FUNCTIONS TO ADJUST TRANSPORT RATES FROM A HELLEY-SMITH SAMPLER TO BEDLOAD TRAPS IN COARSE GRAVEL-BED STREAMS (RATING CURVE APPROACH)

Kristin Bunte, Research Scientist, Colorado State University, Engineering Research Center, Fort Collins, CO, kbunte@engr.colostate.edu; Steven R. Abt, Professor, Colorado State University, Engineering Research Center, Fort Collins, CO, sabt@engr.colostate.edu; Kurt W. Swingle, Environmental Scientist, Boulder, CO, kskb@ix.netcom.com; John P. Potyondy, Program Manager, Stream Systems Technology Center, USDA Forest Service, Fort Collins, CO, jpotyondy@fs.fed.us.

Abstract A method is described for adjusting gravel rating curves from mountain streams measured with a 3-inch Helley-Smith (HS) sampler closer to what is thought to be their true value. The study analyzed the relationship of gravel transport sampled with a HS sampler and with bedload traps, a sampler not restricted by short sampling time, small opening size, and direct bed contact. The computed inter-sampler transport relationships vary among streams and fall into two stream groups. HS adjustment function were computed for each group and are predictable from bedload characteristics as measured by bedload traps and, to a lesser degree, as measured with a HS sampler.

INTRODUCTION

Sampler characteristics affect sampling results in a complex way: small openings do not allow large particles to enter, causing underestimation of transport when it is dominated by large particles. A small bag and handheld deployment require a short sampling time, but short sampling times overestimate low transport rates and underestimate of high transport due to the distribution of short-term transport rates in which small rates are more common than large ones. The contact between the bed and the sampler has a large effect: a sampler perched on cobbles lets fines pass under the sampler, while a sampler set onto a loose bed can easily dislocate particles from their interlock with neighboring particles. These particles are readily then entrained and captured in the sampler, causing oversampling.

Helley-Smith (HS) samplers have a relatively small opening size, a small sampler bag, short sampling times, as well as direct contact with the bed, and sampling results obtained from samplers unrestricted by HS sampler characteristics such as pit traps (Sterling and Church 2002) or bedload traps have been found to differ from those collected with a HS sampler. Bedload traps (described below) were specifically designed to have large openings, large sampler bags, long sampling times, and no direct bed contact. Bunte et al. (2004, 2008) and Bunte and Abt (2009) compared sampling results between bedload traps and a 3-inch, thin-walled, wide-flared HS sampler over a wide range of transport rates in mountain streams. Gravel transport rates q_B of particles > 4 mm collected with bedload traps were between 1E-5 and 1 g/m·s at 50% bankfull flow (Q_{bkf}), whereas those collected with the HS sampler at 50% Q_{bkf} were 1 – 4 orders of magnitude higher; at high transport (at 90 – 140% Q_{bkf}) though, both samplers obtained similar results. The higher HS gravel transport rates at low flows are attributed mainly to two processes: 1) The HS picks up gravels from the bed at low flows when no such particles are transported as bedload yet. This HS propensity became clear when the HS sampler was deployed on ground plates otherwise used for bedload traps, and the HS transport rates were almost as low as those from bedload traps (Bunte and Swingle 2008; Bunte and Abt 2009). 2) The short (2-min or less) HS sampling time explains much of the remaining difference between bedload trap and HS sampling results because it causes an overestimation of lowflow transport and underestimation at high transport (Bunte and Abt 2005; Singh et al. 2009 a and b). As a result of the HS's considerably higher low-flow transport rates, but similar or somewhat lower high-flow transport rates, gravel rating curves in the form $q_B = aQ^b$ derived from HS samples typically have exponents of 2 – 4, whereas bedload traps yield much steeper rating curves with exponents of 7 – 16. Compared to bedload trap rating curves, the flatter and "high ended" HS rating curves overpredict annual gravel load in low-flow years, while underpredicting transport in high-flow years when coarse gravel and cobbles contribute large portions to bedload, hence underestimating annual variability of gravel loads. Rating curves also affect effective discharge that tends to coincide with Q_{bkf} when based on the relatively flat HS gravel rating curves but move to higher flows for steeper bedload trap rating curves (Potyondy et al., this volume). The difference between HS and bedload trap sampling results also affects our understanding of gravel transport and incipient motion (which HS samples place at lower flows than bedload traps). To avoid the consequences brought about by the overly flat HS rating curves, it is desirable to apply adjustment functions with which to convert HS gravel transport rates in mountain streams to those obtained from a sampler without the HS-specific restrictions.

Since the percent differences between HS and bedload traps sampling results are largest at low transport and vary among streams, adjustments for HS gravel transport rates need to be a function of transport rates and some stream

parameters. Two approaches were considered: the rating curve approach is described here. Its advantage over the paired data approach (Bunte and Abt 2009) is that does not hinge on collecting data pairs at the same time and the identical stream location, a requirement that poses a major problem for comparing sampling results from two samplers under temporally and spatially variable transport (Bunte et al. 2010). However, the rating curve approach requires that the relationship between bedload transport and flow can be accurately described by a rating curve (or several sections if needed) and that the relationship remains unchanged for data collected with both samplers.

METHODS

Data collection Field data were collected at nine study sites in wadeable mountain streams with armored, coarse gravel and small cobble beds (see Table 1 in Potyondy et al., this volume) on relatively undisturbed National Forest lands. Streambeds are mostly entrenched such that highflows of l40% Q_{bkf} cause little overbank flooding.

Gravel bedload was sampled with bedload traps that consist of an aluminum frame 0.3 by 0.2 m in size (Bunte et al., 2004, 2007, 2008, and Potyondy et al., this volume). The large sampler opening allows cobbles to enter. Bedload is collected in an attached net 0.9 – 1.6 m long and with a mesh width just below 4 mm. The coarse net allows flow to pass relatively freely. Bedload traps are mounted onto ground plates 0.43 by 0.37 m in size that are anchored on the stream bottom with metal stakes. This set-up permits long sampling times that integrate over short-term fluctuations of transport; it also avoids direct contact of the sampler with the channel bed, and consequently inadvertent particle pick up. These deployment characteristics are crucial for accurate samples, and taken together, should provide bed-load trap sampling results close to truth. Four to six bedload traps spaced 1 - 2 m apart were installed across each study stream. All traps sampled simultaneously, typically for 1 hour per sample, but less when transport rates were high in order not to overfill the sampler net. Bedload was also sampled with a 76 by 76 mm opening, 3.22 opening ratio, thin-walled Helley-Smith sampler with a 0.25 mm mesh bag. Sampling locations were evenly spaced at 0.4 - 1.0 m increments across the stream, yielding 12-18 verticals that were sampled for 2 minutes each, completing one traverse. HS samples were collected either between bedload traps (with somewhat uneven spacing) or about 2 m downstream of the bedload trap cross-section by an operator standing on a low footbridge while bedload traps were removed. Most HS samples were collected by the same operator just before or after a bedload trap sample was taken. Sampled flows ranged from 16% – 150% Q_{bkf}, but not each study site exhibited this range of flows.

Data analysis Three main steps are involved in formulating adjustment functions: 1) data plotting and rating curve fitting; 2) creating data pairs of transport rates predicted from rating curves for both samplers; and 3) formulating, plotting, and analyzing the inter-sampler transport relationship that serves as the adjustment function (Figure 1). The steps are explained below, and an example data set is provided to guide the user through the computations.

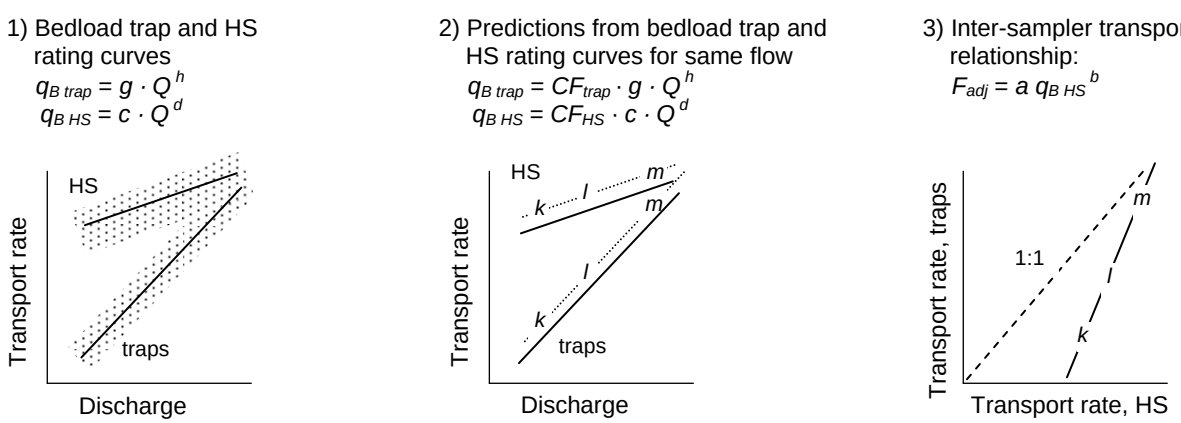

Figure 1 Computation of inter-sampler transport relationships: 1) Gravel bedload rating curves for bedload trap and HS sampler; 2) Data points *k*, *l*, and *m* are transport rates predicted from bedload trap and HS rating curves at the same discharge and bias-corrected; 3) Data *k*, *l*, and *m* from both samplers are paired and plotted versus each other.

Data compilation and plotting Transport rates of gravel particles > 4 mm—both per 0.5 phi size class and for total gravel transport—for the HS sampler and bedload traps were plotted in log-log space over the observed range of flows and transport rates for all study sites (Figure 2). Plotting serves to evaluate whether transport relationships can

be described by a straight-line function or whether two line segments might be needed. Measured zero-values were assigned a value at least one order of magnitude lower than the lowest measured transport rate (1E-6 in this study) to plot them along the x-axis. This study excluded zero values from the analyses, but they might be included at the user's discretion. A small data set (Little Granite Cr.'02) was selected for example computations (Table 1).

Table 1 Gravel transport rates (> 4 mm) collected at Little Granite Cr., 2002.

	Q (m^3/s)	$q_{B\,HS}$ (g/m·s)	Q (m^3/s)	$q_{B\,HS}$ (g/m·s)	Q (m^3/s)	$q_{B\,HS}$ (g/m·s)	Q (m^3/s)	$q_{B\,HS}$ (g/m·s)	Q (m^3/s)	$q_{B\,HS}$ (g/m·s)	Q (m^3/s)	$q_{B\,HS}$ (g/m·s)
Helley-Smith	0.272	1E-6	0.828	1E-6	2.282	0.0825	1.304	0.176	2.171	0.252	1.579	0.0179
	0.627	0.00790	1.192	0.146	2.364	0.167	1.882	0.463	1.669	0.129	1.741	0.0467
	0.596	0.00547	1.060	0.0536	1.862	0.0457	2.422	1.26	1.481	0.0268	1.900	0.127
	0.693	0.0705	1.576	0.652	0.828	0.00398	2.840	1.41	1.384	0.0567		
	Q (m^3/s)	$q_{B\,traps}$ (g/m·s)	Q (m^3/s)	$q_{B\,traps}$ (g/m·s)	Q (m^3/s)	$q_{B\,traps}$ (g/m·s)	Q (m^3/s)	$q_{B\,traps}$ (g/m·s)	Q (m^3/s)	$q_{B\,traps}$ (g/m·s)	Q (m^3/s)	$q_{B\,traps}$ (g/m·s)
Bedload traps	0.272	1E-6	1.854	0.00656	1.074	0.000731	1.511	0.00289	2.233	0.0803	1.473	0.00814
	0.596	1E-6	1.877	0.0140	1.095	0.000999	1.823	0.0684	2.231	0.138	1.598	0.0525
	0.596	1E-6	1.778	0.00235	0.900	0.000133	1.954	0.130	2.235	0.152	1.586	0.00810
	0.596	1E-6	1.945	0.0134	0.899	8.26E-05	1.879	0.103	1.596	0.00369	1.845	0.0313
	0.627	1E-6	2.131	0.0308	0.799	1E-6	1.892	0.00548	1.610	0.0138	1.931	0.119
	0.836	1E-6	2.286	0.0967	0.811	5.74E-05	2.065	0.0428	1.699	0.0660	1.703	0.00958
	1.112	1E-6	1.924	0.0150	0.793	1E-6	2.342	0.253	1.680	0.171	1.140	0.000688
	1.043	1E-6	1.797	0.0143	0.816	0.000103	2.562	0.774	1.458	0.00713		
	1.147	0.000287	1.769	0.00774	0.960	8.29E-05	2.324	0.0405	1.487	0.0145		
	1.372	0.000324	1.078	0.000560	1.123	0.000228	2.670	0.564	1.517	0.0340		
	1.740	0.00578	1.070	0.000461	1.245	0.00387	2.881	0.435	1.354	0.00514		

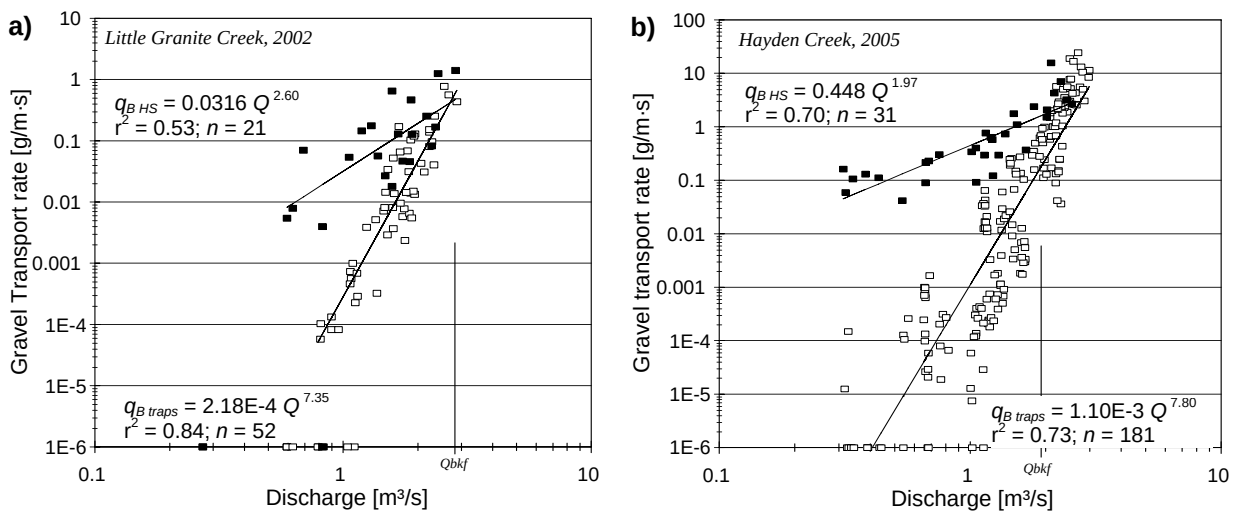

Figure 2 Relationships of gravel bedload transport (< 4 mm) and discharge for HS sampler and bedload traps and fitted rating curves at Little Granite '02 (a) and Hayden Cr. (b) where flows reached 150% Q_{bkf}.

Regression analysis When data in log-log space exhibit a straight-line trend, a power function (i.e., a linear regression to log-transformed data of transport rates *vs*. discharge) is appropriate to describe transport relationships for both samplers. Power functions are frequently applied to bedload transport relationships (e.g., Barry et al. 2004, King et al. 2004, Bunte et al. 2008) and are convenient for subsequent computations. The general form of the bedload transport rating curves fitted to bedload trap and HS data sets at all study sites is

$$q_{B\,HS} = c \cdot Q^{d}; \qquad q_{B\,trap} = g \cdot Q^{h} \tag{1a, 1b}$$

$q_{B\,trap}$ and $q_{B\,HS}$ are total and fractional gravel transport rates predicted for each size class (g/m·s), Q is discharge (m^3/s), g and c are coefficients, and h and d are exponents for bedload traps and the HS sampler, respectively.

Regression analysis typically provides a value for sample size *n*, coefficient of variation *r*, standard error of the *y*-estimate s_y, exponent (*d*, *h*), as well as the constant (log(*c*), log(*g*)) from which the *c*-and *g*-coefficients are computed as $10^{constant}$ (see Table 2 for Little Granite Cr., '02). *p*-values computed from *r* and *n* serve to evaluate the statistical significance of a regression function. *p*-values (two-tailed) smaller than 0.05 typically indicate statistical validity of a fitted relationship. Most fractional and total transport rating curves fitted to bedload trap data had *p*-values << 0.05. HS samples tended to have more data scatter and therefore higher (i.e., less significant) *p*-values. Insignificant transport relationships pose a problem to the rating curve approach and should be avoided. In this study, HS data sets with *p*-values up to 0.1 were considered valid for further analysis because our HS data fell within the envelopes of the large HS data sets that were measured by Ryan et al. (2005) for the same streams at or near our study sites and over a wider range of flows and transport rates. It can be argued that *p*-values for most HS transport relationships in this study would have been < 0.05 if a larger range of flows had occurred and been sampled. *p*-values for fractional transport relationships of the one or two largest collected size classes per study site were typically >> 0.05 for both samplers because small sample sizes and narrow ranges of sampled flows resulted in poorly defined transport relationships. Statistically insignificant rating curves (like those for fractional transport rates of the largest one or two mobile size classes) are not suitable for comparing transport rates between the two samplers. This restriction makes the rating curve approach more suitable for adjusting total gravel transport than fractional gravel transport.

Multiplications with bias correction factors Values for *y* can only be accurately predicted from *x* in a power function relationship if data are perfectly correlated (r^2=1). With any data scatter, the *y*-estimate is underpredicted, and the underprediction increases with the amount of scatter (s_y). Multiplication by a bias correction factor (*CF*) is the standard procedure to adjust for the underestimation. This study used the Ferguson (1986, 1987) bias correction factor CF_{Ferg} or the nonparametric smearing function CF_{Duan} by Duan (1983) when s_y exceeded 0.5 and/or *n* dropped below 30 (in which case CF_{Ferg} tends to overcompensate (Hirsch et al. 1993)). CF_{Ferg} and CF_{Duan} are computed as

$$CF_{Ferg} = \exp\,(2.651 \cdot s_y^2) \tag{2}$$

and

$$CF_{Duan} = \sum_{i=1}^{n} 10^{e_i}/n \tag{3}$$

where s_y is the standard error of the *y*-estimate and e_i are the residuals, i.e., the difference between measured and predicted *y*-values. Values of *CF* for HS samples ranged between 1 and 3 for fractional, and up to 4 for total transport rates, but were somewhat lower for bedload traps which tend to produce less data scatter (see Table 2).

Table 2 Example computations for Little Granite Cr., 2002: Regression table and gravel transport rates predicted from the HS and bedload trap rating curves for specified discharges and log-transformations.

Regression parameters						Paired transport rates, predicted for same *Q*				
	HS	Bedload traps		HS	Bedload traps	*Q* (m^3/s)	$q_{B\,HS\,pred}$ (g/m·s)	$q_{B\,traps\,pred}$ (g/m·s)	log($q_{B\,HS\,pred}$)	log($q_{B\,traps\,pred}$)
Constant	-1.50	-3.55	r^2	0.53	0.84	0.6	0.0161	1.11E-05	-1.79	-4.95
c-, *g*-coeff.	0.0316	2.81E-04	*n*	21	52	1.5	0.174	0.00934	-0.759	-2.03
d-, *h*-exp.	2.60	7.35	CF_{Ferg}	1.92	1.69	2.1	0.418	0.111	-0.379	-0.956
s_y	0.50	0.44	*p*-value	<<0.05	<<0.05	2.9	0.967	1.185	-0.0146	0.074

Creating and plotting data pairs To create data pairs, the power function fitted to the transport relationship of each sampler are used to predict transport rates for bedload traps and the HS sampler for the same specified discharges using Eq. 1 and 2. The predictions are multiplied by CF_{Ferg} or CF_{Duan} for bias correction (Eq. 2 or 3).

$$q_{B\,trap\,pred} = CF \cdot g \cdot Q^h\,; \quad q_{B\,HS\,pred} = CF \cdot c \cdot Q^d \tag{4a; 4b}$$

For the Little Granite Cr. '02 example, the rating curve prediction of the HS gravel transport rate at a discharge of *Q* = 2.1 m^3/s is $q_{B\,HS\,pred} = 2.1^{2.60} \cdot 0.0316 \cdot 1.92 = 0.418$ g/m·s (Table 2). At least two data pairs are needed for each rating curve (or for each rating curve section fitted to parts of the data set), but computing a few more data pairs comes handy for plotting. The paired values (Table 2) are plotted against each other in log-log space in a 1:1 plot with $q_{B\,trap\,pred}$ on the *y*-axis and $q_{B\,HS\,pred}$ on the *x*-axis (Figure 3).

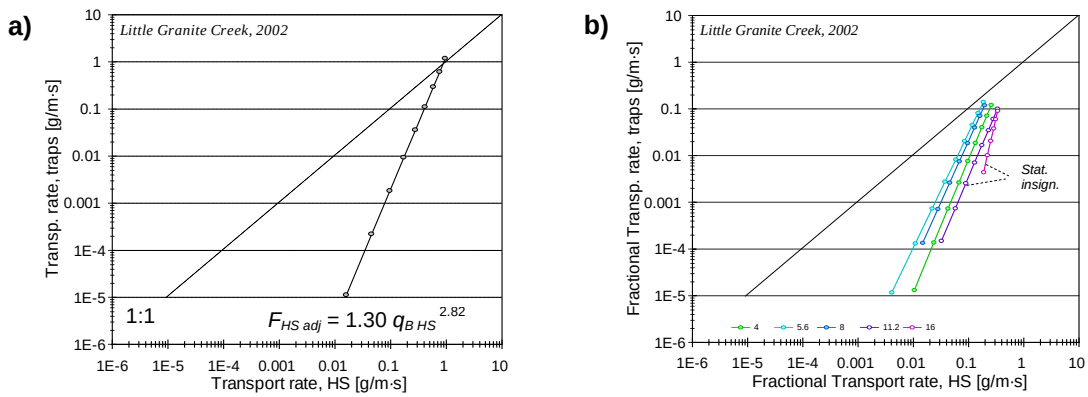

Figure 3 Inter-sampler transport relationship for total gravel transport (a) and fractional gravel transport rates (b).

Inter-sampler transport relationships The line connecting the plotted data pairs is straight in log-log space and describes the inter-sampler transport relationships between bedload traps and the HS sampler for each size fraction. To numerically describe inter-sampler transport relationships ($F_{HS\ adj}$), data pairs of predicted log-transformed transport rates log($q_{B\ trap\ pred}$) are regressed *vs*. predicted log($q_{B\ HS\ pred}$) for specified discharges (Table 2) using again a power function (i.e., linear regression of log-transformed predicted transport rates $q_{B\ trap\ pred}$ *vs*. $q_{B\ HS\ pred}$).

$$F_{HS\ adj} = a \cdot q_{B\ HS\ pred}{}^{b} \tag{5}$$

where a and b are the coefficients and exponents, and the a-coefficient again is computed from 10^{constant}. Multiplication by a bias correction factor CF is not necessary here because this fitted power function has no scatter ($r^2 = 1$). Analyses can be done for total or fractional transport rates. The resulting power functions ($F_{HS\ adj}$) shows how the gap in transport rates measured with the two samplers increases with decreasing transport. This power function (= inter-sampler transport relationship, Eq.5) serves as adjustment function. Adjustment is largest at the lowest transport and becomes negligible at high transport when the function intersects the 1:1 line. The adjustment function $F_{HS\ adj}$ for Little Granite Cr. '02 is = 1.30 $q_{B\ HS\ pred}{}^{2.82}$ where $a = 10^{0.115} = 1.30$. The transport rate at which $F_{HS\ adj}$ (= x) equals $q_{B\ traps\ pred}$ (= y) can be computed from the intersection of $F_{HS\ adj}$ with the 1:1 line as

$$x = a^{1/(1-b)} = 1.30^{(1/1-2.82)} = 0.87 \text{ g/m·s} \quad \text{for the example of Little Granite Cr., '02.} \tag{6}$$

Application of the adjustment function Eq. 5 is the HS adjustment function that may be applied to either individually measured HS gravel transport rates $q_{B\ HS}$ or to the HS gravel transport relationship with discharge $q_{B\ HS} = CF \cdot c\ Q^{d}$ (Eq. 1a) to yield the adjusted HS gravel transport relationship

$$F_{HS\ adj} = a \cdot q_{B\ HS}{}^{b} = a\ (CF \cdot c\ Q^{d})^{b} \tag{7}$$

For the Little Granite Cr. '02 example, the adjusted HS gravel transport rate at a flow Q = 2.1 m^3/s is $F_{HS\ adj}$ = 1.30 $(1.92 \cdot 0.0316 \cdot 2.1^{2.60})^{2.82}$ = 1.30(0.418 g/m·s)$^{2.82}$ = 0.111 g/m·s, the predicted bedload trap transport rate (Table 2).

RESULTS

Total and fractional inter-sampler transport relationships for gravel transport rates were computed for the nine study streams. Examples for two study streams sampled over a wide range of flows are shown in Figure 4. The functions generally have positive slopes and intersect the line of perfect agreement (1:1 line) at high transport rates but fall far below the 1:1 line at low transport rates. The plots show that the HS sampler collects gravel transport rates orders of magnitude higher than bedload traps when transport is low and that both samplers collect similar rates when transport is high. The pattern likewise holds for individual size fractions provided they are sampled sufficiently.

Variability among individual size classes Fractional inter-sampler transport relationships for easily transportable, small gravel sizes plot approximately parallel to each other as well as to the total gravel inter-sampler transport relationship. In four of the study streams, fractional inter-sampler transport relationships are nearly aligned (Figure 4a). Here, the relationships quantifying differences in transport rates between bedload traps and the HS sampler

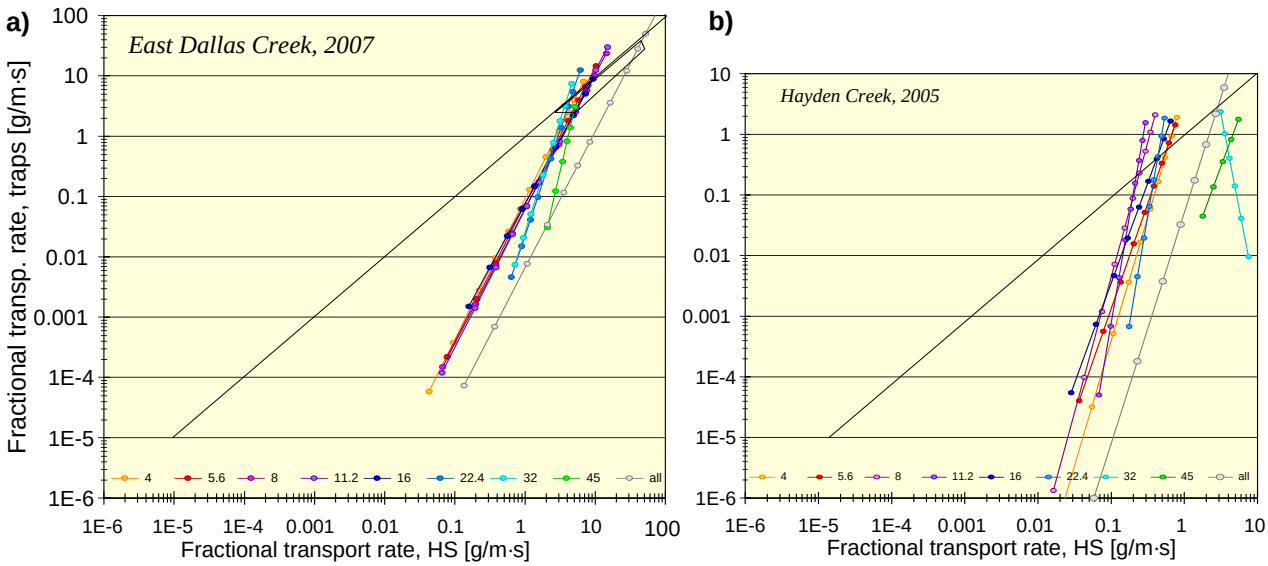

Figure 4 Fitted inter-sampler transport relationships for fractional and total gravel transport rates at two of the study streams where sampling covered 10 - 113% Q_{bkf} (a) and 28 - 150% Q_{bkf} (b). Note the steepening of inter-sampler transport relationships for the coarsest, inadequately sampled size fractions starting at about 22.4 mm.

have similar slopes and intercepts for all but the largest two size classes. In other streams, inter-sampler transport relationships for smaller gravel size classes vary mainly in their intercepts (i.e., they are "stacked"), and the disparity between HS and bedload trap gravel samples increases with decreasing particle size. In some streams, inter-sampler transport relationships of the smaller gravel size fractions vary both in intercepts and slope (Figure 4b). Inter-sampler transport relationships for the coarsest mobile gravel size classes deviate from the near-parallel trend, becoming steeper for increasingly larger particles. This trend is the result of small sample size and poorly defined rating curves. Collecting more samples containing coarse gravel in flows much higher than bankfull would have yielded better-defined coarse-gravel rating curves and likely rendered the inter-sampler transport relationships for coarse gravel similar to those for smaller gravel sizes (until sampled gravel sizes exceed the HS opening size).

Variability among streams Inter-sampler transport relationships combined for all study streams are plotted for individual gravel size classes (Figure 5a-c) as well as for total gravel transport rates (Figure 5d) and show the variability among streams. For total gravel transport, trendlines of inter-sampler relationships appear to originate from a common low range of transport rates for all study streams (see dashed circle in Figure 5d) and disperse among individual streams as transport increases. *b*-exponents, *a*-coefficients, and intersections with the 1:1 line of the inter-sampler relationship for total transport are listed in Table 3 (see Bunte and Abt (2009) for *a*, *b*, and 1:1 line intersections of fractional inter-sampler transport relationships for the study streams).

Table 3 *a*-coefficients and *b*-exponents of best-fit power functions of inter-sampler transport relationships and their intersections with 1:1 line for total gravel transport rates and bedload D_{max} relationships.

	Total gravel transport			Bedload D_{max} size			
Study stream	*a*	*B*	*1:1 line*	*a*	*b*	*1:1 line*	
East Dallas Creek	0.00659	2.26	54.5	1.97	0.0364	29.9	blue group
Halfmoon Creek	0.0191	2.13	33.1	1.37	0.280	32.1	
East St. Louis Cr. '03	0.0573	2.22	10.4	1.85	0.160	14.1	
East St. Louis Cr. '01	0.0870	1.72	29.7	1.18	0.739	5.52	
Cherry Creek	0.285	2.82	1.99	3.22	0.00417	11.9	red group
Little Granite Cr. '99	0.210	3.55	1.85	2.17	0.0489	13.2	
Hayden Creek	0.0498	3.81	2.91	2.27	0.0182	23.6	
Little Granite Cr. '02	1.30	2.82	0.87	8.65E-5	5.15	4.53	

Shading in red and blue denote streams classified as the "red" or "blue" group (see explanation in the text below).

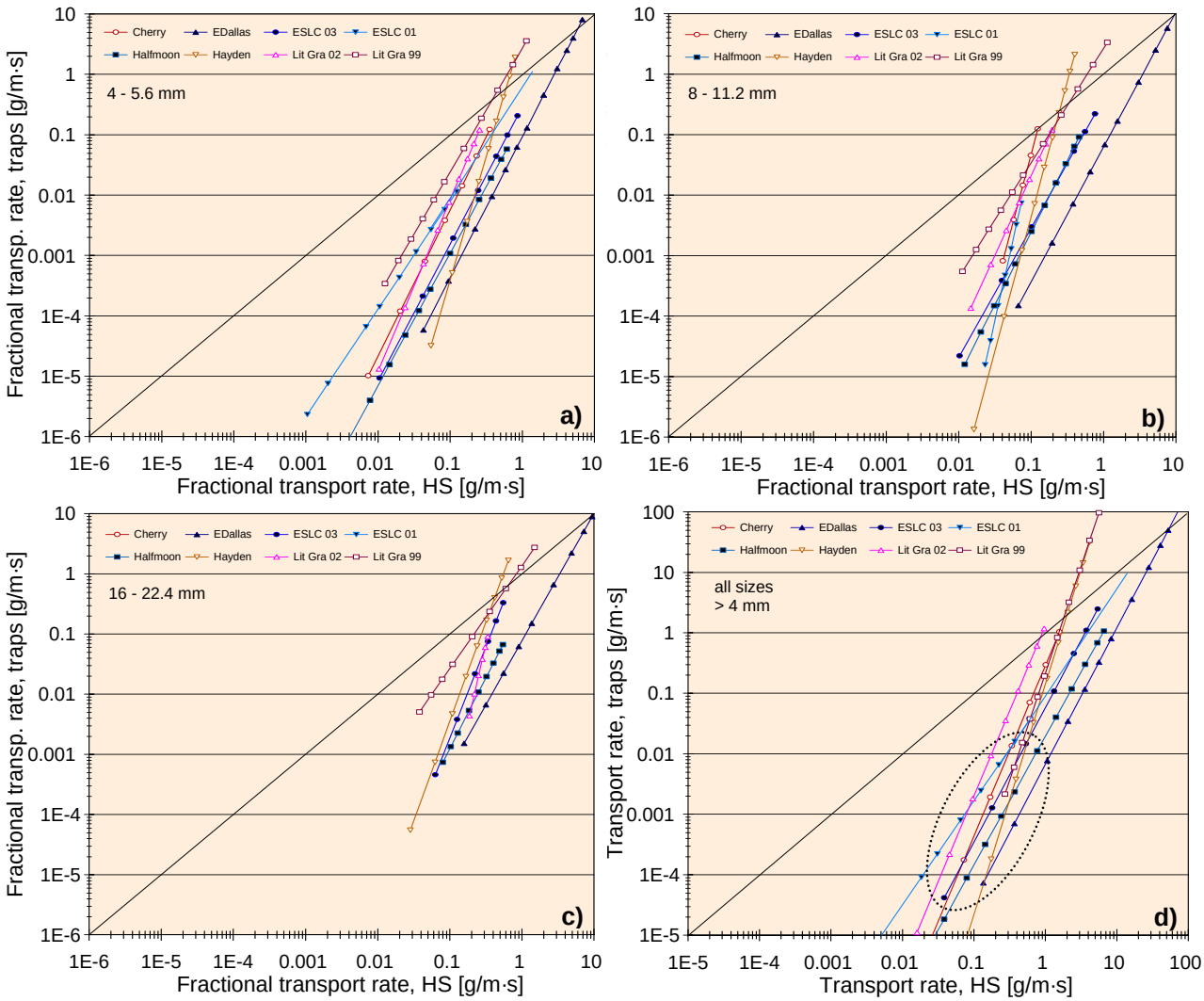

Figure 5: Fitted inter-sampler transport relationships for individual 0.5 phi gravel fractions combined for all study streams (only every other size fraction is shown, plots a – c) and for total gravel transport rates (plot d). Streams falling into the "red" group are indicated by reddish line colors and open symbols, streams in the "blue" group by bluish line colors and closed symbols (see text for explanations).

Channel and bedmaterial characteristics Given that inter-sampler transport relationships differ among streams, some aid in selecting an appropriate adjustment function for a specific stream setting is desirable. However, neither exponents, coefficients, nor the 1:1 line intersections of the inter-sampler relationships for total gravel transport rates were correlated with characteristics of the study streams such as bankfull flow, basin area, bankfull stream width, stream gradient, surface D_{50} and D_{84} sizes, the percent surface and subsurface sediment < 2 and < 8 mm, or the subsurface D_{50} and D_{84} sizes. *b*-exponents, *a*-coefficients, and intersections with the 1:1 line were also not related to the HS rating curves or flow competence curves at any of the study streams. Yet, streams that had steep gravel rating and flow competence curves as measured with bedload traps also had steeper inter-sampler transport relationships and lower intersections with the 1:1 line. However, none of those relationships were sufficiently well defined to predict inter-sampler transport relationships for individual streams. The only exception was a moderately well defined negative relationship of the inter-sampler transport relationship steepness (*b*) with bed armoring (D_{50surf}/D_{50sub}) (Eq. 8). However, bed armoring is an inconvenient predictor: it is laborious to measure in coarse-bedded streams where pebble counts should include ≈ 400 particles and where several subsurface samples that amount to a total of several 100 kg should be collected (Bunte and Abt 2001).

$$b = 5.73\,(D_{50surf}/D_{50sub})^{-1.21} \quad r^2 = 0.69,\ p = 0.0112,\ s_y = 0.071 \qquad (8)$$

Segregation of inter-sampler transport relationships into two stream groups Inter-sampler relationships can be visually segregated into two groups: one group with relatively steep inter-sampler transport relationships (plotted in reddish colors and a reddish shading in Figure 6 (Hayden and Little Granite Cr. '02 fall into this group) and one with flatter relationships (plotted in bluish colors and bluish shading; East Dallas Cr. is an example). Inter-sampler transport relationships of the steep "red" group have exponents of 2.8 – 3.8 and intersect the 1:1 line around 1 - 3 g/m·s (Table 3), meaning that the two samplers differ widely at low transport but obtain similar sampling results during moderate transport. Within the flat "blue" group, exponents range from 1.7 to 2.3 and intersections of the 1:1 line from 10 to 55 g/m·s, which means that both samplers retain their wide low-flow difference at moderate flows and provide similar results when transport is high. A *t*-test with a 0.05 confidence level showed that exponents, coefficients, and intersections with the 1:1 line are significantly different among the two groups, a finding that supports the validity of the visual segregation. Fractional inter-sampler transport relationships of individual study streams can likewise be segregated into two stream groups for the smaller, easily transportable gravel size classes (see Bunte and Abt 2009 for details).

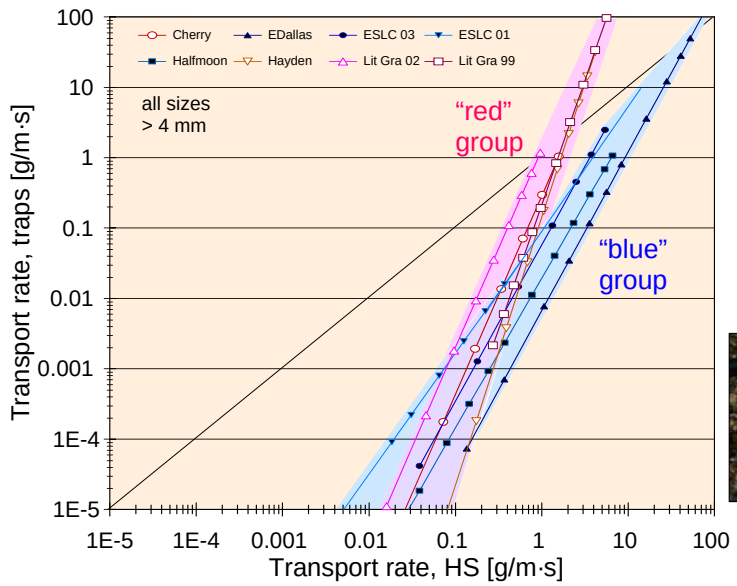

Figure 6 Inter-sampler transport relationships for total gravel transport obtained from the rating curve approach for all study streams. Streams falling into the "red" group are indicated by reddish line colors, open symbols, and red shading; streams in the "blue" group by bluish line colors, closed symbols, and blue shading.

Group-average inter-sampler transport relationships Group-averaged inter-sampler relationships for the "blue" and "red" study streams were formulated from the arithmetic mean of the four exponents and geometric mean of the four coefficients, both for total and fractional transport (Table 4, Figure 7, Eqs. 9 - 12). Also, the fractional group-averaged inter-sampler relationships appear similar enough between individual size classes to describe them by a single function that is suitable for any 0.5 phi gravel size class for each stream group. The two functions (one for "red" and one for "blue" streams) suitable for any 0.5 phi size class (Eqs. 10 and 12) are of similar steepness as the two group-averaged inter-sampler transport relationships for total gravel transport (Eqs. 9 and 11), but their *a*-coefficients (9.35 and 0.325) are more than an order of magnitude higher (0.249 and 0.0282).

Total gravel transport: $F_{HS} = q_{B\,traps} = 0.249 \cdot q_{B\,HS}^{3.25}$ (9)

Any 0.5 phi gravel size class: $F_{HS} = q_{B\,traps} = 9.35 \cdot q_{B\,HS}^{2.97}$ (10)

"red" group: less armoring, steeper rating and flow competence curves; lower sediment supply

and

Total gravel transport: $F_{HS} = q_{B\,traps} = 0.0282 \cdot q_{B\,HS}^{2.08}$ (11)

Any 0.5 phi gravel size class: $F_{HS} = q_{B\,traps} = 0.325 \cdot q_{B\,HS}^{2.23}$ (12)

"blue" group: more armoring, flatter rating and flow competence curves; higher sediment supply

The same analyses conducted for gravel transport rates were repeated for gravel bedload D_{max} sizes.

Table 4 Exponents and coefficients of inter-sampler transport relationship for fractional and total gravel transport rates and the bedload D_{max} size averaged over the four streams falling into the "red" and "blue" stream groups.

		Fractional transport						Total gravel transport	D_{max} (mm)	Avg. for any 0.5 phi size class	
		> 4 mm	>5.6 mm	>8 mm	>11.2 mm	>16 Mm	>22.4 mm				
a-coeff.	Geom. mean	0.213	0.781	0.241	0.414	0.343	0.207	**0.0282**	0.168	**0.325**	"blue" stream group
	CV(%)	143	145	965	174	207	434	**1789**	334	**68.1**	
b-exp.	Arithm. mean	2.14	2.56	2.25	1.94	1.87	2.61	**2.08**	1.59	**2.23**	
	CV(%)	11.6	18.0	69.1	67.6	69.8	66.7	**11.9**	23.9	**13.7**	
a-coeff.	Geom. mean	3.23	5.48	46.2	-	-	-	**0.249**	0.00423	**9.35**	"red" stream group
	CV(%)	8.24	5.43	2.69	-	-	-	**233**	28574	**6.55**	
b-exp.	Arithm. mean	2.85	2.67	3.38	-	-	-	**3.25**	3.20	**2.97**	
	CV(%)	31.3	25.1	39.3	-	-	-	**15.5**	43.2	**12.5**	

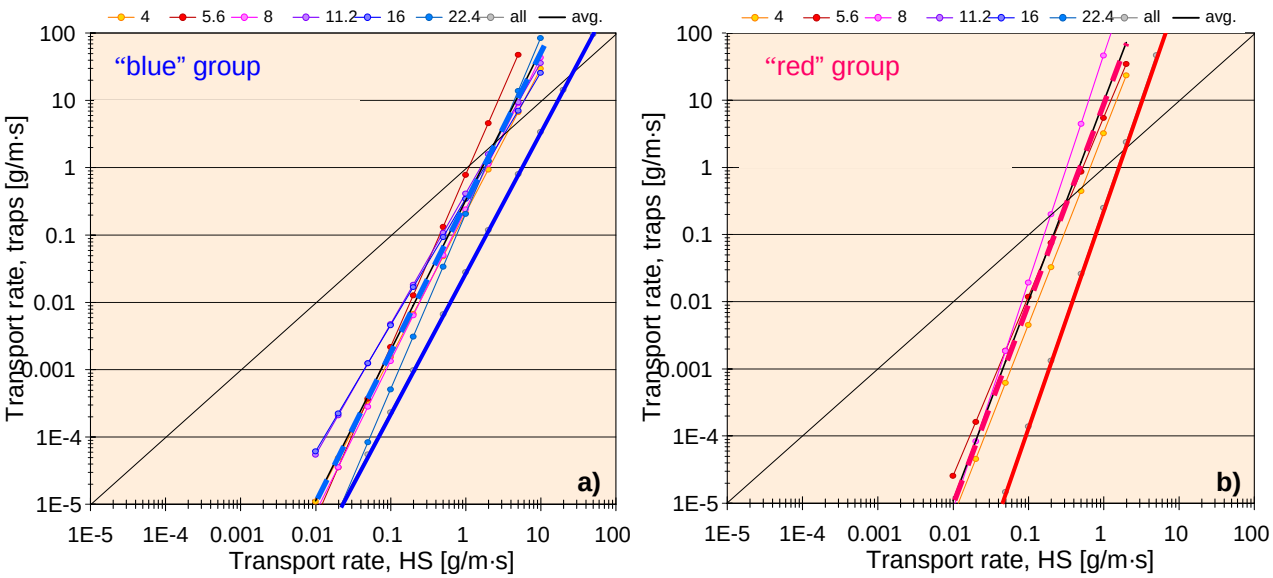

Figure 7 Solid thick blue and red lines show group-average inter-sampler transport relationships for total gravel transport for the "blue" (a) and "red" (b) streams. Thin lines show fractional inter-sampler transport relationships averaged over the "blue" (a) and "red" (b) streams. Dashed thick blue and red lines indicate an average inter-sampler transport relationship applicable to any 0.5 phi gravel size fraction for "blue" and "red" streams.

Bedload D_{max} particle sizes Inter-sampler relationships were computed for the largest particle size contained in each bedload sample (D_{max}) for all study streams (Figure 8a) using the flow competence curves ($D_{max} = j\ Q^{k}$) measured with both samplers. Computational steps were analogous to those described to obtain inter-sampler relationships for gravel transport rates. Results show that during low flow the HS sampler collects larger bedload D_{max} particles than bedload traps, but smaller bedload D_{max} particles than bedload traps at high flow.

Exponents, coefficients, and intersections with the 1:1 line of the inter-sampler transport relationships for gravel bedload D_{max} particle sizes of individual streams (tabled in Bunte and Abt (2009)) were not related to exponents (*h*) and coefficients (*g*) of bedload rating and flow competence curves measured at each stream with bedload traps. However, *b*-exponents of the inter-sampler bedload D_{max} relationships at the study streams were negatively related to the HS-measured flow competence exponent ($r^2 = 0.64$; $p = 0.0176$), while the *a*-coefficients were positively related the HS-measured flow competence exponent ($r^2 = 0.77$; $p = 0.0044$). However, only the latter correlation (if any) is satisfactory for prediction of the HS adjustment function for gravel bedload D_{max} sizes.

Inter-sampler relationships for the bedload D_{max} size can likewise be visually segregated into two groups (Figure 8b) and result in mean *a*-coefficients and *b*-exponents that are statistically different between the two groups. The segregation divides the study streams along the same lines as it did for inter-sampler relationships of transport rates. Streams that have flatter inter-sampler relationships for bedload D_{max} particle sizes (blue group) have flatter inter-sampler transport relationships, while streams with steeper inter-sampler relationships (red group) for bedload D_{max} particle sizes also show steeper inter-sampler transport relationships (compare Figure 8b with Figure 6).

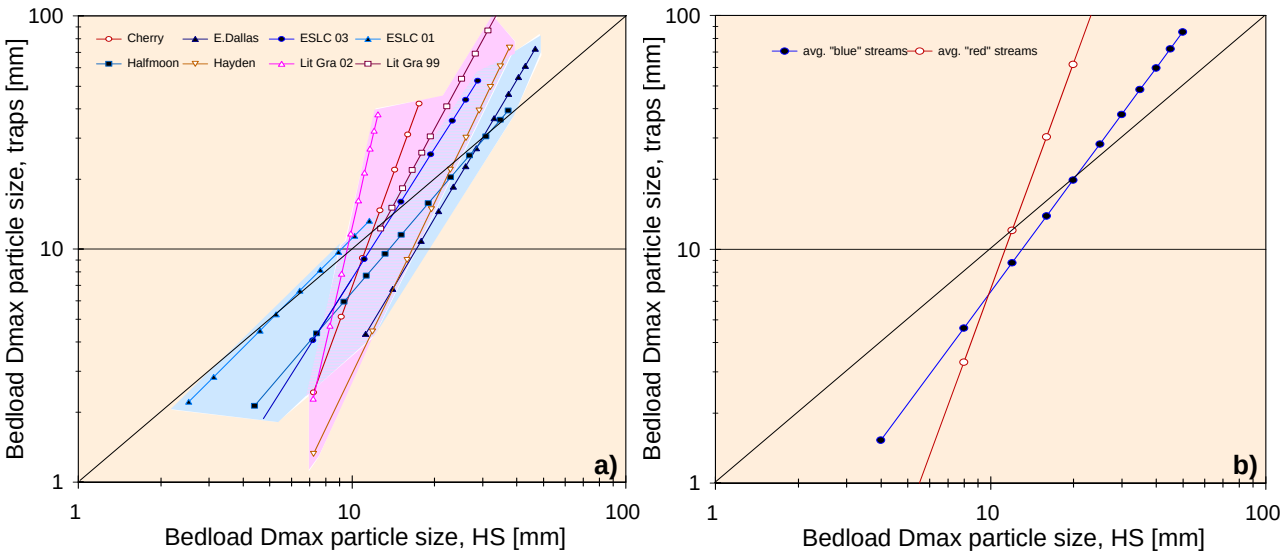

Figure 8 Inter-sampler relationships of bedload D_{max} particle sizes collected with bedload traps and the HS sampler at all study sites (a). Red and blue shading highlights streams of the "red" and "blue stream groups. Bedload D_{max} particle size relationships averaged over study streams within "red" and "blue" stream groups (b).

Exponents, coefficients, and 1:1 intersections of the inter-sampler relationships for bedload D_{max} sizes were likewise averaged over the two stream groups (Table 3). The averaged exponents and coefficients provide adjustment functions for the "red" and "blue" stream groups with which to convert bedload D_{max} particle sizes collected with a 3-inch, thin-walled HS sampler to those that might have been collected with bedload traps (Eqs. 13 and 14).

$$F_{HS\,adj} = D_{max\,traps} = 0.00423 \cdot D_{max\,HS}^{\;3.20} \qquad \text{(red group)} \qquad (13)$$

and

$$F_{HS\,adj} = D_{max\,traps} = 0.168 \cdot D_{max\,HS}^{\;1.59} \qquad \text{(blue group)} \qquad (14)$$

<u>Bedmaterial and bedload conditions in "red" and "blue" streams</u> Correlations between group-averaged inter-sampler relationships and group-averaged channel and transport characteristics would improve our understanding of why the two samplers differed to a certain degree in a particular stream and also permit a user to categorize a study stream into a stream group. A t-test for statistical difference based on whether the 95% confidence interval around the group means overlapped identified average values of channel and transport parameters for the "blue" and the "red" stream group. Bed armoring was statistically different between the "red" and the "blue" stream groups. The group-averaged exponents and coefficients of bedload rating and flow competence curves measured with bedload traps were also statistically different between the two groups. Similarly, the gravel transport rate per unit area (g/m·s/km^2) at 50% Q_{bkf}, the bedload D_{max} size measured at 50% Q_{bkf} and at a transport rate of 1 g/m·s differed among the two stream groups. The value equidistant to both group means served as a threshold among the two steam groups and to indicate whether functions of the "red" or "blue" group should be used for adjustment of HS-sampled transport rates. For HS samples, only the coefficients of the bedload rating and flow competence curves and the gravel transport rate per unit area were statistically different between the two stream groups.

The threshold values for bedmaterial and bedload conditions (Table 5) categorize a study stream as either a "red" or "blue" stream. "Red" differ from "blue" streams by their steep bedload trap rating and flow competence curves, low armoring, and low sediment supply (these interdependencies were also shown by Bunte et al. 2006). Threshold

values in Table 5 are not statistically very stringent. To categorize a study stream before selecting an adjustment function, the user should evaluate several threshold values. If a study stream does not fall clearly into one of the two stream groups, an adjustment function midway between the "red" and the "blue" stream group may be used.

Table 5 Bedmaterial characteristics and conditions of bedload transport that determine the stream group and the respective inter-sampler relationships (rating curve approach).

	Streams in "red" group	Stream in "blue" group
For bedmaterial conditions of:		
Armoring ($D_{50\ surf}/D_{50\ sub}$)	< 2.0	> 2.0[#]
For bedload conditions measured with **bedload traps**:		
Exponent of bedload rating curve	> 8.9	< 8.9
Coefficient of bedload rating curve	< 1.1E-4	> 1.1 E-4
Exponent of flow competence curve	> 1.9	< 1.9
Coefficient of flow competence curve	< 5.30	> 5.30
Bedload D_{max} (mm) at 50% Q_{bkf}	< 11	> 11
Gravel transport rate (g/m·s/km^2) at 50% Q_{bkf}	< 3.9E-5	> 3.9E-5
Bedload D_{max} (mm) at gravel transp. rate of 1 g/m·s	> 40	< 40
For bedload conditions measured with **HS sampler**:		
Exponent of bedload rating curve	< 3.4*	> 3.4*
Coefficient of bedload rating curve	< 0.094	> 0.094
Exponent of flow competence curve	> 0.91*	< 0.91*
Coefficient of flow competence curve	< 9.7	> 9.7
Bedload D_{max} (mm) at 50% Q_{bkf}	< 13*	> 13*
Gravel transport rate (g/m·s/km^2) at 50% Q_{bkf}	< 5.8E-3	> 5.8E-3
Bedload D_{max} (mm) at gravel transp. rate of 1 g/m·s	< 18*	> 18*

[#] Higher value due to higher % subsurface fines; *Difference between red and blue stream group not statistically significant.

Using a correction function to adjust a HS rating curve The group-average exponents and coefficients (Table 4, Eqs. 9 - 12) provide adjustment functions $F_{HS\ adj}$ with which to convert fractional and total transport rates collected with a 3-inch, thin-walled HS sampler to those collected with bedload traps (use Eqs. 13 and 14 for adjusting bedload D_{max} sizes). To adjust a HS rating curve at a study stream, the exponent b and coefficient a of the respective inter-sampler transport relationships is applied to the measured HS power function rating curve ($q_{B\ HS} = c \cdot Q^{\ b}$) to yield $F_{HS\ adj} = a \cdot (CF \cdot c \cdot Q^{\ d})^b$ (Eq. 7). The exponent and coefficient of the adjusted HS rating curve can be computed analytically or be obtained via curve-fitting. Comparing adjusted HS rating curves with those measured using bedload traps shows that for three of the "blue" stream groups, adjusted HS rating curves deviate less than a factor of 2 from the measured bedload trap rating curve. The larger deviation for East St. Louis Creek '01 is attributed to the small range of measured flows and thus less strongly defined gravel rating curves. These results are encouraging but also emphasize the importance of basing computations of adjustment functions on HS measurements that extend over a wide range of flow. On a final note, the inter-sampler transport relationships presented in this study were obtained in mountain coarse gravel- and cobble-bed streams. The specific adjustment functions suggested for conversion of HS sampling results should only be applied to streams with similar characteristics as the study streams. The adjustment functions do not apply to the sand portion of HS sampling results.

DISCUSSION AND CONCLUSIONS

The need for adjustment of HS-collected gravel transport rates depends on circumstances. Adjustment is needed when gravel samples collected at low transport rates are used for further analyses, e.g., to compute incipient gravel motion, annual gravel load in low-flow years, inter-annual gravel load variability, and effective discharge. Adjustment is particularly important for samples collected on loose beds where inadvertent particle dislocation during placement of the HS sampler can overestimate transport rates by orders of magnitude. Conversely, gravel transport rates collected at high transport of ≈2 or ≈20 g/m·s depending on stream group (those transport rates typically occur at bankfull or higher flows in low-supply mountain streams) need little or no adjustment; at these transport rates, gravel samples collected with a HS sampler tend to be similar to those collected with other samplers.

Acknowledgments The project described in this publication was supported by Grant/ Cooperative Agreement Number 08HQGR0142 from the United States Geological Survey. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the USGS. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government. We thank Chuck Troendle for a thoughtful and helpful review of this manuscript.

REFERENCES

Barry, J. J., Buffington, J. M., and King, J. G. (2004). "A general power equation for predicting bed load transport rates in gravel bed rivers," Water Resources Research, 40, W10401, doi:10.1029/2004WR003190.

Bunte, K. (2002). "Testing the sampling efficiency of the bedload traps by comparison with sediment collected in the debris basin at East St. Louis Creek," Report submitted to the Stream Systems Technology Center, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 44 pp.

Bunte, K. and Abt, S.R. (2001). "Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analysis in Sediment Transport, Hydraulics, and Streambed Monitoring," USDA Forest Service, Rocky. Mtn. Res. St., Fort Collins, CO, *Gen. Tech. Rep.* RMRS-GTR-74, 428 pp. http://www.fs.fed.us/rm/pubs/rmrs/gtr_74.html

Bunte, K. and Abt, S. R. (2005). "Effect of sampling time on measured gravel bed load transport rates in a coarse-bedded stream," Water Resources Research, 41, W11405, doi:10.1029/2004WR003880.

Bunte, K., and Abt, S.R. (2009). "Transport relationships between bedload traps and a 3-inch Helley-Smith sampler in coarse gravel-bed streams and development of adjustment functions," Report submitted to the Federal Interagency Sedimentation Project, Vicksburg, MS, 138 pp.

Bunte, K. and Swingle, K.W. (2008). "Bedload traps and the Helley-Smith sampler deployed on the bed and on ground plates: Sampling results from East Dallas Creek, CO," Report submitted to Stream Systems Technology Center, USDA Forest Service, Rocky Mtn. Res. St., Fort Collins, CO, 104 pp.

Bunte, K., Abt, S.R. Potyondy, J.P., and Ryan, S.E. (2004). "Measurement of coarse gravel and cobble transport using a portable bedload trap," J. Hydraulic Engineering 130(9), pp 879-893.

Bunte, K., Abt, S.R., and Swingle, K.W. (2006). "Predictability of bedload rating and flow competence curves from bed armoring, stream width and basin area," Proceedings of the Eighth Federal Interagency Sedimentation Conf., April 2-6, 2006, Session 4A-2, 9 pp http://pubs.usgs.gov/misc_reports/FISC_1947-2006/html/pdf.html

Bunte, K., Swingle, K., and Abt, S.R. (2007). "Guidelines for using bedload traps in coarse-bedded mountain streams: Construction, installation, operation and sample processing," Gen. Tech. Rep. RMRS-GTR-191, Fort Collins, CO, U.S.D.A, Forest Serv., Ry. Mtn. Res. St., 91 pp. http://www.fs.fed.us/rm/pubs/rmrs_gtr191.pdf

Bunte, K., Abt, S.R., Potyondy J.P., and Swingle, K.W. (2008). "A comparison of coarse bedload transport measured with bedload traps and Helley-Smith samplers," Geodinamica Acta 21(1/2), pp 53-66.

Bunte, K., Swingle K.W., and Abt, S.R. (2010). "Necessity and difficulties of field calibration of signals from surrogate techniques in gravel-bed streams: possibilities for bedload trap samples," U.S.G.S. Sci. Inv. Rep., in press.

Duan, N. (1983). "Smearing estimate: a nonparametric retransformation method," J. Am. Stat. Asso. 87, pp 605-610.

Ferguson, R.I. (1986). "River loads underestimated by rating curves," Water Resources Research 22(1), pp 74-76.

Ferguson, R.I. (1987). "Accuracy and precision of methods for estimating river loads," Earth Surface Processes and Landforms 12, pp 95-104.

Hirsch, R.M., Helsel, D.R., Cohn T.A., and Gilroy, E.J. (1993). "Statistical analysis of hydrological data," In: Handbook of Hydrology, Maidment, D.R. (ed.) McGraw-Hill, New York.

King, J.G., Emmett, W.W., Whiting, P.J., Kenworthy R.P., and Barry, J.J. (2004). "Sediment transport data and related Information for Selected Coarse-Bed Streams and Rivers in Idaho," USDA Forest Service, Rocky Mtn. Res. Station, Gen. Tech. Rep. RMRS-GTR 131, 26 pp. http://www.fs.fed.us/rm/pubs/rmrs_gtr131.html

Potyondy, J.P., Bunte, K. Abt S.R., and Swingle, S.W. (2010). "Bedload movement in mountain channels: Insights gained from the use of portable bedload traps," 9th Federal Interagency Sedimentation Conf., Las Vegas, NV.

Ryan, S.E., Porth L.S., and Troendle, C.A. (2005). "Coarse sediment transport in mountain streams in Colorado and Wyoming, USA," Earth Surface Processes and Landforms 30, pp 269–288. DOI: 10.1002/esp.1128.

Singh, A., Fienberg, K., Jerolmack, D.J., Marr, J., and Foufoula-Georgiou, E. (2009a and b). "Experimental evidence for statistical scaling and intermittency in sediment transport rates," Journal of Geophysical Research 114, F01025,doi:10.1029/2007JF000963 and "Corrections" F03019, doi:10.1029/2009JF001427.

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