CHAPTER 5

Sediment Transport Measurements

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5.1 GENERAL

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Sediment erosion, transport, and deposition in fluvial systems are complex processes that are treated in detail in other sections of this book. Development of methods suitable for the collection of data that contribute to understanding these processes is a still-evolving science. Sediment and ancillary data are fundamental requirements for the proper management of river systems, including the design of structures, the determination of aspects of stream behavior, ascertaining the probable effect of removing an existing structure, estimation of bulk erosion, transport, and sediment delivery to the oceans, ascertaining the long-term usefulness of reservoirs and other public works, tracking movement of solid-phase contaminants, restoration of degraded or otherwise modified streams, and assistance in the calibration and validation of numerical models.

This chapter presents techniques for measuring bed-material properties and suspended and bed-load discharges. Well-established and relatively recent, yet adequately tested, sampling equipment and methodologies, with designs that are guided by sound physical and statistical principles, are described. Where appropriate, the theory behind the development of the equipment and guidelines for its use are presented.

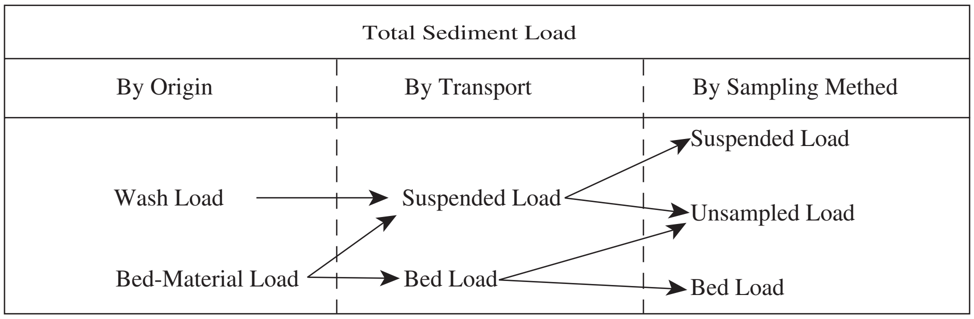
The theory and statistical methods described in the bed-material section represent the developments that have taken place mainly since the 1970s. Research on bed-material sampling techniques commenced later than research in the other two areas discussed in this chapter, and the relevant work is available almost exclusively in journals and conference proceedings. Therefore, emphasis has been placed on several key aspects of the concepts and development of bed-material sampling techniques. Improving and validating existing sediment-sampling techniques remains an active area of research today. It is worth mentioning that the methods discussed in this section can be used to estimate the necessary size of suspended or bed-load samples in order to determine their sediment size characteristics at a desirable level of accuracy.

Many of the concepts described in the section on suspended-sediment sampling were developed in the mid-twentieth century, although several new sampler types and modifications to traditional sampling methods have been developed. The collection of accurate bed-load samples has always been a challenge, because of the spatial and temporal variability associated with its transport. Several studies have successfully sampled bed load on small streams with semipermanent installations. For many projects, however, sampling programs using manually operated portable samplers continue to be the method of choice. The most common types of manually operated samplers, along with several new analyses that define improved techniques for measuring and calculating the accuracy of manually collected bed-load samples, have been reviewed. These new analyses provide needed information on the expected errors associated with bed-load data collected using a given sampling design.

Bed-material sampling is usually conducted during low flows. Bed-load and suspended-sediment sampling can be conducted over the entire hydrograph, although emphasis is usually directed toward higher flows and particularly floodflows.

5.1.1 Terminology

Bed material, suspended sediment, and bed load can be defined by their origin, or operationally by their method of collection (Fig. 5-1). Bed material is the sediment mixture of which the streambed is composed (ASTM International 1998). However, bed-material data will necessarily reflect the attributes of the sampler and its means of deployment. Hence, bed material collected by a US BM-54 would represent the topmost 5 cm of a bed composed of material finer than medium-sized pebbles.



[1]That part of the sediment load that is not collected by the depth-integrating suspended-sediment and pressure-difference bedload samplers used, depending on the type and size of the sampler(s). Unsampled-load sediment can occur in one or more of the following categories: a) sediment that passes under the nozzle of the suspended-sediment sampler when the sampler is touching the streambed and no bedload sampler is used; b) sediment small enough to pass through the bedload sampler's mesh bag; c) sediment in transport above the bedload sampler that is too large to be sampled reliably by the suspended-sediment sampler; and d) material too large to enter the bedload-sampler nozzle.

Fig. 5-1. Components of total sediment load considered by origin, by transport, and by sampling method.

The total amount of sediment in transport can be described by its origin as being composed of bed-material load plus wash load. Bed-material load is that part of the total load that is composed of particle sizes present in appreciable quantities in the shifting portions of the streambed (ASTM International 1998). Wash load is that part of the total load composed of particles, usually finer than 0.062 mm in diameter, that are found, if at all, only in relatively small quantities in the bed (ASTM International 1998). Again, the operational definition of sediment in transport is in part a function of the types of samplers used to obtain the data. Suspended-sediment and bed load discharge are the quantities of suspended sediment and bed load passing through a stream cross section per unit time, respectively. Suspended-sediment discharge can include some of the bed-material load component and includes all of the wash load component. Bed load discharge includes some of the bed-material load component. Data from physical samples of suspended sediment and bedload, necessarily obtained by use of samplers, may not equal the sum of bed-material load plus washload (Fig. 5-1). This is a result of one or more factors associated with the range in size of sediments in transport, and the characteristics and deployment methods of the suspended-sediment and bedload samplers.

5.1.2 History of Development of Sediment-Sampling Equipment

The initial attempts to develop sediment-sampling equipment were made by independent investigators. The equipment lacked calibration and was deployed using widely different operating techniques. Most instruments were designed with limited attention to, or knowledge of, sediment transport concepts or the influence of the equipment on the local flow pattern (Glysson 1989a). As a result, data obtained by different investigators before the 1940s were not comparable, nor could their accuracy be evaluated. It became apparent that reliable sediment data could not be obtained unless equipment, data collection, and analytical methods were standardized.

In 1939, various agencies of the U.S. government organized an interagency program to study methods and equipment used in measuring the sediment discharge of streams and to improve and standardize equipment and methods where practicable (FISP 1941). The Federal Interagency Sedimentation Project (FISP) (Skinner 1989; Glysson and Gray 1997) was created under the sponsorship of the Committee on Sedimentation of the Federal Water Resources Council. The comprehensive study of sampling equipment included suspended-sediment, bed-load, and bed-material samplers. As a result of research conducted by the FISP and others, an integrated system of sediment samplers, sampling, and analytical techniques has been developed and is widely used around the world.

Progress is being made in improving available or devising new technologies to measure selected characteristics of fluvial sediment. Instruments that operate on acoustic, differential density, pump, focused beam reflectance, laser diffraction, nuclear, optical backscatter, optical transmission, and spectral reflectance principles have been developed (Wren et al. 2000). Ideally, a surrogate parameter that varied as a function of the sedimentary property of interest (such as concentration, particle-size distribution, or particle or bed form movement) would be available, which could be automatically monitored and recorded.

The literature is full of descriptions of emerging technologies for measuring selected characteristics of fluvial sediment; for example, see Lee (1990); Mertes et al. (1993); Lodhi et al. (1997); Gray and Schmidt (1998); Agrawal and Pottsmith (2001); Byrne and Patiño (2001); Christiansen et al. (2001); Gartner and Cheng (2001); Land and Jones (2001); Larsen et al. (2001); Rubin et al. (2001); Schoellhamer (2001); Gray et al. (2005). Although some techniques show considerable promise, none is yet commonly accepted nor extensively used. Isokinetic samplers—primarily those developed by the FISP and described by Edwards and Glysson (1999)—generally are considered the standard against which other types of samplers are calibrated (Morris and Fan 1997; Wren et al. 2000). Adoption of any sediment surrogate technology for large-scale sediment-monitoring programs should be predicated on favorable comparisons between an adequate number of comparative data from the surrogate technology and data from isokinetic samplers collected for a sufficient time period over a broad range of flow and sedimentary conditions. Hence, the following sections focus primarily on methods for obtaining bed-material, suspended-sediment and bed-load data available at the advent of the twenty first century.

5.2 BED-MATERIAL MEASUREMENT TECHNIQUES

P. Diplas

5.2.1 Introduction

Many hydraulic, geomorphic, and ecological aspects of river behavior are closely linked to the characteristics of the material composing a river's streambed. Flood levels, sediment transport rates, and streambed stability, for example, depend on the grain-size distribution of the bed material. Similarly, the quality and quantity of stream habitats are greatly influenced by the amount of fine particles present in the streambed. Recent surveys undertaken by the U.S. Environmental Protection Agency (USEPA 1994) and the U.S. Fish and Wildlife Service (USDA 1994) concluded that stream siltation was the most important factor causing water quality impairment and adversely affecting fishery habitats in streams. Various best management practices, such as reforestation and slope stabilization, are typically employed to reduce sediment input into streams and thus minimize the adverse effects of fine sediment on stream ecology. To effectively gauge the success of these practices, the bed-material size distribution within streams must be monitored. It is therefore evident that there is a need to use accurate and efficient techniques for collecting, analyzing, and interpreting results obtained from bed-material samples.

5.2.2 Sediment-sampling Issues

For certain phenomena, and the feasibility study phases of some engineering projects, knowledge of the median grain size, D_{50}, or some other single sediment parameter might be adequate. However, for other cases, knowledge of the entire size distribution, and especially of its tails, might be essential. For example, channel grain roughness is typically associated with the coarser sizes of the bed material, e.g., D_{90}, whereas for spawning habitat studies the size of the finer portions, e.g., D_{10}, is more critical (Waters 1995). An appropriate method should sample the correct bed-material population and collect the entire range of particle sizes available within it in a way that consistently and accurately represents the parent material distribution. The analysis of the sampled material should render an unbiased grain-size distribution, such as that typically provided from a volumetric sample analyzed in terms of weight through the use of a series of sieves. Furthermore, it is desirable to estimate the effort, or sample size, required to determine various sediment sizes with a certain accuracy or degree of precision.

The requirements stated here are rather difficult to meet in the field, especially for the case of gravel-bed streams. The difficulties stem from three ubiquitous characteristics of sediment deposits in gravel streams: the presence of a wide range of sediment sizes, from clay to gravel or coarser particles, which at times may span up to five orders of magnitude; the vertical stratification in terms of particle size (Church et al. 1987; Diplas and Sutherland 1988); and the considerable spatial variability, or patchiness, of bed surface sediments (Mosley and Tindale 1985).

Three distinct horizontal layers are typically present in gravel-bed streams. The top layer, or pavement, is in direct contact with the flow and thus dictates the grain roughness of the channel boundary and the stability of the channel bed. The makeup of the second layer, or subpavement, affects the quality of spawning grounds (Diplas and Parker 1992). The third, or bottom, layer represents the bulk of the subsurface material. Although all three layers seem to contain the same range of particle sizes, the top layer is usually the coarsest and the subpavement has the highest proportion of finer particles. Each of the top two layers is usually as thick as the coarsest particle size present and all three represent different sample populations. In some cases, for example when there is no excess infeed of fine sediment into a river reach due to human activities within the surrounding basin, the second layer is absent. It is this condition that is most frequently mentioned in the literature.

Not only does a gravel bed's composition change vertically, but also it varies laterally and longitudinally. On the stream reach scale, this inhomogeneity can easily be seen on a depositional bar, which contains several distinct areas each having a different particle composition (Bluck 1982; Diplas 1994), and in the contrast between the grain sizes found in pools and in riffles (Sear 1996). On larger scales, the fining of the bed material in the downstream direction has been well documented (Church and Kellerhals 1978; Parker 1991).

The results of extensive sediment sampling undertaken by numerous researchers indicate that there is not a single grain-size distribution type capable of describing the material in different fluvial deposits. Although the lognormal has been proposed in many textbooks as the distribution representing most fluvial sediments, in reality things are more complicated. For example, it has been suggested that in about 50% of the cases, samples obtained from gravel streams possess bimodal distributions (Kondolf and Wolman 1993), whereas there is no convincing evidence to support the use of a single distribution even for materials located within the same stream.

The need to use proper procedures for collecting and analyzing bed-material samples, which take into consideration some of the features observed in natural streams, has only recently been recognized. Such procedures are necessary for field and laboratory studies as well as for calibrating and validating numerical models dealing with stream behavior. Considerable effort has been devoted to this subject during the past two decades.

5.2.3 Sample Collection and Analysis Methods

Some of the methods commonly used for sediment sampling include volumetric, grid, areal, transect, and photographic methods. The analysis of a sample may vary depending on the method used for collecting it.

Volumetric or bulk sampling is the method most commonly used in obtaining the size distribution of the grains in a sediment deposit. The extracted sample consists of a predetermined volume that is large enough so that its dimensions are independent of the dimensions of individual grains (Kellerhals and Bray 1971). The sample is then sieved, and the results are plotted in terms of grain (sieve) size versus percentage by weight passing that sieve size. One tonne of material is considered a practical limit for hand sieving (Church et al. 1987). Dry sieving is usually limited to particles having diameter equal to or coarser than 0.0625 mm. For particles smaller than this size, hydraulic settling methods are typically employed. These two methods may not provide equivalent measures of particle size. Bulk sampling procedures are appropriate for deposits that are isotropic with respect to grain size and other sediment properties (e.g., particle shape and density), such as sandy streams and the bottom layers of gravel streams. Bulk sampling is desirable because it provides unbiased estimates of the size distribution of the sediments available in the deposit. Strictly speaking, for the volumetric sample to be unbiased it should be analyzed in terms of the volumes occupied by the various grain sizes. However, when the specific weight of all the particles in the sample is the same, a condition that is typically met in most samples, this is equivalent to analyzing the sample in terms of weight through the use of the sieves. A question that arises is with respect to the minimum excavation depth necessary to render a sample volumetric. Experiments have indicated that the minimum depth required for a sample to be volumetric is about twice the size of the largest particle present in the sampled deposit (Diplas and Fripp 1992).

The pavement and subpavement layers, though, each having thickness roughly equal to the size of the coarsest particle present, have volumes that are dependent upon the size of the sediments and thus cannot be sampled volumetrically (Kellerhals and Bray 1971). A volumetric sample of a gravel bed would combine the different sample populations found in the pavement, subpavement, and bottom layers. The resulting grain-size distribution would not accurately describe any of these layers. Therefore, in the presence of vertical size (or any other sediment property) stratification, it is necessary to devise surface-oriented methods that would be able to collect sediment from each stratum separately. Such methods should be able to infer three-dimensional information about the makeup of the sediment deposit from things represented on a two-dimensional surface.

Wolman (1954) was the first to introduce the use of the grid method for sampling fluvial sediments. This method is suitable for collecting sediment from a single layer of bed material such as the pavement. The sample consists of only the particles that lie directly below an established grid covering the area of interest. The grid may be established in several ways. A wire mesh may overlie the sampled area or for larger areas a pacing procedure may be used (Kellerhals and Bray 1971). A method used widely in the field is a variant known as Wolman's walk method. In this method an operator paces off at regular intervals and picks up the particle below his toe. Systematic sampling on a predefined, regular grid gives the highest accuracy for a given number of collected stones (Underwood 1970). Random sampling is not as efficient.

The particle's size is usually measured with a gravelometer (Hey and Thorne 1983). Gravelometers, shown in Fig. 5-2, are templates that contain square holes consistent with sieve openings. The smallest aperture that a particle can fit through is recorded as the grain size. Gravelometers are convenient for measuring particles that can be handled with one hand, up to about 216 mm (Church et al. 1987). However, some particles, even smaller than 216 mm, might be buried within the channel bed and thus it might be difficult to remove and measure them (Marcus et al. 1995). A gravelometer, together with waterproof paper or a tape recorder, makes it possible

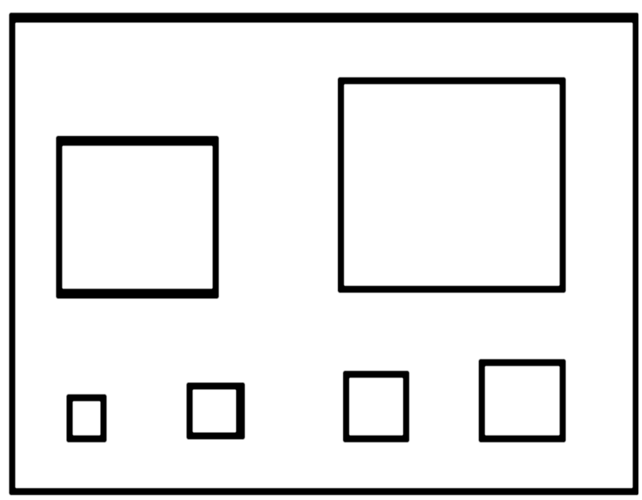


Fig. 5-2. A gravelometer.

for a single operator to sample an area and record the number, size, and possibly location of stones with the help of a GPS apparatus or a well-defined grid, without retaining any of the material (Fripp and Diplas 1993). Larger or embedded stones, however, may have to be measured with a tape. In this case, the intermediate axis is the closest to a sieve diameter. The distribution is obtained by plotting the grain size versus the percentage of stones in the sample that are finer than this size. This method is a type of grid-by-number sampling. In the presence of very large, exposed boulders, areal photos might be necessary to account for their contribution to the overall grain-size distribution.

To reduce the effort spent in the field, an adaptation of the grid-by-number approach has been proposed, using photographs of a sediment deposit, together with a grid of known spacing (Ritter and Helley 1969; Adams 1979). Determining the actual dimensions of the particles from the photographs is the main difficulty encountered in this case. The results seem to be biased, typically smaller than the real particle sizes measured in the field (Kellerhals and Bray 1971; Church et al. 1987). This bias is attributed to imbrication angle, grain packing, shadow effects, and scale distortion, factors that tend to be variable from site to site. To overcome the limitations of the photographic method, Ibbeken and Schleyer (1986), among others, have proposed digitizing the particle outline from an enlarged print and then measuring its dimensions. The use of the photographic method is deemed to be adequate for estimating the median size of a sediment deposit, containing gravel and larger particles, with moderate accuracy (Church et al. 1987). Recent developments in image analysis hold promise for further improvements in the use of the photographic method (Russ and Dehoff 2000).

In the absence of any structural features within a riverbed, the grid spacing does not affect the outcome of a sampling exercise. The only requirement in this case is that if two or more grid points fall on the same particle, the particle must be counted as many times. However, in natural streams, particle clusters and other features tend to dominate the bed morphology (Church et al. 1987; Hassan and Church 2000). To avoid serially correlated results it is therefore recommended that the spacing between grid points be at least $2D_{max}$, where D_{max} is the largest particle size present in the sampled deposit (Rice and Church 1998). About 1,500 particles per day can be measured and recorded in an exposed area by a team of two operators using a gravelometer (Rice and Church 1996). The corresponding time for the case of a submerged deposit will be longer and will depend on the depth and temperature of the water.

An areal sample consists of all the grains that are exposed on the surface of a specified area. One can use wax, clay, or other adhesives, paint, and photographs to sample an area (Kellerhals and Bray 1971; Adams 1979; Diplas and Sutherland 1988; McEwan et al. 2000). If an area is spray-painted, the painted particles can later be picked by hand. Wax poured onto the surface of a sample will harden and remove all of the surface particles and possibly some below that. The wax sample is melted and poured away, leaving the grains to be sieved. Moist pottery clay may also be used to obtain a surface sample; however, unlike wax, it can be used underwater as well as on dry surfaces, making it more suitable for field sampling (Diplas and Fripp 1992). A pistonlike apparatus, shown in Fig. 5-3, contains a round flat plate that is covered with a layer of clay. Surrounding the piston is a plastic shield, which protects the sample from the river's current. The piston is pushed against the surface material and retrieves the gravel sample. Finally, the sample is placed into a sieve with openings smaller than the smallest particle of interest and wet sieved to remove the clay (Fripp and Diplas 1993). The size distribution is obtained by plotting size versus percent weight in total sample. A sample recorded in this manner is known as an area-by-weight sample.

5.2.4 Bias of Sampling Methods

5.2.4.1 Equivalence of Samples Grid and areal sampling techniques allow collecting a sample from a specific population, such as the pavement and subpavement, but cannot be compared to one another because surface-oriented

Fig. 5-3. The device used to collect areal samples. A thin layer of clay has been applied on the flat plate inside the piston.

samples, like all nonvolumetric samples, are biased (Kellerhals and Bray 1971).

In general, for a sampling procedure to be unbiased, the exponent of the removed sample, expressed as D^y, minus the exponent of the method used for analysis, expressed as D^z, should be zero. This renders the sampling procedure dimensionless (Underwood 1970). For example, a bulk sample is unbiased because $y = z = 3$. Similarly, a grid sample analyzed by number is unbiased and equivalent to a volumetric sample because $y = z = 0$. The zero-dimensionality of these sampling and analysis methods allows the presentation of the results as a fraction or percent. Delesse (1848) was the first to show that the volume fraction of solids is equal to their area fraction captured in a planar section ($y = z = 2$). The equivalency of the point count fraction and the volume fraction of solids was demonstrated for the first time by Thomson (1930). An areal sample, though analyzed in terms of weight, is biased. To convert such an areal sample into its volumetric equivalent, Kellerhals and Bray (1971) suggested the formula

$$p(V-W)_i = Cp_i(A)\, D_i^x \tag{5-1}$$

where

$p(V-W)_i$ = percentage of material retained on sieve size i based on a volumetric sample;
$p(A)_i$ = percentage of material retained on sieve size i by an areal sampling method;
$D_i = \sqrt{D_i\, D_{i+1}}$ = geometric mean of two consecutive sieve sizes i and $i+1$; and
C = a constant that is used to adjust the sum of the converted volumetric equivalent percentiles to 100.

The exponent x is equal to $y - z$, and as such it depends on the type of adhesive used in collecting the sample. For example, when an adhesive that removes only the rocks found at the very top of the sampled surface was used ($y = 2$ and $z = 3$), as with clay or adhesive tape, laboratory tests indicated that $x = -1$, in agreement with the theory (Diplas and Sutherland 1988). However, when wax was used as the adhesive, x attained an average value of -0.47 (Diplas and Fripp 1992). Furthermore, the exponent for all the clay samples remained relatively constant, whereas the exponent for the wax samples varied significantly depending on the wax temperature and the makeup of the bed material. Wax penetrates the pores of the surface material and picks up subsurface grains, rendering the sample partly volumetric rather than strictly areal ($2 \le y \le 3$) (Church et al. 1987; Diplas and Fripp 1992). As a result, the value of the exponent x for wax samples can vary between -1 and 0 (Diplas and Sutherland 1988). Therefore, wax does not consistently remove the same material and should be avoided as an adhesive for sampling. Fig. 5-4 shows a clay sample analyzed by weight and a volumetric sample, both obtained from the same deposit. Whereas the areal sample significantly overestimates the grain-size characteristics of the sediment deposit, the converted size distribution (using Eq. 5-1 with $x = -1$) is close to the distribution obtained from the volumetric approach. As explained earlier, a grid-by-number sample is unbiased and thus the exponent x becomes zero. This is demonstrated in Fig. 5-5 for a sample of known volumetric size distribution. A complete list of the values of the exponent x necessary to convert a sample collected and analyzed with one method to that of another is shown in Table 5-1.

An approach to sampling a sediment deposit that has been suggested in the literature is to remove all the material up to the depth of the largest particle present and analyze it by weight. Such a sample provides a volumetric representation of the smallest grains, an areal representation of the coarsest grains, and in between for the intermediate sizes. In this case $2 \le y \le 3$ and $z = 3$. A more accurate statement, though, would be that $y = 3$ for the smallest grains, $y = 2$ for the coarsest ones, and $2 < y < 3$ for the

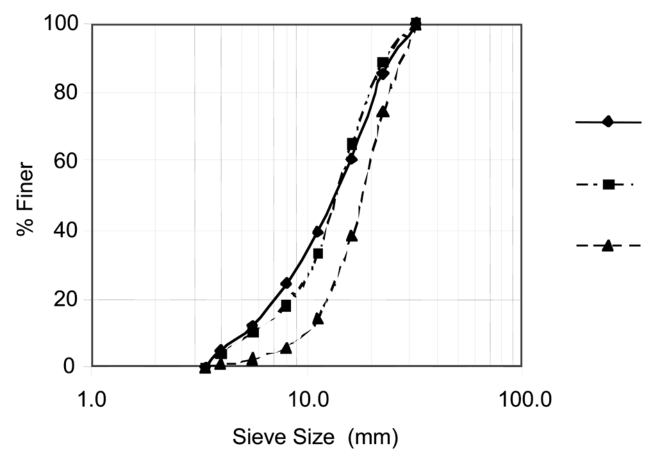


Fig. 5-4. A clay sample analyzed by weight (triangles) and converted using Eq. 5-1 with $x = -1$ (squares). Diamonds represent the results of a volumetric sample of the same deposit analyzed by weight.

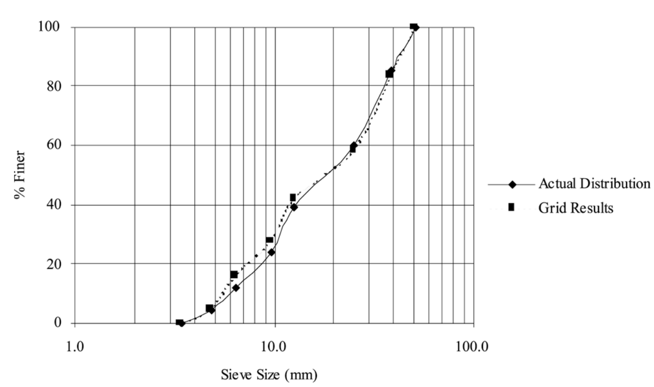


Fig. 5-5. Results of a 400-stone grid sample performed on a natural sediment deposit with the actual grain-size distribution curve.

Table 5-1 Conversions Based on the Recommendations of Kellerhals and Bray (1971)

	Conversion to								
Conversion From	Volume-by-weight	Volume-by-area	Volume-by-number	Grid-by-weight	Grid-by-area	Grid-by-number	Area-by-weight	Area-by-area	Area-by-number
Volume-by-weight	1	$1/D$	$1/D^3$	D^3	D^2	1	D	1	$1/D^2$
Volume-by-area	D	1	$1/D^2$	D^4	D^3	D	D^2	D	$1/D$
Volume-by-number	D^3	D^2	1	D^6	D^5	D^3	D^4	D^3	D
Grid-by-weight	$1/D^3$	$1/D^4$	$1/D^6$	1	$1/D$	$1/D^3$	$1/D^2$	$1/D^3$	$1/D^5$
Grid-by-area	$1/D^2$	$1/D^3$	$1/D^5$	D	1	$1/D^2$	$1/D$	$1/D^2$	$1/D^4$
Grid-by-number	1	$1/D$	$1/D^3$	D^3	D^2	1	D	1	$1/D^2$
Area-by-weight	$1/D$	$1/D^2$	$1/D^4$	D^2	D	$1/D$	1	$1/D$	$1/D^3$
Area-by-area	1	$1/D$	$1/D^3$	D^3	D^2	1	D	1	$1/D^2$
Area-by-number	D^2	D	$1/D$	D^5	D^4	D^2	D^3	D^2	1

intermediate sizes. Therefore, this procedure is biased, resulting in a sample that overestimates the degree of coarseness of the material. To render this sample unbiased, it is necessary to use different values for the exponent x in Eq. (5-1) for the different parts of the sampled material, with $x = 0$ for the smallest particles and $x = -1$ for the coarsest (see Fig. 5-4 in Diplas and Fripp 1992). An average value of x is typically employed in Eq. (5-1) to obtain the approximately equivalent volumetric distribution. Although this value depends on the makeup of the particular deposit, a limited number of tests have indicated that $x \approx -0.4$ for samples having a depth of about D_{90} (Diplas and Fripp 1992).

In most cases, the exponent in Eq. (5-1) assumes values different from unity. This suggests that nonvolumetric samples are nonlinearly biased. Therefore, samples that are not volumetric equivalents cannot be compared directly with each other, even if the samples are collected and analyzed by the same method (Diplas 1992; Diplas and Fripp 1992). In other words, each nonvolumetric sample has its own bias, which depends on the sampling method used and the actual size distribution of the sampled deposit, and must be converted to a volumetric (unbiased) equivalent before comparing it to a sample taken by the same or another method. This is demonstrated in Fig. 5-6, which shows the size distributions of two samples obtained by the use of clay from two different deposits and analyzed by weight through the use of sieves. These deposits have volumetric grain-size distributions with identical median values (8 mm) but different standard deviations. The corresponding median values of the areal samples analyzed by weight, however, are 14.5 and 22.8 mm. Thus, an appropriate method must first sample the correct population, and second convert it to a volumetric equivalent.

5.2.4.2 Truncation of Sample Populations Sediment size distributions also become biased when the technique employed cannot sample the entire range of grain sizes in a representative way, thus resulting in a truncated sample.

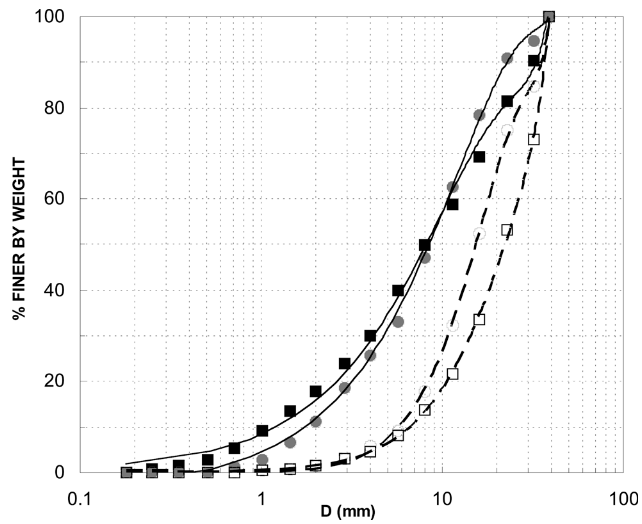


Fig. 5-6. Clay samples (open symbols) of two sediment deposits and the corresponding volumetric samples (solid symbols).

Truncation can occur at either the lower or upper end of a size range. When material smaller or larger than a specific size is truncated from the sample, it changes the frequency distribution of the particles and all its statistical measures (Fripp and Diplas 1993). It is difficult to determine the degree of change because the percentage of the bed material that belongs to the truncated portion of the sample is unknown. Truncation, besides its effect on determining D_{50} and other statistical parameters, may severely affect the estimates for D_{90} and D_{10}.

Truncation of the smaller size particles occurs in the Wolman's walk method and similar grid-sampling techniques. The reason for this is the inability of an operator whose eyes are averted from the sampled location to distinguish among particles smaller than about 15 mm, approximately the width of the index finger, in an unbiased way (Fripp and Diplas 1993). Other researchers suggest that, for a properly trained person, truncation for grid samples starts between 2 and 8 mm (Wolman 1954; Kellerhals and Bray 1971). The more conservative values would be appropriate for sampling under water, where the problem becomes even more difficult because of low water temperature and the use of gloves by operators. One way to partially remedy the problem when the operator is unable to choose between two or more small particles is to designate that the outcome of the trial resulted in a particle smaller than a predetermined size, say 10 mm. Although the shape of the grain-size distribution below this size is not known, the proportion of these particles is estimated, thus avoiding a truncated sample (Petrie and Diplas 2000).

Truncation of the larger particle sizes may occur when clay, or some other adhesive, is used to obtain an areal sample in the presence of very coarse particles. For example, clay is only capable of consistently removing particles less than about 40 mm (Diplas and Fripp 1992).

5.2.4.3 Operator Error The accuracy of a grid sample is influenced by random and systematic errors. The former are due to the natural variability of the grain sizes present within the sediment deposit and their significance is reduced as the sample size increases, according to some statistical criteria. The latter are associated with biases exhibited by the operator and are not affected by the sample size (Hey and Thorne 1983). As a result, as the sample size increases, differences between samples obtained by different operators become more pronounced. Unless special precautions are taken, Hey and Thorne (1983) concluded that systematic, operator-related errors become the dominant type for grid samples exceeding 100 particles. There are two major sources of operator bias: (1) inappropriate selection of particles, and (2) erroneous measurement of their size (Hey and Thorne 1983; Marcus et al. 1995). The first can be rectified by using well-defined grid points that unambiguously identify the particle to be chosen. This is more difficult to accomplish under submerged conditions. Selection and measurement of particles below a size that operators cannot distinguish (e.g., 10 mm) should also be avoided. Much larger errors are exhibited within this smaller size range when samples obtained by different operators are compared (Marcus et al. 1995). The second operator bias can be corrected by using a consistent and repeatable means of measuring the particle size, such as the gravelometer. The best strategy for curtailing systematic sampling errors is to provide the operators with thorough training in the field. It has been suggested that, when possible, a single, carefully trained operator be employed to monitor changes in a sediment deposit over space or time (Hey and Thorne 1983; Marcus et al. 1995; Wohl et al. 1996). Although such an approach does not necessarily preclude the occurrence of bias, it has the potential for providing more consistent results.

5.2.5 Sample Size and Accuracy

5.2.5.1 Determining Sample Size If truncation is not a problem, and a sample is converted to a volumetric equivalent, an unbiased sample has been obtained. However, one important issue remains, and that is its accuracy. How accurate a sample needs to be can vary depending on what the results are being used for. The accuracy with which a sample describes the true statistical parameters of the bed material depends a great deal on its size, the shape of its size distribution, and its standard deviation. Typically, the larger the sample size, the higher the accuracy. Unfortunately, sampling large amounts of material is often physically or economically impractical. Considerable effort has been spent on calculating the minimum sample size needed to obtain a desired level of accuracy. Normally, the sample size is determined either by weight or by the number of stones.

5.2.5.2 Sample Size Determined by Number The size of grid sample necessary to provide consistent estimates of the mean grain size of a sediment deposit has been discussed frequently in the literature. Originally, Wolman (1954) suggested that 100 stones constituted an adequate sample size. Bray (1972) and Church and Kellerhals (1978) found that samples of 50 stones were sufficient. Hey and Thorne (1983) stated that samples as small as 40 stones provide repeatable estimates of the mean grain size, whereas Mosley and Tindale (1985) suggested 70 particles, and Edwards and Glysson (1999) indicated that at least 100 pebbles should be collected. Based on these results and the experience of others (e.g., Yuzyk 1986; Kondolf 1997), it is proposed that 100-stone grid samples be used to provide routine estimates of the sediment mean grain size.

Even more important to consider, though, is the development of methods that specify the sample size necessary to determine a certain sample characteristic, e.g., the median particle diameter, with a desired level of accuracy after the collected material has been analyzed. The level of accuracy may be considered in absolute terms, e.g., mm or ϕ (phi) units, or in relative terms, e.g., percent error. The results of a grid-by-number procedure are presented in terms of frequency by number, a process that is well suited to statistical treatment. Statistical methods can be used in a variety of ways. If the distribution type describing the particle sizes available in a deposit, together with an estimate of its mean and standard deviation values, is known beforehand, well-established methods that are easily accessible from books can be employed (e.g., Gilbert 1987). If such information is not available, as is typically the case, either a two-stage sampling approach or methods that do not require prior knowledge of the distribution should be used.

The first step in a two-stage sampling scheme is to undertake a preliminary or pilot sampling program that will provide an advance estimate of the variation that a particle size of interest, e.g., D_{84}, exhibits (Durand 1971). These results can be used to guide the extent of the sampling effort required to determine this size with a desired degree of accuracy and confidence level. Student's *t*-distribution can be used for that purpose (Gilbert 1987; Durand 1971). This approach is recommended by the International Organization of Standards (ISO 1992).

The bootstrap (Rice and Church 1996) and the binomial (Fripp and Diplas 1993) are two methods that can be used to estimate the sample size necessary to determine the confidence intervals around a *specific* grain-size percentile without knowing or making any assumptions about the grain-size distribution type of the sampled deposit (Petrie and Diplas 2000). The bootstrap is a numerically intensive method that requires a grid sample that is sufficiently large, possibly in excess of 1,000 or even 2,000 stones (Sprent 1998), to accurately represent the population grain-size distribution of the parent material. The sizes of all these stones are recorded and subsequently stored in a computer. The standard error for a given percentile is determined by considering its variation obtained from a great number of subsamples, all drawn from the large grid sample in a random fashion through the use of a computer program. Each subsample has the same number of particles and represents a replicate sample that could have been made in the field. To obtain stable error estimates, it is recommended that more than 100, and preferably closer to 200, sub/replicate samples be considered (Efron and Tibshirani 1991; Rice and Church 1996). The largest subsample size considered with the bootstrap method should not exceed one-third the size of the actual grid sample collected in the field.

The use of binomial distribution for grid sampling was initially suggested by Fripp and Diplas (1993) and modified by Petrie and Diplas (2000) for estimating grid sample errors at specified percentiles. The binomial distribution considers only two possibilities for each particle sampled: (1) it is within a specified size class (e.g., smaller than a certain size) or (2) it is outside the specified size class (Ott 1988). Fig. 5-7 shows the way that the results of this approach can be used when the percentiles of interest are D_{50}, D_{16}, and D_{84}. Based on the accuracy level required, 95% in this case, the necessary sample size that will allow an acceptable error band is determined. For example, a grid sample of 100 stones is necessary to keep the confidence intervals around the median size D_{50} within ±10% (D_{40} and D_{60} of the grain-size distribution). The error around D_{50} in absolute terms, e.g., mm or ϕ (phi) units, is determined after the sample has been collected, analyzed, and plotted in terms of a frequency-by-number distribution so that D_{40} and D_{60} can be determined. It is through this last step that the standard deviation of the grain-size distribution is factored in the error estimate. Fig. 5-8 provides a graph for determining the error bands for D_{10}, D_{30}, D_{70}, and D_{90} at 95% accuracy levels, or confidence coefficient, α, of 0.05. The validity of this approach has been verified through extensive laboratory tests and computer simulations (Diplas and Crowder 1997; Petrie and Diplas 2000).

Except for the case of median size, the confidence intervals obtained through the use of the exact binomial

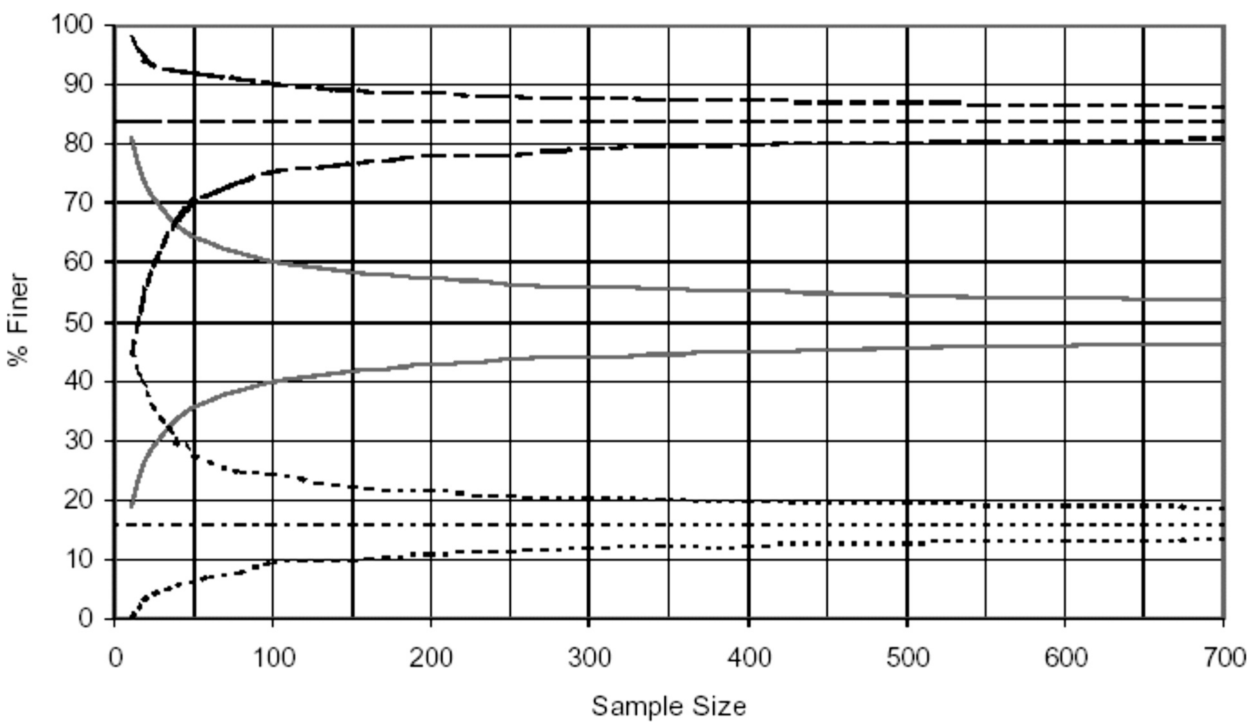


Fig. 5-7. Binomial sample size determination graph for D_{16}, D_{50}, and D_{84} for $\alpha = 0.05$.

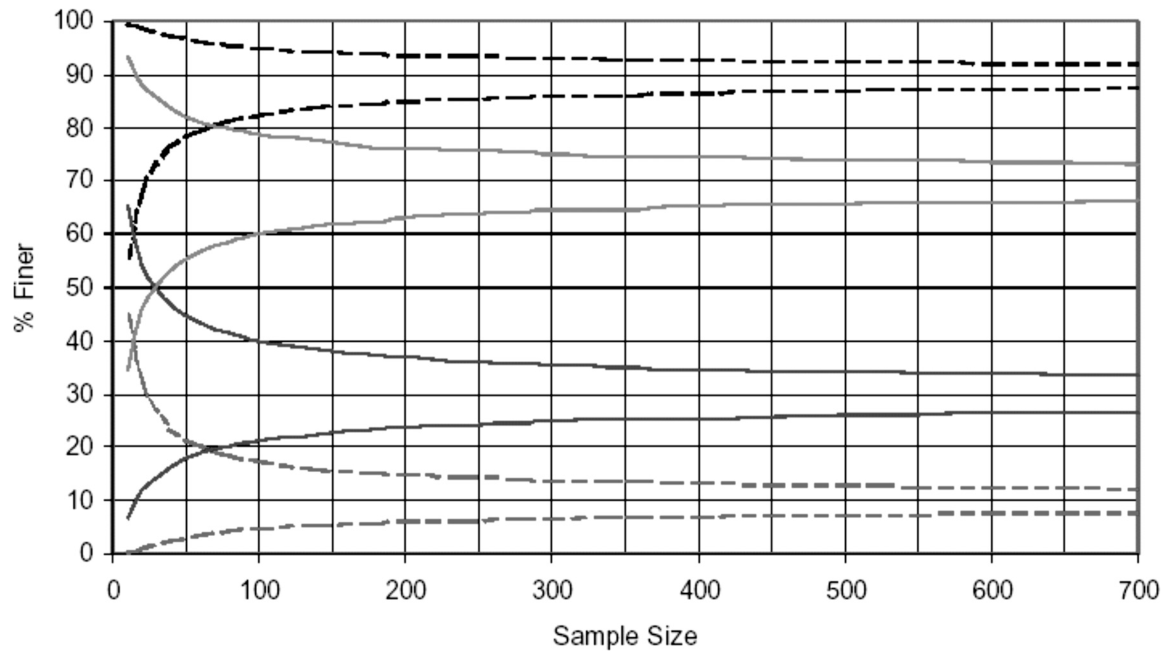


Fig. 5-8. Binomial size determination graph for D_{10}, D_{30}, D_{70}, and D_{90} for $\alpha = 0.05$.

distribution are not symmetric around a specified percentile (Figs. 5-7 and 5-8). As can be seen from Figs. 5-7 and 5-8, the largest percentile error for a given sample size is always that for the median grain size. This does not necessarily mean that D_{50} suffers the largest error in absolute terms. As a matter of fact, because the part of the cumulative distribution around D_{50} tends to have the steepest slope, the median size will typically have the smallest absolute error. Similarly, the fact that two percentiles equidistant from the median size, e.g., D_{10} and D_{90}, have the same relative percent error (Fig. 5-8) does not mean that these sizes will have the same absolute error in mm or ϕ units as well, except for the case of a symmetric distribution. The absolute error depends on the shape of the distribution surrounding the percentile of interest. Thus, the binomial approach supports the well-accepted notion that for a distribution that is skewed toward the coarser grains, a given sample size will result in better estimates of the coarser particles, e.g., D_{90}, than the finer particles, e.g., D_{10}. Furthermore, for two distributions having the same numerical value for a certain percentile, e.g., D_{50}, but different overall ranges of particle sizes, or different standard deviations, the relative percent error will be the same but the absolute error will be larger for the distribution having the larger standard deviation (Fripp and Diplas 1993).

The curves describing the confidence intervals in Figs. 5-7 and 5-8 approximately follow the expression $1/\sqrt{n}$, where n is the number of stones in the sample. This suggests that if a sample is quadrupled in size, a 50% reduction of the percentage error results. For example, Fig. 5-7 indicates that a 400-stone sample provides confidence intervals at a distance of $\pm 5\%$ around the median diameter, compared to $\pm 10\%$ for a sample of 100 stones. It is therefore suggested that for $\alpha = 0.05$, sample sizes larger than 400 stones are not warranted for most studies, because significantly greater effort is required to achieve relatively modest gains in accuracy (Fripp and Diplas 1993; Rice and Church 1996).

The use of the exact binomial distribution in calculating the required sample size, n, given the particle size value of interest (p_i in percent, e.g., D_{84}), the desirable accuracy level, α, and the maximum allowable error, E, requires a rather tedious iterative procedure. Nowadays, though, computer programs are available for these types of calculations. Another, much simpler approach would be to employ the normal approximation of the binomial distribution. This approximation is valid when both np_i and $n(1-p_i)$ are larger than 20, whereas for values between 5 and 20 it can still be employed, especially if the continuity correction is implemented (Ott 1988). Experience has shown that, except for the case of small sample size and the case of the particle size of interest being very fine or very coarse, the estimates obtained by the normal distribution approximate those obtained through the exact binomial fairly well. The required sample size, n, based on the binomial approximation is estimated by the expression

$$n = \frac{z^2_{(\alpha/2)}\, p_i\,(1-p_i)}{E^2} \tag{5-2}$$

where

$z_{(\alpha/2)}$ = a value obtained from tables prepared for the normal distribution curve for a given confidence interval of $100(1-\alpha)$.

As can be seen from Eq. (5-2), in contrast to the results provided by the exact binomial, the normal approximation of the binomial distribution results in symmetric confidence intervals, with the upper confidence limit for p_i given by $\tilde{p}_{iu} = p_i + E$ and the lower limit by $\tilde{p}_{il} = p_i - E$.

Whenever it is desirable to generate confidence intervals about the entire grain-size distribution, the multinomial distribution needs to be employed to account for all possible outcomes of sieve analysis dictated by the number of particle size classes considered (Burdick and Graybill 1992; Petrie and Diplas 2000). Whereas the binomial and bootstrap methods deal with a single size or percentile, one confidence interval at a time, the multinomial approach deals with all size classes at the same time, simultaneous confidence intervals. Therefore, a simultaneous confidence interval with a confidence level of α around a grain-size curve states that there is a probability of $(1-\alpha)$ that the population grain-size curve is within the confidence interval at each size class. As a result, simultaneous confidence intervals are wider than one-at-a-time intervals. The additional parameter that needs to be considered in the multinomial case is the number of sieves or size classes. Even though this number is not known before the sample is collected, it can be estimated by surveying the site and making a visual approximation of the largest and smallest particles present in the deposit. The range of sizes between these two particles, together with the estimated number of particles that need to be removed, will dictate the number of sieves necessary for the analysis of the sample (Emerson and Hoaglin 1983; Russ and Dehoff 2000). Fig. 5-9 shows the error bands around the median size diameter, with $\alpha = 0.05$, calculated using the multinomial distribution for different numbers of sieves k (Petrie and Diplas 2000). The binomial distribution is a special case when $k = 2$. The Goodman (1965) method, one of several techniques that have been proposed for calculating simultaneous confidence intervals for multinomial proportions, has been used to draw these curves. This method is relatively easy to use and consistently meets the required confidence coefficient (May and Johnson 1997). The formula proposed by Goodman is as follows,

$$n(p_i - \hat{p}_i)^2 = \chi^2_{\alpha/k,1}\,\hat{p}_i(1-\hat{p}_i) \quad i = 1, 2, \ldots, k \qquad (5\text{-}3)$$

where

n = sample size;
p_i = sample estimate for proportion of size class i;
$\tilde{p}_i$ = confidence interval proportions for size class i; and
$\chi^2_{\alpha/k,1}$ = upper $100(1-\alpha/k)$ percentage point of the χ^2 distribution with one degree of freedom.

Equation (5-3) provides two p_i values for each size class considered, one corresponding to the proportion for the upper confidence interval ($\tilde{p}_{iu} = p_i + E_{iu}$) and another for the lower confidence interval ($\tilde{p}_{il} = p_i - E_{il}$). For the median size

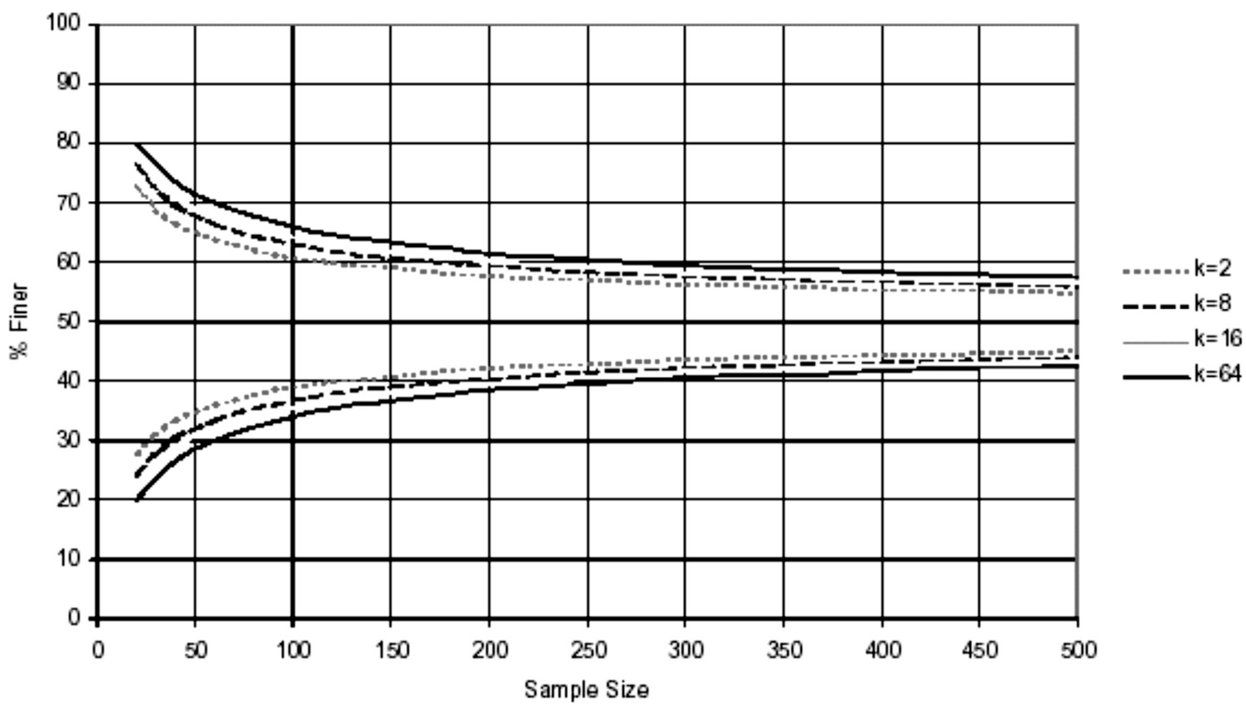


Fig. 5-9. Error bands around D_{50} for different grid sample sizes and numbers of sieves k obtained using the multinomial distribution ($\alpha = 0.05$).

($p_i = D_{50}$), $E_{50u} = E_{50l}$, whereas for every other percentile the upper and lower errors are different.

Fig. 5-9 indicates that a 180-stone grid sample is necessary for estimation of the median size within ±10% when eight sieves are used to analyze it. This is 80% larger than the binomial results for the same error bands (Fig. 5-7). Another way of presenting the multinomial results is shown in Figs. 5-10 to 5-12. In all these cases, the number of stones that need to be collected is determined when the maximum acceptable error, E, the confidence level, α (= 0.05 in all these plots), and the number of sieves that will be used for the analysis are known. Because for the case of the median size the error bands are symmetric, one figure is sufficient (Fig. 5-10). For any other percentile, two figures are necessary, one for the upper and another for the lower confidence limits. Figs. 5-11 and 5-12 represent the respective figures for D_{84}. The expression in Eq. (5-3) dictates that for two grain sizes D_i and D_j with $i + j = 100$, $E_{iu} = E_{jl}$ and $E_{il} = E_{ju}$ Therefore, Figs. 5-12 and 5-11 can be used to determine the upper and lower confidence limits, respectively, for D_{16}. An example showing the entire grain-size distribution obtained from a 50-stone grid sample together with the confidence intervals determined from the multinomial distribution for $\alpha = 0.05$ and $k = 10$ is drawn in Fig. 5-13. For comparison purposes, the exact binomial confidence intervals for the same sample are also included in this figure.

The binomial/multinomial approaches estimate the sample size based on a desirable/acceptable error presented in terms of percentage points. This might be preferable to error estimates in terms of absolute units because in the former case the error scales with the properties of the unknown distribution and its particle sizes. For an appropriate choice of error in terms of absolute units it is necessary to have prior knowledge of the grain size to be considered.

Grid-by-number is the most efficient technique for sampling sediment. It requires the smallest sample size for achieving a given degree of accuracy (Petrie and Diplas 2000; Russ and Dehoff 2000). For nonuniform deposits exhibiting spatial variation in the bed-material size, use a grid of constant size. This approach will sample the various patches proportionally (make grid size sufficiently small to capture the contribution of the patches). Reporting the data in an array form can reveal the spatial characteristics exhibited by the bed material. The method developed by Crowder and Diplas (1997) can be used to identify boundaries of sediment patches and other variations in terms of grain size.

5.2.5.3 Sample Size Determined by Weight The volumetric method is the approach most commonly used for sampling and analyzing mineral aggregates. It is not surprising, therefore, that a large number of recommendations regarding appropriate sample size have been put forth by various researchers and organizations (De Vries 1970; Mosley and Tindale 1985; Church et al. 1987; Fripp and Diplas 1993; Ferguson and Paola 1997; Bunte and Abt 2001). It is worth mentioning that the methods described here can also be used to calculate the weight of material that needs to be collected with bed or suspended-load sampling devices to determine their size distribution or just a representative grain size.

The most widely quoted criteria for sample volumes of fluvial sediments are those proposed by De Vries (1970)

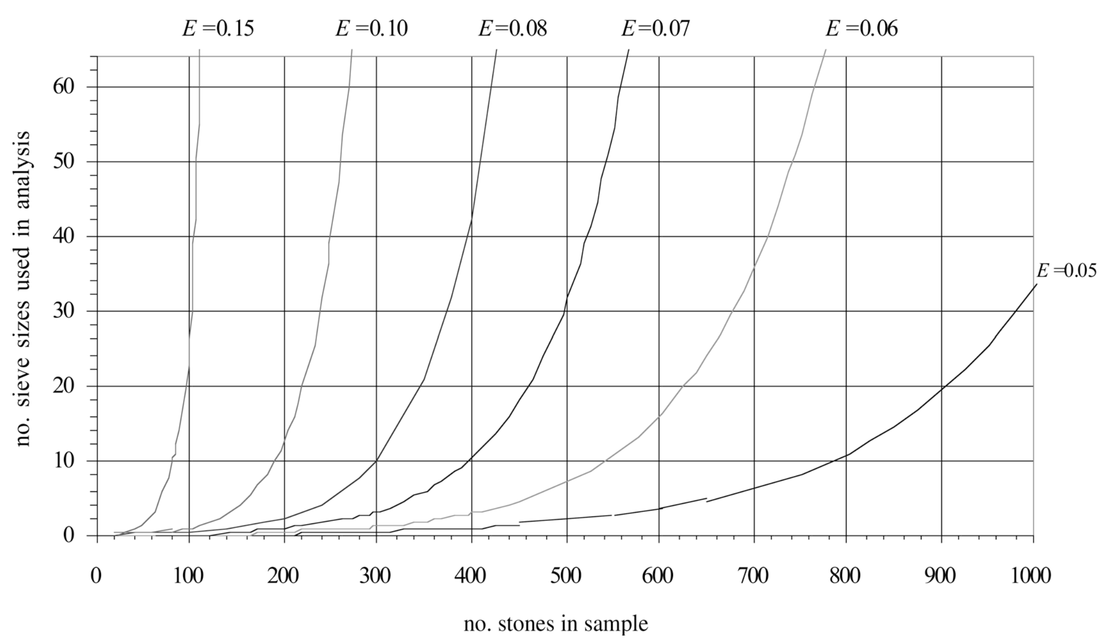


Fig. 5-10. Multinomial sample size determination graph for D_{50} with $\alpha = 0.05$. Petrie and Diplas (2000). Copyright 2000 American Geophysical Union. Reproduced by permission of American Geophysical Union.

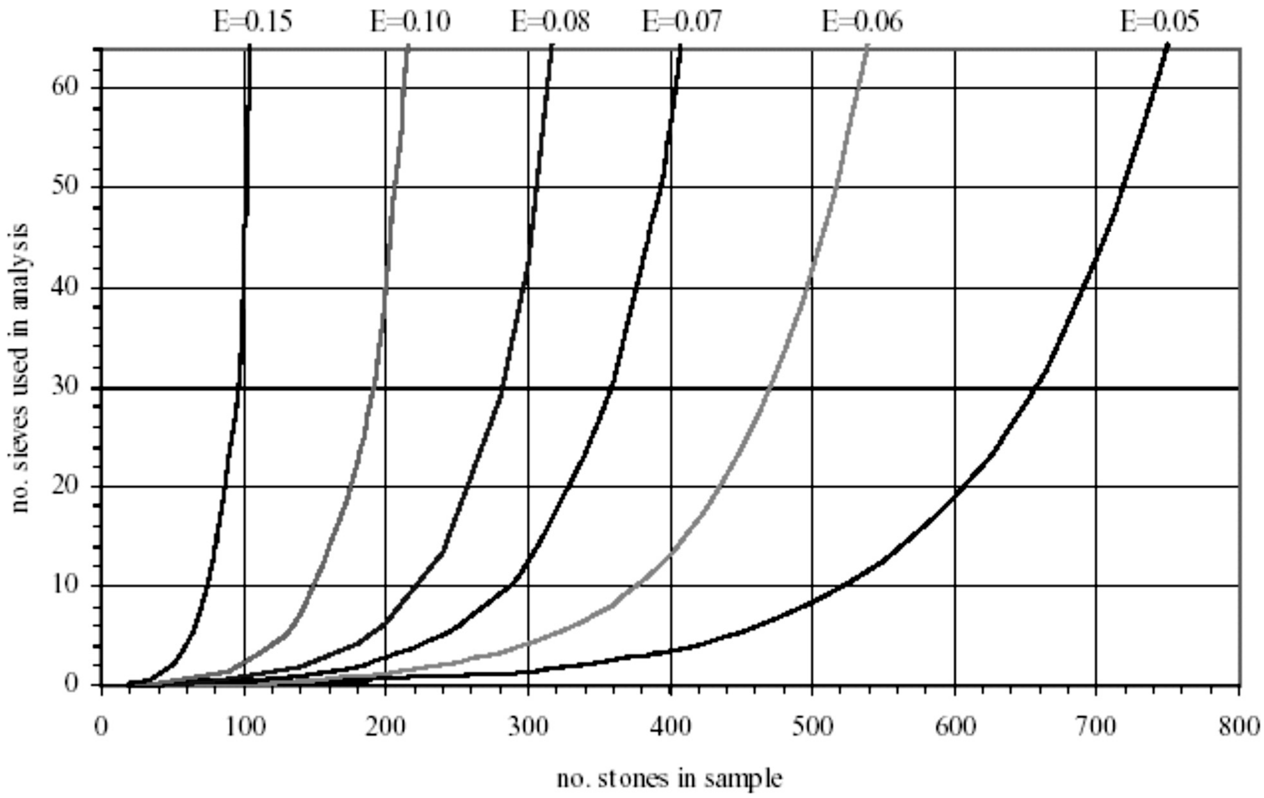


Fig. 5-11. Multinomial sample size determination graph for D_{16} (upper confidence limit) and D_{84} (lower confidence limit) with $\alpha = 0.05$.

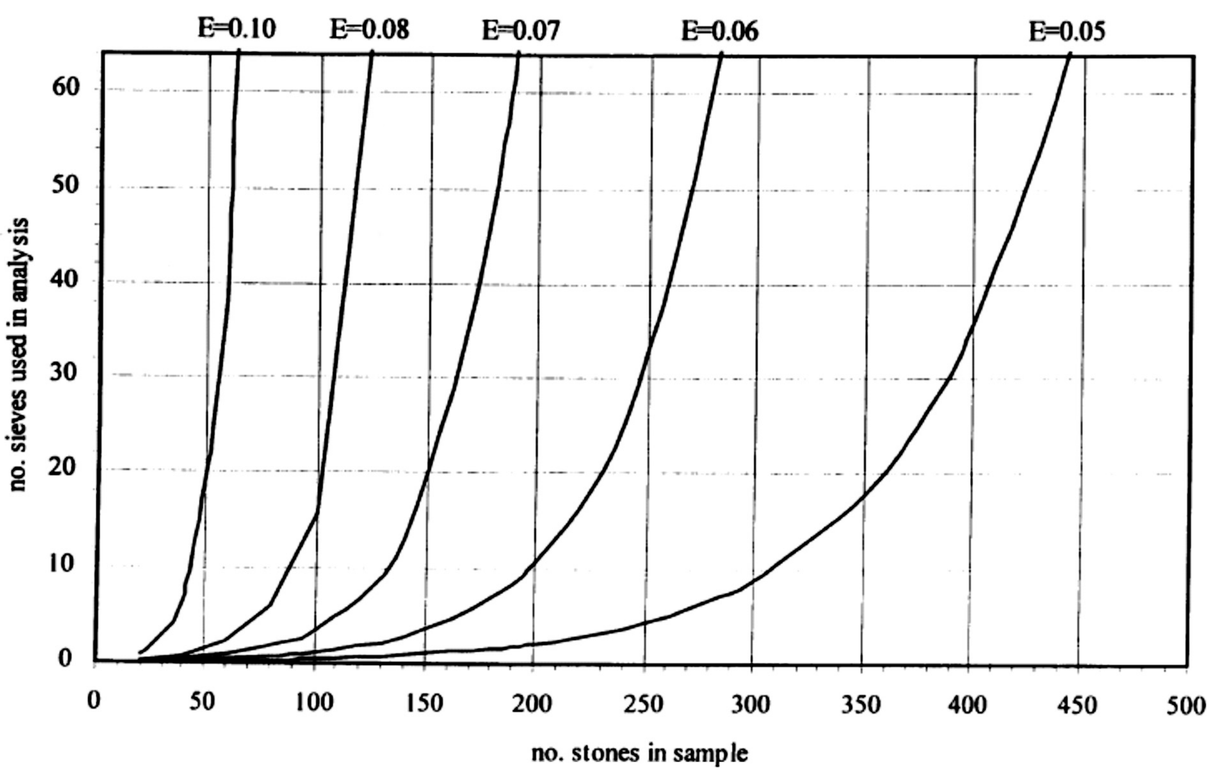


Fig. 5-12. Multinomial sample size determination graph for D_{16} (lower confidence limit) and D_{84} (upper confidence limit) with $\alpha = 0.05$.

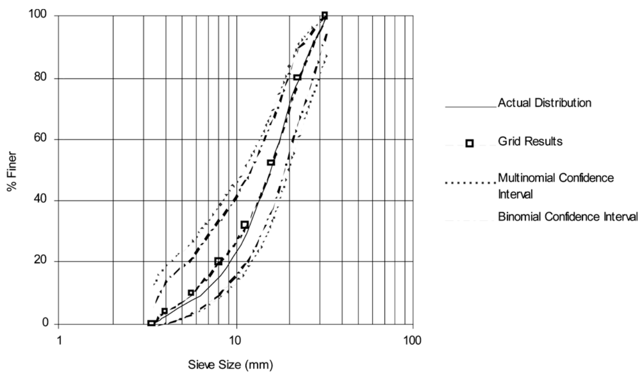


Fig. 5-13. Fifty-stone grid sample results and actual grain-size distribution with 95% multinomial ($k = 10$) and binomial confidence intervals.

and Church et al. (1987). De Vries suggested bulk samples expressed in terms of mass, m, to satisfy three accuracy levels, high, normal, and low. The required total sample mass is obtained as a function of the mass of the D_{84} grain size and can be expressed as follows (Bunte and Abt 2001):

$$m = 0.8 \times 10^{\beta} \rho_s D_{84}^{3} \quad (5\text{-}4)$$

where meters and kilograms are the units of all the terms. The coefficient of 0.8 is based on empirical results obtained from laboratory experiments with sand and fine gravel ($D < 14$ mm); its value might be different for sizes and shapes other than those used by De Vries. The exponent β takes the value of 5 for high, 4 for normal, and 3 for low level of accuracy. Prior knowledge, or estimation, of D_{84} is necessary to determine the sample mass. Because 1 t of material is typically considered the practical limit for hand sieving, excessive amounts of material are required to meet the high-accuracy criterion for sediments coarser than fine gravel. This is a typical requirement of the various methods that have been suggested for volumetric sampling. Although this appears to be a major limitation, the fact is that grain-size stratification in gravel streams precludes the use of the volumetric method in streams that do not possess predominantly sandy or fine gravel sediment deposits.

To provide guidance for obtaining accurate, yet manageable volumetric samples, Church et al. (1987) suggested a sliding method that provides the necessary sample mass based on the D_{max} particle size present in the deposit. For bed material with $D_{max} < 32$ mm, 32 mm $< D_{max} < 128$ mm, and $D_{max} > 128$ mm they suggested that the sample mass, m, be 1,000, 100, and 20 times the mass of D_{max}, respectively. One problem with this approach is that the resulting expression is not a monotonic function of the mass of D_{max}. More specifically, deposits having D_{max} values near the beginning of one of the larger two size ranges require smaller sample masses than deposits having D_{max} values near the end of the previous size range. To remedy this problem and unite the three sample-mass criteria, Yuzyk (1986) proposed a staircase approach, whereas Bunte and Abt (2001) fitted the following regression equation through the corner points of the staircase function,

$$m = 2{,}882\, D_{max} - 47.6 \quad (5\text{-}5)$$

with m in kilograms and D_{max} in meters. Equation (5-5) should be used for $D_{max} > 32$ mm, whereas the Church et al. criterion should be employed for $D_{max} < 32$ mm. It is evident that the Church et al. method and its variations do not maintain consistent accuracy levels for the various size ranges. Furthermore, these methods do not account for the effect of standard deviation (e.g., Gale and Hoare 1994).

To obtain consistent results and volumes that are determined on the basis of a desirable degree of accuracy, two-stage sampling methods need to be employed (Hogan et al. 1993; Ferguson and Paola 1997; Petrie and Diplas 2000). During the first stage, a sample is obtained to approximate the size distribution of the parent material or some of its main characteristics, such as D_{50} and standard deviation. Hogan et al. proposed computer-generated replicate samples, whereas Petrie and Diplas suggested nonlinear transformations of grid-by-number plots and their confidence intervals for determining the necessary volumetric sample size. Though both of these methods are nontrivial to carry out, they are valid for any grain-size distribution. Ferguson and Paola have provided simpler expressions for calculating the sample volume; however, their results are limited to deposits having lognormally distributed particle sizes.

5.3. SUSPENDED-SEDIMENT SAMPLERS AND SAMPLING METHODS

J. Gray, D. Glysson, and T. Edwards

5.3.1 Introduction

This section focuses on collection of suspended-sediment data. It includes criteria for a sediment data set; descriptions of manual suspended-sediment samplers and methods for their deployment; description, installation, and operation of automatic samplers; and a summary of equipment used for obtaining water-sediment subsamples.

The origins of suspended-sediment sampling and transport measurements go back at least to 1808, when Gorsse and Subuors collected samples of the Rhone River at Arles, France. Baumgarten's samples collected in the River Garonne at Marmande, France, from 1839 to 1846 resulted in what were probably the first sediment discharge computations. Sediment discharge measurements in the United States began in 1838 when Captain Talcott sampled the Mississippi River. The fluvial sediment measurements made in the Rio

Grande at Embudo, New Mexico, beginning January 15, 1889 represent the beginning of the U.S. Geological Survey's sediment program (Glysson 1989a). Fluvial sediment measurements have been made regularly in the Rio Grande since 1897; the lower Colorado River since 1909; and the upper Colorado River basin since 1925. A detailed investigation of sediment loads starting in 1942 as part of the Missouri River Project included determination of the feasibility of storage reservoirs on streams transporting heavy sediment loads. Beginning in about 1930, extensive sediment surveys have been made in many other streams of the United States (FISP 1940; Nelson and Benedict 1950; Glysson 1989a; Turcios et al. 2000; USGS 2000b; Turcios and Gray 2001). After the end of World War II, the number of sites at which the USGS collected daily suspended-sediment data increased rapidly, peaking at 360 in 1982 (Glysson 1989a; Osterkamp and Parker 1991). By 2003, only 120 daily-record sediment sites were being operated in the 50 states, although suspended-sediment and bed-load data were being collected periodically at 615 and 49 sites, respectively (USGS 2004).

The earliest suspended-sediment samples were collected using instantaneous samplers, such as the open container or pail used by Riddell in the lower Mississippi River at New Orleans from 1843 to 1848 (Nelson and Benedict 1950). Subsequently developed samplers included those that could be filled at a selected depth below the water surface and horizontal trap-type samplers that aligned in the direction of flow (FISP 1940). After 1900, and particularly during the period from 1925 to 1940, many new sediment samplers were developed. By 1939, at least nine different types of sediment samplers were being used by U.S. Federal agencies (Glysson 1989a). Most of the samplers had been developed by independent investigators, lacked calibration, and were deployed using various operating techniques. A survey of sediment-sampling equipment used in the United States indicated that the 30 instantaneous samplers studied had very limited applicability, either because of poor intake-velocity characteristics or because of the short filament of water-sediment mixture sampled (FISP 1940; 1941; Nelson and Benedict 1950). As a consequence, data reliability and comparability suffered. For example, a consistent decrease in suspended-sediment discharges measured at gauges in the Colorado River Basin—originally attributed to changes in climatic, land use, or other factors—was probably the result of bulk oversampling of sediment by the Colorado sampler, a weighted bottle-type sampler (FISP 1940) used in the southwest United States from the 1920s to the 1940s. Tests of the Colorado sampler by Topping et al. (1996) found that the Colorado sampler preferentially oversampled coarser material, resulting in overestimation of the mass of suspended-phase material by a factor of about 3. This conclusion is consistent with mid-1940s changes in slope in the relations between water discharge and suspended-sediment discharge for three Colorado River Basin stream gauging sites (Thompson 1982; 1984; 1985), although comparative tests at the San Juan River near Bluff, Utah, indicate that the Colorado River Sampler collected an average of 82% of the sediment mass obtained by the US D-43 suspended-sediment sampler (Nelson and Benedict 1950). The US D-43 sampler, which replaced the Colorado River Sampler in the mid-1940s, and subsequently developed isokinetic samplers sample the water-sediment mixture isokinetically, that is, collecting a filament of water at the ambient stream velocity, thereby providing an unbiased sample for subsequent sedimentary analysis.

Paul C. Benedict, the principal U.S. Geological Survey (USGS) engineer involved in the midcentury development of sediment-sampling equipment, once remarked in relation to sampler development during the 1920s and 1930s that "all this development work was being done with no knowledge of the physical laws governing the transport of sediment or of the intake characteristics of the samplers themselves" (Glysson 1989a). The data obtained by the different investigators during this period were not comparable, nor could their accuracy be evaluated. It became apparent that consistent and comparable sediment data could not be obtained unless equipment and data-collection and analytical methods were standardized.

In 1939, various agencies of the U.S. government organized an interagency program to study methods and equipment used in measuring the sediment discharge of streams, and to improve and standardize equipment and methods where practicable (FISP 1941). The Federal Interagency Sedimentation Project (FISP) (Skinner 1989; Glysson and Gray 1997) was created under the sponsorship of the Committee on Sedimentation of the Federal Water Resources Council. The comprehensive study of sampling equipment included suspended-sediment, bed-load, and bed-material samplers. As a result of research conducted by the FISP and others, an integrated system of sediment samplers, sampling, and analytical techniques has been developed and is widely used around the world.

5.3.2 Criteria for a Sediment Data Set

Collection of data to enable reliable sediment-transport estimates is often difficult, time-consuming, and expensive. It is frustrating to obtain data for a location and set of conditions of interest, only to subsequently discover that not all of the requisite parameters were quantified (Glysson 1989b), or that the collected data were inappropriate for the analysis at hand.

The types of data required depend on the goals of the assessment and the intended storage medium for the data. For example, sediment-concentration and water-discharge data are needed to compute continuous records of suspended-sediment discharge (Porterfield 1972; Koltun et al. 1994; McKallip et al. 2001). Other relevant data include particle-size distributions of suspended sediment and bottom material. The integrity of large-scale, long-term monitoring programs, such as the Vigil Network (Osterkamp and Emmett 1992), or that proposed for North America (Osterkamp et al. 1998; 2004), the United States (Osterkamp and Parker 1991), and Canada (Day 1991), is particularly dependent on the reliability and comparability of the data collected.

The most reliable databases accept only selected data types representing sediment and ancillary variables obtained using a consistent set of protocols. For example, sediment data stored by the USGS as part of the National Water Information System—World Wide Web (NWISWeb) and other databases (Turcios et al. 2000; USGS 2000a; 2000b; Turcios and Gray 2001) are collected by techniques described by Edwards and Glysson (1999) and analyzed in a USGS-approved laboratory by techniques described by Guy (1969); Matthes et al. (1991); Knott et al. (1992; 1993); and the USGS (1998a; 1999).

One commonly used analogue for suspended-sediment concentration—total suspended solids (TSS)—is not comparable to suspended-sediment concentration data under some circumstances, and fundamentally is unreliable when applied to open-channel flows (Gray et al. 2000; USGS 2001). TSS data tend to underestimate suspended solid-phase concentrations, by a proportionate amount of 25% to 34% (Gray et al. 2000). This tendency has important ramifications for computing sediment discharges. Instantaneous sediment discharges computed from TSS data may differ substantially from those computed from suspended-sediment concentrations and the same water-discharge time series, with the TSS-generated loads usually biased low (Glysson et al. 2001). This result is of particular concern for sites where the percentage of sand-size material in water samples can exceed about a quarter of the sediment mass percent and where concentrations of sand-size material in transport increase with flow. No broadly applicable and reliable means of adjusting TSS data to estimate suspended-sediment concentration data in open-channel flow has been identified (Glysson et al. 2000).

Glysson (1989b) divided data-set requirements for computing sediment transport using the more common sediment-transport equations for noncohesive sediments into three categories: sediment, hydraulic, and others. Required sediment parameters include suspended-sediment concentration, bed-material particle-size distributions, particle specific gravity, and bed load discharge and particle-size distributions when bed load is the target parameter. Additional sediment parameters are specific diameters, sample method of collection, sampler and nozzle type, the analyzing laboratory, and the method that is used to analyze the samples.

Water discharge, watercourse stage, cross-sectional geometry, width, depth, area, hydraulic radius, and a slope parameter are required hydraulic parameters. Water temperatures should always be measured. Other parameters to be measured include a roughness coefficient, particle shape, bed-form information, and dissolved-solids concentrations. A site description that may include a channel classification based on one or more channel classification schemes should be included.

5.3.3 Units of Measurement

The concentration of suspended sediment is reported in milligrams of sediment per liter of water-sediment mixture (mg/L). However, as a matter of convenience, it is determined in the laboratory in parts per million (ppm), which is the dry weight of suspended material per million equal weights of water-sediment mixture (Porterfield 1972). The units of mg/L and ppm are equivalent at concentrations less than 8,000 mg/L. The equivalent value for mg/L at concentrations ≥8,000 ppm can be calculated using the equation

$$C_{\mathrm{mg/L}} = C_{\mathrm{ppm}}/(1 - C_{\mathrm{ppm}}(6.22 \times 10^{-7}))$$

where
$C_{\mathrm{mg/L}}$ = sediment concentration, in mg/L; and
C_{ppm} = sediment concentration, in ppm.

5.3.4 Samplers and Sampling Methods

The purpose of a suspended-sediment sampler is to obtain a representative sample of the water-sediment mixture moving in the stream in the vicinity of the sampler intake. There are two categories of suspended-sediment samplers: manually operated samplers and automatic samplers. Manually operated samplers include instantaneous and isokinetic samplers. Isokinetic samplers include those with rigid sample bottles (bottle samplers) and with flexible bags (bag samplers). Additional information on samplers for sediment and other water-borne constituents can be obtained from the Federal Interagency Sedimentation Project (FISP 2000; Davis 2005).

5.3.4.1 Manually Operated Samplers

5.3.4.1.1 Instantaneous Samplers Instantaneous samplers are applicable for sampling flows that do not meet the following criteria for deployment of an isokinetic sampler: sampling depths of greater than about 0.3 m and mean velocities greater than approximately 0.5 m/s. At small depths, the part of the stream from the streambed to the isokinetic sampler nozzle, referred to as the unsampled zone, becomes unacceptably large with respect to the total depth. At small velocities, only silt- and clay-size material typically is in suspension, and these finer size fractions tend to be fairly uniformly distributed with depth (Colby 1963; Guy 1970). Under these circumstances, an instantaneous sample from the water column may provide a reasonably accurate estimate of the concentration at the sampled point, or in the sampled vertical. Instantaneous samplers may also be deployed at flow velocities too high to submerge an isokinetic sampler, or when the presence of debris makes normal sample collection dangerous or impossible.

Although nonisokinetic samplers may provide acceptable results under certain sediment-transport conditions, such as when fine material constitutes all or nearly all of the sediment load, conditions for which nonisokinetic sampling is appropriate are often not apparent at the time of collection. The most reliable suspended-sediment samples are obtained using isokinetic samplers.

The simplest instantaneous sampler is an open bottle used to obtain a surface, or dip, sample. The WBH-96 weighted bottle sampler (FISP 2000) is deployed with a hand line in still or slow-moving water. The Van Dorn sampler and Kemmerer sampler are thief-type samplers that are typically used for still-water sampling, such as in lakes and reservoirs, but that may be useful in slow-moving streamflows (Webb and Radtke 1998).

5.3.4.1.2 Isokinetic Samplers Isokinetic samplers are designed to collect a representative velocity-weighted sample of the water-sediment mixture. Water approaching the nozzle of an isokinetic sampler undergoes essentially no change in speed or direction as it enters the nozzle orifice (Fig. 5-14). When deployed using prescribed methods at strategic locations in a cross section, an isokinetic sampler integrates a sample proportionally by velocity and area, resulting in a

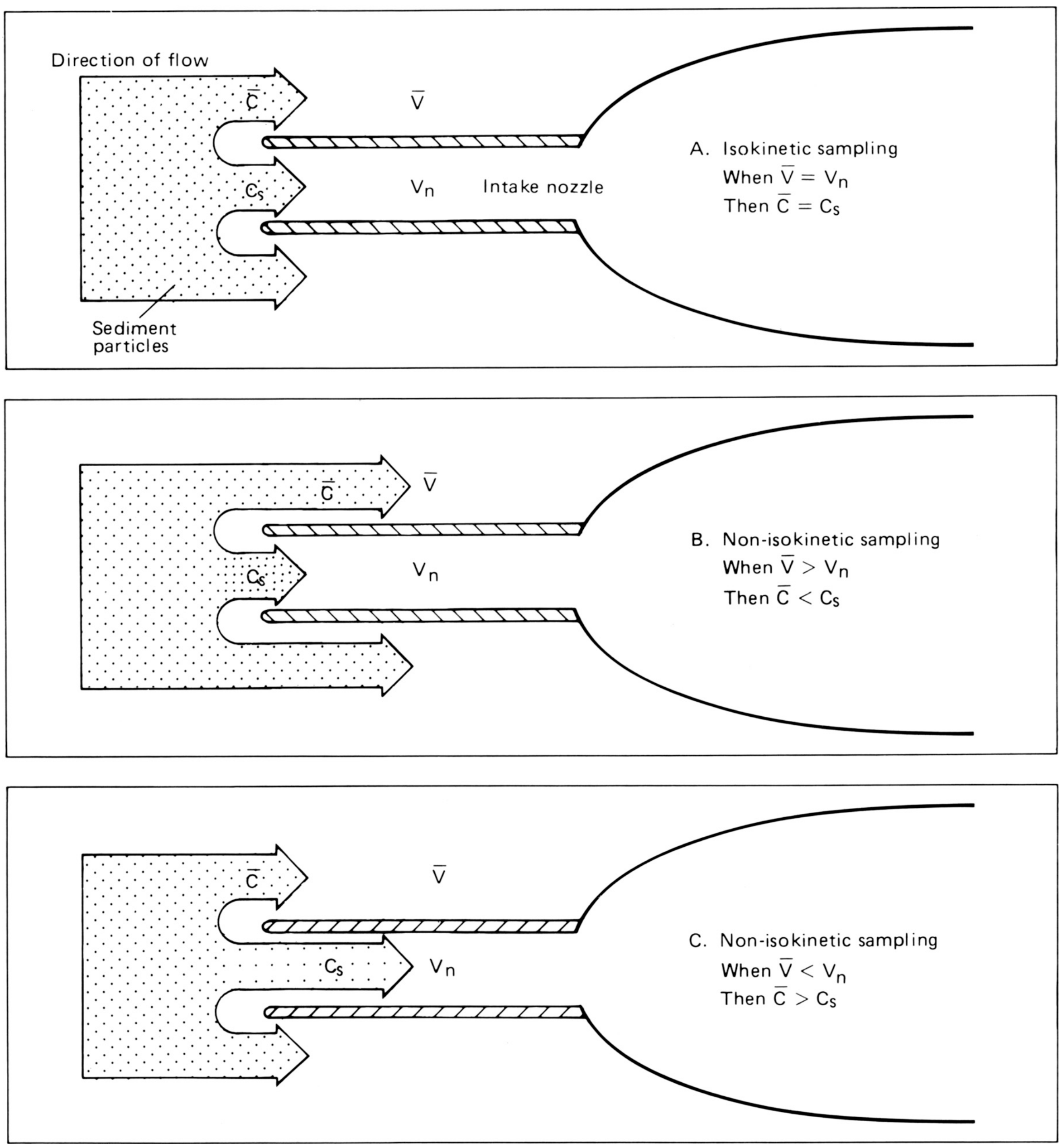


Fig. 5-14. Relation between intake velocity and sample concentration for (A) isokinetic and (B, C) non-isokinetic sample collection of particles larger than 0.062 mm. $\overline{V}$ = mean stream velocity, V_n = velocity in the sampler nozzle, $\overline{C}$ = mean sediment concentration in the stream, and C_s = sample sediment concentration.

discharge-weighted sample. A discharge-weighted sample contains a concentration and size distribution representative of the material in transport at the time the sample was collected.

A list of isokinetic samplers available from the FISP is shown in Table 5-2. FISP isokinetic samplers are designed to sample at a relative sampling rate—a dimensionless value defined as the velocity through the nozzle divided by the approaching stream velocity—of 1.0 at a 1.2 m/s (3.9 ft/s) flow velocity. In practice, FISP isokinetic samplers are designed to ensure that the water velocity entering the nozzle is within 10% of the ambient stream velocity throughout the samplers' operating velocity range (Broderick Davis, Federal Interagency Sedimentation Project, 2001, written communication).

Concentration errors in samples collected with isokinetic-type samplers may stem from a combination of the size of suspended material and the relative sampling rate. The relation between percent error in concentration and relative sampling rate for sediments with a density of 2.65 and median diameters of 0.45, 0.15, 0.06, and 0.01 mm in flows of 1.5 m/s is shown in Fig. 5-15 (adapted from FISP 1941). Under these test conditions, relative sampling rates for 0.45-mm-size sediments can range from 0.75 to 1.3 without introducing more than about a 10% error in sample concentration values. Conversely, at relative sampling rates less than 0.25, resultant concentration errors can exceed 100%. The range of errors tends to decrease with decreasing sediment size. For example, 0.01-mm-size sediments have less than a 5% error for relative sampling rates ranging from about 0.2 to almost 5 (Fig. 5-15). In each case, relative sampling rates less than about 1.0 result in positive concentration bias, and those larger than about 1.0 result in zero or negative concentration bias.

The FISP's suite of depth-integrating samplers and point-integrating samplers (Davis 2005) are isokinetic samplers. A depth-integrating sampler is designed to isokinetically and continuously accumulate a representative sample from a stream vertical while transiting the vertical at a uniform rate (FISP 1952). A depth-integrating sampler collects and accumulates a velocity or discharge-weighted sample as it descends and ascends at a constant rate through the sampling vertical provided that the appropriate transit rate is not exceeded and the sample container does not overfill.

The point-integrating sampler uses an electrically activated valve, enabling the operator to isokinetically sample points in, parts of, or the entire vertical. For stream cross sections less than 9 m deep (30 ft), the full depth can be traversed in one direction at a time by opening the valve and depth integrating either from surface to bottom or vice versa. Stream cross sections deeper than 9 m (30 ft) can be integrated in segments of 9 m (30 ft) or less by collecting integrated-sample pairs consisting of a downward integration and a corresponding upward integration in separate containers.

The FISP (1963) provides the following summary of point-integrating sampler characteristics that make them useful in conditions beyond the limits of the simpler depth-integrating samplers:

> Point-integrating samplers are more versatile than the simpler depth-integrating types. They can be used to collect a suspended-sediment sample representing the mean sediment concentration at any point from the surface of a stream to within several centimeters of the bed, as well as to integrate over a range in depth. These samplers were designed for depth integration of streams too deep (or too swift) to be sampled in a continuous round-trip integration. When depth integrating, sampling can begin at any depth and proceed either upward or downward from that initial point through a maximum vertical distance of 9 m (30 ft).

5.3.4.1.3 Rigid-Bottle Samplers When a rigid-bottle suspended-sediment sampler is submerged with the nozzle pointing directly into flow of sufficient velocity, a part of the streamflow enters the sampler container via the nozzle and air in the container exhausts under the combined effect of three forces:

1. A positive dynamic head at the nozzle entrance due to the flow;
2. A negative head at the end of the air-exhaust tube due to flow separation;
3. A positive pressure due to difference in elevation between the nozzle entrance and the air-exhaust tube.

Under these conditions, a calibrated isokinetic sampler will collect a sample with a sediment concentration and size distribution essentially unchanged from those at the sampling point in the stream, and a representative sample will result. However, when the sample in the container reaches the level of the air exhaust, the intake flow-rate drops, and circulation of the streamflow into the nozzle and out of the air-exhaust tube occurs. Because the velocity of the water flowing through the bottle is less than the stream velocity, coarser particles in transport tend to settle in the sample bottle, causing the sample to become enriched in sediment. Additionally, the resulting subefficient sampling rate may increase the positive concentration bias. Substantial errors in sediment concentration and particle-size distribution can result from samples collected using an incorrect or uncontrolled sample rate. The magnitude of errors tends to increase concomitant with increases in the percentage and size of suspended sand-size material (FISP 1941; Fig. 5-15). Edwards and Glysson (1999) and the USGS (1998b) provide more information on ranges in transit rates required to sample isokinetically.

5.3.4.1.4 Handheld and Handline Samplers: US DH-81, US DH-48, US DH-59, US DH-76, and US DH-95 Where streams are wadable or access can be obtained from a culvert, low bridge span, or cableway, any of six lightweight samplers can be used to obtain suspended-sediment samples via a wading rod or handline. The US

Table 5-2 Designations and Characteristics for Federal Interagency Sedimentation Project (FISP) Manually Operated Isokinetic Samplers (Davis 2005)

Sampler designation[1]	Nozzle inner diameter, cm (in)	Container type and capacity	Mode of suspension	Maximum depth, m (ft)	Minimum isokinetic velocity, m/s (ft/s)	Maximum recommended velocity[2], m/s (ft/s)	Unsampled zone, cm (in)	Mass, kg (weight lbs)
US DH-48	0.48 (3/16)[3] 0.64 ( )	Rigid 0.47 L (pint)	Rod	2.7 (9)	0.5 (1.5)	2.7 (8.9)	8.9 (3.5)	2 (4)
US DH-59	0.48 (3/16)		Handline or	4.6 (15)		1.5 (5.0)	11 (4.5)	10 (22)
US DH-59	0.64 ( )		Cable Reel	2.7 (9)				
US DH-76	0.48 (3/16) 0.64 ( )	Rigid 0.95 L (quart)		4.6 (15)		2.0 (6.6)	8.1 (3.2)	11 (25)
US DH-81	0.48 (3/16)	Rigid 1 L	Rod	2.7 (9)	0.6 (2.0)	1.9 (6.2)	10 (4.0)	0.5 (1)
US DH-81	0.64 ( )	(1.1 quart)				2.3 (7.6)		
US DH-81	0.79 (5/16)					2.1 (7.0)		
US DH-95	0.48 (3/16)		Handline or	4.6 (15)	0.6 (2.1)	1.9 (6.2)	12 (4.8)	13 (29)
US DH-95	0.64 ( )		Cable Reel		0.5 (17)	21. (7.0)		
US DH-95	0.79 (5/16)				0.6 (2.1)	2.3 (7.4)		
US DH-2	0.48 (3/16)			11 (35)	0.6 (2.0)	1.8 (6.0)	8.9 (3.5)	14 (30)
US DH-2	0.64 ( )			6.1 (20)				
US DH-2	0.79 (5/16)			4.0 (13)				
US D-74	0.48 (3/16)	Rigid 0.47 L	Cable Reel	4.6 (15)	0.5 (1.5)	2.0 (6.6)	10 (4.1)	28 (62)
US D-74	0.64 ( )	(1 pint) or 0.95 L		2.7 (9), pint 4.6 (15), quart				
US DH-74AL	0.48 (3/16)	(quart)		4.6 (15)		1.8 (5.9)		19 (42)
US DH-74AL	0.64 ( )			2.7 (9), pint 4.6 (15), quart				
US D-95	0.48 (3/16)	Rigid 1 L		4.6 (15)	0.5 (1.7)	1.9 (6.2)	12 (4.8)	29 (64)
US D-95	0.64 ( )	(1.1 quart)				2.0 (6.7)		
US D-95	0.79 (5/16)				0.6 (2.0)			
US D-96	0.48 (3/16)	Flexible 3-L		34 (110)		3.8 (12.5)	10 (4.0)	60 (132)
US D-96	0.64 ( )	(3.2-quart)		18 (60)				
US D-96	0.79 (5/16)	bag		12 (39)				
US D-96-A1	0.48 (3/16)			34 (110)		1.8 (6.0)		36 (80)
US D-96-A1	0.64 ( )			18 (60)				
US D-96-A1	0.79 (5/16)			12 (39)				
US D-99	0.48 (3/16)	Flexible 6-L (6.3-quart) bag		67 (220)	1.1 (3.5)	4.6 (15.0)	24 (9.5)	125 (275)
US D-99	0.64 ( )	Flexible 6-[4] or 3-L (6.3- or		37 (120)	1.1 (3.5)[4] or 0.6 (2.0)[5]			
US D-99	0.79 (5/16)	3.2-quart) bag[5]		24 (78)				
US p-61-A1	0.48 (3/16)	Rigid 0.47 L		55 (180), pint	0.5 (1.5)	3.0 (10.0)	11 (4.3)	48 (105)
US P-63	0.48 (3/16)	(pint) or		37 (120), quart		4.6 (15.0)	15 (5.9)	91 (200)
US P-72	0.48 (3/16)	0.95 L (quart)		22 (72), pint 16 (51), quart		1.6 (5.3)	11 (4.3)	19 (41)

[1]Samplers designated in *italics* may also be used for water-quality sampling as described in the *U.S. Geological Survey National Field Manual for the Collection of Water Quality-Data* (variously dated).

[2]For rigid-bottle samplers, the maximum recommended velocity for sampler deployment is based either on measured isokinetic limitations or, for prototypes of samplers tested at Anthony Falls Hydraulic Laboratory flume, on the maximum velocities used in tests. Bag samplers were determined to retain isokinetic characteristics at the highest velocities tested. Their maximum recommended velocity was selected to correspond with the velocity at which the angle of the suspension cable was drawn back just shy of "excessive" by testing personnel—25 to 30 degrees—and upon safety considerations.

[3]The 0.48-mm (3/16-in) internal diameter nozzle is designated for use in high-velocity flows.

[4]A minimum isokinetic velocity of 1.1 m/s (3.5 ft/s) applies to the D-99 sampler using a 6-L (6.3-quart) flexible bag and a 0.48-mm (3/16-in) internal diameter nozzle.

[5]A minimum isokinetic velocity of 0.61 m/s (2 ft/s) applies to the D-99 sampler using a 3-L (3.2-quart) flexible bag and a 0.64-mm (-in) or 0.79-mm (5/16-in) internal diameter nozzle.

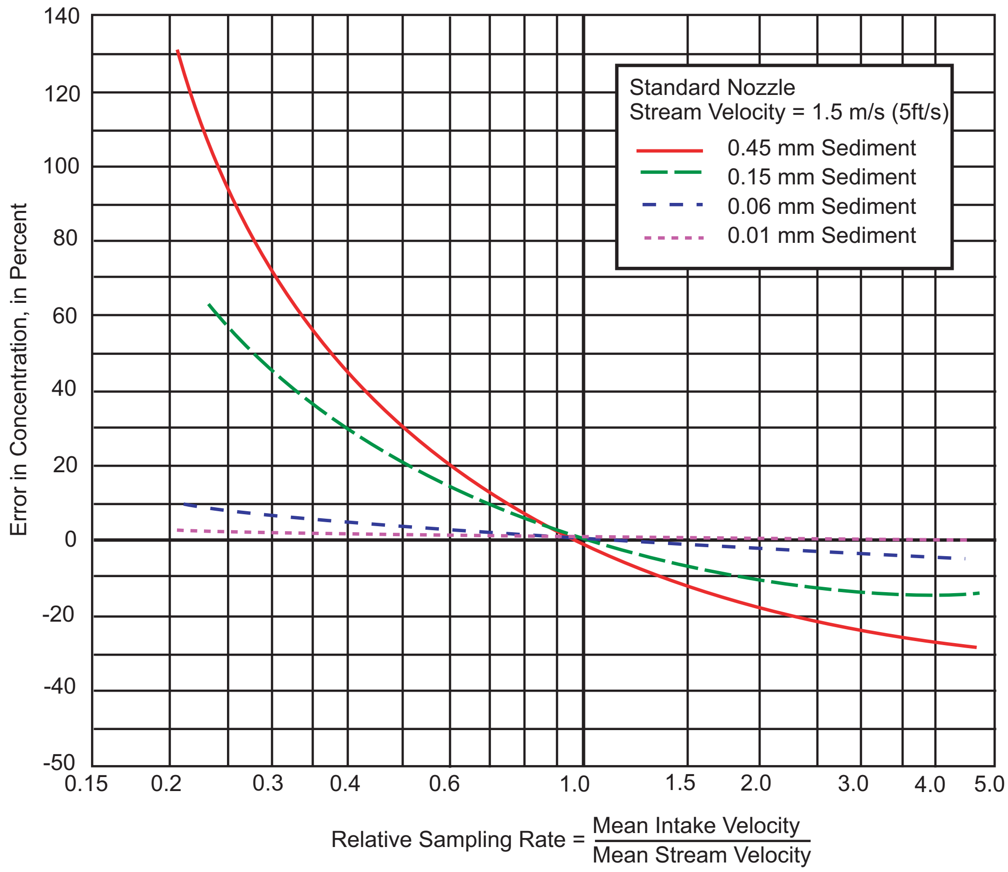


Fig. 5-15. Effect of sampling rate on measured sediment concentration for four sediment size distributions, adapted from Federal Interagency Sedimentation Project (1941).

DH-81 sampler (Fig. 5-16A; Table 5-2), which is deployed by a wading rod, consists of a US DH-81A adapter and US D-77 cap and nozzle (Webb and Radtke 1998; Edwards and Glysson 1999). All parts are autoclavable, enabling the collection of a depth-integrated sample for bacterial analysis. Any bottle having standard mason jar threads can be used with the US DH-81 sampler. The unsampled zone—the distance from the centerline of the nozzle to the streambed when the sampler contacts a flat bed—varies depending on the size of bottle used. The US DH-81 is particularly useful for sampling in cold weather because the plastic sampler head and nozzle attach directly to the bottle, eliminating a metal body. Under subfreezing conditions, a metal sampler body conducts heat away from the nozzle, air exhaust, and bottle more rapidly, resulting in increased potential for ice blockage of the nozzle and/or the exhaust port.

The rod-suspended US DH-48 sampler (Fig. 5-16B; Table 5-2) features a streamlined aluminum casting that partially encloses the sample container (FISP 1952; Edwards and Glysson 1999). The container, usually a 0.45-L glass milk bottle, is sealed against a gasket recessed in the head cavity of the sampler by a hand-operated, spring-tensioned pull-rod assembly at the tail of the sampler.

The US DH-59 and US DH-76 samplers (Figs. 5-16C and D, respectively; Table 5-2) are designed for use in unwadable streams with maximum depths less than 4.6 m and flow velocities up to about 1.5 m/s. The fundamental difference between the samplers is that the US DH-59 accommodates a 0.45-L sample bottle, whereas the US DH-76 uses a 0.9-L container. The tailfin assembly for each sampler ensures sampler alignment parallel to the flow direction with the intake nozzle entrance oriented upstream.

The US DH-95 sampler (Fig. 5-16E) is designed to make possible collection of unbiased samples for trace-element analyses in addition to samples collected for suspended-sediment analyses (McGregor 2000a) in depths less than 4.6 m at flow velocities up to about 2.4 m/s. The sampler is designed to use a 1-L Teflon or plastic bottle, a US D-95 Teflon cap, and a US D-77 sampler cap and nozzle. The bottle cavity is machined from a low-lead bronze casting and is plastic-coated. The tail section is constructed from plastic.

5.3.4.1.5 Cable-and-Reel Samplers: US D-74, US D-95, US P-61A1 US P-63, US P-72 The US D-74 (Figs. 5-17A and B), US D-74AL, and US D-95 (Fig. 5-17C) depth-integrating samplers can be used to obtain suspended-

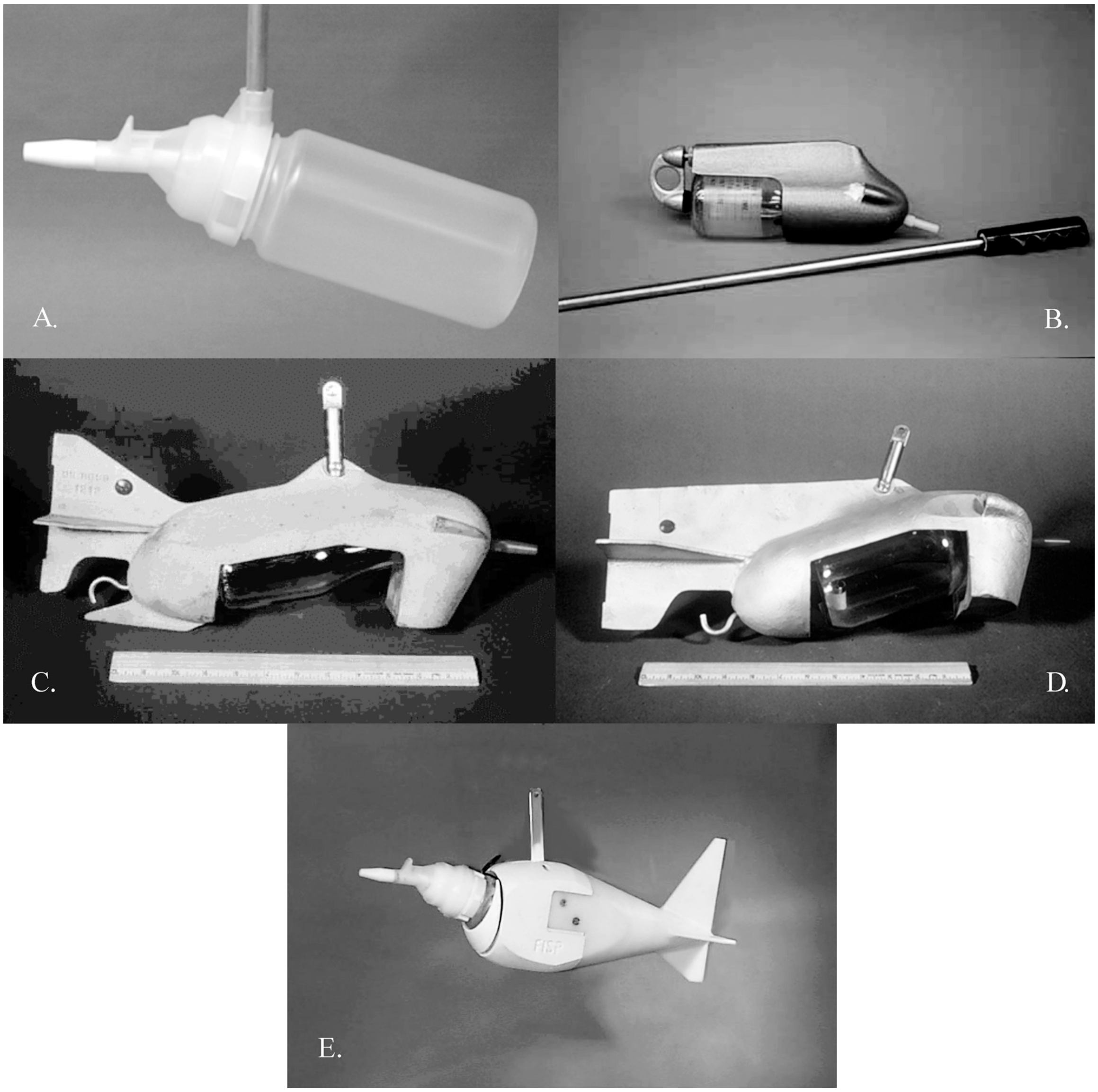


Fig. 5-16. Handheld and hand-line samplers. (A) The US DH-81 suspended sampler with an attached wading rod. (B) The US DH-48 suspended-sediment sampler with an unattached wading rod. (C) The US DH-59 suspended-sediment sampler with hanger bar. (D) The US DH-76 suspended-sediment sampler with hanger bar. (E) The US DH-95 suspended-sediment sampler with hanger bar.

sediment samples in unwadable streams less than 4.6 m deep (Table 5-2). A third cable-and-reel sampler, the US D-77, is being phased out by the USGS and is also no longer being manufactured by the FISP (USGS 2002), although the US D-77 cap and nozzles will continue to be manufactured for use with other FISP samplers.

The bronze US D-74 and aluminum US D-74AL are designed to be suspended from a bridge, cableway, or boat. These samplers replaced the US D-49, which in turn replaced the US D-43 for general use. The US D-74 sampler completely encloses a 0.9-L sample container or a standard 0.45-L milk bottle when an adapter is used. The sampler head is hinged at the bottom and swings downward to provide access to the sample-container chamber. The body includes tail vanes that serve to align the sampler and the intake nozzle with the flow.

The US D-95 sampler, like the US DH-95 (Fig. 5-16E), is designed to make possible collection of unbiased samples for trace-element analyses in streams not exceeding 4.6 m in depth (McGregor 2000b) at stream velocities ranging from 0.5 to 2.3 m/s. The bronze body casting is coated with plastic and the tail section is constructed from plastic to help avoid metal contamination during water-quality sampling.

Point-integrating suspended-sediment samplers in wide use are the US P-61A1 (Fig. 5-17D), US P-63, and US P-72

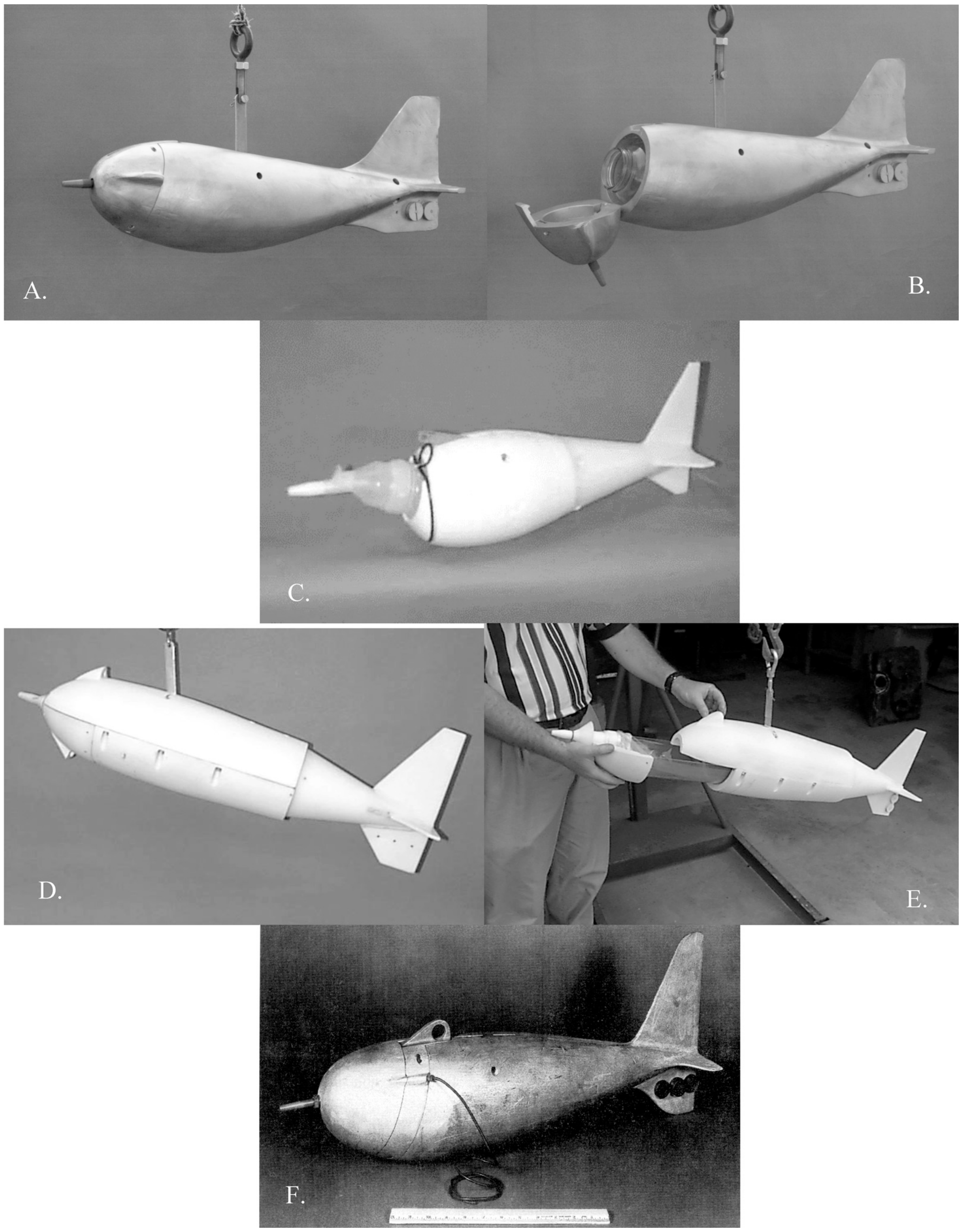


Fig. 5-17. (A) The US D-74 suspended-sediment sampler. (B) The US D-74 suspended-sediment sampler open. (C) The US D-95 suspended-sediment sampler. (D) The US P-61A1 point-integrating suspended-sediment sampler. (E) The US D-96 suspended-sediment sampler. (F) The US D-96 suspended-sediment sampler with tray extended.

(Table 5-2). These samplers also can be used in depth-integration mode.

An operator-controlled sampler solenoid valve powered by a nonsubmersible battery pack makes possible collection of a sample at a discrete depth, or can start and stop depth-integrated sample collection. Automatic pressure equalization at depth precludes a sudden inrush of sample due to a static-head differential when the valve is opened.

The US P-61A1 (Fig. 5-17D; Table 5-2) is calibrated for use in velocities up to 2 m/s, but there is evidence to suggest that it can collect samples isokinetically at velocities of at least 3 m/s (Wayne O'Neal, FISP, 2000, written communication). The US P-63 and US P-72 are lighter and heavier versions and have higher and lower flow-velocity limits, respectively, but otherwise are functionally similar to the US P-61A1.

Because of the comparatively complex nature of point-integrating samplers, the user may find it useful to seek additional information given in FISP reports (1952; 1963; Davis 2005) or to obtain information directly from the FISP (FISP 2000).

5.3.4.1.6 Bag Samplers Samplers using collapsible bags as the sample container have been used since the 1970s (Stevens et al. 1980). Nordin et al. (1983) tested a large-volume bag sampler in the Rio Orinoco and Rio Amazonas, South America. Moody and Meade (1994) deployed a bag sampler of the type devised by Stevens et al. (1980) in the Mississippi River and selected tributaries.

As with rigid-bottle isokinetic samplers, water enters the bag sampler through a nozzle. However, bag samplers have no exhaust port, and the sample container is a collapsible bag. Air is manually expelled from the bag before submersion of the sampler. The transit rate for a bag sampler is constrained by the intake-nozzle and the bag volume, in addition to the maximum rate of 0.4 times the mean flow velocity in the vertical that applies to all depth-integrating samplers. When a Teflon bag is used, they are capable of collecting unbiased samples for trace-element analyses in addition to those collected for suspended-sediment analyses.

The US D-96 collapsible bag sampler (Fig. 5-17E and F; Table 5-2) was the first such sampler developed in part to address the limitations and disadvantages associated with bottle samplers and experimental bag samplers (Davis 2000; Webb and Radtke 1998). This cable-suspended sampler can provide up to 3 L of sample for subsequent unbiased trace-element analyses in addition to physical-sediment analyses. It is fabricated from bronze and aluminum castings with a high-density polyethylene tail. All metal parts are plastic-coated with commercially available "PlastiDip." A sliding tray (Fig. 5-17F) in the sampler holds the nozzle holder with nozzle in place and supports a perfluoroalkoxy bag.

The US D-96 sampler will collect velocity-weighted samples in streams with velocities from 0.6 to 3.8 m/s. At a maximum transit rate of 0.4 times the mean flow velocity in the vertical, the US D-96 sampler is capable of sampling to a depth of 12 m (39 ft) with a 7.9-mm (5/16-in.) nozzle, 18 m (60 ft) with a 6.4-mm (-in.) nozzle, and 34 m (110 ft) with a 4.8-mm (3/16-in.) nozzle (Davis 2000). Bag samplers with smaller and larger capacities than the US D-96 sampler are also available. The 13-kg (29-lb) US DH-2 is a hand-line sampler capable of collecting a 1-L sample. The 125-kg (275-lb) US D-99 is a cable-suspended sampler capable of collecting a 6-L sample.

5.3.4.2 Manual Sampling Methods The most common purpose of sediment sampling is to determine the instantaneous mean discharge-weighted suspended-sediment concentration at a cross section. Derived concentration values are combined with water discharge to compute the measured suspended-sediment discharge. A discharge-weighted suspended-sediment concentration representative of the mean value in the cross section is desired for this purpose and for the development of coefficients to adjust data collected by observers and automatic samplers.

Ideally, the best method for sampling any stream to determine sediment discharge would be to collect the entire flow of the stream over a given time period, remove the water, and weigh the sediment. This method is rarely feasible. Instead, the sediment concentration in the flow is determined by collecting depth-integrated suspended-sediment samples that define the mean discharge-weighted concentration in the sample vertical, and collecting sufficient verticals to define the mean discharge-weighted concentration in the cross section (Edwards and Glysson 1999).

5.3.4.2.1 Single-Vertical Sampling The objective of collecting a single-vertical sample is to obtain a concentration value representative of the mean discharge-weighted suspended-sediment concentration in the vertical being sampled at the time the sample was collected. An isokinetic sampler deployed at a constant rate in a downward and upward transit will collect a sample weighted for the variations in velocity and concentration in the vertical from the surface to the top of the unsampled zone. The following equation demonstrates this concept:

$$C_i = \frac{\int_{B_i+UZ}^{D_i} c_i(s) v_i(s) ds}{\int_{B_i+UZ}^{D_i} v_i(s) ds} \tag{5-6}$$

where

C_i = mean suspended-sediment concentration in vertical *i*;
Bi = elevation of the streambed in vertical *i*;
UZ = distance from the bed to the nozzle of a sampler resting on the bed (unsampled zone);
D_i = elevation of the water surface in vertical *i*;
$c_i(s)$ = concentration at depth *s* in vertical *i*;
s = depth in the vertical; and
v_i = velocity at depth *s* in vertical *i*.

The method used to obtain the mean concentration of suspended sediment in a vertical thus depends on the flow conditions and particle-size distribution of the sediment in transport. These conditions can be generalized to four types of situations:

1. Low velocity ($v < 0.6$ m/s) when little or no sand is being transported in suspension;

2. High velocity ($0.6 \leq v \leq 3.7$ m/s) when depths are less than 5.6 m;
3. High velocity ($0.6 \leq v \leq 3.7$ m/s) when depths are greater than 5.6 m; and
4. Very high velocity ($v > 3.7$ m/s).

First case. In the first case, where $v < 0.6$ m/s, barring extremely shallow depths, the velocity is low enough so that little if any sand is in suspension. The distribution of any silt- and clay-size material (<0.062 mm in diameter; Folk 1974) in transport is relatively uniform from stream surface to bed (Guy 1970). The sampling error for this case is 10% or less with relative sampling rates in a range from about 0.2 to at least 5.0 (Fig. 5-15). Consequently, it is less important to collect the sample isokinetically with fines in suspension than it is when sand-size particles (≥0.062 mm in diameter; Folk 1974) are in suspension. In shallow streams, a sample may be collected by manually submerging an open-mouthed bottle into the stream. The mouth should be pointed upstream and the bottle held tilted upward at approximately a 45° angle from the streambed. The bottle should be filled by moving it from the surface to the streambed and back. An unsampled zone of about 8 cm should be maintained in order to obtain samples that are compatible with depth-integrated samples collected at higher velocities and to avoid collecting streambed material. If the stream is not wadable, a weighted-bottle type sampler, such as the US WBH-96, may be used (Webb and Radtke 1998). Samples collected in this manner are not discharge-weighted.

Second case. In the second case, when $0.6 \leq v \leq 3.7$ m/s and the depth is less than 4.6 m, a depth-integrating sampler described in Table 5-2 that is suitable for the ambient streamflow condition should be used. The method of sample collection basically is the same for all these samplers, whether used while wading or deployed from a bridge, cableway, or boat. Insert a clean sample container into the sampler and ensure that the air-exhaust tube and/or nozzle is unobstructed. Then lower the sampler to the water surface so that the nozzle is above the water, and the lower tail vane or back of the sampler is in the water to orient it parallel to the flow. The sampler then is lowered at a constant rate until it touches the bottom. It is immediately retrieved at a constant rate until it clears the water surface. Although the ascending transit rate need not be equal to the descending rate, in practice it is simpler to maintain a constant rate in both directions. However, both rates must be constant to obtain a velocity- or discharge-weighted sample. The rates should be such that the bottle fills to near its optimum level (Johnson 1997; Edwards and Glysson 1999).

For streams that transport heavy loads of sand, and perhaps for some other streams, at least two complete depth integrations of the sample vertical should be made as close together in time as possible, one bottle for each integration. Each bottle then constitutes a sample and can be analyzed separately or, for the purposes of computing the sediment record (a time series of sediment discharges often reported as daily values), concentration values representing two or more bottles can be averaged as a set and tagged with a single time of collection. This set is used as a single sediment-concentration value for computing the sediment record. Analytical results from two or more individual bottles for a given observation are useful for checking sediment variations among bottles, which is advantageous in the event that sediment concentrations in samples collected consecutively from the same vertical differ markedly. Immediately after collection, the sample should be inspected by briefly swirling or agitating the container and then observing the quantity of sand particles that collect in the bottom of the container. If there is an unusually large estimated mass of sand among bottles with similar sample volumes, or the mass of sand inexplicably differs among the bottles, at least one more sample from the same vertical should be taken immediately. The sample container suspected of having too much sand should be marked as having "excess sand," or, if it is likely to be contaminated, the sample should be discarded. If a container is overfilled or if water is ejected from the nozzle when the sampler is raised past the water surface, the sample should be discarded. A clean container must be used to resample the vertical.

Third case. In the third case, where $0.6 \leq v \leq 3.7$ m/s and the depth is greater than 4.6 m, rigid-bottle depth-integrating samplers cannot be used because the depth exceeds the maximum allowable depth for these samplers. In this case, one of the point-integrating or bag-type samplers must be used. The method for collection of a sample using the bag-type sampler is similar to that used with the depth-integrating samplers.

The point samplers may be used to collect depth-integrated samples in verticals where the depth is greater than 4.6 m. For streams with depths of 4.6 to 9.1 m, a procedure for sampling modified from that described by Edwards and Glysson (1999) is as follows:

1. Insert a clean bottle in the sampler and close the sampler head.
2. Lower the sampler to the streambed, keeping the solenoid valve closed; note the depth to the bed.
3. Start raising the sampler to the surface, using a constant transit rate. Open the valve at the same time the sampler begins the upward transit.
4. Keep the valve open until after the sampler has cleared the water surface. Close the valve.
5. Remove the bottle containing the sample, check the volume of the sample, and mark the appropriate information on the bottle. (If the sample volume exceeds allowable limits, discard the sample and repeat depth integration using a higher transit rate.)
6. Insert another clean bottle into the sampler and close the sampler head.
7. Lower the sampler until the lower tail vane is touching the water, allowing the sampler to align parallel to the flow.

8. Open the valve and lower the sampler at a constant transit rate until the sampler touches the bed.
9. Close the valve the instant the sampler touches the bed (by noting the depth to the streambed in step 2 above, the operator will know when the sampler is approaching the bed).

If the stream depth is greater than 9.1 m, the process is similar, except that the descending and ascending integrations are broken into segments no larger than 9.1 m. Samples collected by this technique may be composited for each vertical if the same transit rate is used. Otherwise, samples should be analyzed separately. A single mean concentration is computed for the vertical.

Fourth case. In the fourth case, where $v > 3.7$ m/s, the velocities are too large to deploy depth- or point-integrating samplers safely. In this case, and when the presence of debris, ice in flow, or other factors makes normal sample collection dangerous or impossible, surface or dip samples may be collected.

A surface sample is one taken on or near the surface of the water, with or without an isokinetic sampler. At some locations, stream velocities can be so large that even the heaviest, most streamlined samplers will not reach the streambed in one or more sampled verticals. Under such conditions, it can be expected that all but perhaps the largest sediment particles in suspension will be well mixed within the flow; and, therefore, a sample from near the surface, non-depth-integrated, may contain a concentration and size distribution representative of the entire vertical. However, results from these samples should be correlated with those from depth-integrated samples collected under more normal flow conditions as soon as possible after the large velocities diminish. Along with the depth-integrated sample, a sample should be collected in a manner duplicating the sampling procedure used to collect the surface or dip sample. Analytical results from these samples will be used to adjust those from the surface or dip sample collected during the higher flow, if necessary, to facilitate the use of these data in sediment-discharge computations and data analyses.

5.3.4.2.2 Multivertical Sampling A depth-integrated sample collected using the procedures outlined in the previous section will accurately represent the discharge-weighted suspended-sediment concentration in a vertical at the time of the sample collection. Samples collected at appropriately spaced verticals can be used to calculate the instantaneous sediment concentration at a cross section. The International Standards Organization (ISO 1993) lists three methods for suspended-sediment data collection in a cross section: the equal-discharge-increment, equal-width-increment, and equal-area-increment methods. The equal-area-increment method is rarely used in the United States. The first two methods are described in the following sections (Edwards and Glysson 1999).

5.3.4.2.3 The Equal-Discharge-Increment Method With the equal-discharge-increment (EDI) method, samples are obtained from the locations representing equal increments of discharge. The EDI method requires that three criteria be met:

1. Samples are collected isokinetically;
2. The vertical represents the mean concentration and particle-size distribution for the subsection sampled;
3. The discharges on both sides of the sampling vertical are predetermined proportions of the total discharge, which requires information on the lateral distribution of discharge in the cross section.

The mean discharge-weighted suspended-sediment concentration in a cross section using the EDI method is calculated from the mean concentrations from individual verticals (see "Single Vertical Sampling") as follows:

$$C_{xs} = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{5-7}$$

where

C_{xs} = mean discharge-weighted suspended-sediment concentration in the cross section;
n = number of verticals used in the EDI measurement; and
C_i = mean concentration in the vertical i (see Eq. (5-6)).

The distribution of discharge can be derived from a discharge measurement made immediately prior to selecting sampling verticals (Rantz 1982), or, if the channel is relatively stable, on an analysis of the lateral distribution of discharges measured over a range of historical flows. If such knowledge can be obtained, the EDI method can save time and labor (compared to the equal-width-increment method, discussed in the next section), especially on larger streams, because fewer verticals are required (Hubbell et al. 1956).

The inverse of the number of verticals, n, to be sampled by the EDI method is multiplied by 100% to derive $q_{percent}$, the percentage of discharge to be represented in samples collected in each vertical. The location of a vertical nearest the left bank is selected at a point at which the cumulative discharge to the left of the vertical is one-half of the total discharge times $q_{percent}$. The location of a vertical nearest the right bank is selected at a point at which the cumulative discharge to the right of the vertical is one-half of the total discharge times $q_{percent}$. All other verticals are selected at points where the cumulative discharge between adjacent verticals is equal to the total discharge times $q_{percent}$.

For example, from the discussion in the previous paragraph, samples are to be collected from five increments of equal discharge from a 100-m-wide cross section of a river flowing at 500 m^3/s. The percentage of the total discharge to be represented in samples collected from each vertical is 1/5 times 100%, or 20%. The location of the vertical nearest the left bank is selected at the point at which the cumulative discharge to the left of that vertical is 0.5 times 500 m^3/s times 20%, or at the point in the cross section where 50 m^3/s of discharge occurs between the vertical and the left bank. Likewise, the vertical nearest the right bank is selected at the point at which 50 m^3/s occurs between that vertical and the right bank. The other three verticals are located at points separating adjacent verticals by discharges of 100 m^3/s, the product of the total river discharge of 500 m^3/s, times q_{percent}, 20%. The location of each vertical represents the centroid of the discharge in its respective subarea, with each subarea containing equal increments of discharge.

Samples are collected from each EDI method vertical as described previously in the "single-vertical" section. The descending and ascending transit rates in any one vertical need not be equal, nor do the rates need to be equal from vertical to vertical. Although different diameter nozzles for the isokinetic sampler can be used from vertical to vertical, it complicates the data-collection procedure and hence the practice is discouraged.

The EDI method requires a minimum of four verticals; rarely are more than nine verticals necessary. The greater the potential heterogeneity in the distribution of suspended-sediment concentrations and particle-size distributions in the cross section, the more verticals should be selected.

If an equal amount of sample is collected at each vertical, the samples can be composited and analyzed as a single sample. In most cases, the samples are analyzed separately and the results of the analyses are added and then divided by the number of subsections to derive a mean discharge-weighted sediment concentration. One advantage of this method is that data describing the cross-sectional variation in concentrations are produced. Additionally, a bottle containing an abnormally large sediment concentration compared to others in the set (because of recirculation or to punching the nozzle into the bed) can be identified and excluded from the calculated mean cross-sectional suspended-sediment concentration to preclude a biased result.

The bed of a sand channel can shift substantially, at single points and across segments of the width, over a period ranging from weeks to fractions of an hour. This not only makes it difficult at best to establish a relation between stage and the cross-sectional discharge distribution from one visit to the next, but also makes it impossible to be certain the discharge distribution does not change between the time of the water-discharge measurement and sample collection (see Guy 1970). Under conditions where the lateral distribution of flow changes rapidly, the EDI method may yield unreliable results.

5.3.4.2.4 The Equal-Width-Increment Method A cross-sectional suspended-sediment sample obtained by the equal-width-increment (EWI) method requires a sample volume proportional to the amount of flow at each of 10 or more equally spaced verticals in the cross-section (Edwards and Glysson 1999). Equal spacing between EWI verticals across the stream and sampling at an equal transit rate at all verticals yields a cumulative sample volume proportional to the total discharge. This method first was used by Colby in 1946 (FISP 1963) and is used most often in relatively shallow, wadable streams and/or sand-bed streams where the distribution of water discharge in the cross section is unstable. It also is useful where suspended-sediment concentrations in the cross section are substantially heterogeneous, such as in streams where tributary flow has not completely mixed with the flow.

The mean discharge-weighted suspended-sediment concentration in a cross section using the EWI method is calculated from the mean concentrations from individual verticals (see "Single Vertical Sampling") as follows:

$$C_{xs} = \frac{\sum_{j=1}^{J} \mathrm{Vol}_j C_j}{\sum_{J=1}^{J} \mathrm{Vol}_j} \tag{5-8}$$

where

C_{xs} = mean discharge-weighted suspended-sediment concentration in the cross section;
J = number of sample bottles used in the EWI measurement;
C_j = concentration in the sample bottles j; and
Vol_j = the total volume of water collected in sample bottle j.

The number of verticals required for an EWI sediment-discharge measurement depends on the distribution of concentrations and flow in the cross section at the time of sampling, as well as on the a relative assessment of the desired accuracy of the result. For many streams, statistical approaches and experience are needed to determine the desirable number of verticals. Until such experience is gained, the number of verticals used should be larger than that deemed to be minimally necessary. In all cases, a minimum of 10 verticals should be used for streams exceeding 1.5 m wide. For streams less than 1.5 m wide, as many verticals as possible should be used, as long as they are spaced a minimum of 7.6 cm apart, to allow discrete sampling of each vertical and to avoid overlaps. Through general experience with similar streams, field personnel can estimate the required minimum number of verticals to yield a desired level of accuracy. For all but the widest and shallowest streams, 20 verticals usually are ample.

The width of the increments to be sampled, or the distance between verticals, is determined by dividing the stream width by the number of verticals, n, necessary to collect a discharge-weighted suspended-sediment sample representative of the sediment concentration of the flow in the cross section. The locations of the two verticals nearest to the banks are at a distance of one-half of the total width divided by n. The locations of the other verticals are separated from adjacent verticals by a distance of the total width divided by n. The locations of these verticals represent the centroid of subareas with boundaries one-half the distance to adjacent verticals. Hence, only the widths of the subareas necessarily are equal.

The EWI sampling method requires use of the same size nozzle for a given measurement, and all verticals must be traversed using a transit rate that will not result in overfilling the sample bottle at the deepest and fastest vertical in the cross section. The descending and ascending transit rates must be equal for all verticals and during the sampling traverse of each vertical. By using this equal-transit-rate technique with a standard depth- or point-integrating sampler at each vertical, a volume of water proportional to the flow in the vertical will be collected.

For example, from the previous paragraphs, samples from 12 verticals are to be collected from a stream with a surface width of 120 m with zero width referenced to the left bank. The location of the leftmost vertical is at a distance of one-half of 120 m divided by 12, or 5 m from the left bank. The 12 verticals are located 10 m apart with the rightmost vertical 5 m from the right bank. The second vertical from the left bank is located at 15 m, and the 12th vertical from the left bank is located at 115 m.

Because the maximum transit rate must not exceed 0.1 v_m, 0.2 v_m, or 0.4 v_m (a 0.4 v_m, transit rate applies to all bag samplers) depending on the nozzle size and bottle volume (v_m equals the mean ambient velocity in the sampled vertical), and because the minimum rate must be sufficiently fast to keep from overfilling any of the sample bottles, the transit rate to be used for all verticals is limited by conditions at the vertical containing the largest discharge per unit width, or, in operational terms, the largest product of depth times mean velocity. A discharge measurement can be made to determine the location of this vertical. In practice, this location often is estimated by sounding for depth and acquiring a feel for the relative velocity with a sampler or wading rod. The transit rate required at the maximum discharge vertical then must be used at all other verticals in the cross section and usually is set to provide the maximum sample volume in a round-trip transit. It is permissible to sample at multiple verticals using the same bottle as long as the bottle is not overfilled. If a bottle is overfilled, the contents must be discarded, and all verticals previously sampled using that bottle must be resampled, using a sufficient number of bottles to avoid overfilling.

5.3.4.2.5 Advantages of the Equal-Discharge-Increment and Equal-Width-Increment Methods Some advantages and disadvantages of both the EDI and EWI methods have been noted in the previous discussion. It must be remembered, however, that both methods, if properly used, will yield similar cross-sectionally averaged results.

The advantages of the EDI method are as follows:

1. Fewer requisite verticals typically result in a reduced collection time, which is particularly advantageous during periods of rapidly changing discharge;
2. Bottles composing a sample set may be composited for single laboratory analysis when equal volumes of sample are collected from each vertical;
3. The cross-sectional variation in concentration can be determined if samples are analyzed individually;
4. Duplicate cross-sectional samples can be collected during the measurement;
5. A variable transit rate can be used among verticals.

The advantages of the EWI method are as follows:

1. No antecedent knowledge of flow distribution in the cross section is required;
2. Variations in the distribution of concentration in the cross section may be better integrated in the composite cross section sample due to the larger number of verticals sampled;
3. Analytical time and costs are minimized as sample bottles are composited for single laboratory analysis;
4. This method is easily learned and used due to the straightforward spacing of sample verticals based on stream width, rather than on the cross-sectional distribution of discharge;
5. Generally, less total time is required on site if no discharge measurement is deemed necessary and the cross section is relatively stable during the measurement.

The advantages of one method are, in many cases, the disadvantages of the other. The USGS (1998b) considers the EDI method the most universally applicable and useful discharge-weighted sampling method.

5.3.4.2.6 Transit Rates for Suspended-Sediment Sampling A sample obtained with an isokinetic sampler using depth integration is quantitatively weighted according to the velocities through which it passes. Therefore, if the sampling vertical represents a specific width of flow, the sample is considered to be discharge weighted because, with a uniform transit rate, the suspended sediment conveyed at varying velocities throughout the sampled vertical is given equal time to enter the sampler.

The transit rate used with any depth-integrating sampler must be regulated to make possible the collection of representative samples (i.e., isokinetically collected). An insufficient transit rate can result in an unacceptable sample due to overfilling of the sample container. An excessive transit rate can result in intake velocities less than the stream velocity due to a large entrance angle between the nozzle and streamflow lines caused by the vertical movement of the sampler in the flow (FISP 1952). Transit rates should never exceed the product of 0.4 and the mean velocity (0.4 v_m) in a vertical with any isokinetic sampler.

Additional limitations may be imposed on maximum transit rates for rigid-bottle depth-integrating samplers due to changes in hydrostatic pressure during deployment. The maximum allowable transit rate is attained when the rate of change in the internal pressure due to filling equals the rate of change of hydrostatic pressure. If the sampler is lowered too fast in the vertical, inflow through the nozzle is insufficient to increase the pressure in the container at the same rate; consequently, hydrostatic pressure increases at a greater rate than pressure in the container. The resulting pressure imbalance causes the sample to enter the nozzle at a velocity greater than the ambient stream velocity. Stream water can also enter the exhaust port under these circumstances. Both potential outcomes result in violation of isokinetic sampling principles (Stevens et al. 1980). Likewise, if the sampler is raised too rapidly, the hydrostatic pressure will decrease at a greater rate than the pressure inside the container. This pressure imbalance will result in reduced flow of sample into the container with respect to the ambient stream velocity. Either outcome—larger or smaller intake velocities with respect to the ambient stream velocity—can result in collection of a sample that contains neither a representative concentration nor particle-size distribution of suspended sediment.

The maximum allowable transit rate for rigid-bottle samplers can be determined with knowledge about (1) the depth of the sample vertical, (2) the mean velocity of the vertical, (3) the nozzle size being used, and (4) the sample bottle size used in the sampler. Different combinations of nozzle diameters and bottle volumes result in maximum transit rates ranging from about $0.1v_m$ to $0.4v_m$. Tables providing isokinetic transit rates as a function of nozzle diameters and bottle volumes are provided by the USGS (1998b). Graphs delineating permissible and optimal transit rates for a combination of sample container and nozzle sizes as a function of stream depth and mean velocity are provided by Edwards and Glysson (1999). A vertical transit pacer is available to assist in quantifying the transit rate for a reel-deployed sampler (FISP 2001).

5.3.4.2.7 Point-Integrated Sampling A point-integrated sample is a sample of the water-sediment mixture collected isokinetically from a single point in the cross section. Point-integrated samples are collected using one of the point-integrating samplers previously presented. Multiple point samples may be used to define the distribution of sediment in a vertical, the vertical and horizontal distributions of sediment in a cross section, and the mean cross-sectional sediment concentration.

The purpose for which point samples are to be collected determines the collection method to be used. If samples are collected for the purpose of defining the horizontal and vertical distribution of concentration and/or particle-size distributions, samples collected at numerous points in the cross section with any of the "P" type samplers will be sufficient. Normally, 5 to 10 verticals are sufficient for horizontal definition of suspended-sediment concentrations. Vertical distributions can be adequately defined by obtaining samples from a number of points in each sample vertical. Specifically, samples should be taken with the sampler lightly touching the bed, 0.3 m off the bed, at from 6 to 10 additional points in the vertical above that point, and from near the surface. Each point sample should be analyzed separately.

If point samples are collected to define the mean concentration in a vertical, 5 to 10 samples should be collected from the vertical. The sampling time for each sample (the elapsed time that the nozzle is open) must be equal. This result will ensure that sample volumes collected are proportional to the flow at the point of collection. These samples may be composited for a single laboratory analysis. If the EDI method is used to define the stationing of the verticals, the sampling time may be varied among verticals. If the EWI method is used, a constant time for collecting samples from all verticals must be used.

The mean discharge-weighted suspended-sediment concentration in a cross section using the point-integration method is calculated from the mean concentrations from individual sampling points as follows:

$$C_{xs} = \frac{1}{n}\sum_{i=1}^{n}\left\{\frac{\sum_{d=1}^{D_i}\mathrm{Vol}_{id}C_{id}}{\sum_{d=1}^{D_i}\mathrm{Vol}_{id}}\right\} \tag{5-9}$$

where

C_{xs} = mean discharge-weighted suspended-sediment concentration in the cross section;
D_i = total number of points sampled in vertical i;
n = number of verticals in which point samples are collected;
C_{id} = suspended-sediment concentration in a sample from point d of vertical i; and
Vol_{id} = volume of sample collected from point d of vertical i.

If multiple points are sampled with a single bottle, computation of the mean sample concentration is accomplished by treating the contents of the bottle as if collected at a single point.

5.3.5 Automatic Samplers

Some sediment-monitoring programs and studies include sites where collection of sediment samples is required at a frequency, at a time, and/or under a set of conditions that cannot be accommodated through manual sampling. Safety considerations, remoteness or inaccessibility of site location, flow conditions, operational costs, and other factors may render manual collection of sediment and flow data at a site impractical or impossible. In lieu of manual sampling, automatic samplers may be deployed to accommodate sediment data-collection needs at some sites.

Automatic samplers are useful for collecting suspended-sediment samples during periods of rapid discharge changes from storm-runoff and in reducing the need for manual measurements associated with intensive sediment-collection programs (FISP 1981). However, under some circumstances, use of automatic samplers to collect data can actually result in costs greater than those for an observer at the same site. Automatic samplers, and particularly pumping samplers, often require more frequent site visits by the field personnel than would be required at the conventional observer station, owing to their mechanical complexity, power requirements, and limited sample capacity. Use of automatic samplers does not preclude the need for collecting medium- and high-flow cross-sectional samples. Additionally, use of automatic samplers typically results in reduced data quality. This result is particularly true for automatic sample collection from streams conveying high percentages of suspended sand-size material.

As noted previously, emerging technologies for monitoring suspended sediment show great promise, although none is commonly accepted nor extensively used. The most commonly used automatic samplers are automatic pumping samplers, which require power to obtain water samples. Single-stage samplers, which rely on changes in stream stage and/or velocity to collect water-sediment samples on the rising phase of a hydrograph, are also available.

5.3.5.1 Automatic Pumping Samplers Automatic pumping samplers generally consist of a pump, bottle-container unit, and sample distribution, activation, and intake systems. Ideally, this combination of components should be designed to meet the following criteria (Bent et al. 2001; Edwards and Glysson 1999):

1. Stream velocity and sampler intake velocity should be equal to allow for isokinetic sample collection if the intake is aligned into the approaching flow;
2. A suspended-sediment sample should be delivered from stream to sample container without a change in sediment concentration or particle-size distribution;
3. Cross contamination of samples caused by residual sediment in the sampler plumbing between sample-collection periods should be prevented;
4. The sampler should be capable of sampling over the full range of suspended-sediment concentrations and particle sizes;
5. Sample container volumes should meet minimum sample analysis volume requirements;
6. The inside diameter of the intake should be at least three times the diameter of the largest particles sampled, although small enough to maintain a mean sample velocity that will substantially exceed the fall velocity of those particles;
7. The sampler should be capable of vertical pumping lift elevations of about 10 m from intake to sample container for clear water;
8. The sampler should be capable of collecting a reasonable number of samples—usually at least 24—dependent upon the purpose of sample collection and the flow conditions;
9. Some provision should be made for protection against freezing, evaporation, and dust contamination of collected samples;
10. The sample container unit should be constructed to facilitate removal and transport as a unit;
11. The sampling cycle should be initiated in response to a timing device, flow change, or external signal based on a set of criteria that maximizes the potential for collecting samples at desired points over one or more hydrographs;
12. The capability of recording the sample-collection date and time should be present;
13. The provision for operation using ac power or dc battery power should be present.

Nearly all of the automatic pumping samplers in use today are available commercially. The PS-69, CS-77, and PS-82 pumping samplers are no longer manufactured.

The ISCO 6700 and American Sigma 900 automatic pumping samplers, for example, share various features for collecting water samples. Both are computer-controlled portable samplers capable of collecting up to 24 1-L samples based on time, flow, and/or other user-selected criteria. They use built-in peristaltic pumps and operate on ac power or dc battery power. Both samplers feature a back-flush cycle to reduce cross contamination between consecutively collected samples.

Neither sampler is capable of sampling clear freshwater if the peristaltic pump is at an elevation of about 9.7 m or more above that of the water surface. Cavitation can occur at smaller heads with larger specific gravities associated with increasing suspended-sediment concentrations and/or lower barometric pressures. Where lift requirements potentially exceed the capacity of a sampler, an auxiliary pump may be used to pump water to the sampler under a positive pressure. Gray and Fisk (1992) describe an automatic pumping sampling system used to collect samples of highly concentrated streamflow in Arizona and New Mexico. An auxiliary pump in a diving bell affixed at an elevation of a meter or two above that of the water surface at low flow pumps stream water to a gauging station. In the gauging station, a commercial sampler modified to collect 9-L samples periodically draws an aliquot of the pumpage from the auxiliary pump via a Y connector in the intake line. A data-collection platform controls collection of up to 24 samples based on time, stage, and rate-of-stage-change criteria. The data-collection platform records hydrologic information and data related to the number and times of samples collected and periodically updates a USGS database via satellite.

5.3.5.1.1 Installation and Use Criteria The decision to use a pumping sampler for collection of sediment samples usually is based on physical and fiscal criteria. Installation of an automatic pumping sampler requires careful planning before installation, including selection of the sampler site location and an evaluation of available or newly collected data to maximize the potential to collect useful pumping sampler data.

Before installation of an automatic pumping sampler, many of the problems associated with installing stream-gauging equipment must be addressed. In addition, specific data concerning the sediment-transport characteristics at the proposed sampling site must be obtained and evaluated prior to emplacement of the sampler and location of the intake within the streamflow. Logistically, the sample site must be evaluated as to accessibility, availability of electrical power, location of a bridge, cableway, or other means to safely obtain manual measurements at the site, and normal range of ambient air temperatures inherent in local weather conditions. The availability of a local observer to collect periodic reference samples also should be considered. The sediment-transport characteristics should include detailed information on the distribution of concentrations and particle sizes throughout the sampled cross section over a range of discharges. Glysson (1989b) describes other information requirements associated with collection of sediment data.

5.3.5.1.2 Placement and Orientation of Sampler Intake The primary concept to consider when placing a sampler intake in the streamflow at a sample cross section is that only one point in the flow is being sampled. Therefore, to yield the most reliable and representative data, the intake should be placed at the point where the concentration and particle-size distribution are most representative of the mean sediment concentration for the cross section over the full range of flows. This idealistic concept has great merit, but the mean cross section concentration almost never exists at the same point under varying streamflow conditions. It is even less likely that specific guidelines for locating an intake under given stream conditions at one stage would produce the same intake location relative to the flow conditions at a different stage. These guidelines would have even less transfer value from cross section to cross section and stream to stream. For these reasons, some generalized guidelines are outlined here and should be considered on a case-by-case basis in placing a sampler intake in the streamflow at any given cross section (Edwards and Glysson 1999):

1. Select a stable cross section in a reach with reasonably uniform depths and widths to maximize the stability of the relation between sediment concentration at a point and the mean sediment concentration in the cross section. This guideline is of primary importance in the decision to use a pumping sampler in a given situation; if a reasonably stable relation between the sample-point concentration and mean cross section concentration cannot be attained by the following outlined steps, an alternate location for the installation should be considered.
2. Consider only the part of the vertical that could be sampled using a standard US depth- or point-integrating suspended-sediment sampler, excluding the unsampled zone, because data collected with a depth- or point-integrating sampler will be used to calibrate the pumping sampler.
3. Determine, if possible, the depth of the point of mean sediment concentration in each vertical for each size class of particles finer than 0.25 mm from a series of carefully collected point-integrated samples.
4. Determine, if possible, the mean depth of occurrence of the mean sediment concentration in each vertical for all particles finer than 0.25 mm.
5. Use the mean depth of occurrence of the mean sediment concentration in the cross section as a reference depth for placement of the intake.
6. Identify or install a means to fix the intake at the desired location in flow. The attachment feature and intake should have a high probability of remaining in place at high flows and should be not be prone to collecting debris.
7. Adjust the depth location of the intake to avoid interference by dune migration or contamination by bed material.
8. Adjust the depth location of the intake to ensure submergence at all times.
9. Locate the intake in the flow at a distance far enough from the bank to eliminate any possible bank effects. Avoid placing the intake in an eddy.
10. Place the intake in a zone of high velocity and turbulence to improve sediment distribution by mixing, reduce possible deposition on or near the intake, and provide for rapid removal of any particles disturbed during a purge cycle.

Because of the generalized nature of these guidelines and because selected guidelines may prove to be mutually exclusive, it will often be impossible to satisfy them all when situating a pumping sampler intake into streamflows. The investigator is encouraged, however, to try to satisfy these guidelines or, at the very least, to satisfy as many as possible and to minimize the effects of those not satisfied.

The orientation of the pumping sampler intake nozzle can drastically affect sampling efficiency. There are five ways in which an intake could be oriented to the flow (see Fig. 5-18): (1) normal and pointing directly upstream (Fig. 5-18A), (2) normal and horizontal to the flow (Fig. 5-18B), (3) normal and vertical with the orifice up (Fig. 5-18C), (4) normal and vertical with the orifice down (Fig. 5-18D), and (5) normal and pointing directly downstream (Fig. 5-18E). Of these five orientations, A, C, and D should be avoided because of high sampling errors and trash-collection problems. Orientation B, with the nozzle positioned normal and horizontal to the flow, is the most common alternative used. The major problem with this orientation is that sand-size particles may not be adequately sampled (see the following section on pumped-sample data analysis). Orientation E, pointing directly downstream, may be advantageous over orientation B (Winterstein and Stefan 1986). When the

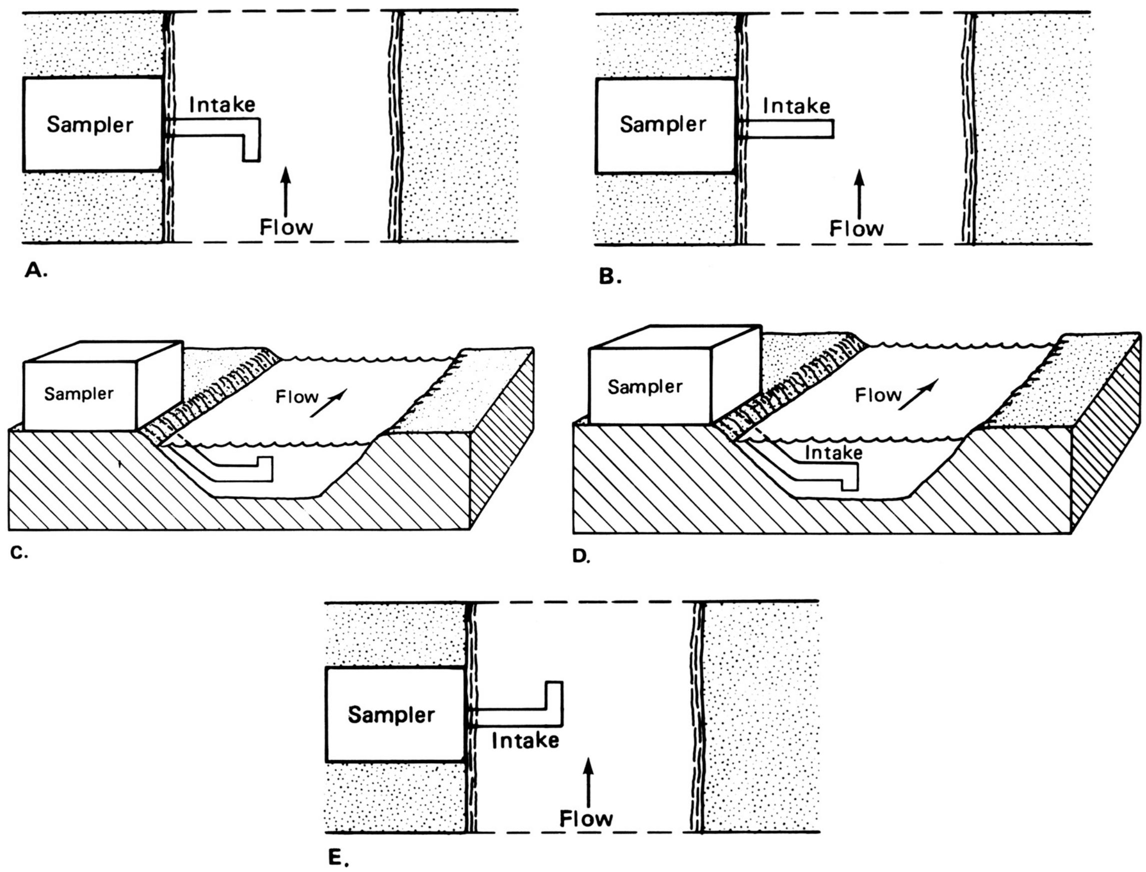


Fig. 5-18. Examples of pumping-sampler intake orientations. (A) Normal and pointing directly upstream. (B) Normal and horizontal to flow. (C) Normal and vertical with the orifice up. (D) Normal and vertical with the orifice down. (E) Normal and pointing directly downstream.

intake is pointing downstream, a small eddy is formed at the intake, which envelops the sand particles and thus allows the sampler to collect a more representative sample of the coarse load. Regardless of the intake orientation selected, the ratios of concentrations representative of the mean cross-sectional concentration and those from pumped samples are needed to define the sampling efficiency over a broad range of flows.

5.3.5.1.3 Activation The advent of the microprocessor as an integral part of the sampler, or as an external controller, provides many options for controlling pumping samplers that can be tailored to data-collection requirements on-hand. Gray and Fisk (1992) describe a method for controlling an automatic water sampler based on time, stage, and rate-of-stage-change criteria. Their technique is designed to provide adequate definition of the flood hydrograph to make possible reliable computations of daily sediment and associated solid-phase radionuclide discharges. Lewis (1996) describes a means for controlling an automatic sediment sampler based on real-time turbidity measurements. A technique for controlling an automatic water sampler that provides unbiased estimates of suspended-sediment discharges, based on time-stratified sampling and selection at list time, is described by Thomas (1985; 1991), and Thomas and Lewis (1993a).

5.3.5.2 Single-Stage Samplers Single-stage samplers were developed to meet the urgent needs for instruments useful in obtaining sediment data on streams where remoteness of site location and/or rapid changes in stage make it impractical to use a conventional depth-integrating sampler. They are generally less reliable, both in operation and in data accuracy, than depth-integrating samplers. However, even approximate information on the concentration of sediment between visits to the stream can be important if nothing better is available (FISP 1961; Edwards and Glysson 1999).

The US U-59 series single-stage samplers designed and tested by the FISP consist of a 0.45-L milk bottle or other sample container, a 4.7-mm inside diameter air exhaust, and a 4.7- or 6.4-mm inside diameter intake constructed of copper tubing. Each tube is bent to an appropriate shape and inserted through a stopper sized to fit and seal the mouth of the sample container. There are four models of US U-59 samplers. That designated US U-59A is designed for collection of silt- and clay-size sediments in low (less than about 0.7

m/s stream velocities. Those designated US U-59B, US U-59C, and US U-59D are for collection of sand-size and finer material in stream velocities less than 1, 1.6, and 2.1 m/s, respectively. A US U-59D single-stage suspended-sediment sampler is shown in Fig. 5-19A.

The US U-59 series of samplers obtains a sample on the rising phase of the hydrograph from a point near the water surface when the water level inside the intake tube reaches the weir elevation. As the sample siphons from the intake orifice into the sample bottle, air from the sample bottle vents out of the exhaust tube. The sampler is designed to cease filling when the sample elevation reaches the inner exhaust tube orifice. The sample velocity in the intake tube is a function of various factors, including stream velocity, intake orifice orientation, turbulence, and the presence of obstructions in the intake or exhaust tube.

The sampling operation just described is somewhat idealistic because, in reality, the operation is affected by various factors including flow velocity and turbulence. These factors alter the effective pressure at the nozzle entrance, which in turn alters the sampler's intake velocity.

The US U-59 sampler has many limitations with respect to good sampling objectives. It is a type of point sampler because it samples a single point in the stream at whatever stage the intake nozzle is positioned when immersed in flow. Its primary purpose is to collect a sample automatically, and it is used at stations on flashy streams or other locations that are difficult to visit in time to manually collect samples. Besides being automatic, the US U-59 is simple and inexpensive compared to automatic pumping samplers; a bank of them can be used to obtain a sample at various elevations during the rising hydrograph. However, despite these seemingly important advantages, the US U-59 sampler has many limitations. Following are the most important of these limitations:

1. Samples are collected at or near the stream surface, so that, in the analysis of the data, theoretical adjustments for vertical distribution of sediment concentration or size are necessary.
2. Samples usually are obtained near the edge of the stream or near a pier or abutment; therefore, theoretical adjustments for lateral variations in sediment distribution are required.
3. Even though combinations of size, shape, and orientation of intake and air-exhaust tubes are available, the installed system may not result in intake ratios sufficiently close to unity to sample sands accurately at parts of the runoff hydrograph.
4. Covers or other protection from trash, drift, and vandalism often create unnatural flow lines at the point of sampling.
5. Water from condensation may accumulate in the sample container prior to sampling.
6. Sometimes the sediment content of the sample changes during subsequent submergence.
7. The device is not adapted to sampling on falling stages or on secondary rises.
8. No specific sampler design is best for all stream conditions.
9. The time and gauge height at which a sample was taken may be uncertain.
10. At high velocities, flow can circulate into the intake nozzle and out the air exhaust. This can result in an

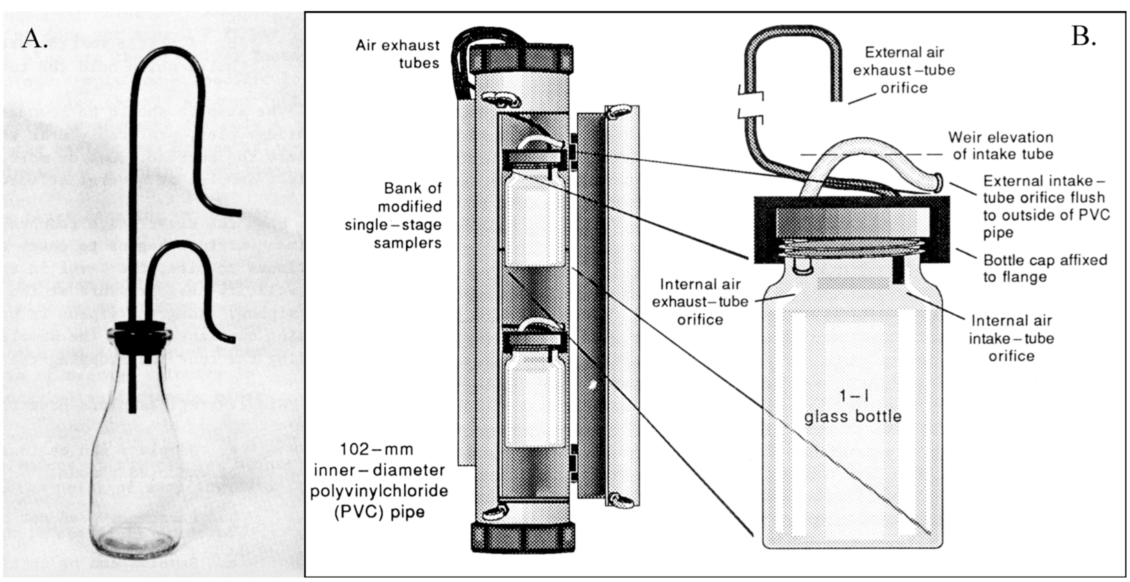


Fig. 5-19. (A) US U-59D single-stage suspended-sediment sampler and (B) Modified single-stage sampler. Reprinted from Gray and Fisk (1992) with permission.

increase in the concentration of coarse material in the sample by at least an order of magnitude.

Gray and Fisk (1992) developed a modified single-stage sampler that provides a measure of protection against vandalism and flood damage while minimizing the potential for water circulation (Fig. 5-19B). Various single-stage samplers are arranged vertically inside a protective polyvinyl chloride (PVC) pipe capped at both ends. Screw-cap 0.9-L bottles are used to provide a larger sample volume and a more positive seal. External air-exhaust orifices extend through the top cap to the highest elevation feasible for the site, reducing the potential for its inundation. External intake orifices are set flush with the exterior PVC pipe so that debris cannot snag on them. A hinged lockable door provides access to the 0.9-L sample bottles.

The US U-73 single-stage sampler is more sophisticated than the previously described single-stage samplers. It can be used to obtain samples on the rising and falling phases of a hydrograph. Additionally, it features an exterior design that allows for a degree of protection from trash or drift without additional covers or deflection shields. Aside from these advantages, the US U-73 has the same limitations and should be used under the same conditions as the US U-59 sampler. Although the US U-73 sampler is no longer stocked by the FISP, plans are available for its construction (FISP 2000).

The investigator using single-stage samplers may find protective measures necessary to avoid blockage of intakes or air exhausts due to nesting insects. In freezing temperatures, precautions against sample-container breakage due to expansion of a freezing sample are advised.

The percent sand-size material should be analyzed for all samples collected by single-stage samplers. This analysis will help identify instances of bias in concentrations resulting from sample recirculation.

5.3.6 Subsampling Equipment

Samples of water-sediment mixtures are sometimes subsampled, or split into multiple parts to make possible different analytical determinations on the subsamples. The validity of data obtained from subsamples depends on their comparability of selected constituent concentrations to those in the original sample. Subsamples tend to have larger constituent variances than the original, and also may be biased. Subsampling should be avoided unless it is necessary to achieve the ends of the sampling program.

Before 1976, USGS guidelines on manual sample splitting required compositing the water sample into a large, clean jug or bottle, shaking it for uniform mixing, and then withdrawing the required number of samples (USGS 1976). In 1976, the 14-L churn splitter was introduced to facilitate the withdrawal of a representative subsample of a water sediment mixture (Capel and Larson 1996; Lane et al. 2003). A fluoropolymer version of the churn splitter for trace-element subsampling is also available (FISP 2002). The cone splitter, a device developed to split water samples for suspended sediment and other water-quality constituents into up to 10 equal and representative aliquots, was introduced for widescale use in 1980 (Capel and Nacionales 1995; Capel and Larsen 1996).

Based on test results on the sediment-splitting efficiency of the churn and cone splitters (USGS 1997), the USGS has approved the use of the churn splitter for providing subsampling when the original sample's sediment concentration is less than 1,000 mg/L at mean particle sizes less than 0.25 mm. The cone splitter is approved for providing subsamples at sediment concentrations up to 10,000 mg/L at mean particle sizes less than 0.25 mm. The test data suggests that the cone splitter's acceptable concentration range exceeds 10,000 mg/L, and may be as large as 100,000 mg/L.

5.4. BED LOAD SAMPLERS

R. Kuhnle

The part of the total sediment load that is transported by traction or saltation on or immediately above the streambed is termed the bed load. Sediment transported as bed load can range in size from fine sands to coarse gravel depending on the flow strength. The separation of sediment in transport into bed load and suspended load is artificial, as there is often no clear-cut break between the two groups. The distinction is convenient, however, because most suspended sediment samplers currently in use have an unsampled zone that extends from the bed to several centimeters up into the flow. The sediment in transport in this zone near the bed is often referred to as the unmeasured load and consists of the bed load plus the lowermost fraction of the suspended load.

Knowledge of the rate of bed load transport is important for several reasons. The bed load is part of the total sediment load that represents net erosion from upstream areas of the watershed. Sediment conveyed downstream may fill reservoirs and channels, which impedes navigation, may increase the likelihood of flooding, and may degrade water quality and aquatic habitats. Local erosion and deposition of the bed material may also cause instability of the channel banks. Any long-term program of channel stabilization or rectification must take into account the transport of bed load and ensure that sediment is not accumulating or eroding.

The rate and size of sediment in transport as bed load varies dramatically with time at a point, and spatially at a given time over a cross section of a channel (Figs. 5-20A and B), even when the flow is steady (Ehrenberger 1932; Leopold and Emmett 1976; Carey 1985; Hubbell et al. 1985; Iseya and Ikeda 1987; Kuhnle and Southard 1988; Whiting et al. 1988; Kuhnle et al. 1989; Gray et al. 1991). This creates the challenge of designing a sampler that will sample with equal efficiency over widely varying transport rates, and collect enough samples at a point and across the cross section to adequately define the mean rate for a given flow strength.

The determination of bed load has relied on three general methods (Hubbell 1964): direct measurement, using bed load transport relations, or measuring the erosion or deposition of bed-material sediment in a confined area. None of these techniques is suitable for a wide range of uses. Direct measurements suffer from the difficulty of deploying the samplers and collecting a sufficient number of samples, whereas no one bed load transport relation has been shown to have general applicability (e.g., Gomez and Church 1989; Vanoni 1975, pp. 221–222), and many areas do not have a convenient area to carry out erosion or deposition measurements. Therefore, no general empirical or theoretical technique is completely adequate for determining the discharge of bed load in natural streams and rivers.

The placement of any type of bed load sampler onto a bed must alter the local flow pattern and movement of sediment to some extent. The degree of disturbance a sampler will cause in local conditions is dependent on many things; among them are the shape and size of the sampler, the local flow velocity, the characteristics of the bed-material sediment, and the presence or absence of bed forms. The degree to which the sampler affects the local flow conditions will be reflected in the efficiency of the sampler in collecting samples of the bed load. To estimate the relation between the sampled rate and the true rate, the sampler will need to be calibrated. The calibration of a sampler is plagued by the problem of comparing the amount of sediment collected by the sampler to the undisturbed bed load movement that would have occurred if the sampler had not been in place (Einstein 1937). Due to the extreme variability of bed load transport processes this is an extremely difficult problem to solve and persists to this day.

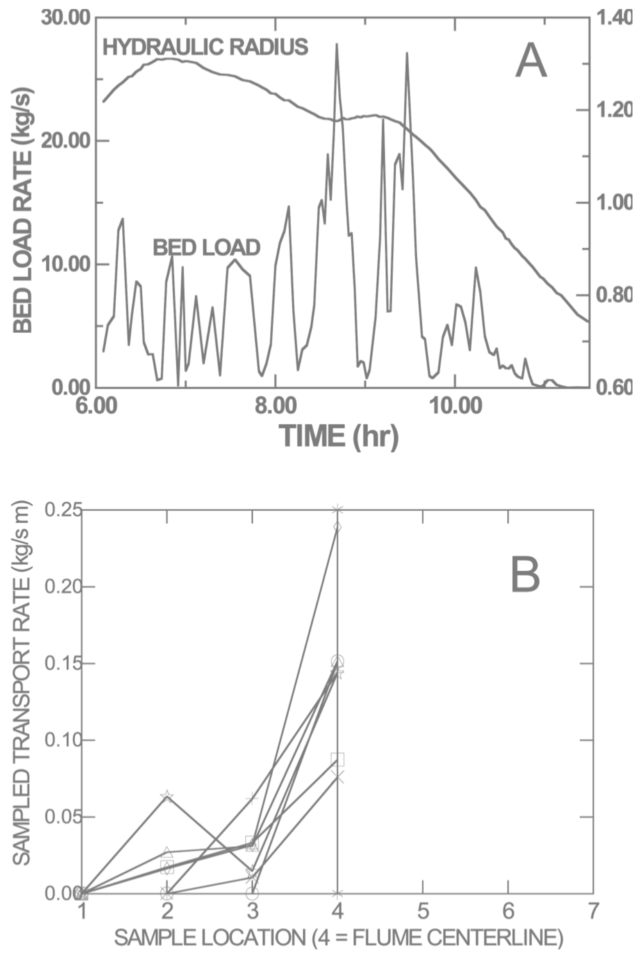


Fig. 5-20. (A) Bed load transport rate and flow changes with time, Goodwin Creek, station 2. Samples were collected in the center of the structure during runoff event on 11/08/86 (Kuhnle et al. 1989). (B) Plots of lateral sets of samples collected at Goodwin Creek, station 2, during 02/27/87 transport event. The distance between sample locations is 1.5 m. Lateral samples were collected on one side of the structure centerline (Kuhnle 1992b).

5.4.1 Types of Bed Load Samplers

Over the past 100 years, several types of bed load samplers have been developed by researchers at a variety of locations. These samplers may be generalized into three types: samplers installed into the bed of a channel (pit and trough samplers), manually operated portable samplers, and noninvasive samplers. Each of these sampler types has its use in the sampling of bed load. Perhaps the most accurate of these three types are the pit or trough samplers; however, the difficulty and high cost of their installation and servicing preclude their use in many studies. Portable samplers have the advantage of low setup costs, but personnel must be on site continuously during sample collection, sampler deployment may be difficult, and the number of samples needed to characterize temporal and spatial variability is usually large. Also, no generally accepted method has been developed for calibrating portable samplers. Samplers that use noninvasive techniques show much promise, but have not been developed to the point where they can be widely useful for the measurement of bed load transport.

5.4.1.1 Manually Operated Portable Samplers Bed load samplers of this type have been developed and used in many countries to determine rates of bed load movement for sediment varying in size from 1 to 300 mm (FIARBC 1940; Hubbell 1964). The development of bed load samplers has often been associated with individual project studies. These samplers have been classified as to their type of construction and principle of operation, mainly as basket samplers, pan or tray samplers, and pressure-difference samplers (Hubbell 1964). Basket and pan samplers cause an increased resistance to flow through the sampler and water velocity in the sampler is therefore lower than in the free stream. This reduction in flow velocity in the sampler reduces the shear stress and the rate of bed load transport in the vicinity of the sampler, with the result that some particles accumulate at the entrance to the sampler and others are diverted away. The pressure-difference type samplers are designed to eliminate the reduction in water velocity in the sampler, and thus any reduction in the rate of bed load movement at the entrance to the sampler. The velocity in the sampler is made equal to that of the flow by creating a decrease in pressure at the exit of the sampler nozzle by having a gradual increase in area. Pressure-difference samplers generally have a hydraulic efficiency (ratio of flow velocity in sampler to flow velocity for same location without sampler) of about one or greater (Hubbell et al. 1985). One key parameter in the design of pressure-difference samplers is to make the hydraulic efficiency large enough to prevent sediment from depositing in front of the sampler, but not so large as to cause scouring of the bed and oversampling.

For a bed load sampler to operate correctly, it should be used within the range of conditions for which it was designed. The most restrictive of these design elements include bed load particle sizes as compared to the inlet opening of the sampler; bed load rates as compared to the size of the catchment volume; water depth according to whether the sampler was designed for wading or cable suspension; and flow velocities as related to resistance of the sampler in the flow and range of calibration velocities. Only a few of these types of samplers have been calibrated and there is no widespread agreement on the methodology to use to calibrate a bed load sampler (Engel and Lau 1980; Hubbell et al. 1985; Thomas and Lewis 1993b). Calibrations of these samplers indicate a mean efficiency of about 45% for basket or pan type and vary from 80% to 180% for pressure-difference types. These efficiencies may vary with transport rate, sediment size, and sediment gradation.

Descriptions of some pressure-difference bed load samplers that are in current use are presented in Table 5-3. These include the Federal Interagency Sedimentation Project BL-84 (Fig. 5-21) (Davis 2005); the 7.62-cm-square Helley-Smith (Helley and Smith 1971); the 15.24-cm-square Helley-Smith; the Toutle River-2 (Childers 1992); the Elwha River (Childers et al. 2000); the Delft-Nile sampler (Van Rijn and Gaweesh 1992); and the BTMA-2 (Duizendstra 1999). Typical problems with operation of pressure-difference samplers include the following (Van Rijn and Gaweesh 1992):

1. The initial effect: Sand particles of the bed may be stirred up and trapped when the instrument is placed on the bed (oversampling).
2. The gap effect: A gap between the bed and the sampler mouth may be present initially or generated at a later stage under the mouth of the sampler due to migrating ripples or erosion processes (undersampling).
3. The blocking effect: Blocking of the bag material by sand, silt, clay particles, and organic materials will reduce the hydraulic coefficient and thus the sampling efficiency (undersampling).
4. The scooping effect: The instrument may drift downstream during lowering to the bed, and may be pulled forward (scoop) over the bed when raised again so that it acts as a grab sampler (oversampling).

Five types of conditions occurring during collection of bed load samples with the Delft-Nile sampler were recognized by Gaweesh and Van Rijn (1994) using a video camera mounted near the sampler on the Nile and Rhine Rivers. Two of these types of conditions (the gap effect and scooping effect) were found to result in either significant under- or oversampling by the Delft-Nile sampler. Gaweesh and Van Rijn (1994) recommended removing the highest and lowest 10% of the collected samples based on the fact that these two types each occurred approximately 10% of the time. This technique was found to improve the results of their field bed load sampling.

Table 5-3 Portable Bed Load Samplers

Sampler name	Sediment sizes (mm)	Entrance width (m)	Entrance height (m)	Type of sampler	Hydraulic efficiency (%)	Sampling efficiency (%)	Capacity of sampler (kg)
FISP BL-84[a]	1–38	0.076	0.076	c, w	135[b]	100–140[b–e]	10
Helley-Smith[f]	1–38	0.076	0.076	c, w	154[g]	100–180[d,e,h,i]	10
Helley-Smith[f]	1–76	0.152	0.152	c, w	154[g]	100–180[d,e,h,i]	10
Toutle River-2[e]	1–150	0.305	0.152	c	140[b]	80–116[b,c,e]	60
Elwha River[j]	1–100	0.203	0.102	c, w	140[b]	80–116[b,c,e]	30
Delft-Nile[k]	0.25–0.85	0.096	0.055	c	100[k]	120–140[k]	24
BTMA-2[l]	0.5–150	0.30	0.30	c	100[est]	unknown	300

Note: est, estimated.
[a]Hubbell et al. 1985; [b]Hubbell et al. 1987; [c]Hubbell and Stevens 1986; [d]Childers 1991; [e]Childers 1992; [f]Helley and Smith 1971; [g]Druffel et al. 1976; [h]Emmett 1980; [i]Huanjin 1991; [j]Childers et al. 2000; [k]Van Rijn and Gaweesh 1992; [l]Duizendstra in press.

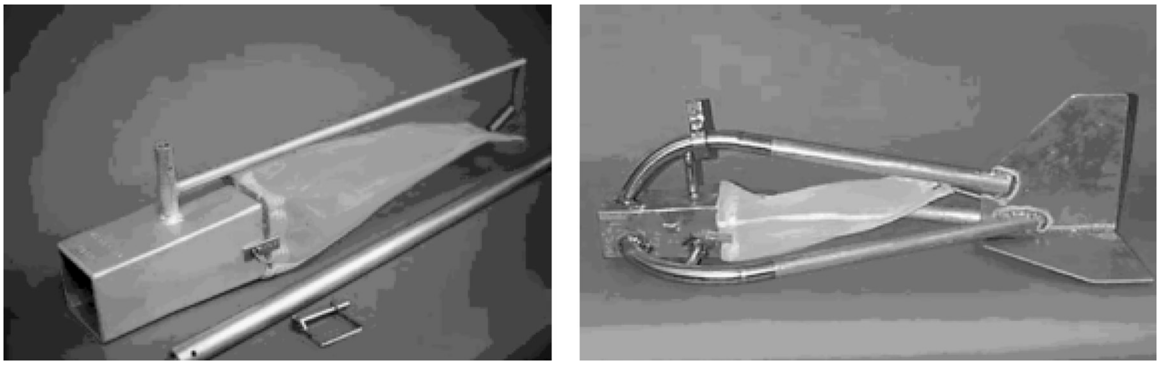


Fig. 5-21. Photograph of Federal Interagency Sedimentation Project BL-84 samplers. (A) Hand version: BLH-84. (B) Cable-mounted version: BL-84. The ratio of the inlet area to the outlet area is 1.40 on this sampler.

The orientation of the Helley-Smith sampler with respect to the mean flow velocity vector has also been found by Gaudet et al. (1994) to affect the efficiency of sediment sampling. If the sampler was misaligned as little as 10° from the mean flow velocity vector, significant decreases in sediment sampler efficiency were found by Gaudet et al. (1994). Although misalignment may not be a problem in many situations, sampling in complex flow fields could be affected by this problem.

These potential problems with pressure-difference samplers have been recognized by researchers over the years and design and sampling procedure changes have been made to correct for these problems. Stay lines have been used successfully by several researchers to aid in controlling the sampler in high-velocity conditions (Childers 1992). Samplers with flexible bottoms, guide fins, larger collection bags (Bunte et al. 2001), bottom sensors, and underwater video cameras (Dixon and Ryan 2001) have been designed to solve these problems. The BTMA-2 sampler (Duizendstra 1999) is perhaps the most advanced system in use to date to avoid the problems outlined above that occur with pressure-difference samplers.

5.4.1.1.1 Manually Operated Portable Sampler Calibrations Most types of portable samplers cause some degree of disruption to the flow and some degree of disruption to the transport of bed material as well. Unless steps are taken in portable sampler design to increase the flow through the sampler, sediment will tend to be deposited in front of or inside the sampler orifice and low and erratic sampling efficiencies will result. To improve the sediment-sampling efficiency of portable samplers, pressure difference nozzles were designed (Helley and Smith 1971) to increase the flow of water through the sampler. Thus hydraulic efficiency in pressure difference samplers is designed to be equal to or greater than 100% (Druffel et al. 1976). Hydraulic efficiencies are readily measured in laboratory flumes, however, sediment-sampling efficiencies are much more difficult to measure.

Unless a sampler works perfectly and collects an unbiased sample of the sediment in transport, a calibration coefficient is needed to correct the sampled rate to the actual rate.

$$q_b = \alpha c_s \qquad (5\text{-}10)$$

where

q_b = actual bed load transport rate;
c_s = sampled transport rate; and
α = calibration coefficient.

Equation (5-10) assumes that the actual bed load rate is a linear function of the sampled rate. In general,

$$q_b = f(c_s) \qquad (5\text{-}11)$$

where q_b is an unknown function of c_s. If q_b is not a linear function of c_s, their mean values will not satisfy equation (5-10) and the use of means will lead to erroneous results (de Vries 1973). This complicates considerably the calibration of bed load samplers. One proposed solution to this problem is to compare the actual and sampled bed load transport rates that occur for the same probability (Einstein 1937; de Vries 1973; Hubbell et al. 1985). This procedure was termed "probability matching" by Hubbell et al. (1985) and was used to define composite calibration curves for several portable samplers. The results from the probability matching procedure were disputed by Thomas and Lewis (1993b). As an alternate method of analysis, Thomas and Lewis (1993b) transformed the sampler and bed load trap data from Hubbell et al. (1985) to obtain a linear relation between the two variables. Their results from this transformed data indicated that pressure-difference samplers with higher nozzle ratios (3.22) collected more sediment than the ones with lower ratios (1.4), and that samplers with smaller orifices performed more uniformly than ones with larger orifices (0.076 m square versus 0.152 m square).

Other researchers have worked on the problem of portable bed load sampler calibration (Emmett 1980; Engel and Lau 1980; Ryan and Porth 1999). Engel and Lau (1980) developed a dimensional analysis technique and used it with data collected from a scale model of a basket sampler to calculate a calibration curve for the full-sized basket sampler used by the Water Survey of Canada. The efficiency of the basket sampler was found to vary from about 50% at low trap numbers (low transport rates) to about 25% at high trap numbers. Emmett (1980) calculated calibration curves for the original version of the Helley-Smith sampler (Helley and Smith 1971), using data collected on the East Fork River. Bed load transport data collected using the trough conveyor-belt sampler on the East Fork River, when compared to data collected with the Helley-Smith sampler, yielded efficiencies near 100% for grain sizes from 0.5 to 16 mm. Ryan and Porth (1999) compared data collected from three pressure difference samplers, the original Helley-Smith sampler, the BL-84, and an original design Helley-Smith sampler constructed of sheet metal. The data from the three samplers were compared to data on bed load obtained from surveying sediment accumulation in a weir pond. Calculations of annual bed load for all three samplers (Ryan and Porth 1999) were well within an order of magnitude of the accumulations measured in the weir pond. Studies comparing different portable samplers to each other have been made by Childers et al. (1989); Childers (1991; 1992); Gray et al. (1991); and Pitlick (1988). These studies demonstrate that relatively minor differences in sampler design can cause large differences in the size of the collected samples. The original version of the Helley-Smith sampler has been shown in one study to have an sediment efficiency of nearly 100% (Emmett 1980) for one set of conditions and to oversample for another set of conditions (Hubbell et al. 1985). Gray et al. (1991) found that the original Helley-Smith sampler tended to collect more material at high sediment transport rates and collect less material at lower rates than an early version of the BL-84 bed load sampler. The sometimes conflicting results, however, serve to underline the complexity of the transport of bed load by streams and rivers and to highlight the importance of the conditions of the streams in which the measurements are collected.

5.4.1.2 Pit and Trough Samplers One of the most accurate ways to sample bed load is through the use of carefully designed and installed pit or trough samplers (Hubbell 1964; Poreh et al. 1970). These samplers are installed in the bed of the channel by burying the sampler so that the top is flush with the surface of the bed. Pit and trough samplers range from simple containers to complicated weighing and recording instruments. Basic ones consist of small containers that catch and retain all bed load sediment that is transported to the sampler (e.g., Waslenchuk 1976; Murphy and Amin 1979; Church et al. 1991; Wilcock et al. 1996). Samplers of this type capture the total or minimum amount (if the sampler is filled in an unknown time) of sediment transported as bed load during the measurement period. For studies in which information on the beginning of bed load transport and the rates of transport during the measurement periods are needed, recording pit samplers (Fig. 5-22) have been designed and used successfully (Reid et al. 1980; Lewis 1991; Kuhnle 1992; Laronne et al. 1992).

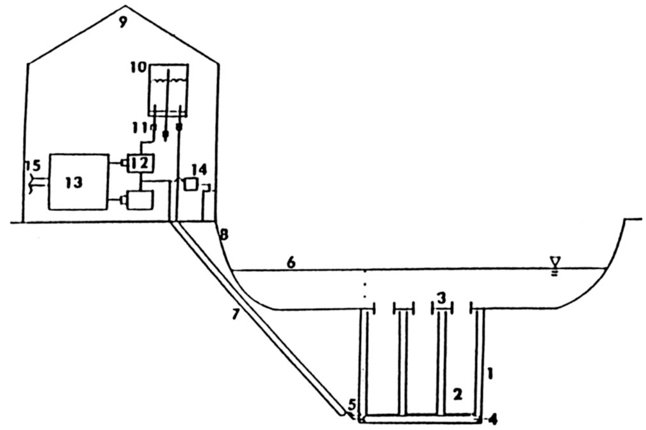


Fig. 5-22. Schematic cross section of box sampler: (1) outer box, (2) inner box, (3) slotted cover, (4) pressure pillow, (5) bubble tube outlet, (6) water surface, (7) tubes from bubbler and pillow, (8) stream bank, (9) instrument house, (10) air trap, (11) valves, (12) pressure transducer, (13) power supply, (14) bubble gauge, and (15) wires to remote telemetry system (Kuhnle 1991).

For sand-bedded channels, experiments have shown that samplers having slot widths of 100 to 200 grain diameters collect nearly 100% of the bed load (Einstein 1944). Sand particles often move by making brief excursions into the flowing water and then falling back to the bed. The specification of slot widths for sand grains was determined from the probable lengths of these excursions. As particle sizes increase into the gravel size range, transport occurs with grains spending progressively more time in contact with the bed (gravel-size grains usually slide or roll along the bed) and the parameter for slot widths from Einstein is no longer applicable. Poreh et al. (1970) have shown in a laboratory flume that when the ratio of the stream parallel slot length to the sediment grain diameter is about 35 for grain sizes between 1.88 and 4.5 mm, the efficiency of a channel-wide pit sampler approaches 100%. Poreh et al. (1970) also recommend using an unerodable apron upstream of the sampler to reduce the effect of bed forms on sampler performance. Slot lengths parallel to flow should not be made too much larger than necessary as secondary flows in the trap increase with slot length (Ethembabaogla 1978) and may cause smaller grains moving as bed load to be excluded from the trap (Wilcock et al. 1996). Some pit samplers (Kuhnle 1992) have incorporated flow transverse vanes to break up secondary flows in the sampler. Another potential problem with pit traps with widths narrower than the channel width is the lateral entry of sediment into the slot. Emmett (1980) calculated that when only part of the slot was used to sample on the East Fork River, bed load transport was consistently overestimated by a factor of 1.3 compared to using the whole width of the slot. Lewis (1991) described the use of low-profile fences along the top of the sampler cover to minimize the possibility of lateral entry of sediment into the sampler.

Most pit samplers have been designed to be installed permanently at one location. Installation of pit samplers requires access to the streambed. After sediment transport events, pit samplers usually must be emptied manually or with a slurry pump. These requirements favor installations on streams that either are ephemeral or drop to very low base flows between sediment transport events (Reid et al. 1980; Lewis 1991; Kuhnle 1992; Laronne et al. 1992). More complicated pit-type bed load samplers with systems to continuously remove the accumulated bed load sediment have been constructed on larger streams; however, the cost of the installation and servicing rises considerably (Enoree River, FIARBC 1940; East Fork River, Leopold and Emmett 1976; Emmett 1980).

Einstein (1944) and Hubbell (1964) have described a semiportable pit sampler for use in sand-bedded streams that automatically dredges a place in the bed of the stream for the sediment trap. Following installation of the sediment trap, a valve is thrown and the dredging pump is used to continuously remove the sediment as it accumulates in the trap. The sediment and water slurry is then routed to a weighing tank and then returned to the stream. Some preliminary investigations have been conducted with a sampler of this type by Einstein (1944) and Hubbell (1964). The sampler would be restricted to streams with sand beds and low flow velocities. For most streams, several of these samplers would need to be used simultaneously to assure adequate coverage of the cross section.

5.4.1.3 Vortex Tube Bed Load Samplers Vortex tubes have been used to sample bed load successfully at several locations (Milhous 1973; Hayward and Sutherland 1974; O'Leary and Beschta 1981; Tacconi and Billi 1987). The design of these samplers was based on a vortex tube sand trap that was designed for excluding unwanted bed load sediment from irrigation and other canals (Robinson 1962). These samplers consist of a 45º diagonal slot in a concrete broad crested weir constructed across the channel at the measurement site (Fig. 5-23). A vortex is generated in the diagonal slot and from 5% to 15% of the flow carries the bed load sediment to a trap on the side of the channel. The sediment is then weighed and sampled and returned to the stream downstream of the weir. Robinson (1962) reports that when designed correctly, such samplers remove approximately 80% of the sediment with size greater than 0.5 mm from the stream. The efficiency of these samplers for smaller and larger grain sizes would be expected to be lesser and greater respectively. Milhous (1973) estimates that the overall efficiency of the vortex tube sampler on Oak Creek to range from 85% for low transport rates to 95% for higher sediment transport rates with all grains larger than 4.76 mm trapped.

Vortex tube samplers have been shown to be effective bed load samplers on small gravel-bed streams. These samplers have many of the same disadvantages, however, as pit samplers. They are not portable and the initial construction cost is high. One important advantage that vortex tube samplers have over pit samplers is that the sediment is delivered to the side of the stream and does not need to be removed from the sampler after the transport event. Therefore, the sampler will not fill before the transport event is completed.

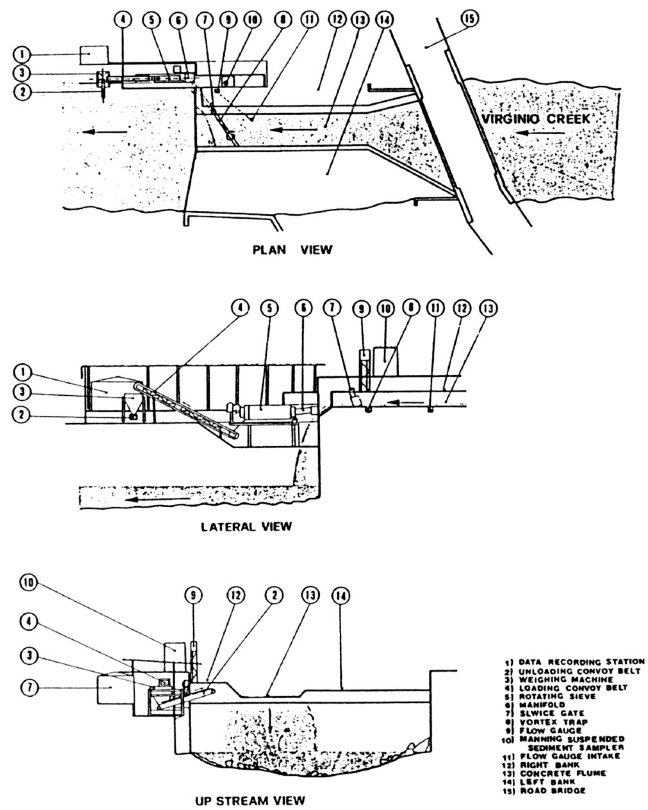


Fig. 5-23. Sketch of bed load measuring station using a vortex-tube trap on Virginio Creek (from Tacconi and Billi 1987, p. 586). Copyright 1987, John Wiley and Sons Ltd. Reproduced with permission.

5.4.1.4 Other Methods Several other methods have been used experimentally to measure the rate of bed load transport. These methods include particle imaging (Drake et al. 1988), bed form tracking (Simons et al. 1965; Willis 1968; Willis and Kennedy 1977; Engel and Lau 1980; Kuhnle and Derrow 1994; Garcia 1998; Tate and Rubin 1998; Dinehart 2001; Rubin et al. 2001), magnetic tracking (Reid et al. 1984; Carling et al. 1993), and acoustic techniques (Thorne et al. 1989). Although these methods show varying degrees of promise for improved samplers, none has been developed to the extent that it can be considered a standard technique for sampling bed load in streams and rivers. Such things as the necessity of clear water, bed forms, magnetic bed material, or the calibration of sediment generated noise all currently combine to limit the extent that the above techniques will be usable.

5.4.1.5 Summary A variety of sampler types are available to sample the bed loads of streams and rivers. It is clear that no one sampler type is generally superior to the others for the collection of bed load data. All of the types reviewed above have advantages and disadvantages in different situations. Pit and trough samplers have been shown to operate reliably on relatively small gravel-bed streams; however, their use on larger streams and rivers would be very difficult. Portable samplers are generally inexpensive to acquire, but may be expensive to operate and suffer from uncertain calibrations. Bed load samplers that use acoustic, optical, magnetic, bed form tracking, or other emerging technologies have shown a great deal of promise, but have not been proven to be reliable to date except under controlled laboratory conditions.

5.4.2 Bed Load Discharge Measurements

Measurement of bed load is difficult because it is highly variable in both space and time (Ehrenberger 1932; Hubbell 1964; Leopold and Emmett 1976; Carey 1985; Hubbell 1987; Whiting et al. 1988; Dinehart 1989; Kuhnle et al. 1989; Wathen et al. 1995; Powell et al. 1998). Bed load generally varies greatly both longitudinally along the channel and transversely across a cross section. These variations are caused by several factors and are difficult to predict. Causes of the variations include the presence of dunes or other bed forms; locally varying shear stress due to bed topography, secondary flow, or turbulence changes; varying supply of bed material from upstream sources; and changes in bed surface grain sizes. The design of bed load sampling needs to account for the spatial and temporal variability inherent in the processes of bed load transport. Pit, vortex-tube, or other samplers that sample for long periods of time and encompass a significant portion of the width of a stream cross section integrate the fluctuations in bed load transport rate in a cross section. In many instances time, monetary constraints, or logistics precludes the use of these types of samplers, however. The use of portable samplers that essentially only collect samples at a point for short periods of time is often the only practical way to collect samples of bed load. To effectively use portable samplers, the number and location of the samples collected must be carefully designed to assure sufficient information about the temporal and spatial variability is collected. To accomplish this task, information on the scales of spatial and temporal variability is needed.

Several studies have concentrated on the temporal variability of bed load transport. Carey (1985) and Carey and Hubbell (1986) have shown that a series of 120 bed load samples collected at a point in a sand-bed stream yielded a distribution very similar to that proposed by Hamamori (1962). Hubbell and Stevens (1986) showed that bed load data collected in a large flume at the Saint Anthony Falls Hydraulic Laboratory, as well as bed load data from other researchers, were reasonably well approximated by the Hamamori distribution. Kuhnle (1996) showed that sample durations of several minutes to tens of minutes were required to obtain an adequate estimate of the mean bed load transport rate in laboratory flume experiments. Gomez et al. (1990), using the flume data collected by Hubbell et al. (1987), determined that at-a-point bed load transport samples should cover the movement of at least one primary bed form past the sampling location. Preferably, more than one primary bed form should be covered by the sampling period. Gaweesh and Van Rijn (1994) found that 25 samples should be taken distributed along the bed form length to adequately represent the variability of bed load transport in sand-bed rivers.

Only a limited number of studies have documented spatial variability by collecting bed load samples simultaneously at several locations across a channel (Leopold and Emmett 1976; Hubbell et al. 1987; Powell et al. 1998). Emmett (1980) tested the Helley-Smith sampler using the bed load rates calculated from the East Fork River trough sampler. This study yielded a calibration of the Helley-Smith sampler on the East Fork River and a test of the sampling technique used with the Helley-Smith sampler to arrive at a mean cross-sectional bed load rate. Emmett found that sometimes all or most of the bed load transport occurred in a narrow part of the channel. The location of this high-transport zone was stable on short time scales (hours), but not necessarily for longer periods of time. Emmett (1980) recommended that two sampling traverses should be conducted, each of which should consist of at least 20 equally spaced cross-channel locations, to describe the spatial variation across the channel. It was recommended that spacings between samples range from 0.5 to 15 m apart.

Hubbell and Stevens (1986; Hubbell 1987) generated simulated bed load data that varied in time according to the Hamamori (1962) distribution and assumed several different patterns of lateral variation in bed load transport. The generated bed load record was "sampled" using traverses of 4 and 20 equal positions across the cross section. In cross sections in which the lateral variability was moderately nonuniform, the numbers of samples needed to predict the mean transport rate to within 30% were comparable for sampling designs that collected samples at 4 and 20 positions in each transect. For nonuniform lateral distributions the number of samples required for the 4-position transect was approximately double that required for the 20-position.

Gaweesh and Van Rijn (1994) determined the number of positions required to obtain relative errors in bed load transport rates less than 20% over the width of the Nile River at several cross sections. This analysis was based on measured flow velocities on the cross sections and applying the transport formula of Engelund and Hansen (1967) at each potential sampled position. Gaweesh and Van Rijn (1994) concluded that irregular cross sections should be divided into seven subsections and 25 samples should be collected distributed equally along the bed form length at each subsection to obtain an overall relative error of 20%.

Gomez and Troutman (1997) conducted a study in which process errors due to different sampling techniques were evaluated for simulated bed load records that represented the temporal and lateral variations that would be expected for dune beds. Gomez and Troutman found that four or five sampling traverses, and collection of 20 to 40 samples at a rate of five or six samples per hour, were necessary to adequately sample the bed load of a hypothetical stream. These samples would be collected over a period of 3 to 8 h, which would allow a number of bed forms to pass through the sampling section.

The accuracy associated with the collection of bed load transport on a large sand-gravel-bed river was calculated by Kleinhans and Ten Brinke (2001). They evaluated the uncertainty of the integrated transport for bed load by assuming the transport samples were normally distributed without measurement and prediction errors. This evaluation was applied to sediment transport data collected using modified Helley-Smith samplers on the Waal River in the Netherlands. Their calculations yielded an uncertainty of 10% to 20% in integrated bed load transport, using five subsections and 30 samples/subsection. A major problem identified in this study was the long periods of time required for the collection of these samples (3.5 days) and the changes in discharge that occurred over that time.

Studies that yield guidance on the numbers of traverses and samples that are required to reliably calculate the mean bed load rate are useful, but suffer from several shortcomings. Perhaps most critical of these shortcomings is the fact that the time and length scales of temporal and lateral variability in streams are poorly known and generally vary with time at a given location and from stream to stream. To design an adequate sampling strategy these time and length scales must be known at least approximately before the sampling procedure is defined. In the recommendations previously reviewed above (Emmett 1980; Hubbell and Stevens 1986; Gaweesh and Van Rijn 1994; Gomez and Troutman 1997; Kleinhans and Ten Brinke 2001), the amount of time required to collect the recommended number of samples is too long for many streams. Flow in many streams and rivers is not steady for periods of hours to days. For streams in which variable flow is the norm, portable samplers will not be practical unless many flow events can be sampled. Edwards and Glysson (1999) concluded that no one sampling protocol can be used at all stations. They recommend that to the extent possible, a sampling protocol should be derived for each site where bed load is to be sampled. Initial samples collected can provide information to serve as a basis for developing the sampling plan.

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