Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **30**, 1405–1417 (2005)
Published online 16 August 2005 in Wiley InterScience (www.interscience.wiley.com). **DOI:** 10.1002/esp.1202

Biases of submerged bulk and freeze-core samples†

André Zimmermann,[1]* Moise Coulombe-Pontbriand[2] and Michel Lapointe[3]
[1] *Department of Geography, University of British Columbia, Vancouver, BC, Canada*
[2] *Recon Inc., Calgary, Alberta, Canada*
[3] *Department of Geography, McGill University, Montreal, PQ, Canada*

Correspondence to: A. Zimmermann, Department of Geography, University of British Columbia, 1984 West Mall, Vancouver, BC, V6T 1Z2, Canada. E-mail: andre.zimmermann@mail.mcgill.ca

† *A contribution to the scientific program of CIRSA, the Centre Interuniversitaire de Recherche sur le Saumon Atlantique.*

Received 4 February 2004; Revised 30 September 2004; Accepted 18 November 2004

Abstract

Freeze-coring and bulk sampling are routine methods used to sample subsurface spawning gravel under shallow water. Both methods have limitations. Freeze-coring is not believed to representatively sample coarse grain sizes and the sample volumes are relatively small. Conversely, when bulk sampling, even within an enclosure, some fine sediment is suspended and washed away from the sample. This paper assesses the biases in sampling performance between the two methods and determines whether the loss of fines that occurs when bulk sampling could be predicted and thus corrected for.

At six riffles the spawning substrate was sampled under approximately 50 cm of water with a bulk sample and three adjacent freeze-cores. For each riffle, data from the two samples were combined using the method of Fripp and Diplas (1993) and the resultant composite sample was compared with the original freeze-core and bulk samples to assess the relative precision and biases of the two techniques.

On average, the D_{50} of the bulk samples was 4 mm larger and a one-third loss of the <2 mm fraction occurred compared with the composite samples. In contrast, freeze-core samples contain on average 32% more sediment >16 mm compared with composite samples. Based on six samples, taken from six riffles, the amount of sediment finer than 0·5 mm lost using our bulk sampling technique with an enclosure appears to be predictable and correctable.

Keywords: **sediment sampling; sub-aqueous; freeze-core; bulk sample; gravel-bed**

Introduction

Freeze-core and bulk samples extracted using shovel-like devices are two commonly used methods to determine the subsurface grain size distribution of gravel-bed river sediments. Biologists and geomorphologists use freeze-core and bulk samples to quantify fish and macroinvertebrate habitat (e.g. Milan *et al*., 2000; Payne and Lapointe, 1997; Scrivener and Brownlee, 1989) and to monitor changes in gravel substrate as a result of development (Adams and Beschta, 1980; Petts and Thoms, 1986; Petts *et al*., 1989; Rood and Church, 1994; Spillos and Rothwell, 1998; Thoms, 1987). In addition, subsurface sediment composition is needed when studying gravel transport processes (Parker and Klingeman, 1982) and when searching for gold deposits (Hughes *et al*., 1995; Petts *et al*., 1991).

Despite their extensive use, both the sub-aqueous freeze-core and bulk sampling methods are biased. The use of freeze-cores is believed to imprecisely sample coarse sediment and the samples are too small to establish with any precision the coarse end of the grain size distribution (Klingeman, 1987; Rood and Church, 1994). Increasing the number of freeze-core samples to attain a reasonable total sample weight (see, e.g., Church *et al*., 1987; Milan *et al*., 1999; Thoms, 1992) does not necessarily resolve the problem as uncertainty remains as to whether or not the proportion of coarser grains that remain attached to the freeze-core is representatively sampled (Klingeman, 1987; Petts and Thoms, 1986). While truncating the sample to remove the largest grains is a possible solution (Milan *et al*., 1999), if the entire grain size distribution of the population is sought, truncation cannot be used as it biases the whole grain size distribution (Fripp and Diplas, 1993). The physical impact and displacement that occurs when inserting the freeze-core tube may also bias the grain size distribution near the core in some manner.

The principle problem with sub-aqueous bulk samples is that some fine sediment is washed out of the sample and lost. It is possible that there may also be a bias introduced when shovelling sediment out of the sampling hole as larger stones are easier to identify underwater than fines and the larger stones must generally be removed before the fines can be removed.

Due to the sampling problems with freeze-core and bulk samples, other methods of sampling the subsurface grain size distribution are sought. McNeil samplers (McNeil and Ahnell, 1964) are an alternative means of sampling sub-aqueous substrate; however, they are limited to fine gravel and shallow water depths. In addition, fine sediment is lost with McNeil samplers unless special care is taken to trap the fine sediment suspended in the water (Rood and Church, 1994). Alternatively, depending on the nature of the project, subsurface bulk samples can be taken from dry gravel bars where the loss of fine sediment is not a problem (e.g. Mosley and Tindale, 1985; Rice and Haschenburger, 2004). Unfortunately, many studies require knowledge about the substrate that remains underwater during low flow conditions (e.g. spawning habitat surveys). Combining freeze-core and bulk samples may provide a sampling procedure that is unbiased and can be used to sample substrate underwater. The objectives of this paper are to quantify the relative biases of the freeze-core and bulk sampling techniques against more accurate composite samples and to examine whether systematic losses of fines can be predicted. If so, this might provide a means of correcting bulk sample data, thereby avoiding the costly and difficult work associated with freeze-coring (Rood and Church, 1994). We are not aware of any attempt to combine the freeze-core and bulk sampling methods, nor an evaluation of the biases of these two techniques.

Methods

The approach used exploits the fact that freeze-cores tend to sample coarse fractions inaccurately while bulk samples tend to inaccurately sample the finer fractions. To quantify the individual biases of both bulk and freeze-core samples, three freeze-cores were first paired with a bulk sample and combined to create an unbiased composite grain size distribution using the methods of Fripp and Diplas (1992, 1993). In order to combine the samples, the grain size classes where both methods sampled sediment in an identical manner were identified (the so called match fraction; Rice and Haschenburger, 2004). The match fraction was identified by comparing the rate of change between adjacent grain size classes (F_i/F_{i-1}, where F_i is the amount of sediment in fraction i and F_{i-1} is the amount of sediment in the next finer fraction). Over the range of fractions for which the difference in these ratios was near zero, the two methods were considered to be sampling the sediment in an identical manner. Once the match fraction was determined, the bulk sample data was used to reconstruct the full grain size distribution for the portion of the sample composed of sediment the same size as or larger than the match fraction. The freeze-core data were then matched to the bulk sample data using the match fraction and used to complete the portion of the grain size distribution finer than the match fraction. For more information on the method see Fripp and Diplas (1992, 1993) and Rice and Haschenburger (2004).

In total seven composite grain size distributions were created from samples collected at seven different riffles in four different streams within the Cascapédia River watershed, Québec (Figure 1). The seven submerged riffles had particularly coarse substrate (subsurface D_{90} = 75–230 mm, average = 135 mm; D_{50} = 18–46 mm, average = 33 mm) and a relatively large silt fraction ($D < 64$ µm, average = 1·2%), which is particularly difficult to sample underwater.

To take the freeze-core samples, freeze-core tubes built to the specifications of Rood and Church (1994) were driven into the riverbed to a depth of 30 cm. About 8 litres of liquid nitrogen was then poured into each tube at a slow continuous rate. Once all the liquid nitrogen had been poured, the tubes were left to sit for approximately 45 seconds till the freezing process was completed. The freeze-core was then removed with the sample attached (Figure 2). The surface layer (surface sediment to a depth of the D_{90}) did not freeze to the core and thus the surface sediment was not included in the freeze-core samples. The surface layer was also excluded from the bulk samples. Freeze-core samples varied in weight from 1 to 9·3 kg with an average weight of 4·6 kg. The samples were taken to the laboratory, dried and mechanically sieved at phi intervals and in some cases at $^1/_2$ phi intervals. The largest stone collected by an individual freeze-core varied between 32 and 128 mm. The samples were not truncated.

At each of the seven riffles sampled, three freeze-core samples were collected. One core was extracted immediately downstream of the area that would later be bulk sampled; the remaining two were extracted on either side of the same area. At each sampling site (one per riffle) it was assumed that the three freeze-cores and the bulk sample were sampling sediment from the same population of bed material. The data from different riffles was not combined.

At each study riffle, the bulk sample was then taken with a flow isolation cell (Coulombe-Pontbriand and Lapointe, 2004; Payne and Lapointe, 1997). The flow isolation cell attempts to let water flow through the cell into a mesh (77 µm) bag downstream. Our cell was outfitted with three centimetres of soft foam along its base in order to reduce the size of the gaps between the rough river bed and the base of the cell and further reduce water flow over the sample

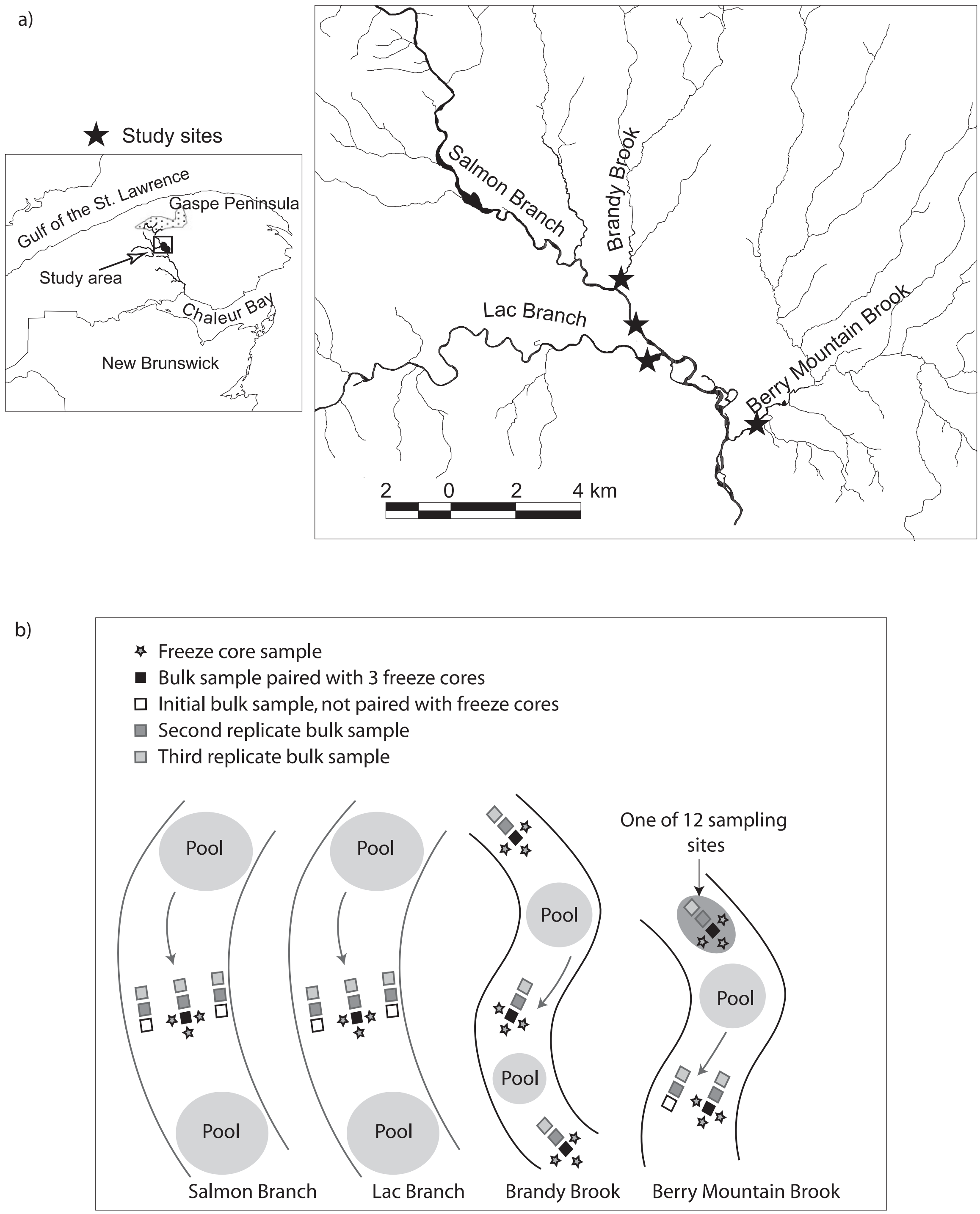

Figure 1. Map illustrating location of study streams (a) and a schematic of the sampling strategy at the seven riffles (b). The riffles are implicit between the pools.

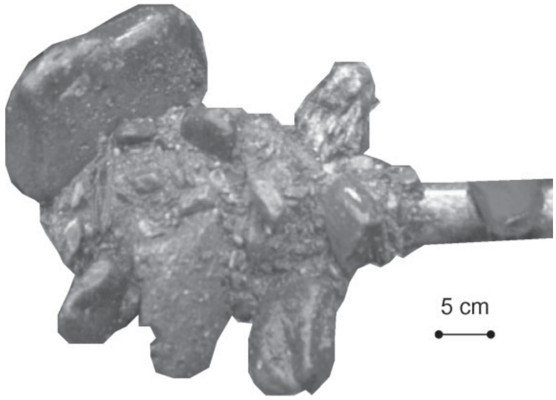

Figure 2. Freeze-core sample.

Figure 3. Flow isolation cell used for bulk sampling; note fines in suspension.

hole and the loss of fine sediment. Some very fine sediment was, however, still entrained from under the cell (Figure 3). Once the cell was in place the bed surface layer was removed to a depth of about the D_{90} of the surface. The underlying sediment was then sampled until the hole was about 30 cm deep and 65 cm in diameter. On average subsurface samples contained 130 kg of dry sediment. The largest stone in the samples was generally between 128 and 256 mm in diameter, thus the precision of the samples varied between 2 and 18%, assuming the stone was approximately ellipsoidal (Church *et al*., 1987). Milan *et al*. (1999) note that the precision of the sample may differ slightly from what is predicted with the Church *et al*. (1987) criteria if the stone's shape differs significantly from an ellipsoid. The excavated sediment was subsequently sieved to 16 mm at phi increments in the field. Five kilogram and larger sub-samples of the sediment less than 16 mm (the 16 mm sub-samples were sampled at a 0·1% accuracy based on Church *et al*., 1987) were taken to a laboratory, dried and sieved at the same intervals as the freeze-core samples.

During the research, 29 additional bulk samples were also collected to increase the amount of information about the study sites and examine seasonal changes in substrate (see Zimmermann and Lapointe, in press). While this data was not used to examine the biases of bulk or freeze-core samples, it does help illustrate the precision of bulk samples. The additional bulk samples were taken from the same seven riffles that were sampled with the freeze-cores (see Figure 1). At each of the four streams three sampling sites were chosen for a total of 12 sites. Seven of these sites corresponded to the original seven bulk sampling sites while the remaining five sampling sites were new. Within a stream, the three sampling sites were located either on the same riffle, where the channel width allowed, or on consecutive riffles. On each of these 12 sampling sites, three bulk samples were extracted. Each subsequent sample was taken 1–2 m upstream of the previous bulk sample as variability in grain size is greater across the stream channel than along the stream channel (Adams and Beschta, 1980). The first sample was taken in July, the second in September and the third in November. Between the sampling periods a few modest sediment transporting events occurred that transported fine gravel and sand but no major events occurred (see Zimmermann and Lapointe, in press, for details). As no significant change in bed texture (ANOVA, $p > 0{\cdot}1$) was observed among the replicate samples (Zimmermann and Lapointe, in press), these bulk samples have been treated as replicates and are used here to assess the precision (i.e. repeatability) of bulk sampling.

Results

Table I illustrates the sample weights for both the three combined freeze-cores and the paired bulk samples for each of the seven original study sites. To construct the composite grain size distribution, the match fraction was determined by subtracting the weight ratio between adjacent grain size classes (F_i/F_{i-1}) for the three combined freeze-cores from the weight ratio for the paired bulk sample. As an example, a ratio difference of 1 could reflect a weight ratio for a given pair of adjacent fractions of 1:1 using one sample method and 2:1 with the other. For each grain size class the absolute values of these differences for each of the seven study sites are plotted in Figure 4. For the grain size classes between 2·8 and 11·2 mm the difference between the ratios is consistently near zero at all sites, indicating that this is the best match fraction. Once the match fraction was determined, the portion of the bulk grain size distribution larger than 2 mm was used as the coarse limb of the composite sample. The freeze-core data was then scaled up so that the amount of freeze-core sediment in the 2–11·2 mm grain size class matched the amount of sediment between 2 and 11·2 mm measured with the bulk sample. The scaled up data was then used to complete the fine end of the grain size distribution for the 2 mm and finer grain size classes of the composite grain size distribution (bottom of Table I).

The three freeze-core samples from the Salmon site had a total weight of only 2·9 kg and have thus been excluded from further analysis as this is felt to be too small a sample to be accurate. The data also plotted as an outlier for much of the analysis, suggesting the small sample size affected the results.

To assess the precision (repeatability) of the bulk samples, a coefficient of variation was calculated for each grain size fraction and each of the 12 bulk sample sites that were repeatedly ($n = 3$) sampled (see Figure 1). In the same manner, for each grain size class, six different freeze-core coefficients of variation were calculated, one for each riffle that was repeatedly ($n = 3$) sampled with freeze-cores, excluding the data from the Salmon site (see Figure 1). The mean coefficient of variation from the 12 bulk sampling sites and six freeze-core sampling sites (excluding the freeze-core sample from the Salmon site) characterized the average variability of bulk and freeze-core samples for this study (Figure 5(a)). Figure 5(b) illustrates the proportion of the sample that the largest stone in a grain size class would contribute to the sample according to the average size of the sediment samples. An ellipsoidal shape and a bulk density of 2650 kg/m^3 have been assumed as per Church *et al.* (1987).

Repeated freeze-core samples yield greater imprecision (random variation measure as coefficient of variation) in fractional contents than bulk samples for all grain size classes coarser than 1 mm (Figure 5(a)). Precision is comparable to that of bulk samples for grain size classes finer than 1 mm. As expected, based on Church *et al.* (1987) and Gale and Hoare (1994), when the largest stone occupies more than 1% of the total sample weight the coefficient of variability significantly increases for both bulk and freeze-core samples. As a result, bulk samples generally yield much more precise gravel and cobble content data since it is much easier to take larger substrate samples with bulk samples than with freeze-cores.

To construct a composite sample, it is necessary to ensure that the three freeze-cores provide an accurate sample of the sediment finer than 11·2 mm. Figure 5(a) shows that the coefficient of variation, based on three freeze-cores, remains relatively low (under 0·5) for all of the 16 mm and finer grain size classes but increases rapidly for coarser fractions. In addition, if the Church *et al.* (1987) method is applied, an 11·2 mm stone would on average make up only 0·2% of the weight of a three freeze-core sample. This level of precision is felt to be sufficient to ensure that the matching of the bulk and freeze-core samples is reasonably precise. Milan *et al.* (1999) argues that if the stones are not ellipsoidal, the level of precision may vary slightly from the predicted 0·2%. Thoms (1992) has illustrated that five freeze-cores are needed to sample substrate composed entirely of sediment finer than 32 mm. For the purpose of our study, three freeze-cores were used since this study is only concerned with accurate samples of sediment finer than 11·2 mm. As we will illustrate, no number of replicate freeze-cores would permit an accurate sample of a population if sediment larger than 16 mm exists within the population.

Table I. For each sample site the mass of sediment (kg) in each grain size class based on three freeze cores, a bulk and the composite sample

		Largest grain in grain size class (mm)																	
Sample type	**Sample site**	**256**	**128**	**90**	**64**	**45**	**32**	**16**	**11·2**	**8**	**5·6**	**4**	**2·8**	**2**	**1**	**0·5**	**0·25**	**0·125**	**0·064**	**Total sample weight (kg)**
Freeze-cores	Berry lower		2·0	2·8	1·3	0·9	1·6	0·8	0·4	0·3	0·4	0·3	0·3	0·4	0·3	0·3	0·1	0·1	0·1	12·2
Freeze-cores	Berry upper	2·4	5·0	3·4	0·7	0·9	2·0	0·6	0·6	0·5	0·5	0·4	0·4	0·5	0·3	0·3	0·1	0·1	0·1	18·8
Freeze-cores	Brandy lower		4·4	1·8	0·5	2·2	2·2	1·1	0·9	0·8	0·7	0·6	0·4	0·6	0·6	0·5	0·3	0·3	0·2	18·2
Freeze-cores	Brandy middle		2·8	3·3	1·1	1·2	1·9	0·9	0·6	0·5	0·5	0·4	0·3	0·6	0·5	0·3	0·2	0·2	0·2	15·5
Freeze-cores	Brandy upper		2·3	1·9	1·1	1·8	1·5	0·7	0·5	0·4	0·5	0·4	0·3	0·5	0·5	0·3	0·2	0·1	0·1	13·2
Freeze-cores	Lac			1·1	1·2	1·8	2·8	0·7	0·6	0·5	0·4	0·3	0·3	0·5	0·5	0·5	0·2	0·1	0·1	11·6
Freeze-cores	Salmon					0·2	0·4	0·5	0·3	0·2	0·2	0·1	0·1	0·2	0·2	0·2	0·1	0·1	0·0	2·9[1]
Bulk	Berry lower	20·0	5·9	18·4	10·4	9·5	15·1	4·5	5·3	5·0	4·8	4·2	4·8	7·5	4·4	2·2	0·6	0·2	0·3	123·2
Bulk	Berry upper	29·1	15·8	12·6	9·2	12·5	14·8	6·1	6·1	5·6	5·3	4·3	3·3	3·2	1·5	1·6	0·5	0·2	0·2	131·7
Bulk	Brandy lower	20·6	17·8	10·3	9·4	8·4	14·5	4·6	5·5	5·5	4·8	3·4	3·0	3·7	4·6	1·7	0·5	0·5	0·6	119·2
Bulk	Brandy middle	12·3	11·0	14·0	12·1	9·2	16·0	4·4	5·0	5·8	5·3	4·8	4·7	7·4	4·3	1·4	0·6	0·4	0·8	119·6
Bulk	Brandy upper	3·6	12·2	16·6	12·0	11·3	19·7	9·2	8·1	8·2	7·3	6·0	5·0	6·5	4·2	1·8	0·7	0·4	0·8	133·7
Bulk	Lac		3·5	15·6	10·7	14·9	22·9	7·3	9·4	7·3	7·3	4·9	5·1	8·5	6·2	3·1	0·7	0·2	0·2	127·7
Bulk	Salmon	18·7	13·5	13·5	12·4	10·9	19·3	7·6	7·7	6·8	5·7	4·1	3·7	6·0	5·6	1·9	0·3	0·1	0·2	138·1
Composite	Berry lower	20·0	5·9	18·4	10·4	9·5	15·1	4·5	5·3	5·0	4·8	4·2	4·8	5·5	4·7	4·0	1·6	0·9	1·1	125·7
Composite	Berry upper	29·1	15·8	12·6	9·2	12·5	14·8	6·1	6·1	5·6	5·3	4·3	3·3	5·4	3·4	2·8	1·5	0·8	0·8	139·2
Composite	Brandy lower	20·6	17·8	10·3	9·4	8·4	14·5	4·6	5·5	5·5	4·8	3·4	3·0	4·2	4·1	3·6	2·1	2·2	1·6	125·4
Composite	Brandy middle	12·3	11·0	14·0	12·1	9·2	16·0	4·4	5·0	5·8	5·3	4·8	4·7	6·8	6·1	3·5	2·1	2·1	1·9	127·2
Composite	Brandy upper	3·6	12·2	16·6	12·0	11·3	19·7	9·2	8·1	8·2	7·3	6·0	5·0	8·9	7·8	5·4	3·2	1·9	2·4	148·8
Composite	Lac		3·5	15·6	10·7	14.9	22·9	7·3	9·4	7·3	7·3	4·9	5·1	7·7	7·5	7·3	3·4	1·6	1·7	138·0
Composite	Salmon	18·7	13·5	13·5	12·4	10·9	19·3	7·6	7·7	6·8	5·7	4·1	3·7	5·3	5·2	4·4	2·9	1·4	1·3	144·3

[1]Due to the small total sample weight of the three freeze-cores from the Salmon site the data from the Salmon site was not used to examine the biases of freeze-core or bulk samples.

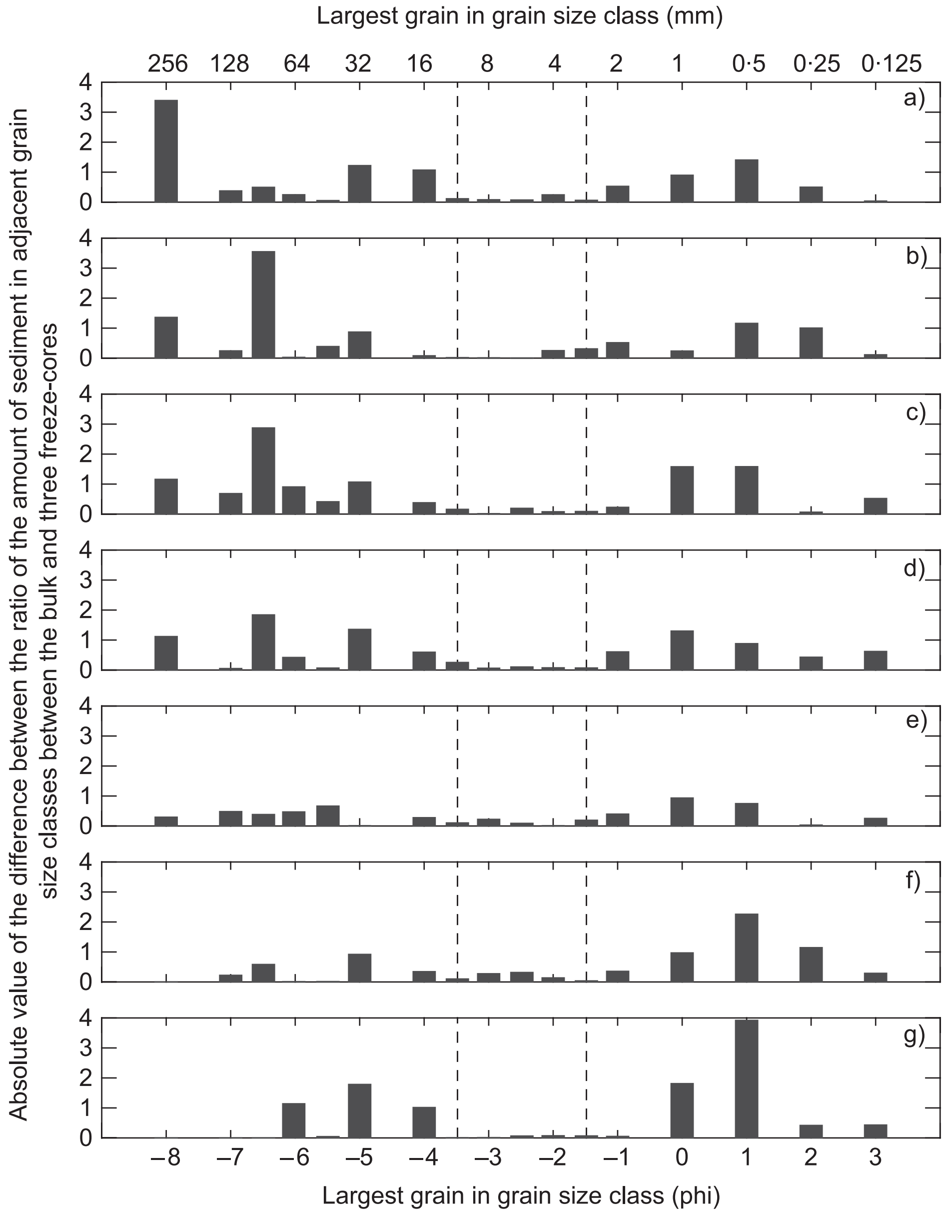

Figure 4. The absolute value of the ratio of the amount of sediment in adjacent grain size classes for three combined freeze-cores, minus the conjugate ratio from the paired bulk sample for the seven study riffles: (a) Berry lower; (b) Berry upper; (c) Brandy lower; (d) Brandy middle; (e) Brandy upper; (f) Lac; (g) Salmon. Sediment texture analysed at phi and $^{1}/_{2}$ phi intervals. Dashed lines mark the interval over which freeze-cores and bulk samples are believed to be unbiased. The absolute values of the differences are plotted against the largest grain size class in the ratio (i.e. 4 mm = 4/2·8 mm).

The accuracy of the composite samples was still largely limited by the proportion of the sample that the largest stone contributed (see Church *et al*., 1987). To increase the overall accuracy of the sample, larger samples or bulk samples combined with grid by number samples should be taken (see Rice and Haschenburger, 2004).

Freeze-core biases: grain size specific sampling efficiencies

To compare mean freeze-core sample data with the more accurate composite samples the entire freeze-core sample was scaled up such that the mass of sediment in the 2–11·2 mm grain size class matched the amount of sediment in the

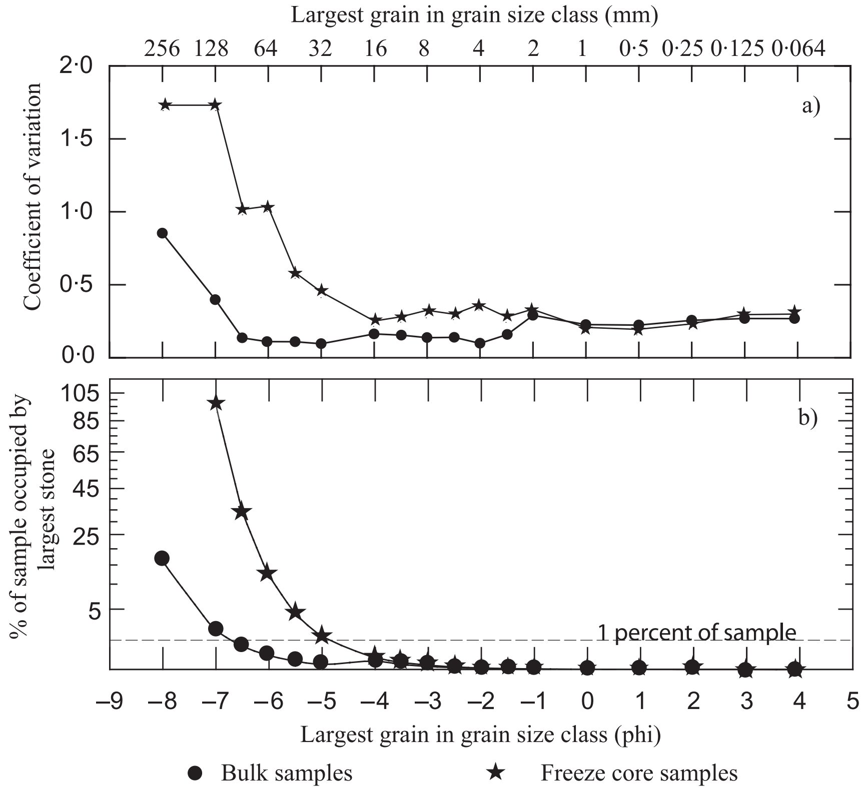

Figure 5. (a) Mean coefficient of variation from 12 bulk sample groups and six freeze-core sample groups (excluding data from Salmon); each group had three samples. (b) The percentage of the sample weight that the largest stone in each grain size class would contribute to the overall weight of the sample.

composite sample. The scaled up freeze-core sample was then compared with the composite sample in two different ways. First, the efficiency (or relative bias) of the sampling techniques at capturing sediment was estimated for each individual grain size class (Figure 6(a)). For each grain size class, the amount of sediment collected with the freeze-cores was divided by the amount of sediment in the paired composite sample. A ratio greater than one, for instance, would imply the freeze-core captured more sediment than the composite sample.

Figure 6(a) illustrates that on average the freeze-core samples over-sample sediment in the grain size classes between 16 and 128 mm, and under-sample the largest stones (128–256 mm). Individual coarse gravel and cobbles (16–128 mm) protrude out of the sample, as illustrated in Figure 2, which may explain why these stones are systematically over-sampled. The 128–256 mm stones were rarely captured, even when they were present in the substrate (present six of seven times, captured only once).

As a second means of comparing freeze-core samples with composite samples, the magnitude of the difference between the two methods was examined with respect to the total weight of the composite sample (Figure 6(b)) rather than just the amount of sediment in the grain size class (Figure 6(a)). Thus, the effect the biases have in relation to the total mass of the sample is illustrated. Figure 6(b) also illustrates the cumulative percentage different (total) between the two techniques. The cumulative percentage different was determined by dividing the total amount of sediment in the three freeze-core samples by the total amount of sediment in the composite sample.

With respect to the total weight of the sample, once scaled up to match the weight in the composite sample over the 2–11·2 mm interval, on average 32% more (mainly coarse) sediment was captured with the three freeze-core samples compared with a composite sample. The results varied greatly as anywhere between 45% more sediment and 3% less sediment was collected with the freeze-core samples (Figure 6(b)). Individual grain size classes can be over-represented in freeze-core samples by as much as 20% of the total weight of the composite sample. Results confirm, with the exception of the 256 mm grain size class, that the larger grain size classes are increasingly over represented in freeze-core samples. Freeze-cores alone clearly do not accurately sample substrates that contain sediment larger than 16 mm.

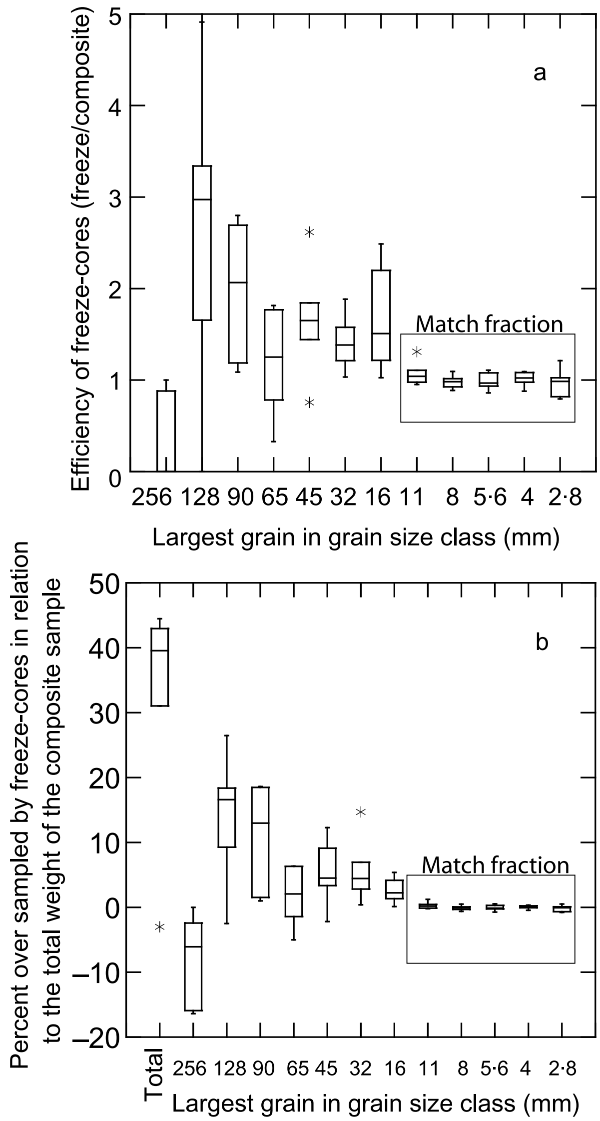

Figure 6. (a) The efficiency of freeze-cores compared with composite samples for six riffles sampled (i.e. $n = 6$, Salmon data excluded). The efficiency was calculated by dividing the mass of sediment in each grain size class from the freeze-core sample by the mass of sediment in the same grain size class from the composite sample. Note that the efficiency is at a minimum of zero when no sediment in a grain size class is measured with the freeze-cores. (b) The percentage over-sampled with three freeze-cores in relation to the total sample weight of the composite samples based on six paired samples. See the text for details. The middle line represents the median, boxes the first quartile and lines the second quartile.

Bulk sample biases: grain size specific sampling efficiencies

Next, to compare the bulk samples to the composite samples, the same analysis as was preformed on the freeze-core data was reproduced with the bulk sample data, except that the analysis focused on the grain size classes finer than the match fraction (<2 mm). The relative efficiency of bulk samples relative to composite samples at capturing sediment on a per grain size class basis is illustrated in Figure 7(a). A ratio less than one implies the bulk samples under-sample sediment compared with a composite sample. As a second means of comparing bulk samples with composite samples, the difference between the two methods with respect to the total weight of the composite sample was evaluated (Figure 7(b)).

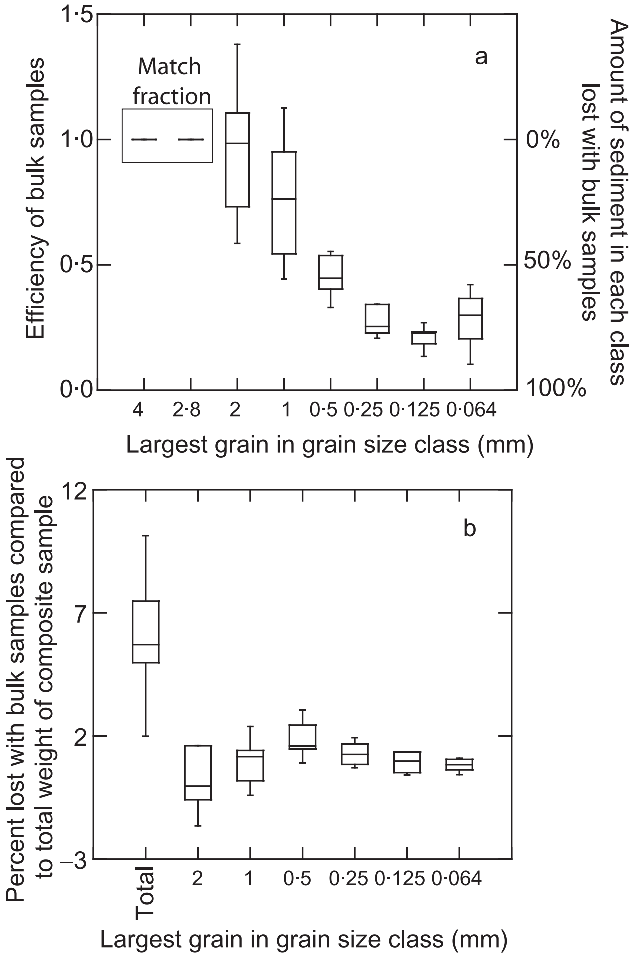

Figure 7. (a) The efficiency of bulk samples compared with composite samples for six riffles (i.e. $n = 6$, Salmon data excluded). The efficiency was calculated by dividing the mass of sediment in each grain size class from the bulk sample by the mass of sediment in the same grain size class from the composite sample. (b) The percentage lost with bulk samples compared to the composite samples for six riffles. The total percentage lost was determined by calculating the ratio between the total mass in the composite sample and the total mass in the bulk sample. The middle line represents the median, boxes the first quartile and lines the second quartile.

The grain size distribution of the composite samples was consistently finer than that of the bulk samples. As illustrated in Figure 7(b), in relation to the total weight of the sample, the seven bulk samples lost anywhere from 2 to 10% of the sediment finer than 2 mm (average = 5·4%; median = 6%). This on average corresponds to a loss of over one-third (38%) of the amount of sediment finer than 2 mm as no sediment larger than 2 mm was lost. As a result grain size descriptors such as the D_{50} (reduced 4 mm) and the percentage of the sample composed of sand (increased 5·4%) differed significantly (t-test, $n = 7$, $p < 0·003$) between bulk samples and composite samples. Figure 7(a) shows that the proportion of the sediment lost in relation to the amount present, on a per grain size class basis, increases for smaller sediments.

Do systematic and predictable losses occur with bulk samples?

The hypothesis that systematic and predictable, and therefore correctable, losses of fine sediment with bulk samples occurs was tested with the data from the six bulk samples (excluding the Salmon site) and their paired composite samples for the 2 mm and finer grain size classes. The results are summarized in Table II.

A significant positive relationship ($p < 0·05$) was found between the amount of sediment measured by composite samples and the amount of sediment measured by bulk samples for the less than 63, 125, 250 and 500 μm grain size

Table II. Comparing composite samples and bulk samples for sand and silt grain size classes based on six sets of paired samples (excludes data from Salmon site)

Grain size class	*P*-value of slope of regression	r^2	% composite	Bulk % of sample Ave.	Bulk % of sample Max.	Bulk % of sample Min.	Composite % of sample Ave.	Composite % of sample Max.	Composite % of sample Min.	Paired *t*-test, *p*-value
<64 μm	0·04	0·68	$=1{\cdot}35 \times \%\ \text{bulk} + 0{\cdot}66$	0·37	0·67	0·12	1·2	1·6	0·54	<0·001
64–125 μm	0·02	0·79	$=3{\cdot}82 \times \%\ \text{bulk} + 0{\cdot}18$	0·26	0·43	0·10	1·2	1·8	0·54	=0·002
125–250 μm	0·008	0·86	$=7{\cdot}52 \times \%\ \text{bulk} - 1{\cdot}8$	0·47	0·55	0·39	1·7	2·4	1·1	=0·001
250–500 μm	0·017	0·79	$=2{\cdot}1 \times \%\ \text{bulk} + 0{\cdot}039$	1·6	2·4	1·2	3·3	5·3	2·1	=0·002
0·5–1 mm	0·12	0·49		3·4	4·8	1·1	4·1	5·4	2·4	0·10
1–2 mm	0·13	0·48		4·9	6·6	2·4	4·7	6·0	3·4	0·80

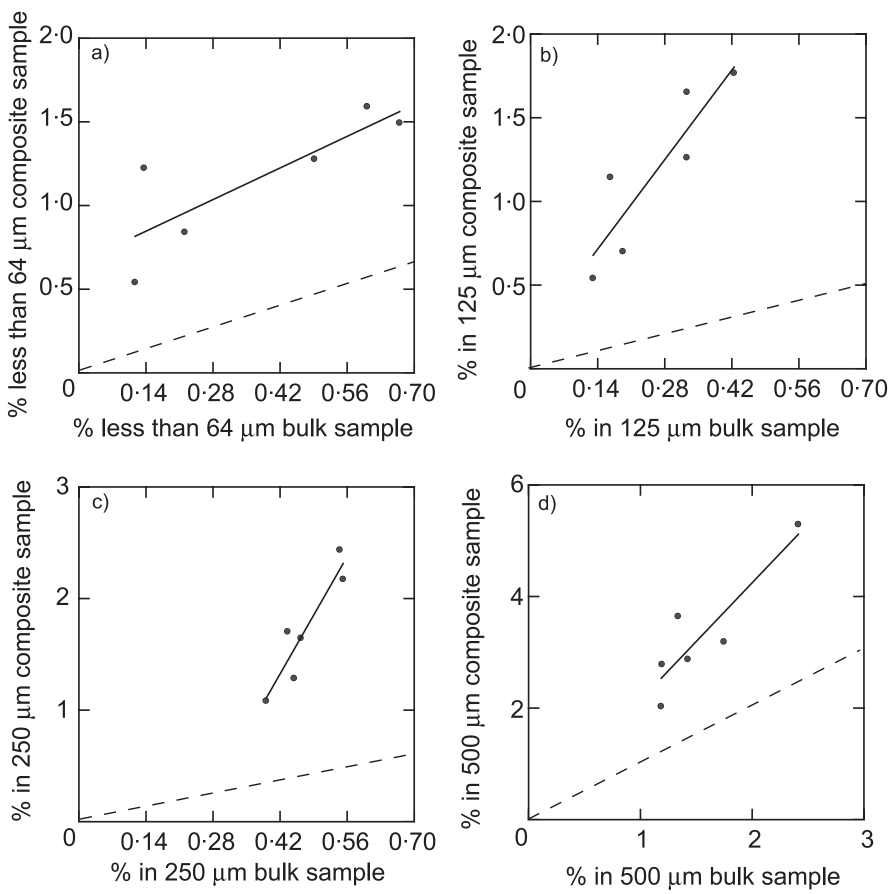

Figure 8. Relationships between the amount of sediment measured with bulk samples and the amount measured with a composite sample for four grain size classes based on samples taken from six riffles (Salmon data excluded): the four grain size classes are the <64 (a), the 125 (b), the 250 (c), and the 500 μm (d) grain size classes. The solid line indicates the best fit linear regression relationship and the dashed line represents the 1:1 line, which the data would be expected to follow if the two methods were equivalent.

classes (Figure 8). For the four finest grain size classes, bulk samples always sample less fine sediment than composite samples. For the 1 and 2 mm grain size classes, composite samples were not statistically different from bulk samples (paired t-test, $p = 0{\cdot}10$ and $0{\cdot}8$ respectively). This suggests that medium and coarse sands were not easily suspended while sampling and were representatively sampled using our bulk sampling technique.

The relationships in Table II could be used to correct bulk samples taken in similar conditions, thereby limiting the need for costly and difficult freeze-core sampling (Rood and Church, 1994). The coefficients in Table II, however, are unlikely to be universal as the type of flow isolation cell used, compactness of the substrate and the water velocity at the sampling locations may affect the coefficients. Studies performed under different conditions would require the fitting of site specific correction equations.

Discussion

As early as 1973 (Walkotten, 1973), freeze-cores were used to sample river substrate. While Klingeman (1987) raised the concern that freeze-cores may be biased towards coarse substrate and Thoms (1992) showed that samples from gravels containing sediment larger than 64 mm had an unexplained bias whereas those containing sediment finer than 32 mm were not biased, the amount of bias associated with freeze-cores has not been documented and researchers have continued to use freeze-cores in coarse substrate (e.g. Milan *et al*., 1999). While this practice is entirely reasonable when a sample of the fine matrix fraction alone is sought (up to pea gravel, Figure 6) (see, e.g., Hughes *et al*., 1995; Petts *et al*., 1991, 1989), our results have clearly demonstrated that freeze-cores cannot be used to construct a complete grain size distribution in cobble-gravel-bed rivers. Using freeze-cores alone can result in substantial errors that may effect the interpretation of channel stability as the coarse fraction can be substantially over-estimated.

Thoms (1992) also notes that bulk samples or grab samples have been plagued by the loss of fines due to washout when sampling. Herein the amount of sediment actually lost with bulk samples has been shown to be significant (Figure 7). Nonetheless bulk sampling remains an attractive technique as it can be used to acquire large, unbiased samples of the coarse fraction of the substrate (diameter > 2 mm, Figure 7) and is relatively easy to complete in remote settings. The ability to correct for the loss of fines while bulk sampling holds some promise that bulk samples alone may be used if a lower level of precision is acceptable. Using uncorrected bulk samples can result in errors and some caution is warranted. As an example, egg emergence predictions based on the sand index (Peterson and Metcalfe, 1981) for the data from the Lac branch are 80% using uncorrected bulk sample data and 10% using the composite grain size distribution. While this is an extreme example, the other streams had similar, albeit not so extreme changes (Brandy, 90% bulk, 50% composite; Berry Mountain, 90% bulk, 80% composite; Salmon site, 90% bulk, 70% composite). Bulk samples alone can be used if the purpose of a project is only to compare sites within a single study as the relative rank of the sites is preserved. In general, however, some caution is needed when using uncorrected submerged bulk sample data.

Conclusion

Our results show that freeze-core and bulk samples can be combined using the Fripp–Diplas (1993) method to overcome the biases associated with each technique. The biases are demonstrated to be significant. In particular, sediment finer than 2 mm is underestimated with bulk samples (especially for particles finer than 0·5 mm) and material coarser than 16 mm is demonstrated to be over-estimated with freeze-core samples. The biases associated with the techniques are sufficiently large that predictions based on either technique can be outright incorrect. Freeze-cores rarely sample sediment larger than 128 mm even when it is present in the population and salmon emergence predictions can be as high as 80% using bulk samples, but as low as 10% if a combined sample is used. Clearly caution should be used if bulk or freeze-core samples are to be used alone.

The loss of fine sediment when bulk sampling with our flow isolation cell does appear to be predictable and correctable, suggesting that calibration relationships can be used to estimate the amount of fines lost with a particular bulk sampling technique. This would enable researchers to predict the loss of fines and reduce the number of freeze-core samples that must be paired with bulk samples in order to accurately measure the complete grain size distribution of sub-aqueous cobble-gravel substrate.

Acknowledgements

This work was funded by the National Science and Engineering Research Council of Canada (NSERC) in the form of postgraduate scholarships for Zimmermann and Coulombe-Pontbriand. The field work was funded by M. Lapointe's NSERC operating grant, CIRSA and the Cascapédia Society Inc. Northwest Hydraulic Consultants lent us the freeze-coring equipment and Laura Lapp and Erich Zimmermann were terrific assistants in the field. The paper has also benefited greatly from the comments of an anonymous reviewer as well as comments from Dr. Marwan Hassan (Department of Geography, UBC).

References

Adams JN, Beschta RL. 1980. Gravel bed composition in Oregon coastal streams. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 1514–1521.

Church MA, McLean DG, Wolcott JF. 1987. River bed gravels: sampling and analysis. In *Sediment Transport in Gravel-Bed Rivers*, Thorne CR, Bathurst JC, Hey RD (eds). Wiley: Chichester; 43–88.

Coulombe-Pontbriand M, Lapointe M. 2004. Geomorphic controls, riffle substrate quality and spawning site selection in two semi-alluvial salmon rivers in the Gaspé Peninsula, Canada. *Rivers Research and Applications* **20**: 577–590.

Fripp J, Diplas P. 1992. Surface sampling of dry and underwater sediment deposits. In *Hydraulic Engineering: Saving a Threatened Resources – in Search of Solutions*, Jennings M, Bhowmik NG (eds). ASCE: Baltimore, MD; 853–858.

Fripp JB, Diplas P. 1993. Surface sampling in gravel streams. *Journal of Hydraulic Engineering, ASCE* **119**(4): 473–490.

Gale SJ, Hoare PG. 1994. Reply: Bulk sampling of coarse clastic sediments for particle size analysis. *Earth Surface Processes and Landforms* **19**: 263–268.

Hughes N, Coats JS, Petts GE. 1995. Local variability of gold in active stream sediments. *Journal of Geochemical Exploration* **54**: 137–148.

Klingeman PW. 1987. Discussion of Church MA, McLean DG, Wolcott JF 1987. In *Sediment Transport in Gravel-Bed Rivers*, Thorne CR, Bathurst JC, Hey RD (eds). Wiley: Chichester; 81–83.

McNeil JW, Ahnell WH. 1964. *Success of Pink Salmon Spawning Relative to Size of Spawning Bed Materials*. US Fish and Wildlife Service Special Scientific Report Fisheries No. 469, p. 15.

Milan DJ, Heritage GL, Large ARG, Brunsdon CF. 1999. Influence of particle shape and sorting upon sample size estimates for a coarse-grained upland stream. *Sedimentary Geology* **129**: 85–100.

Milan DJ, Petts GE, Sambrook H. 2000. Regional variations in the sediment structure of trout streams in southern England: benchmark data for siltation assessment and restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems* **10**: 407–420.

Mosley MP, Tindale DS. 1985. Sediment variability and bed material sampling in gravel-bed rivers. *Earth Surface Processes and Landforms* **10**: 465–482.

Parker G, Klingeman PC. 1982. On why gravel bed streams are paved. *Water Resources Research* **18**(5): 1409–1423.

Payne BA, Lapointe MF. 1997. Channel morphology and lateral stability: effects on distribution of spawning and rearing habitat for Atlantic salmon in a wandering cobble-bed river. *Canadian Journal of Fisheries and Aquatic Sciences* **54**: 2627–2636.

Peterson RH, Metcalfe JL. 1981. *Emergence of Atlantic Salmon Fry from Gravels of Varying Compositions: A Laboratory Study*, No. 1020, Fisheries and Environmental Sciences, Department of Fisheries and Oceans, Biological Station, St-Andrews, New Brunswick, August, p. 15.

Petts GE, Coats JS, Hughes N. 1991. Freeze-sampling method of collecting drainage sediments for gold exploration. *Transactions of the Institution of Mining and Metallurgy, Section B: Applied Earth Sciences* **100** (January–April): B28–B32.

Petts GE, Thoms MC. 1986. Channel aggradation below Chew Valley Lake, Somerset, UK *Catena* **13**: 305–320.

Petts GE, Thoms MC, Brittan K, Atkin B. 1989. A freeze-coring technique applied to pollution by fine sediments in gravel-bed rivers. *The Science of the Total Environment* **84**: 259–272.

Rice S, Haschenburger J. 2004. A hybrid method for size characterization of coarse subsurface fluvial sediments. *Earth Surface Processes and Landforms* **29**(3): 401–421.

Rood K, Church M. 1994. Modified freeze-core technique for sampling the permanently wetted streambed. *North American Journal of Fisheries Management* **14**: 852–861.

Scrivener JC, Brownlee MJ. 1989. Effects of forest harvesting on spawning gravel and incubation survival of Chum (*Oncorhynchus keta*) and Coho salmon (*O. kitsutch*) in Carnation Creek, British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences* **46**: 681–695.

Spillos LC, Rothwell RL. 1998. Freeze-core sampling for sediment intrusion from road and stream crossings in Alberta's foothills: a preliminary discussion. In *Forest-Fish Conference: Land Management Practices Affecting Aquatic Ecosystems*, Brewin MK, Monita DMA (eds). Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre: Calgary, Alberta; 445–450.

Thoms MC. 1987. Channel sedimentation within the urbanized river Tame, UK *Regulated Rivers: Research and Management* **1**: 229–246.

Thoms MC. 1992. A comparison of grab- and freeze-sampling techniques in the collection of gravel bed river sediment. *Sedimentary Geology* **78**: 191–200.

Walkotten WJ. 1973. *A Freezing Technique for Sampling Streambed Gravels.* US Forest Service Pacific Northwest Forest and Range Experiment Station Research Note, No. PNW-281.

Zimmermann AE, Lapointe M. In press. Sediment infiltration traps: their use to monitor salmonid spawning habitat in headwater tributaries of the Cascapedia River, Québec. *Hydrological Processes*.

