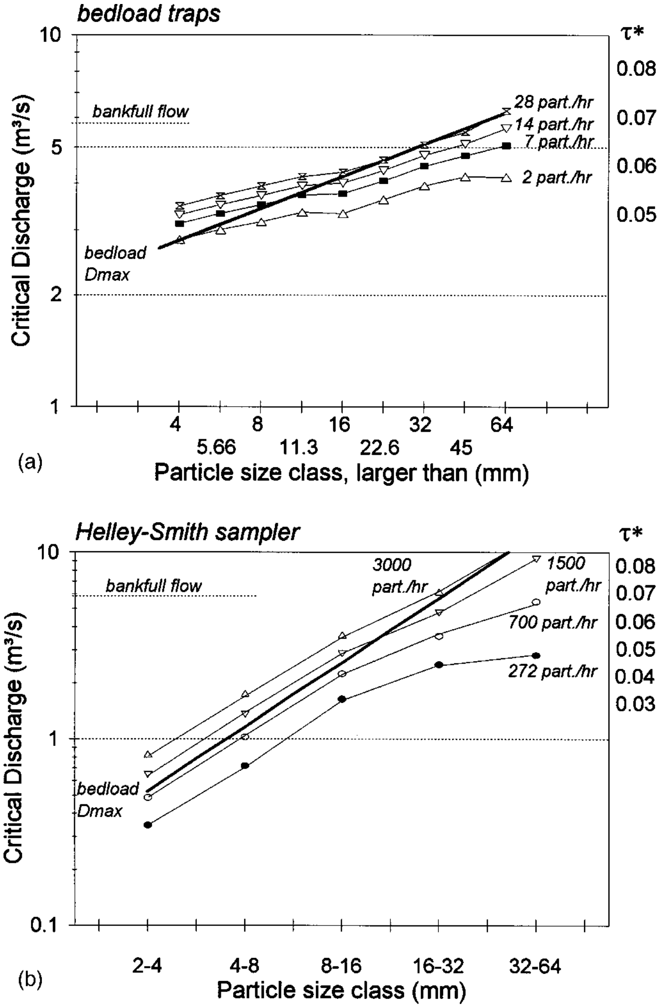

Fig. 10. Critical flow for various particle-size classes at Little Granite Creek based on the largest grain method (thick line) and a small transport rate method (thin lines) computed from bedload samples obtained (a) with the bedload traps and (b) with a Helley–Smith sampler.

The variability in transport rates that results from collecting one particle or none is considerably reduced when sampling over a long duration with a wide sampler. For example, one particle collected in a bedload trap 0.3 m wide, spaced in 1 m increments during a sampling duration of 1 h results in a transport rate of 3.3 particles/m h. This rate oversamples the true transport rate of 2 particles/m h assumed above by a factor of only 1.65. Thus during low transport rates, high sampling intensity (longer sampling duration, greater width covered) increases the representativeness of samples and decreases the variability. Ideally, sampling duration needs to exceed the average frequency with which infrequently moving particles pass the site. A short sampling time can only yield representative transport rates if a large number of particles are in motion per time at high transport rates, so that several particles can enter the sampler during the sampling time. In this situation, which occurs at high transport rates near bankfull flow when a large number of small and moderate particle sizes are in motion, rating curves obtained from different sampling intensities approach each other [Figs. 7(a and b)]. At high flows above bankfull, the Helley–Smith rating curve is lower than the one from the bedload traps at Little Granite Creek. This is attributed to the small 0.076 by 0.076 m opening size of the Helley–Smith sampler that prohibits large gravel and small cobble particles from entering the sampler and contributing to the measured transport rate. Although allocation of infrequently moving particles collected by chance to a short (2 min) sampling time results in an overprediction of the transport rate, it is not likely to happen often. Thus chance alone cannot explain the three to four orders of magnitude difference between the rating curves for Helley–Smith and bedload trap samples for flows around 50% of bankfull. Other factors need to be considered.

Hydraulic and Sampling Efficiency of Bedload Traps

Preliminary assessments of hydraulic and sampling efficiency for the bedload traps indicated no major over- or undersampling. The smooth ground plate in front of the bedload trap increases the near-bottom flow velocity by approximately 30% (coefficient of variation about 150%) compared to the bed in front of the ground plates, but bed coarsening that might indicate increased gravel entrainment in front of the traps was not observed. However, a small dip sometimes developed along the front edge of the ground plate at low transport. A small gravel particle entering the dip may swirl around for some time before moving onto the ground plate, delaying particle collection. Once on the smooth ground plate, particles move immediately into the trap. Assuming again a true transport rate of two particles per hour, losing one particle in the swirl halves the transport rate. By comparison, short sampling times for the Helley–Smith sampler at low transport may roughly double the transport rate. Acting in opposite directions for both sampling devices, both effects contribute to a more noticeable difference, but do not explain a several order of magnitude difference in transport rates during incipient gravel motion. The sampling efficiency of bedload traps was evaluated by comparing seasonal gravel load computed from bedload trap samples with the gravel mass collected in a debris basin. Bedload trap load and debris basin load were within a factor of −1.8 to +1.2, depending on how gravel transport at times not sampled with the bedload traps was accounted for (Bunte and Swingle 2003).

Inadvertent Particle Entrainment

The Helley–Smith sampler has been observed to occasionally dislodge a particle upon placement and to capture the detached particle due to its high hydraulic efficiency (154%) (Hubbell et al. 1985), particularly when a thin-walled sampler is used. However, these effects are not well-quantified in the literature. The minimum influence of excess entrainment was evaluated by assuming that one gravel particle (4–16 mm) is inadvertently entrained at one of the 10 or 20 measured verticals. As the average mass of a particle 4–5.6 and 11.3–16 mm is 0.21 and 4.3 g, respectively [Eq. (1*a*)], transport rates resulting from collecting one of those particles in a Helley–Smith sampler is 0.011 and 0.24 g/s, respectively, at St. Louis Creek where samples were collected at 13 verticals for 2 min each in a stream 6.5 m wide. These transport rates were added to a range of assumed transport rates. Results are shown in Table 4. When the assumed gravel transport rate is 0.0001 g/s or less, adding one particle collected in a Helley–Smith sample yields transport rates of 0.01 to 0.24 g/s. This increases transport by at least two to three orders of magnitude [see Fig. 7(a)] and introduces a large oversampling error at very low transport. An error from inadvertent particle entrainment decreases for higher transport rates. Adding one gravel particle to the lowest measurable Helley–Smith transport rate of 0.01–0.24 g/s for small and medium gravel would increase transport by a factor of 1–25 and on average double the transport rate. Given the one to two order of natural variability of transport rates, this increase is relatively small.

Table 4. Effect of Adding One Particle 4–16 mm Collected in a Helley–Smith Sampler (H–S Q_{bi}) at St. Louis Creek to Various Transport Rates

Transport rate (g/s)	Addition of H–S Q_{bi} to transport rate (g/s)		Factor of increase	
	4–5.6 mm	11.3–16 mm	4–5.6 mm	11.3–16 mm
0	0.011	0.24	Large	
0.0001	0.011	0.24	115	2,360
0.001	0.012	0.24	12	237
0.010	0.021	0.25	2.1	25
0.100	0.11	0.34	1.1	3

Estimating Minimum and Maximum Time for Representative Sampling

Dietrich and Whiting (1989) proposed a method for estimating minimum sampling time ($t_{s(i)}$) 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’’ (Dietrich and Whiting 1989, p. 36). Solved for sampling time, the equation is

$$t_{s(i)} = \frac{\overline{m_i}}{q_b \cdot f_i \cdot w_s} \tag{5}$$

where $t_{s(i)}$=sampling time for the *i*th size fraction; $\overline{m_i}$=average mass of a particle in the *i*th size class [e.g., Eq. (1)]; q_b=total sampled bedload-transport rate per unit width; f_i=percent frequency of the *i*th size class in the expected bedload sample; and w_s=sampler width. Eq. (5) assumes that particles move regularly. Since the frequency of particle movement is typically irregular, Eq. (5) should be increased by a factor dependent on the degree of irregularity. The maximum sampling time $t_{s(\max)}$ allowable before the sampler fills to capacity can be obtained by modifying Eq. (5)

$$t_{s(\max)} = \frac{m_{s(\max)}}{q_b \cdot w_s} \tag{6}$$

where $m_{s(\max)}$=maximum mass that a sampler can hold without decreasing the sampling efficiency.

In fully developed transport, when many particle sizes present in the bed are potentially mobile, the parameter f_i in Eq. (5) can be approximated from the subsurface bed material particle-size distribution. At lower transport rates, bedload particle-size distributions are finer. To estimate these, two stages of low transport were defined: marginal transport of 0.0001–0.001 g/m s and moderate transport of 0.01–0.1 g/m s. Based on samples from the bedload traps at St. Louis Creek, marginal and moderate transport rates had maximum bedload particle sizes of the size classes larger than 16, and larger than 64 mm, respectively. Truncation of the subsurface bed material distribution at the size classes larger than 16 and 64 mm, respectively, and readjustment of the remaining size classes to 100% yielded estimates of bedload particle-size distributions for marginal and moderate flows (Fig. 11).

The range of particle sizes that according to the Dietrich–Whiting criterion can be sampled representatively for specified transport rates is indicated by bold lines in Figs. 12(a) (for bedload traps) and 12(b) (for a Helley–Smith sampler). At St. Louis Creek, particles 4–5.6 mm (f_i=16%) are just moving frequently

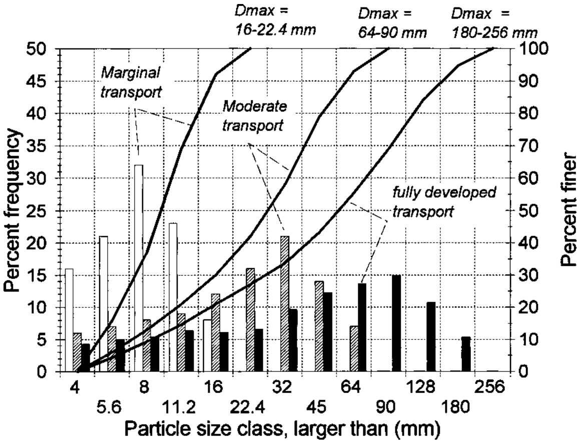

Fig. 11. Frequency (bars) and cumulative frequency of bedload particle-size distributions estimated for marginal and moderate transport at St. Louis Creek. The subsurface bed material size distribution is used for fully developed transport.

enough at marginal transport (0.001 g/m s) at a flow of 2.2 m^3/s (55% of bankfull) to be collected by 1-h sampling with the bedload traps. At fully developed transport (10 g/m s), Eq. (5) indicates that 1-h deployment provides representative samples of particles up to the 76–107 mm size class. However, even though the 200 by 300 mm opening size of the bedload traps allows large cobbles to enter the sampler, particles this large cannot be sampled representatively with the current specifications of the sampler bag because the minimum sampling time necessary for representative sampling ($t_{s(i)}$) exceeds the maximum allowable sampling time ($t_{s(\max)}$) after which the sampler fills beyond capacity ($t_{s(i)}>t_{s(\max)}$). The largest particle size class that can be sampled representatively is 90–128 mm because the 20 kg capacity of a bedload trap restricts sampling time to a maximum of 109 min when transport rates are 10 g/m s [Eq. (6)] and to 10.9 min when transport is as high as 100 g/m s. This restriction may explain why bedload particle-size distributions collected with the bedload traps ceased to become coarser as flows exceeded bankfull and did not match the subsurface particle-size distribution (Fig. 6). A larger bag and/or larger mesh width is needed for representative sampling of large cobbles.

Particle sizes that can be sampled representatively with 2-min sampling and a Helley–Smith sampler 0.076 m wide are much smaller than the particles measurable in a bedload trap with 1-h sampling. Particles of 4–5.6 mm are transported too infrequently during marginal and moderate transport rates for representative sampling at 2 min [Eq. (5)]. Transport rates have to exceed 0.6 g/m s before 4 mm particles can be sampled representatively and 12–18 mm is the largest size class that can be collected during a transport rate of 10 g/m s. Particles 27–38 mm can only be sampled representatively during very high transport rates of 100 g/m s.

Summary and Conclusion

Portable bedload traps were developed to provide representative samples of gravel and small cobble transport during low and high transport rates in wadable streams at undeveloped and remote sites. Bedload trap dimensions and deployment allow for a long sampling duration of about 1 h per sample with optimal ground contact and without inadvertent particle entrainment near the bedload trap entrances.

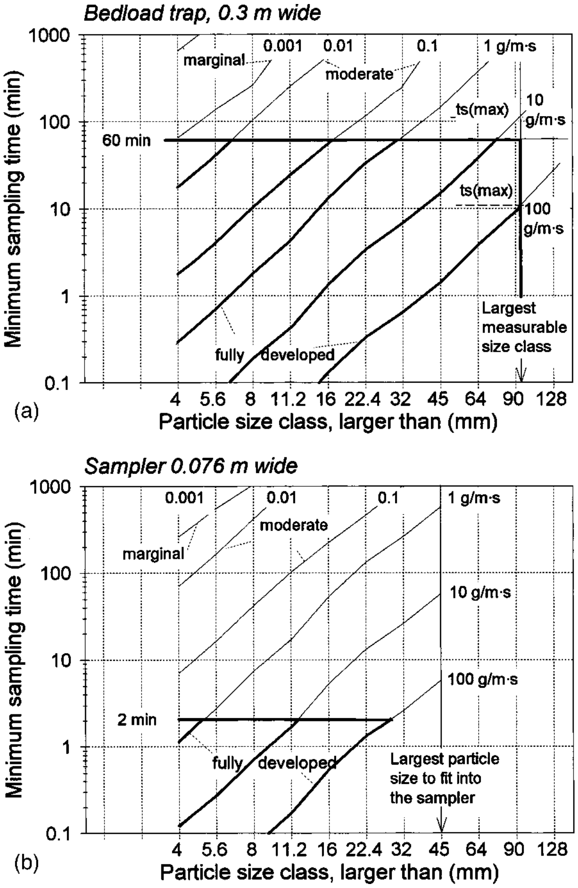

Fig. 12. (a) and (b) Minimum sampling time computed from Eq. (5) for specified particle sizes during specified transport rates at St. Louis Creek and for typical sampling schemes of the bedload traps (a) and the Helley–Smith sampler (b). Thick lines show particle sizes and transport rates suitable for indicated sampler and sampling time.

Bedload traps were field tested in several mountain gravel/cobble-bed rivers and were easy to operate in moderately high flows. The practical limit of bedload trap operation is the limit of wadability. As bedload traps facilitate collection of a wide range of transport rates averaged over long time periods, the resulting bedload rating curves are steep and relatively well-defined. Fractional rating curves, based on both particle mass and number transport rates, were less steep than the rating curves obtained for total transport, particularly for the coarsest particle sizes. Bedload mass transported in mobile size classes is approximately proportional to the size-distribution of the subsurface. Samples collected with the bedload traps coarsened markedly with increasing flow up to about bankfull but did not reach the coarseness of the subsurface bed material distribution. The flow competence curve relating the largest bedload particle size to flow is steep and has relatively little data scatter. Estimates of critical flow obtained from the flow competence and the small transport rate methods are similar for bedload traps. Thus bedload traps appear to be suitable for directly measuring incipient motion, an advantage that circumvents assumptions necessary in purely computational methods.

Sampling results obtained from bedload traps were generally different from those obtained from Helley–Smith samples. Bedload rating curves fitted to Helley–Smith samples were flatter and had lower exponents. At flows below bankfull, gravel transport rates from Helley–Smith samples were generally higher than those from the bedload traps (three to four orders at 50% of bankfull flow). Near bankfull flow, transport rates measured with both samplers become more similar. The flow competence curve computed from Helley–Smith samples has a larger data scatter and is less steep. Results from the two methods of estimating critical flow are dissimilar.

The discrepancy between bedload trap and Helley-Smith bedload samples is in part attributable to sampling intensity, which is a factor of about 50 higher for bedload traps, predominantly due to their long sampling time. Short sampling times cause high variability during periods of low transport, and fitted rating curves indicate higher transport rates than those obtained from long sampling times even when legitimate zero values are included in the analysis. Although sampling time contributes, its effect is not large enough to explain why transport rates are orders of magnitude higher for Helley–Smith samples at low flow compared to bedload traps. Inadvertent particle entrainment is a possibility for Helley–Smith samplers but was not empirically quantified.

According to the criterion from Dietrich and Whiting (1989), the 1-h sampling time used for bedload traps sufficed for collecting representative samples at all measured transport rates, whereas the Helley–Smith samples provided representative gravel samples only during high transport rates. Cobbles larger than 128 mm cannot be sampled representatively with the bedload traps because the necessary sampling time exceeds the time in which the bag fills beyond capacity (estimated as 40% of bag volume).

Bedload traps provide a portable and easy to use means of measuring gravel transport in wadable coarse-grained channels, and the method appears to properly characterize the nature of coarse sediment transport in these systems. However, while bedload traps seem to be well-suited in wadable streams, they are not suitable for collecting particles smaller than 4 mm or in unwadable flows. In situations where a significant portion of the total load consists of fines, or at sites where conditions prohibit the use of a fixed-bed sampler, a hand-held Helley–Smith sampler may be more useful.

Acknowledgments

Sean McCoy, Kurt Swingle, Dan Armstrong, Rhett Travis, Dan Mastburgen, and Brian Smith helped with field and laboratory work, Chad Lipscomb and Chris Thornton provided organizational support. The shop of the Engineering Research Center, Colorado State University, constructed the metal parts of the sampler. This study was funded by the Stream Systems Technology Center, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colo. Comments by Peter Wilcock, John Gray, and anonymous reviewers helped clarify the manuscript.

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