Bed load bias: Comparison of measurements obtained using two (76 and 152 mm) Helley-Smith samplers in a gravel bed river

Damia Vericat

Department of Environment and Soil Sciences, University of Lleida, Lleida, Spain

Michael Church

Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada

Ramon J. Batalla

Department of Environment and Soil Sciences, University of Lleida, Lleida, Spain

Forestry Institute of Catalonia, Solsona, Spain

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[1] We assess how the size of the Helley-Smith (HS) bed load sampler nozzle affects the accuracy of bed load sampling. Semitheoretical considerations show that the larger grains resident on the streambed can influence the sample either by blocking the sampler entrance or by causing the sampler to rest in a "perched" position. Probabilities for interference can be derived from the distribution of grain sizes but they do not capture the actual complexity of the influence of the bed on sampler performance. We therefore make an empirical comparison of sediment trapped by HS samplers with 76- and 152-mm intakes during floods in the gravel bed lower Ebro River. Most bed load rates appeared higher when sampled with the HS152. The largest clasts collected by the HS76 also tend to be smaller than those obtained with the HS152 at the same flow. Analyzing paired bed load samples, we find the probability of a bed load sample collected with the HS152 to be biased is around 43% in the conditions of the present study, whereas 65% of samples were biased when obtained with the HS76. The analysis emphasizes the influence of bed material texture over sampler performance and demonstrates that the use of samplers with intake size much larger than bed grain size (i.e., $\sim 5D$) will increase the accuracy of bed load grain size distributions and the precision of annual load estimates in gravel bed rivers.

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1. Introduction

[2] Bed load transport can be highly variable [*Einstein*, 1937; *Gomez et al.*, 1989]. This circumstance presents important problems for the calibration and use of bed load samplers [*Emmett*, 1980; *Hubbell*, 1987]. Bed load measurement remains a major obstacle to understanding sediment transport in gravel bed rivers.

[3] The most widely deployed bed load samplers are the basket types, in which the moving sediment enters a nozzle and is trapped in a bag or basket [*Hubbell*, 1964]. The more advanced designs maintain ambient fluid pressures in the entrance (e.g., the VÚV sampler of *Novak* [1957]). *Helley and Smith* [1971] designed one such sampler for use in natural streams carrying fine gravels that has been widely adopted. First tests in a flume transporting sand showed that the sampler might consistently overregister by about 50%. Helley and Smith observed that, when the sampler was raised from the bed, it tended to scoop additional material, and emphasized that the performance of the sampler would depend on the bed material size. *Johnson et al.* [1977] reported clogging of the sampler's bag as another source of bias for the Helley-Smith (hereafter HS) design. In the East Fork River, Wyoming, *Emmett* [1980] completed the first field calibration of the original device. He reported for the 76-mm intake HS sampler an efficiency of 1 (i.e., the real bed load rate tends to be the same as that collected with the sampler) for particles between 0.5 and 16 mm, approximately the range of sizes for which the sampler was designed. *Hubbell* [1987] determined in a laboratory flume that the device's efficiency decreases as grain size and bed load rates increase. Changes in the efficiency of modified HS samplers have also been reported. For instance, *Gaudet et al.* [1994],on the basis of flume experiments with sand, reported that a standard sampler systematically trapped more material than one with 30 mm opening, while *Ryan and Porth* [1999] found, on the basis of measurements in two cobble bed streams, that slight modifications of three HS samplers of 76-mm intake generated substantially different collections of bed load.

[4] Various attempts have been made to asses the efficiency of this sampler in gravel bed rivers. In the Drau River of

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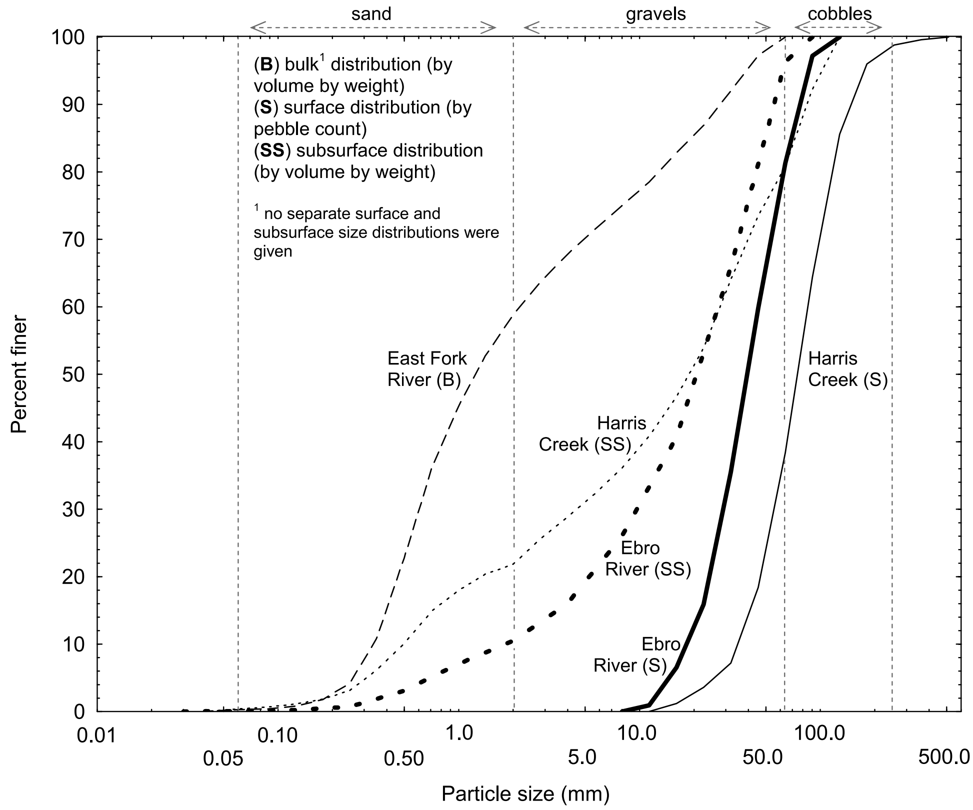


Figure 1. Ebro River bed surface and subsurface grain size distributions at Móra d'Ebre B bar, bulk grain size distribution in the East Fork River [*Emmett*, 1980], and grain size distributions for bed surface (obtained in riffles) and subsurface material in Harris Creek [*Sterling and Church*, 2002].

Austria, a coarse gravel channel ($D_{50\text{-}s}$ = 65 mm), *Habersack et al.* [2001] reported for a 152-mm intake HS sampler an efficiency close to unity by comparing the device's bed load catch with that of a continuous recording slot sampler. However, in Harris Creek (median surface material between 45 mm and 75 mm), British Columbia, *Sterling and Church* [2002], by comparing magnitude and grain size distributions of sediment samples collected by a pit trap and by a standard HS sampler (76-mm intake), reported a clear bias of the bed load samples collected with the HS device including substantial overregistration of sand sizes. They attributed the overcatch to the propensity for the sampler to capture low-flying suspended material (a deliberate design feature to complement standard DH series suspended sediment samplers). *Bunte et al.* [2004] tested bed load transport measurements in two gravel and cobble bedded rivers and concluded that HS measurements were biased as bed load ratings constructed using observations obtained with larger intakes and nonrecording bed load traps were better defined and steeper than those obtained with a standard HS sampler (76-mm intake). Even so, and as a consequence of the lack of choices, this sampler has often been deployed in coarse gravel bed rivers [e.g., *Andrews*, 1994], and even on cobble beds [e.g., *Ryan and Porth*, 1999], without attempt to reassess the sampler's efficiency or accuracy. In particular, no assessment has been made of the relation between sampler intake dimension, river bed material size, and the probability that the samples will be biased.

[5] These concerns motivated our efforts to understand how the size of the HS sampler's nozzle might affect the accuracy of the sampling and the precision of bed load measurements and summary loads. We first present some semitheoretical considerations based on the relative size of the sampler intake and the resident bed material, and then proceed to field evaluation of the equivalence of the sediment trapped by two HS samplers respectively with 76- and 152-mm intake. We subsequently compare the bed load yields predicted by the load-rating curves elaborated by the two devices.

2. Methods

2.1. Study Site

[6] Bed load was sampled in the lower Ebro River (NE Iberian Peninsula) at Móra d'Ebre Monitoring Section (MEMS) (see *Vericat and Batalla* [2005] for details). Mean annual discharge is 430 m^3 s^{-1} at Tortosa, 49 km downstream from MEMS, where maximum peak flow was estimated by *Novoa* [1984] to be around 12,000 m^3 s^{-1} in 1907. Today, close to 190 reservoirs impound almost 60% of the catchment's annual runoff, most of them constructed between 1950 and 1975, reducing magnitude and frequency of floods in the lowermost reaches of the basin [*Batalla et al.*, 2006]. The maximum discharge recorded at Tortosa in the postdams period has been 3300 m^3 s^{-1} in 1982. The median slope at the sampling section is 8.5×10^{-4} [*Vericat and Batalla*, 2006]. Bed material was characterized before the bed load samples were taken. Riverbed sampling was conduced at low-flow stages to assure access to active bed material exposed in bars. Surface and subsurface materials

were sampled at the two exposed bars closest to MEMS. Móra d'Ebre A bar is located about 1 km upstream, while Móra d'Ebre B is just 100 m downstream. Surface and subsurface size distributions show only small differences between the bars (less than 5%); therefore the closest bar (Móra d'Ebre B) has been chosen to characterize the river bed material at MEMS. The median surface material size ($D_{50\text{-}s}$) is 39 mm (Figure 1) and maximum surface particle ($D_{95\text{-}s}$) 86 mm. However, subsurface bed material median size ($D_{50\text{-}ss}$) is 21 mm while $D_{95\text{-}ss}$ is 62 mm (Figure 1). The armor ratio (A_r), measured as the ratio of median surface to median subsurface bed material size, is 1.9.

2.2. Sampling Program

[7] Bed load transport was sampled from a bridge at a single vertical (see *Vericat and Batalla* [2006] for details) during 2003–2004 using a 29-kg cable suspended HS sampler with 76-mm intake (HS76), and a 76-kg cable suspended HS sampler with 152-mm intake (HS152). Both samplers were operated using an automatic crane with a constant velocity engine. Fifty-four bed load samples were obtained with the HS76, while 47 were taken with the HS152. Twenty-three of these samples were paired; that is, they were obtained with only a few minutes difference in time (the recovery and deployment time for the samplers). The sampling time for both devices was 5 minutes. Water depth at the place where bed load was sampled ranged from 3 to 5 meters, while mean velocity varied from 1.5 to 2 m s^{-1}. The samples were taken to the laboratory where they were dried, sieved and weighed. The samples were truncated at 1 mm (excluding in any case no more than 5% of the total sample weight) before obtaining the total mass and grain size distribution in order to avoid including particles that could be transported in suspension. Samples ranged from a few grams to around 10 kg. Discharge during sampling ranged from 500 to 1,350 m^3 s^{-1}, that is, specific discharges at the vertical ranged from 4.5 to 10.6 m^2 s^{-1}.

2.3. General Comparison Between the HS Samplers

[8] Power law load-rating relations [*Barry et al.*, 2004] between specific discharge at the sampling vertical (q in m^2 s^{-1}) and bed load transport rates (i_b in g $m^{-1}s^{-1}$) differentiated by sampler have been constructed for the samples collected. Figure 2a shows that the upper envelope (defined by highest rates) for each device is practically the same. The particular trend line shown in Figure 2a for the upper envelope is discussed later in the paper (see section 4.1). However, for a given specific discharge the bed load rate collected by each device can differ by more than an order of magnitude (in some cases, 2 orders). This difference could be attributed to bias between samplers or to different conditions when the samples were taken (i.e., samples were not, in general, obtained at the same time, so that river bed features and transport could be different at each sampling). Furthermore, it is evident that each sampler can return an equally wide range of catches at essentially the same flow.

[9] Temporal variations in bed load transport under near-steady conditions have been reported by various observers [e.g., *Hamamori*, 1962; *Reid and Frostick*, 1986; *Gomez et al.*, 1989; *Kuhnle*, 1992] and also could influence the comparison of samples. Figure 3 shows that in different rivers, bed load transport presents high temporal variability which has been attributed to the stochastic behavior of the sediment transport. Nevertheless, the lowest bed load transport rates for the range in specific stream power (ω) are those collected with an HS76, and are probably influenced by a not strictly appropriate selection of the sampler according to riverbed material. The data from Goodwin Creek [*Kuhnle*, 1992] were obtained with a modified HS76 deployed on an artificial surface for which, due the sampling procedure, sampler efficiency was 100%. Under such conditions, the high variability of bed load rates under similar specific power would be attributed to the natural behavior of the bed load transport rates rather than to bias during the sampling. Various laboratory experiments corroborate the high bed load variability [e.g., *Kuhnle and Southard*, 1988]. The balance of the data in Figure 3 show that the MEMS data are typical of bed load transport observation in gravel bed channels and exhibit similar variability. There is no immediately obvious reason to conclude that MEMS data are biased.

[10] A mean load-rating curve for the data of each sampler was defined by averaging the samples in 1 m^2 s^{-1} wide bins from 4 to 11 m^2 s^{-1} (Figure 2b) in order to reduce the temporal variability of the bed load transport cited above, hence to define the mean apparent bed load transport rate ($i_{b\text{-}m}$ in g $m^{-1}s^{-1}$) given specific flow (i.e., q) for each device [e.g., *Kuhnle*, 1992]. Figure 2b reveals an apparent bias between the two samplers. The scatter of the mean rates is also higher for the HS76 than for the HS152 and, as a consequence, the correlation of the averaged data with specific discharge is greater for the HS152 (r^2 = 0.95) than for the HS76 (r^2 = 0.85).

3. Sources of Bias

3.1. Sampler Efficiency

[11] The relation between bed material size and the sampler intake width (Figure 4a) must be an important determinant of sampler efficiency which may not be constant for all sediment sizes (Figure 4a). According to *Emmett* [1980], the efficiency of the HS76 is close to unity for particle sizes between 0.5 and 16 mm, but decreases when the particles transported are larger than 16 mm. The intake width of his sampler (W_{HS76}) was 76 mm. The ratio between the b axis of the largest clast size for which the efficiency was considered by *Emmett* [1980] to be close to 100% and the sampler's intake width is 0.21. Emmett also reported that the efficiency decreased to 70% for particles between 16 and 32 mm (D_i/W_{HS76} = 0.42 when D_i = 32 mm). Trap efficiency obviously goes to zero when the particle size is the same as the sampler's intake. According to the movement of particles during their transport, the a axis of the particles may actually be the critical axis to be compared with the sampler's width, especially in rivers with highly nonequant particles (which is not the case in the Ebro: see Figure 4). Nevertheless, a axis values are not often available. This first observation from *Emmett*'s [1980] calibration gives some indication, then, of the propensity of the moving grain D_i to fit into the sampler opening, which will become a more severely limiting factor as $D_i \rightarrow W$.

[12] *Sterling and Church* [2002], by comparing magnitude and grain size distributions of sediment samples collected by a pit trap and a standard HS sampler (76-mm intake), reported efficiencies higher than 1 for particles

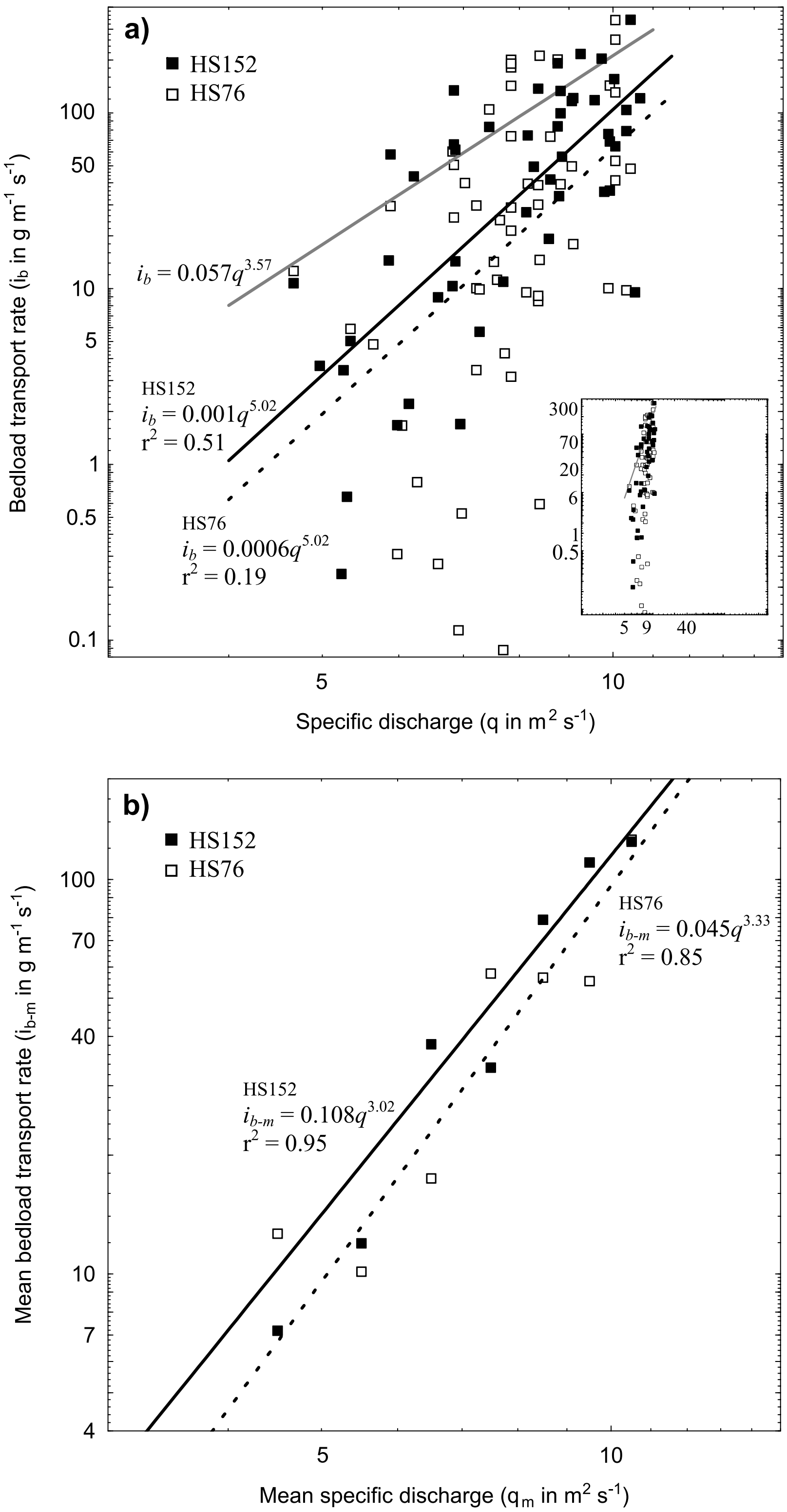
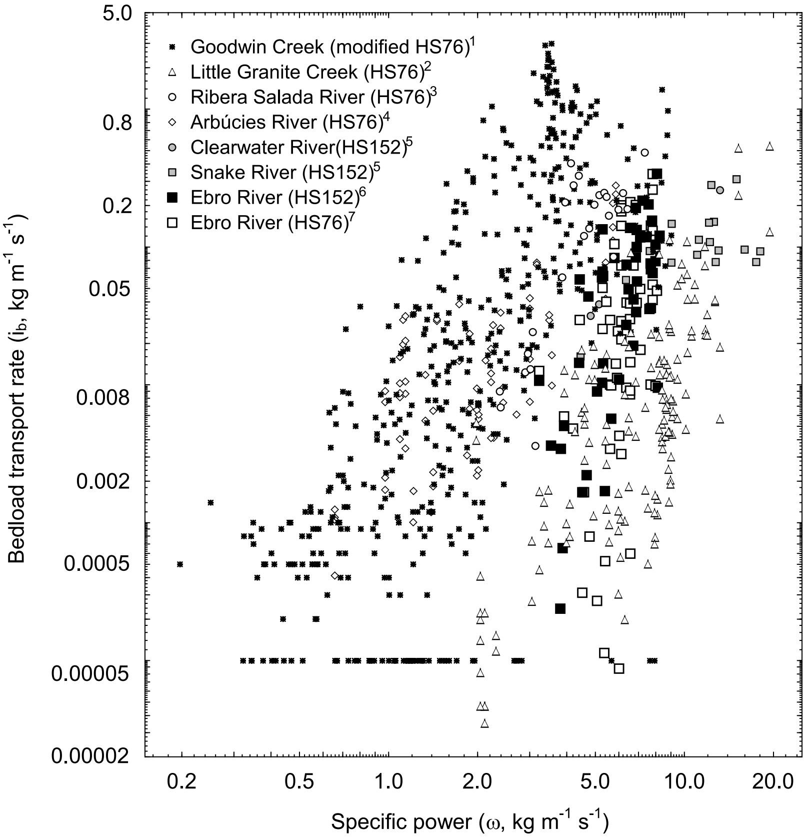


Figure 2. (a) Data for all bed load samples obtained during the hydrological year 2003–2004 with power law relation for each sampler based on all the observations. Note that the shaded relation defines the underlying bed load transport relation according to equation (2). (b) Mean load-rating curve corresponding to each Helley-Smith sampler bed load database, obtained by averaging all samples in 1 m^2 s^{-1} bins from 4 to 11 m^2 s^{-1}. The relation for each device is statistically significant ($p < 0.01$). Note the stretched x axes in these plots. Inset shows data plotted on commensurably scaled axes: The displayed relation defines the underlying bed load transport relation according to equation (2). See section 4.1 for details.



[1]data from *Kuhnle* [1992]
[2]data from *Ryan and Emmett* [2002]
[3]data from *Batalla et al.* [2005]
[4]data from *Batalla* [1997]
[5]data from *Jones and Seitz* [1980]
[6]data from this study (HS152)
[7]data from this study (HS76)

Figure 3. Relation between specific stream power (ω) and bed load transport rate (i_b) for different fluvial environments; Ebro River data emphasized. The data are not normalized.

smaller than 0.5 mm, presumably because the sampler was catching suspended sand, while efficiencies declined for particles between 0.5 and 16 mm. They estimated a median efficiency of 0 for particles larger than 8 mm, while the pit trap collected particles up to 45.3 mm. Compared with *Emmett*'s [1980] calibration, in spite of using the same HS sampler, there is a large difference in the sampler's apparent grain size-dependent efficiency. In the study by Sterling and Church the trapping efficiency declined for all sizes larger than coarse sand and approached zero when the *b* axis exceeded 10% of the sampler's width, while in *Emmett*'s [1980] study the efficiency decreased when the particle size exceeded 20% of the sampler's width, or some modestly larger proportion.

[13] Comparing bed material grain size distributions from each study section (Figure 1) we can see that the relation between the characteristic bed material size and the sampler intake is greatly different. The largest particles in East Fork River [*Emmett*, 1980] attain 64 mm, while the median surface material in Harris Creek [*Sterling and Church*, 2002] is 75 mm. Thus, in Harris Creek half of the surface material exceeds in size the sampler's width while, in East Fork River, bed particles do not attain a size equivalent to the sampler's width. Two principal sources of interference with the collection of bed load using the HS sampler can be invoked to explain the differences between the outcomes: "blockage" of the sampler's intake (Figure 4b), and "perching" of the sampler's intake (Figure 4c). In addition, *Gaudet et al.* [1994] showed that off-line sampler alignment relative to the flow substantially reduced sampler catch.

3.2. Sources of Interference

[14] When the sampler is positioned immediately downstream from a coarse clast (Figure 4b), the flow may be competent to move the clast, or it may not be competent so that the clast remains to block the entrance of the sampler. In the first case, as we have explained above, the propensity for that clast to pass through the intake will be related to the ratio D_i/W_s. As shear stress increases larger clasts may be mobilized and, consequently, the bias should increase because of the increasing ratio D_i/W_s. However, when the flow strength is not high enough to move the clast, it will block the entrance of the sampler, reducing the sampler's operative width and decreasing the probability to catch the moving sizes. The minimum distance between the sampler and an immobile D_i for interference by blocking will be

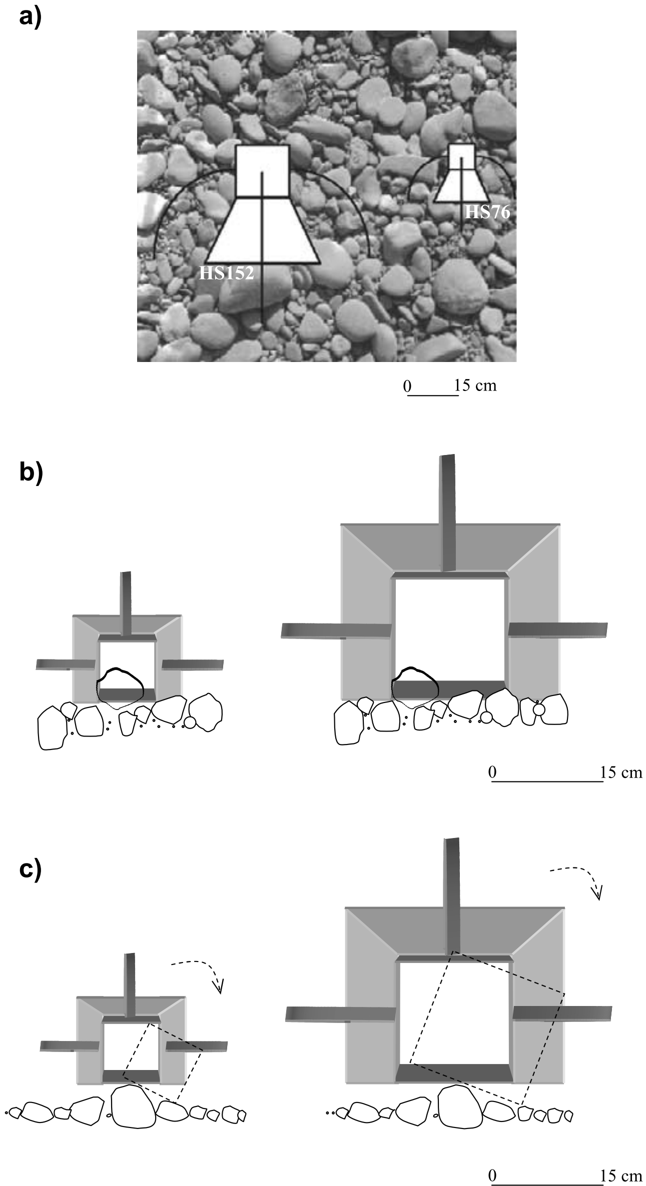


Figure 4. (a) River bed surface material at MEMS (Móra d'Ebre B) bar and scaled plan of the two Helley-Smith samplers (76- and 152-mm intakes). Note the difference between the sampler nozzles (W_s) in relation to the bed material. Possible sources of errors related to the bed material size and the Helley-Smith samplers' nozzle size are (b) blockage of the HS nozzle when the sampler is located behind a coarse particle (front view) and (c) sampler perched, i.e., not resting flush with the bed surface, due to the bed roughness (front view). Note that the samplers can be tilted by excentric support.

related to the eddy structure of the flow around the blocking clast, hence the trajectory of the moving grains, their mechanism of transport, and the riverbed configuration and evolution during sampling. For any grain size D_i, the ratio D_i/W_s indicates the capacity of the grain to interfere with bed load sampling by decreasing the sampler's effective intake width and by diverting oncoming grains. Blockage of the Helley-Smith sampler has been demonstrated (but not quantified) as a source of interference with bed load sampling by *Duizendstra* [2001a, 2001b], citing evidence from underwater video recordings.

[15] Bed load size distributions obtained during the field calibration in East Fork River [*Emmett*, 1980] show that the maximum sizes transported were between 32 and 45.3 mm. Consequently, only a small proportion of the bed material remained immobile during Emmett's calibration. An immobile clast of 45.3 mm could decrease the sampler's effective opening width by about 60%, decreasing the propensity of the moving particles to pass through the sampler opening. However, the small proportion of these sizes in the river bed material yields only a small probability that the sampler might be positioned immediately downstream from a coarse immobile clast. On the other hand, in Harris Creek [*Sterling and Church*, 2002] all the material apparently transported was much smaller than the median size of the bed surface material. Maximum sizes in the bed load samples collected by the pit trap attained 45.3 mm, while the HS sampler collected maximum sizes of 16 mm. Large, immobile particles might decrease the sampler's effective opening width. Indeed, the bed surface grain size distribution (Figure 1) shows that the entire sampler opening might be blocked. The sampler's efficiency by grain size will be decreased as the effective opening decreases, so that fine particles traveling in saltation or suspension can still pass through the remaining nozzle opening, while many or all rolling clasts may be excluded.

[16] The sampler also may not repose squarely on the bed, it may perch on a large clast (Figure 4c), in which case moving sediment may pass beneath the sampler's mouth. *Duizendstra* [2001a, 2001b] observed that sampler tilting interfered with bed load sampling. If the sampler settles onto a clast of diameter D_i, smaller material is almost certain not to be sampled if it moves by rolling, although saltating grains may still be trapped. Indeed, one might easily assume that it will require a clast with $D > 2D_i$ to achieve the necessary elevation to surmount the step. This assumption may not be strictly true because the sampler may be tilted (dashed configuration in Figure 4c) so that part of the smaller material can be trapped while, on the other hand, clasts larger than $2D_i$ may not be able to surmount the step that is encountered. The particle *c* axis or some fraction of it, according to clast exposure, may be the critical measure in this instance. Our overall knowledge of the situation remains rudimentary at best.

3.3. Probability of Interference

[17] The bulk grain size distribution in East Fork River (no separate surface size distribution was given) and the surface distribution in Harris Creek (Figure 1) were converted to line-by-number distributions following a conversion factor of $1/D$ [after *Kellerhals and Bray*, 1971]. The line-by-number distribution represents the collection of all clasts falling under a straight line across a sampling plane [*Muir*, 1969; *Kellerhals and Bray*, 1971]. Thus the distribution can be interpreted as the probability for the sampler to encounter a clast of given size D_i. The probability is the same for the sampler to be positioned immediately downstream from such a clast (source of blockage, Figure 4b), or for the sampler to settle onto it (source of perching, Figure 4c). Therefore the integral of the probability density function (i.e., the cumulative density function) quantifies the probability for the sampler to be blocked by a clast

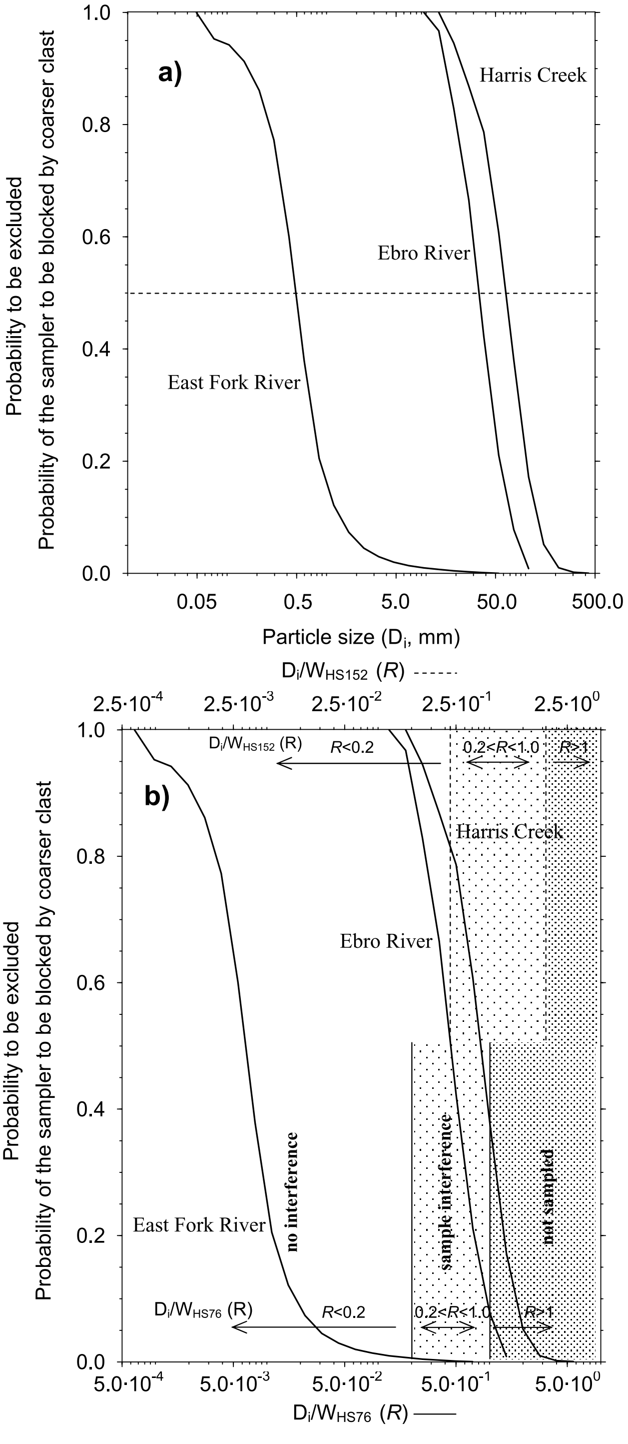


Figure 5. (a) Frequency-by-number clast size cumulative distribution functions at East Fork River, Harris Creek, and Ebro River; also, theoretical probabilities of interference with the sampler by blockage or by perching. The dashed line represents a probability of 0.5. (b) As Figure 5a but scaled for sampler intake width 76 mm on the lower abscissa, 152 mm on the upper abscissa.

coarser than D_i and the probability for a moving stone, D_i, not to be sampled because the sampler's nozzle is perched.

[18] Figure 5a shows the cumulative density function at East Fork River and at Harris Creek. In East Fork River the sampler intake has probability 0.5 (50%) to be blocked by clasts coarser than 0.5 mm, while sizes larger than 60 mm have probability 0.5 to block the entrance of the sampler in Harris Creek, reducing the sampler's effective exposure in much greater degree than in East Fork River. Again, as we have explained above, when the sampler is positioned immediately downstream from a particular clast the flow may or may not be competent to move it, so that the interference with the bed load sample by blockage of the sampler will actually be determined jointly by the flow competence and the size of the particle that is positioned in front of the sampler. The probability for the sampler to be blocked by a size coarser than the largest size trapped during the field calibrations is around 0.1% in East Fork (D_i = 45.3 mm) and 73% in Harris Creek (D_i = 45.3 mm), a difference that clearly helps to explain the variation in sampler performances between the two streams.

[19] Figure 5a also quantifies the probability for a moving stone, D_i, not to be sampled because of perching of the sampler's nozzle, tilt not being considered. The probability to be excluded should be higher for the small particles and should decrease as their sizes increase. A moving size of 1.0 mm has a probability to be excluded at East Fork River of 0.5 (considering a doubling of sizes to overcome the perching elevation), while the efficiency of the HS sampler for this size reported by *Emmett*'s [1980] calibration was 1.0. This suggests that the relative weight of the HS76 compared with the compactability of the relatively fine river bed might allow a readjustment of the sampler attitude so that the probability will be less than that assessed in Figure 5a; indeed, perching must become a negligible problem in sufficiently fine gravel (for which the sampler was originally designed). The much coarser bed surface size distribution at Harris Creek is apt to be much more refractory. A moving D_i of 6.5 mm (again, doubling D_i to overcome the step) has a probability to be excluded of 1. However, *Sterling and Church* [2002] reported efficiencies close to 100% for particles as fine as 0.5 mm. This discrepancy may be related to the configuration of the upstream approach that may steer the fine material into the sampler, and to fine particles traveling in saltation or suspension, or may merely reflect the circumstance that the sampler (visually placed) was not normally perched.

[20] These assessments show that coarse bedded rivers potentially more strongly interfere with sampler performance, and this can explain part of the difference between sampler efficiency calculated for the Harris Creek observations [*Sterling and Church*, 2002] and for East Fork River [*Emmett*, 1980]. Figure 5b shows rescalings of Figure 5a for the two sampler sizes discussed in this paper, and defines regions of limited efficiency [*Emmett*, 1980] (section 3.1) for each sampler. However, the examples we have discussed also reveal significant further complications in sampler performance so that, in practice, it is not possible to partition the sources of impaired sampler efficiency discussed above, nor to assign simple probabilities. Therefore we turn to empirical results.

4. Analysis of the Ebro Paired Samples

4.1. Sampler Efficiency

[21] Twenty-three pairs of bed load samples were obtained, each in immediate succession, on the same

Table 1. Paired Samples Collected Successively With Both HS76 and HS152 Devices[a]

Sample	Specific Discharge, $m^2\ s^{-1}$	Standardized Collection Rate, $g\ m^{-1}\ s^{-1}$		Maximum Particle Size, mm		Classification Group
		HS76	HS152	HS76	HS152	
1	5.35	5.8	4.5	22	29	A
2	6.08	*29.5*	*58.2*	46	47	A
3	7.99	37.6	*73.7*	52	58	A
4	9.85	50.4	64.4	47	58	A
5	9.97	9.8	75.9	38	45	B
6	9.74	*143.2*	68.7	44	49	B
7	9.07	17.9	*121.6*	31	49	B
8	8.13	9.6	27.3	33	41	B
9	7.69	0.1	10.9	11	35	B
10	5.98	0.3	1.7	9	24	B
11	4.67	*12.6*	*10.7*	34	36	A
12	7.44	*104.4*	*83.1*	48	53	A
13	9.07	43.7	*116.6*	53	54	B
14	10.42	46.5	*338.8*	36	55	B
15	10.32	9.3	103.7	23	54	B
16	8.76	*201.7*	*191.9*	51	75	A
17	8.82	39.4	*99.9*	43	55	B
18	8.61	*73.5*	41.8	52	46	A
19	7.27	9.9	5.7	36	32	A
20	6.59	0.3	9.0	13	43	B
21	6.84	*50.3*	*65.9*	67	40	A
22	6.84	25.4	*134.2*	32	45	B
23	6.82	17.6	*30.0*	45	51	A

[a]The paired samples were identified for which the fluxes fall within and without (i.e., groups A and B, respectively) the range 0.5–2 times each other. The italicized collection rates represent the 19 samples used to construct equation (2).

vertical at the MEMS station (Table 1). The samples plotted against the discharge show, again, that the upper envelopes for each device are similar (Figure 6a). However, clear differences can be observed for samples collected at the same time. We sometimes obtained similar bed load rates using both devices, but large differences also occurred. For instance, at 8.8 $m^2\ s^{-1}$ the bed load rate sampled by the HS152 was 192 $g\ m^{-1}\ s^{-1}$, while by the HS76 it was 202 $g\ m^{-1}\ s^{-1}$ Yet with a specific discharge of 10.4 $m^2\ s^{-1}$, the bed load rate for the HS152 was 339 $g\ m^{-1}\ s^{-1}$ and 47 $g\ m^{-1}\ s^{-1}$ for the HS76 (Table 1). In general, the HS152 collected the larger samples (Figure 6b). A paired-sample, one-tailed *t* test was applied to the $\log_{10}$-transformed data to determine whether the mean sample size differs significantly between samplers (in effect, whether the mean percentage difference is other than zero). The difference between the bed load rates sampled by the HS152 and by the HS76 is statistically significant (p = 0.0011).

[22] Comparing bed load grain size distributions and bed surface grain size distribution, it appears that river bed material was only partially mobilized during the sampling. The coarsest sample collected with either HS sampler falls at about the 90th percentile of the river bed surface size distribution. Further insight into sampler performance may be gained by examining the largest material retained in each sample (Table 1). Maximum grain size increases with specific discharge (Figure 7a). However, a more definitive relation is observed between maximum grain size and sample mass (Figure 7b), suggesting that maximum observed grain size may be an artifact of sample adequacy (the relatively rare large stones being least apt to be caught in a representative fashion in a small sample). The presence of a large stone may in some cases be the reason for a high observed transport rate. The HS152 sampler nearly always catches larger stones than the HS76 device (Figure 7c). A paired-sample, one-tailed *t* test on $\log_{10}$-transformed data ($D_{\max\text{-}bl}$) reveals a statistically significantly difference (p =

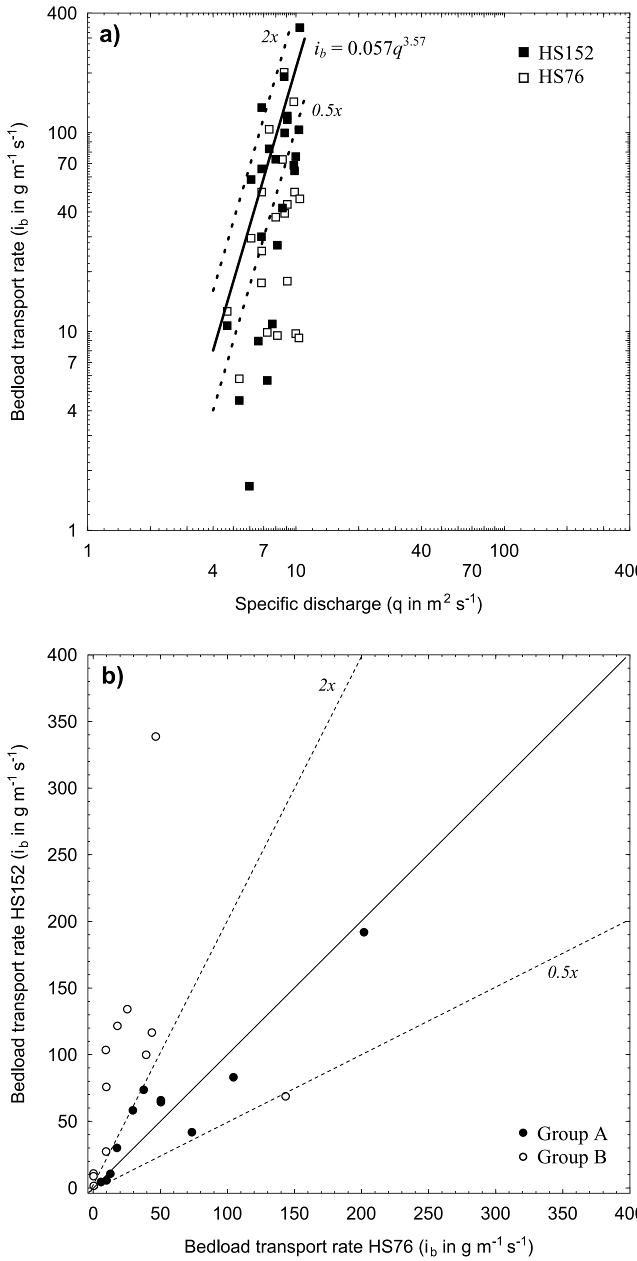


Figure 6. (a) Load-rating relations for all paired bed load samples obtained with HS152 and HS76 samplers (Table 1). Solid line defines the underlying bed load transport relation according to equation (2), while dashed lines show 0.5 and 2 times lines about the regression. All data within this range were used to construct equation (2) and are identified in Table 1. (b) Correlation of paired bed load sample flux estimates. In this plot, sample pairs for which the fluxes fall within (group A) and without (group B) the range 0.5–2 times are identified (see section 4.2).

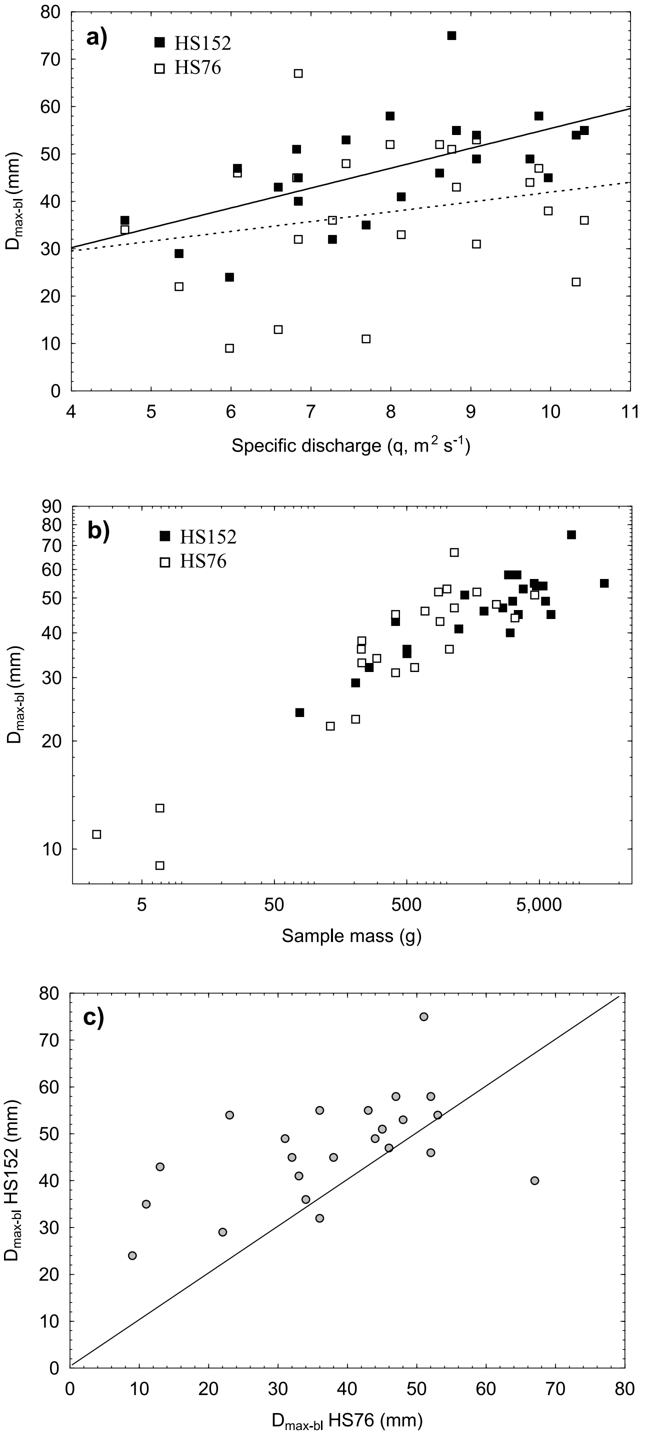


Figure 7. (a) Relation between $D_{\max-bl}$ and specific discharge for each sampler. Note that solid and dashed lines define linear statistical relations ($p < 0.01$) for the HS152 and HS76, respectively. (b) Relation between $D_{\text{max-}bl}$ by sampler and sample mass; (c) correlation of $D_{\text{max-}bl}$ obtained by each device.

0.0013) directly confirming the different performance of the two samplers.

[23] Using the ratio $D_{\text{max-}bl}/W_s$, calculated as the quotient between the size of the b axis of the maximum particle caught and the sampler's intake, we compare the relative size of the largest particles collected by each device. For samples collected with the HS152 $D_{\text{max-}bl}/W_s$ ranged from 0.2 to 0.5, and the maximum particle sampled never exceeded half of the sampler's intake width, possibly because such material was not moving. However, for the samples obtained with the HS76 $D_{\text{max-}bl}/W_s$ varied from 0.1 to 0.9 and the largest sizes trapped by the HS152 might, in many of the cases, have been excluded from the HS76 intake. In contrast, the maximum size collected with the HS152 has probability about 0.4 to be excluded from the sampler in a simple situation (Figure 5). Consequently, it appears that samples collected with the HS76 are subject to greater bias against large grain sizes than those obtained with the HS152.

[24] The observed differences between the paired samples may in fact be related either to sampler bias or to temporal bed load variability. We did not replicate measurements in quick succession with the same sampler, so we cannot assess temporal variability directly. Let us suppose that the underlying bed load transport relation is $i_b = aq^c$, which is the most frequently applied empirical model for the process [e.g., *Whiting et al.*, 1999; *Emmett and Wolman*, 2001; *Barry et al.*, 2004], and that for an individual sampler, the observed relation is $i_{bW} = aq^c \cdot b_W$, where b_W indicates a fractional efficiency or bias factor for a sampler with intake width W. Then an individual observation is represented, under logarithmic transformation, by

$$\log i_{bW} = \log a + c \log q + \log b_{iW} + \log e \qquad (1)$$

in which e indicates a random temporal fluctuation in transport, distributed as $N(0, \sigma_e^2)$. Since b_W takes on a particular value for each observation, $\log b_{iW}$ is also a random variable with distribution $N(\overline{\log b_W}, \sigma_b)$. The linearized model is convenient because the log-transformed variates are more nearly normally distributed than the raw data.

[25] We can study the relative bias of the two samplers by defining $R_{HS} = i_{b76}/i_{b152}$. $\text{Log}R_{HS} = \log b_{i76} - \log b_{i152} + \log e_{i76} - \log e_{i152}$ and, on the assumption that the bias of the observation is uncorrelated with the temporal fluctuations in transport, the distribution of $\log R_{HS}$ is $N(\overline{\log b_{76} - \log b_{152}}, 2\sigma_b^2 + 2\sigma_e^2)$. The distribution of $\log R_{HS}$ can be assessed directly from the data (Table 1), and it is found that $\overline{\log R_{HS}} = -0.43$ (implying that the transport observed with the 76 mm sampler is, on average, only 40% of that observed in the same flow with the 152 mm sampler). However, $\sigma = \pm 0.42$, with contributions from both the bias factor and from transport fluctuations, implying a substantial range in the relative performance of the two samplers.

[26] We can examine the absolute bias of the samplers only if we know the underlying transport relation, that is, only if we know the true amount of material moving. We do not know that. However, inspection reveals a relatively homogeneous group of data near the upper envelope of the scatter (Figure 6a). The measurements identified in Figure 6a and in Table 1 were selected to essay an approximation of the underlying transport relation. They yield the result

$$logi_{bW} = -1.24 + 3.57 \log q \qquad (2)$$

with $r^2 = 0.81$ and standard error of estimate 0.17 log units. The back-transformed result is $i_b = 0.057q^{3.57}$, with standard error of estimate +48% or −32%. The selected data in fact scatter within a range between 0.5 and 2 times about the relation, which is usual for sediment transport observations. The exponent is reasonable for a gravel bed river with partial transport [*Whiting et al.*, 1999; *Emmett and Wolman*, 2001]. By comparing the transport samples with transport predicted from this equation we find the mean efficiency for the HS152 to be 0.514 and, for the HS76, 0.192. The ratio of these two values is 0.37, which is not dissimilar to the relative efficiency calculated directly from the measurements. Similar results on the relative efficiency of the samplers are arrived at by regression on all of the data, using a dummy variable to discriminate the two samplers (R.I. Ferguson, personal communication, 2005). Hence the analysis appears to be relatively robust.

4.2. Comparison of Grain Size Distributions

[27] Figure 6b identifies the paired samples for which the fluxes fall within (group A) and without (group B) a factor 2 of each other (group A is not the same as the data selected to estimate equation (2), since pairs of samples that both appear to be biased may have similar sample size, hence fall within the group A defined here). Sample groups are identified in Table 1. We compare the grain size distributions of these samples, and of the balance of the samples, to see if further light can be thrown on sampler performance.

[28] Considering that the HS152 has a higher probability to collect unbiased bed load samples or, at least, to collect a wider range of sizes without bias, R_{HS} can be interpreted as a relative efficiency for the HS76. Here median relative efficiency has been calculated by one phi grain size classes over all samples and is found not to diverge dramatically from 100% among group A samples (11 samples; Figure 8). In fact, the relative efficiency of the HS76 appears to increase at the coarser extreme of the size range, perhaps indicating the large weight proportion of the $D_{\max\text{-}bl}$ in the total mass. Median efficiency by grain size for the samples in group B (12 samples) shows that the HS76 comparatively undercatches material in all the fractions (Figure 8). The maximum efficiency is 0.24 for particles between 1 mm and 2 mm, while the minimum efficiency is 0.10 for particles between 2 and 4 mm. In only three of the HS76 samples in this group were there particles between 16 and 32 mm.

[29] We have also compared characteristic percentiles (i.e., D_5, D_{50} and D_{95}) of the bed load grain size distributions for each device. For this purpose we have divided the samples of group A in two subgroups: (1) the five pairs of data that went into computing equation (2) and (2) the remaining 6 samples whose relative size does not vary by more than 2 times (Table 1). Samples in both subgroups have practically equivalent grain size distributions. On this evidence, these samples may be characterized as genuinely unbiased. Of the samples in subgroup 2, 3 contributed the larger observation to the computation of equation (2), but the remaining 3 appear to have low catches. This may, however, simply represent transport variation. Bed load grain size distributions for the samples in group B were also compared. The characteristic percentiles differ between samples. Differences range between 10% and 290%, the largest differences being associated with the largest sizes (e.g., D_{95}). The HS152 generally caught coarser sizes, thus it appears that catch discrepancies can be assigned largely to the more severe limitation of the smaller sampler to catch the largest material.

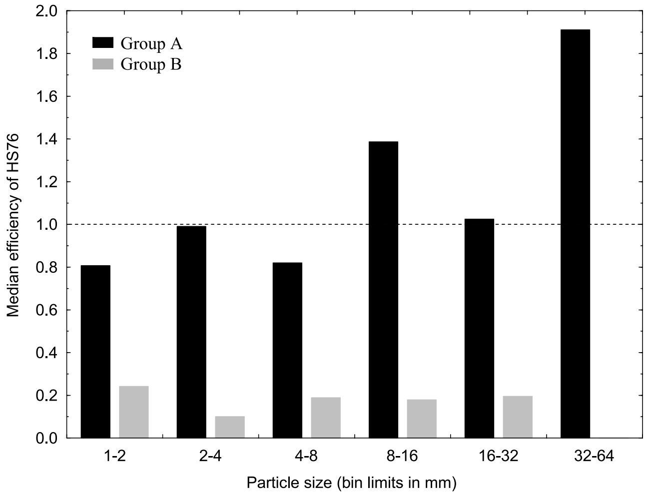


Figure 8. Estimated relative efficiency by grain size for the HS76 bed load samples calculated by dividing each collection rate by size obtained with the HS76 by the rate by size collected with the HS152.

4.3. Sources and Probability of Bias in the Ebro Paired Samples

[30] According to Figure 5, the samplers at MEMS have probability 0.5 to be blocked by a particle larger than 32 mm, some of which were moving when the samplers were operated. However, the coarsest 20% of the bed surface material at MEMS, that is, sizes larger than 64 mm, were not generally sampled and probably mostly not entrained. Considering an immobile size D_i = 64 mm, the probability that the HS samplers may be placed just below a clast coarser than 64 mm is 0.2, a probability much higher than that estimated for immobile particles in East Fork River and lower than that in Harris Creek (Figure 5). On the other hand, while the probability for each sampler to be perched is the same, the greater width of the HS152 may increase its propensity to be tilted so that it may catch more material and yield less biased samples.

[31] Change of the sampler's effective intake width influences the probability of a moving grain D_i to fit into the effective nozzle opening. Normally entrained sizes could cover up to 40% of the HS152 opening width and 80% of HS76 width. Assuming that the samplers were blocked by an immobile clast of D_i = 64 mm, the opening width would remain sufficient to catch particles up to 88 mm (*b* axis) in the case of the HS152, but only sizes around 12 mm with the HS76. Three HS76 samples in group B indeed have $D_{\max\text{-}bl}$ close to 12 mm (Table 1) while, at the same time, the HS152 collected sizes almost three times larger, reflecting the possibility that the HS76 was highly blocked during sampling. The other samples in group B show that $D_{\max\text{-}bl}$ obtained with the HS76 is generally finer (in varying degree) than that for the HS152 (Table 1).

[32] We may examine the empirical probability for bias in individual samples by considering the frequency distribution of departures from the estimated transport relation of equation (2), that is, the values $\log i_{b\text{-}obs} - \log i_{b\text{-}pred}$, which transform from $i_{b\text{-}obs}/i_{b\text{-}pred}$. Figure 9a shows the distribution

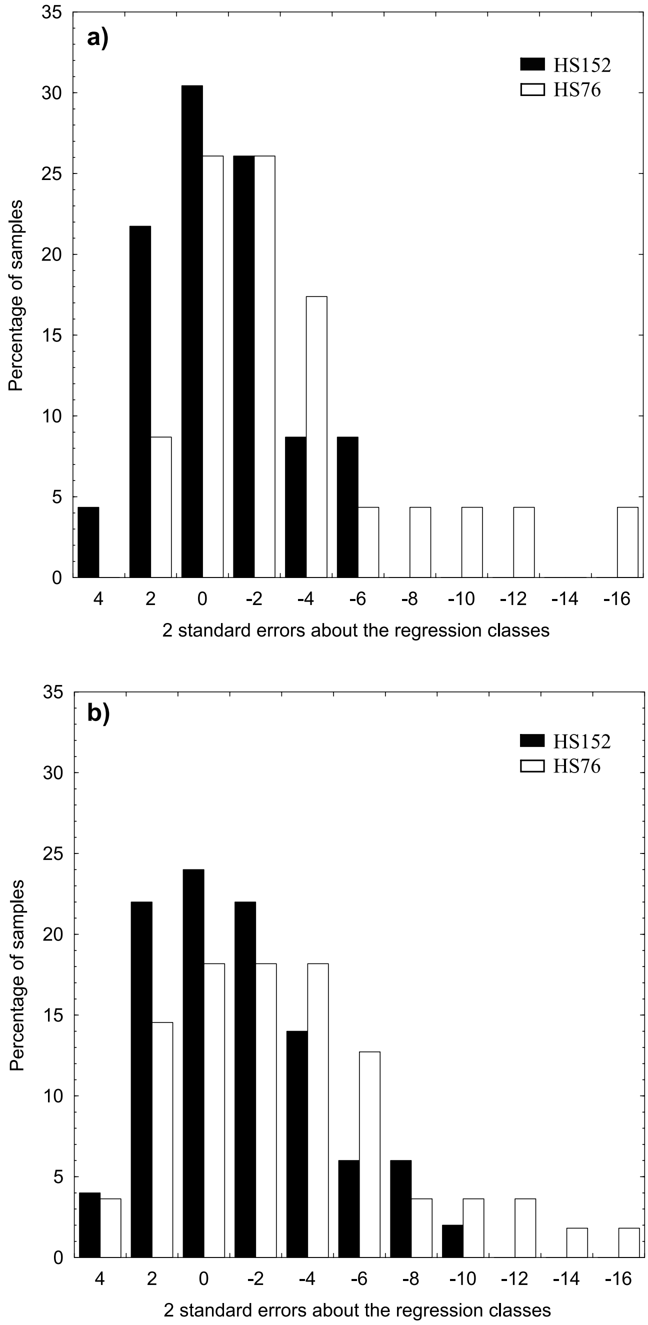


Figure 9. Sampler bias estimated by comparing the departure of (a) paired and (b) unpaired sample catches from the result predicted by equation (2). Bins are scaled by 2 standard errors of estimate of equation (2). See text for details on the construction of the equation. Note that the class designator represents the upper bound of the class.

of the departures, binned in units of 2 standard errors about the regression. It is apparent that, on this criterion, a large proportion of the samples from both samplers is negatively biased. Furthermore, the distributions are relatively smooth, indicating that bias is indeed a random factor, as assumed above. Altogether, 65% of the HS76 samples fall outside the expected range of fluctuations (2 standard errors about the regression), while 43% of the HS152 observations are apparently biased. The distribution of values for the HS152 is, however, tighter, with no value exceeding −10 standard error of estimate units whereas the largest negative departures for the HS76 are >16 and >12 units below the expected values. In these cases, the estimated fluxes were 0.1 and 0.3 g m^{-1} s^{-1}, whereas the paired catch with the HS152 was about 10 g m^{-1} s^{-1} in each case (and classified as biased). These must surely represent cases of complete blockage of the HS76 sampler. One HS152 sample indicates positive bias. The value falls 2.44 standard error of estimate units above the expected value and might be either a real positive excursion or the consequence of scooping bed material. Similar behavior was found analyzing the distribution of the departures for the unpaired samples (Figure 9b), except that somewhat larger negative departures were also observed for the HS152 sampler. Altogether, 50% of the HS152 samples in this group are negatively biased, while 61% of the HS76 samples are biased.

5. Bias in Annual Bed Load Yield for the Ebro Samples

[33] The samples collected with each HS sampler were used to make various sediment load computations. For that purpose the relations in Figure 2b and the underlying transport relation in equation (2) have been used. In Figure 2b the data for each device were group averaged to define a mean transport rate for each Helley-Smith device, all samples considered, while the relation in equation (2) is an attempt (not necessary successful) to arrive at the unbiased underlying relation by data selection. Annual loads were estimated according to the flow duration curve method [*Walling*, 1984].

[34] The sediment load estimated for the 2003–2004 hydrological year changes by about 24% between the two mean load-rating curves, the load estimated from HS76 measurements (61×10^3 t) being lower than that for the HS152 (i.e., 81×10^3 t). The annual load computed with equation (2) (i.e., 124×10^3 t) is higher than the above reported loads, being 2 and 1.5 times higher than those for the HS76 and HS152, respectively.

[35] It is clear, as shown in Figure 3 and in flume experiments [e.g., *Kuhnle and Southard*, 1988], that high variability in bed load rates under a similar threshold would be more likely attributed to the natural behavior of the bed load transport than to bias during the sampling; consequently, assessing the efficiency of samplers remains a difficult exercise. Selecting for use samplers with geometries that interfere less with sampling, will reduce the problem of bias and increase the precision of annual loads estimated in gravel bed rivers. Moreover, an adequate sampler opening is strictly necessary, as shown by the results of the paired sampling, in order to assess accurately the grain size distributions of bed load samples.

6. Summary and Conclusions

[36] Field calibrations of the standard HS sampler (76-mm) by *Emmett* [1980] and by *Sterling and Church* [2002] were compared. Two sources of interference with the collection of bed load using the HS sampler, both related to the relation between sampler intake dimension and river bed material size, are invoked to explain the differences between the calibrations. These are (1) blockage of the sampler's

nozzle, related to the proportion of coarser immobile clasts in the bed, and (2) perching of the sampler's intake. The relative weight of the HS compared with the river bed material might influence the degree of interference posed by the second effect.

[37] Because of complexities in the possible juxtaposition of the samplers and clasts resident on the streambed, a quantitative model of probabilities for these biases remains elusive but these factors must be recognized as important when selecting methods to make measurements of bed load transport in a particular stream.

[38] The bed load samples obtained in the gravel bedded Ebro River using two HS samplers of different size show clear bias of the smaller with respect to the larger. Twenty-three of the bed load samples were paired, and their analysis leads to the following conclusions.

[39] 1. The bed load rates of the paired samples and the largest particles captured in these samples are statistically significantly different. The HS76 tends to catch less material and the largest sizes are smaller than those obtained with the HS152.

[40] 2. Comparing samples and samplers' intakes we assessed the probability of interference with each sampler. The probability for a bed load sample collected at MEMS with the HS152 to be biased was 43%, whereas 65% of the HS76 samples were biased. However, these figures probably depend on the flows that were sampled and certainly depend upon the state of the bed.

[41] 3. The results obtained with the larger sampler were less severely biased: on average, a sample caught with the HS76 was only 40% of the HS152 catch. Exclusion of the largest mobile clasts may play an important part in this difference.

[42] 4. Samples taken with each sampler exhibited a continuous range of bias, confirming that the actual conditions encountered at the bed are variable and making the actual bias a random effect.

[43] Annual loads assessed with each sampler differ by around 25% using the mean load-rating curves for each device. Comparing these loads with the annual load computing by the estimated underlying load-rating curve the difference is much larger, being twice that calculated using the mean load-rating curve for the HS76.

[44] Our results show that two contextual issues are necessary to take in to account when a sampling program is defined. It is necessary to collect a significant number of samples under steady conditions in order to define accurate mean bed load rates for different flow strengths, and to asses the error around the load estimates due to the bed load temporal variability [e.g., *Gomez and Troutman*, 1997]. That error is not fully isolated in this study. Furthermore, the possibility for sampler bias and the sediment size related limit of sampler efficiency mean that it may be difficult to determine flow competence and the size distribution of the load from sample catch. In this respect, it appears that the sampler intake opening should remain greater than 5 times the diameter (conservatively of the *a* axis) of the largest stones apt to move in the stream.

[45] Readers are finally reminded that the results in this paper can be interpreted only qualitatively since the reference transport rates derived from equation (2) are based on an arbitrary selection of samples that we judge to have been "unbiased". That selection, in turn, has established a probably narrow range of "normal" temporal variation in load. Consequently, the components of variance in equation (1) may not be correctly divided. We have no doubt at all, however, that the results are indicative of important phenomena associated with sediment transport measurement that have been too little studied and require substantial further attention.

Notation

A_r	armor ratio, equal to $D_{50\text{-}s}/D_{50\text{-}ss}$
d	Water depth at vertical where the samples were collected (m).
$D_{50\text{-}s}$	Median surface grain size (mm).
$D_{50\text{-}ss}$	Median subsurface grain size (mm).
$D_{95\text{-}s}$	Percentile 95 of the surface grain size distribution (mm).
$D_{95\text{-}ss}$	Percentile 95 of the subsurface grain size distribution (mm).
D_i	Particle size i (mm).
$D_{\text{max-}bl}$	Maximum bed load grain size (mm).
i_b	Bed load transport rate (g m^{-1} s^{-1} or kg m^{-1} s^{-1}).
$i_{b\text{-}m}$	Mean bed load transport rate (g m^{-1} s^{-1}).
q	Specific discharge ($q = d \cdot v$) at the vertical where the samples were collected (m^2 s^{-1}).
R_{HS}	i_{bHS76}/i_{bHS152}.
v	Mean velocity at vertical where the samples were collected (m s^{-1}).
W_s	Bed load sampler's nozzle width (mm).
W_{HS152}	Helley-Smith sampler's nozzle width of 152 mm.
W_{HS76}	Helley-Smith sampler's nozzle width of 76 mm.
ω	Specific stream power (kg m^{-1}s^{-1}) [i.e., *Bagnold*, 1980].

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R. J. Batalla and D. Vericat, Department of Environment and Soil Sciences, University of Lleida, Avenida Alcalde Rovira Roure 191, E-25198 Lleida, Spain. (dvericat@macs.udl.es)

M. Church, Department of Geography, University of British Columbia, Vancouver, BC, Canada V6T 1Z2.