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A total of 468 bed material samples were collected at cross sections of the sand bed of the South Saskatchewan River at Saskatoon to assess the random and systematic errors in the results from four commonly used samplers. Statistically significant differences in particle size distribution occur between the results obtained from different samplers at the same location, in part due to variability in retention of the small particles. The differences are greatest in silty sand and least in well-sorted, medium sand. The precision of results from repetitive samples at the same location using the same sampler depends on both the sampler and the composition of the bed material. Except in well-sorted, medium sand, a single sample at a vertical is inadequate to determine the particle size of a given size fraction to within 10% with a probability of error of 0.1. In some cases 10 or more samples may be required. The magnitude of these statistical errors at a given location is generally less than the within-reach variability in bed material particle size, and therefore the appropriate choice of sample location is critical.

Introduction

Bed material sampling of sand bed rivers is routinely carried out by researchers and government agencies for a wide variety of purposes. In North America the sampling equipment and procedures developed by the United States Federal Inter-Agency Sedimentation Project [*Witzigman*, 1965; *Federal Inter-Agency Sedimentation Project*, 1986] are fairly standard. Information on sampler operation, maximum sample mass, and the suitability to certain flow and bed material conditions is readily available for the commonly used samplers, but to our knowledge there has been no attempt to measure the precision (variability in measurements from a single sampler at a given location due to random error) and reproducibility of results (differences in measurements between samplers at a given location due to systematic error) from these samplers in the field. Nor has the magnitude of these random and systematic errors in sampling been compared to the variability in bed material particle size typically found within a river reach. This contrasts with the situation for gravel bed streams where the minimum sample size and the comparability of various methods of sampling and analysis have been carefully assessed [*Church et al.*, 1987].

In Canada the Water Survey of Canada (Environment Canada) has routinely collected bed material data since the mid-1950s. In order to begin to standardize the samplers and methods used, field tests were designed to compare the performance of four commonly used samplers. Specifically, the purposes of the study were (1) to establish whether there are systematic differences between samplers in the particle size distribution sampled at a given location, (2) to determine the precision of repeated measurements using the same sampler at a given location, and hence to establish the number of samples to be collected at a given location in order to measure various percentiles of the particle size distribution to a predetermined level of precision, (3) to ensure that the mass of individual samples typically collected by each sampler is sufficiently large to overcome bias (and thus systematic error) due to underrepresentation of particular size fractions (this is a problem in gravel bed streams where very large sample masses are required to accumulate sufficient particles in the coarse tail of the distribution [*De Vries*, 1970; *International Standards Organization (ISO)*, 1977; *Church et al.*, 1987]), and (4) to compare the magnitude of the sampling errors at a given location within a river reach with the variability in bed material particle size over the whole reach.

This paper summarizes the results of these tests which are more fully reported by *Ashmore et al.* [1988]. It is not an attempt to quantify all the potential sampling errors, but it is the first attempt to examine these aspects of bed material sampling in sand bed rivers. We expect that it may assist in the design of data collection programs for a wide variety of purposes including sediment transport and scour, routing of sediment-attached pollutants, and monitoring of fish habitat.

Bed Material Sampling and Samplers

Sand bed rivers are defined as those in which the median particle size and the bulk of the bed sediment is sand

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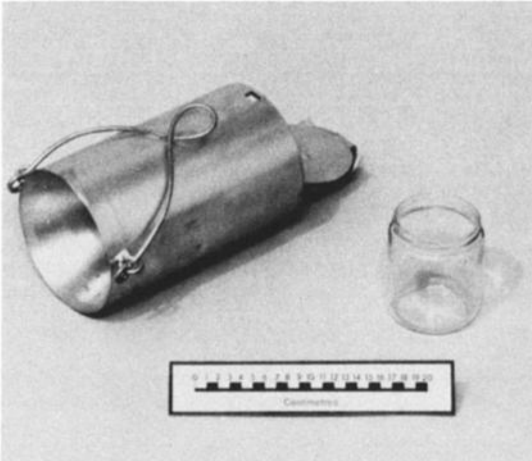

Fig. 1*a*. Canadian Drag Bucket.

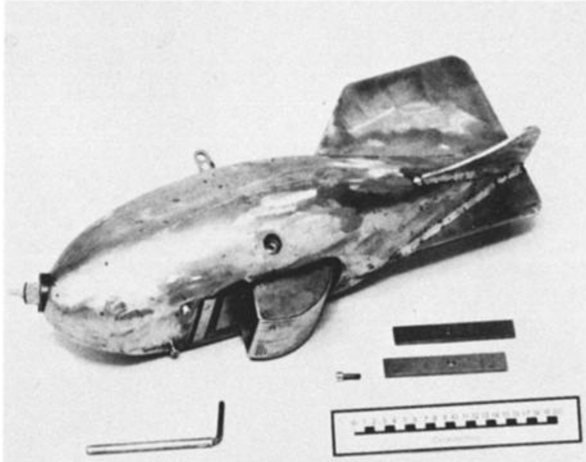

Fig. 1*b*. US BM-54.

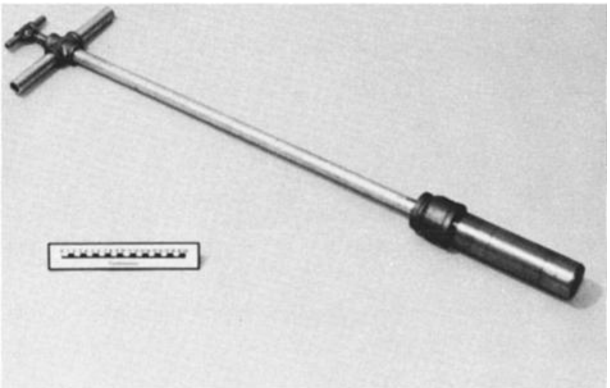

Fig. 1*c*. US BMH-53.

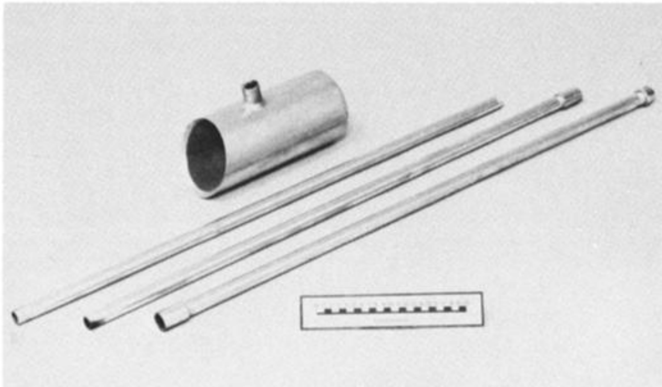

Fig. 1*d*. Scoop.

Fig. 1. Bed material samplers.

(0.062–2 mm). In most cases a certain proportion of the bed material will fall outside this range. This is certainly the case for streams on the Canadian prairies, for example, *Shaw and Kellerhals* [1982] show bed material size distribution curves from sand bed rivers in Alberta with up to 10% gravel and 30% silt and clay.

Unlike gravel bed streams, sand bed streams can be assumed to have a homogeneous particle size distribution within the sampled layer (the upper few centimeters of the bed), and therefore a bulk sample is all that is required to characterize the particle size distribution.

There is a wide variety of bed material samplers available for use in sand bed streams [*Witzigman*, 1965; *Vanoni*, 1975; *ISO*, 1977; *Jansen*, 1979; *Garde and Ranga Raju*, 1985; *Federal Inter-Agency Sedimentation Project*, 1986]. Four samplers were selected for this study: Canadian Drag Bucket (sometimes referred to as a Lane or pipe dredge), US BM-54, US BMH-53, and Scoop [*Cashman*, 1988]. Photographs of each of these samplers appear in Figure 1.

The Canadian Drag Bucket (CDB) (Figure 1*a*) consists of a cylindrical steel body approximately 0.23 m long and 0.14 m in diameter with a funnel-shaped opening at one end. A 0.45 liter glass sample jar screws inside the body. A rope is attached to the handle of the sampler and a sample is collected by throwing the sampler, waiting for it to settle to the bed, and then slowly dragging the sampler upstream along the bed. The water in the sampler is decanted immediately after collection.

The US BM-54 sampler (Figure 1*b*) has a streamlined cast iron body with tail vanes, an overall length of 0.60 m, and weight of 45 kg. A 0.2 liter hinged, spring-loaded bucket is contained inside the bottom of the sampler. The cable-suspended sampler is lowered to the bed with the bucket open. When the sampler hits the bed, the release of tension on the suspension cable triggers the bucket which rotates through 180°, digging and enclosing a sample as it does so. In field tests this sampler was the most convenient to use during repetitive sampling at a single location.

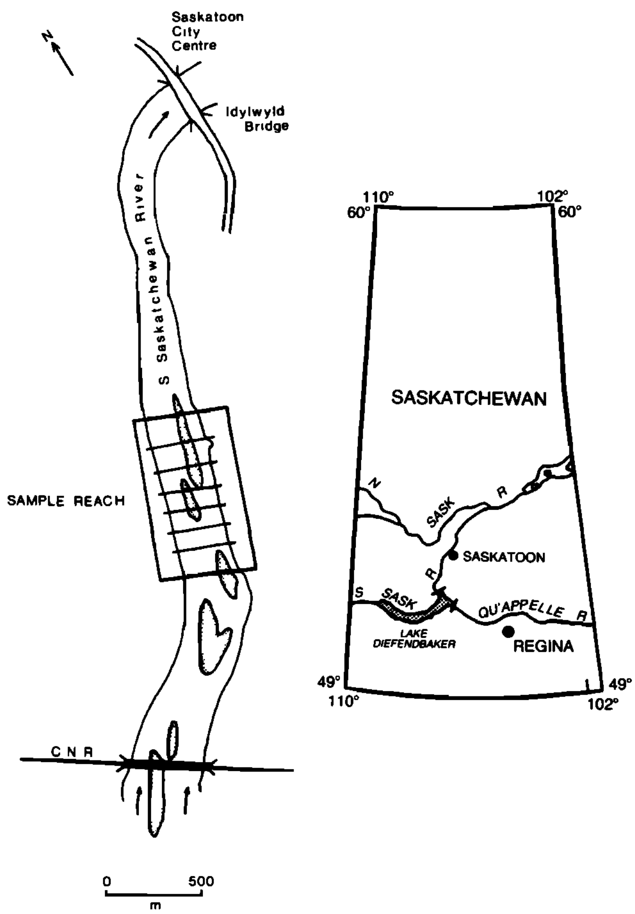

Fig. 2*a*. Reach location, South Saskatchewan River at Saskatoon.

The US BMH-53 sampler (Figure 1*c*) was designed for use in water shallow enough to wade and consists of a 0.20-m-long cylinder 0.05 m in diameter, weighing 3.4 kg. The cylinder contains a retractable piston operated by a rod that passes through the handle of the sampler. The piston is retracted as the sampler is pushed into the bed and creates sufficient suction to retain the sample while the sampler is withdrawn. Only the upper 0.025–0.05 m of the sample is retained for analysis (to correspond with the typical depth of penetration of the other samplers).

The Scoop sampler (Figure 1*d*) has a cylindrical steel body 0.26 m long and 0.10 m in diameter with a volume of 2.0 liters and weight of 8.2 kg. The cylinder is closed at one end, and the open end is bevelled to a cutting edge. Sections of steel rod are fastened into the side of the cylinder to lower the sampler to the bed. The sample is collected by scooping upstream and then rotating the sampler to face upward and downstream, as the sample is brought up to the surface, to minimize the loss of fine sediment. The water in the sampler is decanted immediately after collection.

Data Collection

Sampling was carried out in the South Saskatchewan River at Saskatoon (Figure 2*a*) on September 2 and 3, 1987. In this reach the river is approximately 250 m wide, and the channel is straight, although there are several vegetated and unvegetated sand bars both within and adjacent to the sampled reach. The right bank consists of recently dumped, vegetated fill. Discharge in the river is controlled 100 km upstream at Gardiner Dam (Lake Diefenbaker) (see Figure 2*a*) and varied from 47 to 56 $m^3 s^{-1}$ during sampling.

Six cross sections spaced approximately 100 m apart were surveyed. At one of these cross sections (referred to as the "center" cross section, XC on Figure 2*b*) three verticals were positioned across the channel. The samples collected at these three locations form the bulk of the data used to measure the precision and reproducibility of samples using the four different samplers. At verticals 1 and 3 (with depths of 1.58 and 1.98 m, respectively), using the Canadian Drag Bucket, Scoop, and US BM-54 samplers, 50 samples were collected with each, while at vertical 2, where the water was very shallow (0.22 m), the US BMH-53 was used instead of the US BM-54. At the remainder of the cross sections (X1 to X5, Figure 2*b*), single samples were collected at several verticals with the Scoop sampler to obtain data on variability in particle size within the reach.

Particle size analyses were carried out in the Water Survey of Canada laboratory in Regina. Most of the samples were dried and sieved down to 0.0625 mm, using Environment Canada procedures [*Environment Canada*, 1987]. The sieve sizes used are 16, 8, 4, 2, 1, 0.5, 0.35, 0.25, 0.177, 0.125, and 0.063 mm. In the case of Scoop samples, 25–50 from vertical 3, and all of the BM-54 samples from vertical 3, wet sieving was used because of their large fine fraction.

Results

Reproducibility of Particle Size Distribution Between Different Samplers

Table 1 shows the mean, standard deviation, and coefficient of variation of five percentiles (D_5, D_{16}, D_{50}, D_{64}, and D_{95}) of the particle size distribution and the sorting coefficient $(D_{84}/D_{16})^{1/2}$ for the 50 samples collected by each sampler at the three center cross-section verticals. The particle size curves are displayed in Figure 3 for visual comparison. There are some clear differences in the particle size distributions obtained from different samplers at a given vertical. The percentage differences $(\{[D_1 - D_2]/[D_1 + D_2]/2\} \times 100$, where D_1 and D_2 are the mean particle size of a given percentile of the particle size distribution from two different samplers) and the *t* test results of the between-sampler differences are given in Table 2.

At vertical 1 all three samplers yielded results slightly different from each other. The Canadian Drag Bucket samples are coarser on average than those from the other two samplers which gave results very close to each other. This may indicate a loss of part of the fine fraction from the Canadian Drag Bucket. The *t* test results show that differences between the samplers in the mean particle size of the five percentiles of the size distribution are significantly different from each other (even though the absolute differences in size are only 0.01 mm in some cases), except for the coarse tail of the BM-54 and Scoop samples. Similarly, the sorting coefficients are significantly different in each case, being highest for the Scoop and lowest for the BM-54.

In vertical 2, where the bed consists of well-sorted medium sand, the absolute differences in particle size between the samplers are very small. However, there are some statistically significant differences, especially between the

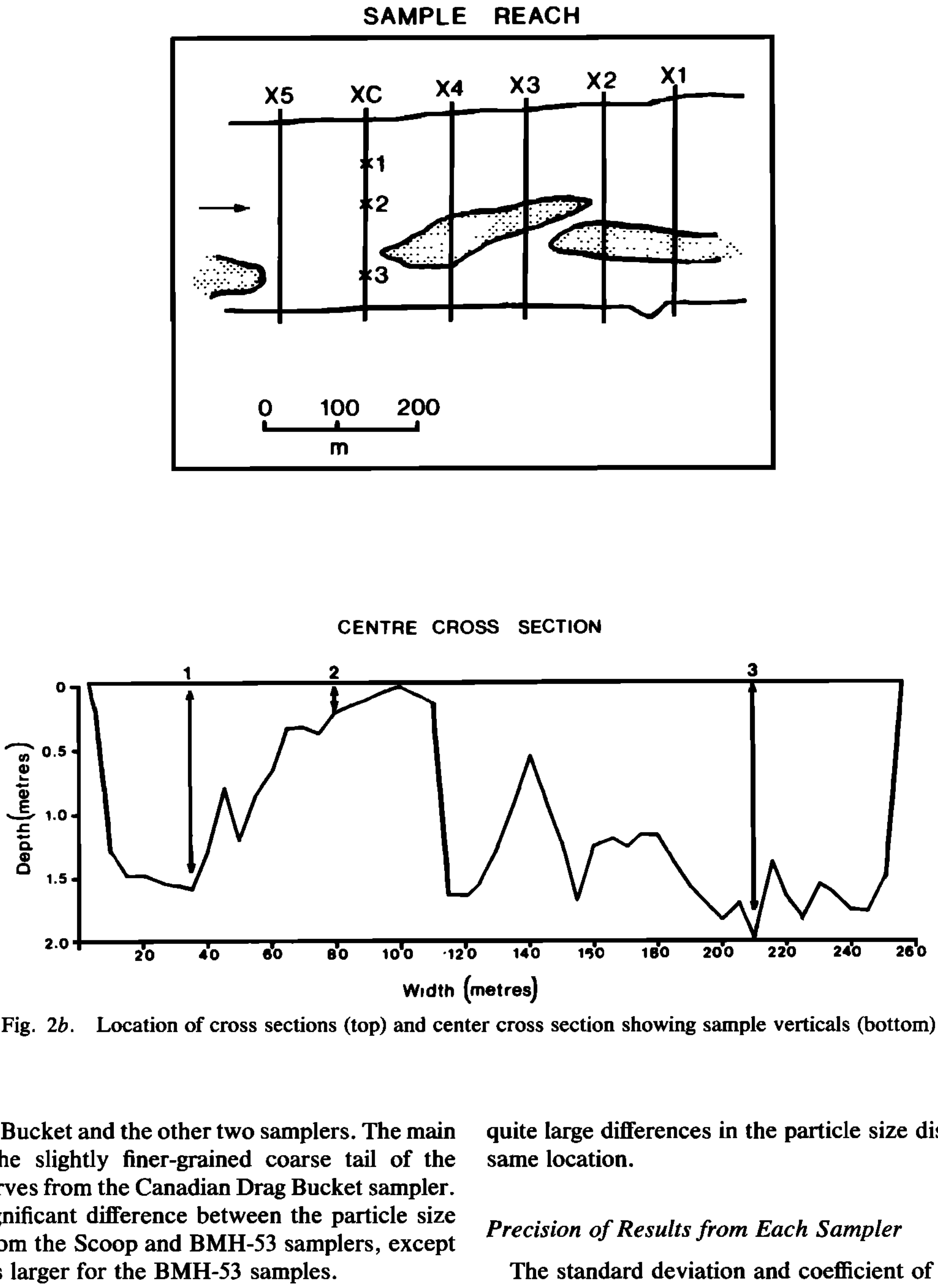

Fig. 2*b*. Location of cross sections (top) and center cross section showing sample verticals (bottom).

Canadian Drag Bucket and the other two samplers. The main difference is the slightly finer-grained coarse tail of the particle size curves from the Canadian Drag Bucket sampler. There is no significant difference between the particle size distributions from the Scoop and BMH-53 samplers, except for D_5 which is larger for the BMH-53 samples.

Comparison of the curves from vertical 3 is hampered by the large percentage of sediment in the samples smaller than 0.0625 mm. However, some comparisons are possible, and the most striking result from this vertical is the marked difference between the BM-54 samples and those from the other two samplers in the retention of the very small particles. Thus most of the BM-54 samples have between 20 and 50% silt and clay while the other samplers have a maximum of only 20–30%. From the particle size curves it is apparent that the Canadian Drag Bucket retained a slightly higher proportion of the fine sediment than the Scoop, although the results from these two samplers differ significantly only at the coarse end of the size range.

In general, there is evidence of bias in the results obtained from different samplers. This is especially true for the smaller particle sizes where differences between samplers in the collection and/or retention of the finer sediment leads to quite large differences in the particle size distribution at the same location.

Precision of Results from Each Sampler

The standard deviation and coefficient of variation of the mean are listed in Table 1 for each percentile of the 50 particle size distributions from each sampler at each vertical. Not surprisingly, the variability typically is least for D_{50} and greatest for the tails of the distribution. This is an important result because many resistance and sediment transport equations require the use of percentiles of the particle size distribution other than D_{50}.

Among the various samplers the results differ between verticals, particularly because of the failure of the Canadian Drag Bucket and Scoop samplers to retain the fine sediment at vertical 3. Ignoring vertical 3, the coefficient of variation at a given vertical is lowest for the BMH-53 and the BM-54 samplers. However, the particle size distribution of the bed material also has an influence; variability is much greater for all the samplers in the smaller sands of vertical 1 than in the better sorted, medium sand of vertical 2.

The precision of repeated samples has direct conse-

TABLE 1. Between-Sampler Comparison of Bed Material Particle Size

	D_5	D_{16}	D_{50}	D_{84}	D_{95}	$(D_{84}/D_{16})^{1/2}$
			Vertical 1			
Scoop						
Mean, mm	···	0.08	0.16	0.24	0.31	1.73
standard deviation	···	0.01	0.01	0.02	0.07	0.13
COVM*	···	0.018	0.009	0.012	0.032	0.010
CDB†						
Mean, mm	···	0.11	0.20	0.30	0.41	1.65
standard deviation	···	0.02	0.03	0.07	0.10	0.09
COVM	···	0.026	0.021	0.033	0.035	0.008
US BM-54						
Mean, mm	···	0.10	0.17	0.24	0.30	1.55
standard deviation	···	0.01	0.01	0.02	0.11	0.11
COVM	···	0.001	0.008	0.0012	0.052	0.010
			Vertical 2			
Scoop						
Mean, mm	0.13	0.23	0.36	0.48	0.62	1.41
standard deviation	0.03	0.01	0.01	0.01	0.04	0.03
COVM	0.033	0.006	0.004	0.003	0.009	0.003
CDB						
Mean, mm	0.14	0.22	0.35	0.47	0.58	1.46
standard deviation	0.02	0.01	0.01	0.01	0.02	0.02
COVM	0.020	0.006	0.004	0.003	0.009	0.003
US BMH-53						
Mean, mm	0.16	0.24	0.36	0.48	0.61	1.41
standard deviation	0.01	0.01	0.01	0.01	0.04	0.02
COVM	0.009	0.006	0.004	0.003	0.009	0.002
			Vertical 3			
Scoop						
Mean, mm	···	0.09	0.18	0.26	0.32	1.70
standard deviation	···	0.03	0.04	0.07	0.07	0.11
COVM	···	0.047	0.031	0.038	0.031	0.009
CDB						
Mean, mm	···	0.10	0.17	0.28	0.37	1.67
standard deviation	···	0.03	0.05	0.07	0.08	0.34
COVM	···	0.042	0.42	0.035	0.031	0.029
US BM-54						
Mean, mm	···	···	0.13	0.22	0.27	···
standard deviation	···	···	0.05	0.07	0.09	···
COVM	···	···	0.054	0.045	0.047	

Dots indicate that the particle size is less than 0.062 mm.
*COVM is the coefficient of variation of the mean for each percentile, which is (standard deviation/mean)/square root of sample size.
†CDB is Canadian Drag Bucket.

quences for the number of samples that need to be taken to obtain a given level of precision in the estimation of the bed material particle size distribution. Assuming a normal distribution of the 50 measurements of particle size of a given percentile of the distribution, the number of samples needed to estimate the mean particle size of that percentile to within 10% with a probability of 90% can be calculated and is given in Table 3 for each percentile, sampler, and vertical.

For estimation of D_{50} the number of samples required varies considerably. In the well-sorted sand of vertical 2 one sample is adequate, while in the fine sand, silt, and clay of vertical 3 the number of samples needed may be greater than 10 and as high as 41. Vertical 1 falls in between the other two with 2–15 samples being required. For the tails of the distribution the number of samples required is often greater than for D_{50}.

The required number of samples for a predetermined level of precision also depends on the sampler type. At vertical 1 the BM-54 and Scoop samplers require the fewest samples, while at vertical 2 the samplers differ only for D_5, for which the BMH-53 has the smallest required sample size. At vertical 3 the marked differences in the percentage of silt and clay between the BM-54 and the other two samplers results in much larger sample requirements for the BM-54. However, in this case the difference occurs because of the differences between the samplers in the retention of fine sediment in the sampler. The required number of samples is also greater for the tails of the particle size distribution than for the median.

These data are not adequate to establish comprehensive, universal guidelines for the number of samples, but it is apparent that in many cases a single sample is inadequate, and 10 or more may be required at some verticals depending upon the sampler used, the characteristics of the bed material at that location, and the percentile of the particle size distribution to be measured.

Comparison of the Average Sampled Mass

In order to ensure that the mass of the samples collected were sufficient to preclude bias due to inadequate sample mass the average, maximum, and minimum mass of the 50 samples collected by each sampler at the three verticals in

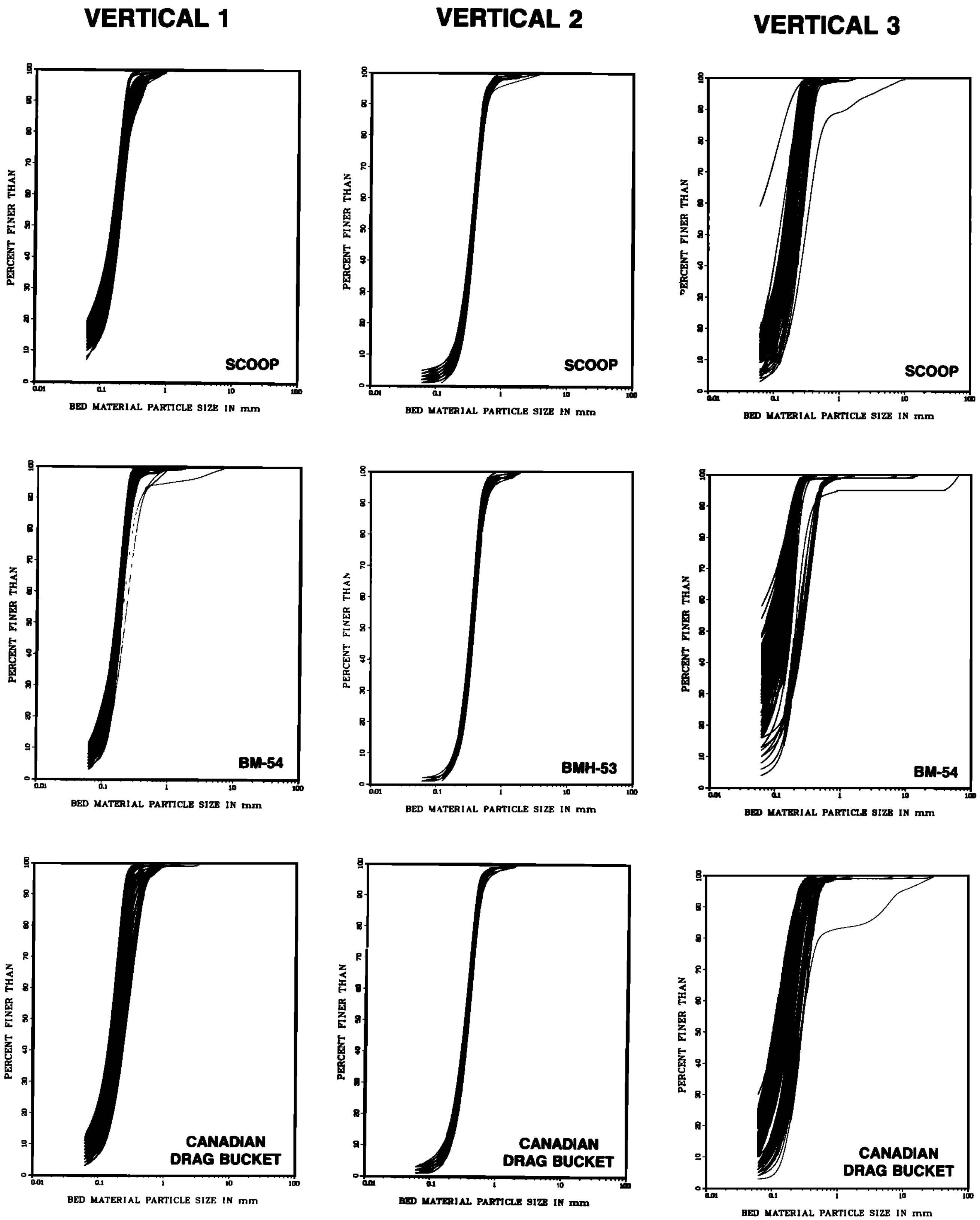

Fig. 3. Particle size distribution curves from center cross section.

the center cross section were measured and are given in Table 4. Both the BMH-53 and BM-54 give samples with an average mass of 0.2–0.3 kg. The upper limit of sample mass for the BM-54 is constrained by the volume of the sample bucket to about 0.45 kg. Some very small samples (down to 0.016 kg) were also obtained. The mass of the sample from the BMH-53 depends in part on the sampler but is also affected by the operator's choice of where to cut the core.

The Canadian Drag Bucket samples averaged 0.5–0.6 kg, with a maximum of over 1 kg. In deep water the Scoop

TABLE 2. Percentage Differences and t Test Results of Between-Sampler Comparisons of Mean Particle Size

	D_5	D_{16}	D_{50}	D_{84}	D_{95}	$(D_{84}/D_{16})^{1/2}$
			Vertical 1			
BM-54/CDB						
t	···	3.16	6.71	5.83	5.23	4.97
Percent difference	···	−9.5	−16.2	−22.2	−30.9	
BM-54/Scoop						
t	···	10.00	5.00	0.00	0.54	7.47
Percent difference	···	+22.2	+6.1	0.0	−3.3	
Scoop/CDB						
t	···	9.49	8.94	5.83	5.79	3.58
Percent difference	···	−31.6	−22.2	−22.2	−27.8	
			Vertical 2			
BMH-53/CDB						
t	6.32	10.00	5.00	5.00	4.74	12.50
Percent difference	+13.3	+8.7	+2.8	+2.1	+5.0	
BMH-53/Scoop						
t	6.71	0.00	0.00	0.00	1.25	0.00
Percent difference	+20.7	+4.2	0.0	0.0	−1.6	
Scoop/CDB						
t	1.67	10.00	5.00	5.00	6.32	9.81
Percent difference	−7.4	+4.4	+2.8	+2.1	+6.7	
			Vertical 3			
BM-54/CDB						
t	···	···	4.00	4.29	5.87	···
Percent difference	···	···	−26.7	−24.0	−31.2	
BM-54/Scoop						
t	···	···	5.52	2.86	3.10	···
Percent difference	···	···	−32.2	−16.7	−16.9	
Scoop/CDB						
t	···	1.67	1.10	1.43	3.33	0.59
Percent difference	···	−10.5	+5.7	−7.4	−14.4	

One-tailed test, $t = 1.67$, for $n = 50$ and $\alpha = 0.05$.
Two-tailed test, $t = 2.00$, for $n = 50$ and $\alpha = 0.05$.

sampler yielded approximately 0.5–0.6 kg, but in shallow water (vertical 2), where it was easier to get leverage on the sampler, the average mass was over 1.1 kg, with a maximum of 1.6 kg. While the absolute variability in sample mass was lowest for the BM-54, the relative variability (coefficient of variation) was similar for all the samplers.

Note that in all cases these average and maximum sample masses are smaller than the maximum sample masses calculated by *De Vries* [1970] and *ISO* [1977] from the sampler dimensions, assuming complete filling of the sampler. The average sample masses are more than adequate to satisfy the "high accuracy" ISO criterion (a probability of 0.1 in the determination of the mass of D_{84}, with a coefficient of variation of 1%), provided D_{84} is less than 1 mm. The smallest single sample obtained (0.016 kg) is still large enough to satisfy the "low accuracy" criterion for D_{84} up to 2 mm. The D_{84} of the South Saskatchewan River samples is less than 0.5 mm, and therefore the sample mass collected by all of the samplers is normally adequate to satisfy the ISO accuracy criteria.

TABLE 3. Approximate Number of Samples Needed to Estimate the Mean Within 10% With an Error of 90%

	D_5	D_{16}	D_{50}	D_{84}	D_{95}	$(D_{84}/D_{16})^{1/2}$
			Vertical 1			
Scoop	···	4	1	2	14	2
CDB	···	9	6	15	17	1
BM-54	···	3	1	2	37	1
			Vertical 2			
Scoop	15	1	1	1	1	1
CDB	6	1	1	1	1	1
BMH-53	1	1	1	1	1	1
			Vertical 3			
Scoop	···	31	14	20	13	1
CDB	···	25	24	17	13	12
BM-54	···	···	41	28	31	···

TABLE 4. Average Mass of Samples

Sampler	Vertical	Mean, kg	Standard Deviation	Minimum, kg	Maximum, kg
Scoop	1	0.528	0.240	0.120	1.192
	2	1.102	0.323	0.604	1.658
	3	0.630	0.371	0.039	1.489
CDB	1	0.496	0.228	0.075	0.975
	2	0.555	0.145	0.235	0.865
	3	0.550	0.251	0.058	1.024
BM-54	1	0.223	0.068	0.016	0.315
	3	0.246	0.104	0.044	0.450
BMH-53	2	0.272	0.111	0.116	0.702

Within-Reach Variability in Particle Size

A total of 18 single Scoop samples were collected in cross sections 1–5 (Figure 4, Table 5). In some cases the variation in grain size can be related to features in the channel. For example, the accumulation of fines in the lee of an island was apparent in the samples from cross section 5, while in cross section 1 the deeper right channel had coarser bed material than the left channel.

For the sample as a whole the coefficient of variation of the size of a given percentile due to spatial sorting of the bed material is quite similar for all the percentiles of the size distribution, varying from 25.6 to 33.3%. The absolute range of particle size observed within the reach is very large. The D_{50} ranges from 0.080 to 0.413 mm and D_{84} from 0.146 to 0.578 mm. These differences and errors are at least as great as those due to sampling and clearly have to be taken into account in any sampling program designed to routinely characterize the bed material; selection of the appropriate sampling location is as or more important than selection of the most reliable sampler and collection of sufficient numbers of samples.

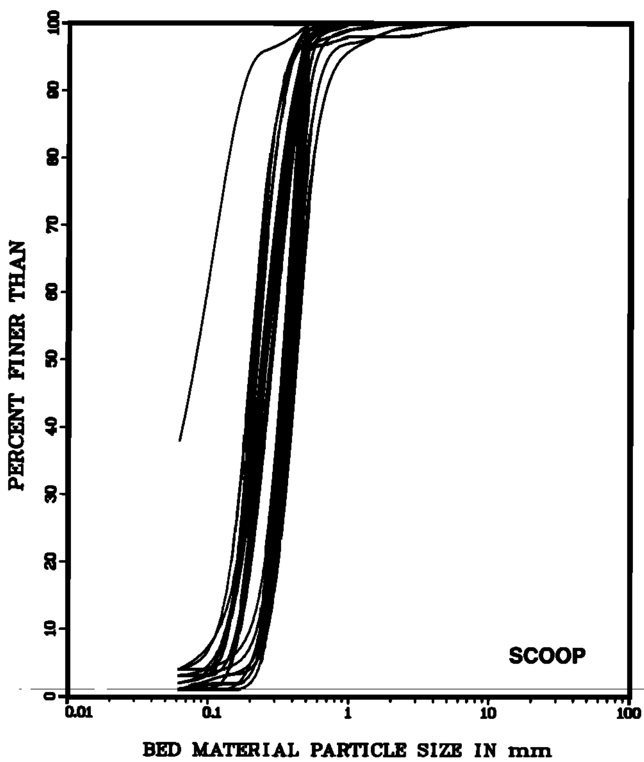

Fig. 4. Within-reach variability in particle size distribution from cross sections 1–5 (Figure 2*b*).

CONCLUSIONS

On the basis of field trials of four commonly used bed material samplers, the following conclusions are drawn about the precision and reproducibility of bed material sampling in sand bed rivers:

1. Significant differences exist between the average particle size distributions of 50 replicate samples obtained by the BM-54, BMH-53, Canadian Drag Bucket, and Scoop samplers at a given location. However, the magnitude and direction of these differences varies among the samplers and also differs at each location. The differences are least (less than 5%) in well-sorted, medium sand and greatest in fine, silty sand (up to 31% in the tails of the distribution and 28% for D_{50}). A major reason for these differences is the failure of the open samplers (Scoop and Canadian Drag Bucket) to collect and/or retain small particles during sampling and sampler recovery. Differences also result from the necessity to decant water from these samplers in the field.

2. The random error in replicate samples from one sampler at a given vertical is large enough in many cases that multiple samples (often at least 10 and occasionally more) are needed to estimate the mean within 10% with a probability of error of 0.1. Seldom is such replicate sampling undertaken. Precision is lowest (and thus the required sample size is largest) for the tails of the distribution. Only in the well-sorted, medium sand of vertical 2 would one sample be sufficient to satisfy these statistical limits of precision. The samplers differ in their precision, and although these differences depend upon the particle size distribution that is being sampled, overall the Scoop and Canadian Drag Bucket are the least precise.

3. The average sample mass collected by the four samplers is lowest for the BM-54 (0.2 kg) and greatest for the Scoop (0.6 − 1.1 kg). In all cases these masses are sufficiently great to satisfy the *ISO* [1977] "high accuracy" criterion for bias due to inadequate sample mass.

4. Spatial variability in the particle size distribution within the sampled reach exceeds the random and systematic errors due to sampling at a single location. Any sampling strategy employed must take this variability into account; the sample location is at least as important as the choice of sampler and the number of samples collected in obtaining a representative particle size distribution of the bed material.

TABLE 5. Within-Reach Variability in Bed Material Particle Size

	Particle size, mm				
	D_5	D_{16}	D_{50}	D_{84}	D_{95}
Mean	0.15	0.21	0.29	0.39	0.48
Standard deviation	0.05	0.06	0.08	0.10	0.14
Coefficient of variation, %	33.3	28.6	27.6	25.6	29.2
Maximum	0.24	0.29	0.41	0.58	0.88
Minimum	<0.06	<0.06	0.08	0.15	0.21

$n = 18$.

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