4. Sampling procedures and equipment

Bed material in gravel and cobble-bed streams can be sampled by two different methods:

1. ***Surface sampling**:* samples a preselected number of surface particles from a predefined sampling area, and
2. ***Volumetric sampling**:* samples a preselected sediment volume from a predefined sedimentary layer.

The study objective determines whether to sample the surface sediment or a particular sedimentary layer. Fig. 4.1 presents the basic four stratigraphic units that are common in armored gravel-bed rivers and that are commonly sampled.

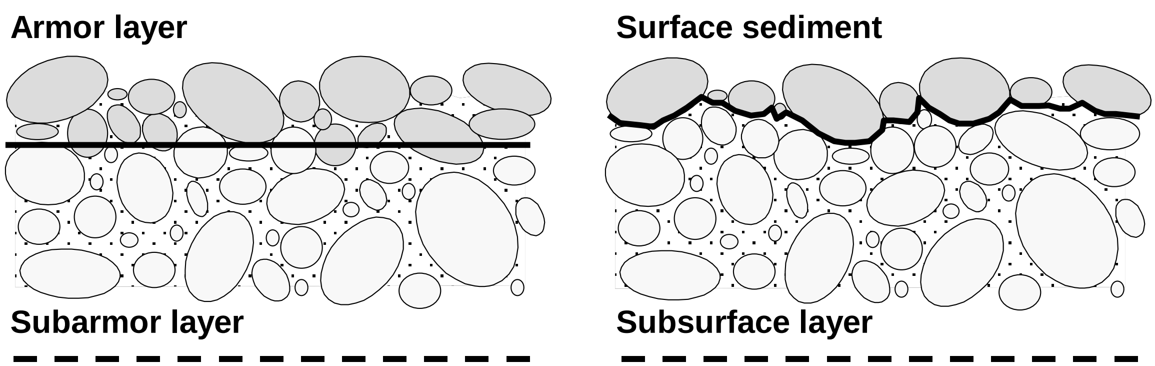

Fig. 4.1: Stratigraphy of an armored bed distinguishing between armor layer, subarmor layer, surface sediment, and subsurface layer.

Surface particles can only be sampled using surface sampling techniques (Section 4.1). Bed-material layers, such as the armor, subarmor, and subsurface layer, which may be infilled and censored (Section 3.3.1), have a specific thickness, and can therefore only be sampled by taking a volumetric sample (Section 4.2).

The procedural details with which a selected method is then performed depends on natural factors such as stream size, stream morphology, flow conditions, and the bed-material particle-size distribution. For example, sampling equipment and procedures must be suitable for the bed-material particle sizes, which in mountain streams may range from sand to boulders. Limited road access in remote areas dictates that equipment must be portable, and pristine conditions in sensitive environments may require sampling the bed in a non-destructive way. Sampling in submerged conditions must address poor visibility of the bed under water, and the tendency of fine particles to be washed away by the flow.

Man-made factors also play an important role in the selection of sampling procedures. A study might not be able to afford a great deal of field time, but may instead have lab time to analyze samples or photographs taken of the streambed. The study objective or the streambed conditions may require using several different sampling methods or procedures, which then need to be selected to facilitate a comparison or combination of sampling results. A limited budget forces project managers to reduce the extent of the study or to opt for fast and simplistic field techniques performed by minimally-trained seasonal field crews, both of which might compromise the study objective.

The user must also consider the form of particle-size analysis applied to the sample. Particles per size class can be either counted or weighed, and size distributions may be explained in terms of frequency-by-number or frequency-by weight (Section 2.1.4.1). However, number- or weight-based particle-size analyses yield different results.

The user must also consider that different sampling procedures yield different particle-size distributions. A pebble count and an areal sample collected from the same surface yield different particle-size distributions even when the same method of particle-size analysis was used for both samples. In order to compare or combine particle-size distributions from pebble counts and from areal samples, the distribution of areal samples should first be converted (Section 4.3.3). However, the numerical value of conversion factors depends on the exact procedure with which the areal sample was taken (Section 4.3.2).

4.1 Surface sampling

Surface sampling collects bed-surface particles that are exposed on top of the streambed whether the bed is dry or submerged. The vertical extent of the surface sediment is equal to the diameter of one particle, i.e., the particle that is exposed on the surface at any given point (Fig. 4.1). Lacking a distinct vertical dimension, surface sediment can only be sampled by surface sampling methods, but not by methods that collect a volume of sediment. Although most surface particles are easy to identify, problems arise when small particles are surrounded by large particles, and when particles are partially exposed only, or partially hidden under neighboring particles (e.g., when the surface is imbricated or clustered (Sections 3.4.2 and 3.4.3)). At some point the question arises as to how much of a particle needs to be actually visible at the surface to qualify as a surface particle.

Bed-surface sediment can be sampled by three methods:

- ***pebble counts:*** (line counts) select and hand-pick a preset number of surface particles at even-spaced increments along transects that may be parallel and span a relatively large sampling area (≈ 100 m^2) (Section 4.1.1.);

- ***grid counts:*** select particles at a preset number of even-spaced grid points that span a relatively small sampling area (≈ 1-10 m^2), hand-picking particles or measuring particle sizes on photographs (Section 4.1.2), and
- ***areal samples:*** include *all* surface particles contained within a small preset area (≈ 0.1 -1 m^2) of the streambed, often using adhesives to ensure that small particles are included representatively in the sample (Section 4.1.3).

The three sampling methods differ in several points including the spacing between sampled particles, the size of the sampling area covered, suitability for small and large particle sizes, field time vs. lab time, and the comparability of sampling results. These factors should be taken into account when selecting a sampling method. Differences between the three surface sampling methods are summarized in Table 4.1.

Table 4.1: Comparison between pebble counts, grid counts, and areal samples

Pebble counts	**Grid counts**	**Areal samples**
Sample a *preset number* of particles in wide and approximately even-spaced increments of at least D_{max} size	Sample a *preset number* of particles under a grid of approximately D_{max} size	Sample *all* surface particles within a small *predefined* sampling area
Cover a large sampling area	Sample several small areas within a reach or cover small areas of homogeneous sediment (facies patch)	Focus on point locations and require several samples to be taken within the sampling area
Suitable for gravel and cobbles, not for sand	Suitable for gravel, not for sand	Suitable for sand to medium gravel not for coarse gravel or cobbles
Long field time, no lab time	*Hand-picking*: long field time no lab time; *Photographs*: short field time, long lab time	Both field time and lab time
Sampled particle sizes comparable and combinable with particle sizes from grid counts and volumetric samples	Sampled particle sizes comparable and combinable with particle sizes from pebble counts and volumetric samples	Sampled particle sizes not directly comparable and combinable with particle sizes from pebble or grid counts, or volumetric samples

Pebble counts focus on mid-sized and large particles, while neglecting fines and are suitable for covering large sampling areas by parallel transects. Pebble counts take between 0.5 and 2 hours per sample, depending on the number of particles to be collected and the difficulty involved in dislodging particles from the bed; however, no further laboratory time is needed. Grid counts performed in the field select particles under a grid. The grid may consist of elastic bands stretched over a rigid frame. Grid counts are usually conducted on small sampling areas. Surface sampling of small areas lends itself to using photographs on which grids can be superimposed for later analysis.

Photographing a sediment surface takes very little field time per sample, but analyzing the photographs requires a relatively large amount of laboratory time (Sections 4.1.2.2 and 4.1.3.3). Areal samples require both field time for taking the sample, and lab time for sieve analysis. Areal samples are suitable for gravel sediment that contains a relatively large amount of sand and fine gravel, because areal samples, which focus on a small sampling area, are capable of including these fines, whereas pebble counts and grid counts tend to neglect them.

Particle-size distributions obtained from pebble counts and grid samples are mutually comparable and combinable. Both distributions are also comparable and combinable with distributions obtained from volumetric samples (Section 4.3). Particle-size distributions of areal samples need to be converted into an equivalent volumetric or grid distribution before making a comparison or combination with size distributions from pebble counts or volumetric samples (Sections 4.3 and 4.4).

4.1.1 Pebble counts along transects

Pebble counts are used to determine the particle-size characteristics of gravel and cobble surface sediment and can be performed on dry beds as well as on inundated beds, as long as the streams are wadable. Percentile values of the cumulative particle-size frequency distribution and the percent fines are used for many applications including computations of incipient bedload motion, channel-bed roughness, stream morphology studies, cumulative watershed effects analysis, and stream habitat evaluation.

4.1.1.1 Heel-to-toe walks and sampling along a measuring tape

A pebble count samples a *preset number of particles in even-spaced increments along transects*. Two methods are usually used to determine the transect locations, the spacing between selected particles, and identification of the particle to be selected: a heel-to-toe walk and sampling at even-spaced marks along a measuring tape. The main differences between these two methods are summarized in Table 4.2.

Wolman pebble count with heel-to-toe walk

Two techniques of particle selection are commonly used for pebble counts. The first technique was proposed by Wolman (1954). An operator traverses a gravel surface along a grid pattern. The grid may be established by pacing or laid out by lines or a tape. A particle is collected in the vicinity of each grid point. Wolman (1954) emphasizes that the particle to be included in the sample must be selected at random. As a means to achieve this randomness, he proposes to pick up the particle from beneath the tip of the boot while looking away. The spacing between selected particles is determined by the size of the grid needed to cover the sampling area with 100 grid points (Wolman 1954). Wolman’s methodology is often interpreted as traversing a sampling area with heel-to-toe steps, paces, strides, or several steps at a time and picking up the particle first touched by a pointed vertical finger, eyes averted, under the tip of the boot (e.g., Leopold 1970; Hey and Thorne 1983; Fripp and Diplas 1993; Potyondy and Hardy 1994; Kondolf 1997a; Marcus et al. 1995; Bevenger and King 1995). The method is most popular because no specific field equipment is required to lay out the grid. The step-spacing can be adjusted to the size of the area to be covered or the size of particles in the stream, and the procedure can be done in wadable flows (Yuzyk 1986).

Systematic sampling at even-spaced marks along a measuring tape

A more systematic way of sampling surface bed-material with pebble counts is to stretch a measuring tape in several transects across the sampling area. Particles are selected at intersections with even-spaced marks along the edge of the tape, for example at marks in 1 foot or 0.5 m intervals (e.g., Wohl et al. 1996) or exactly under the grid points of the established measuring grid (Hey and Thorne 1983; Yuzyk and Winkler 1991). The spacing between particles depends on the bed-material particle size and is set to a value larger than the *b*-axis of the D_{max} particle size of concern. This spacing is necessary in order to prevent double counting of large particles, which should be avoided because it causes a serially correlated sample and bias towards large particle sizes (Section 4.1.1.4).

Table 4.2: Overview of differences between heel-to-toe sampling and systematic sampling along a measuring tape and potential operator bias and variability in poorly sorted gravel and cobble-bed streams.

	Heel-to-toe steps	**Systematic sampling along a tape**
Step spacing:	1 - 2 paces (0.3 - 0.6 m), regardless of bed material size	1 - 2 times the D_{max} particle size, in accordance with bed material size
Particle selection on dry surfaces:	Blind touch at the tip of the boot	Visual correspondence with even-spaced marks on measuring tape
Possible improvements:	Keep finger straight to avoid touching neighboring particles	Use pin or awl for more precise identification of particle to select
Particle selection under water:	Blind touch at the tip of the boot	Visual correspondence with even-spaced marks on a measuring tape as best as possible; otherwise blind touch
Sampling path:	Along an imaginary line at operator's discretion	Along a tape, strictly predetermined
Possibility for operator bias:		
- against fines	Higher	Lower
- against cobbles & boulders	Higher	Lower
Variability between:		
- samples	Higher	Lower
- operators	Higher	Lower

Results of pebble counts can vary greatly between the two methods. The traditional Wolman pebble count with its blind touch, heel-to-toe steps, and walking along imaginary lines allows the operator more latitude in particle selection, the spacing between particles, and the sampling path than sampling at preset intervals along a measuring tape stretched in transects across the reach. This methodological difference and its effects are discussed in more detail in Sections 4.1.1.3 – 4.1.1.5. Data recording and analysis is the same for all pebble count methods (Section 4.1.1.7).

4.1.1.2 Sources of errors in pebble counts

Particle-size distributions obtained from pebble counts must be accurate in order to be useful for a study objective. Estimates of bedload transport rates, for example, vary significantly if the bed-material percentile particle-size used for the computation varies slightly (Gessler et al. 1993; Bunte 1994). Particle-size distributions recorded from pebble counts also need to be accurate for streambed monitoring that compares bed-material size parameters between reaches or over time (Potyondy and Hardy 1994; Bevenger and King 1995; MacDonald et al. 1997; Schnackenberg and MacDonald 1998). The detection of small changes in a percentile of concern or the percent fines is important for a prompt onset of remedial actions. However, pebble counts, which appear to be simple and straight forward on first view, provide many opportunities for sampling errors. Pebble counts are usually subject to operator error and statistical error which are summarized below and discussed in greater detail in the following sections.

Operator error

Particles to be included in a sample must not be affected by operator preferences. However, operators are likely to introduce errors into pebble counts by favoring mid-sized and handy particles, while avoiding very small and very large particles that are difficult to pick up (Section 4.1.1.3 and 4.1.1.4). These preferences may be voluntary or involuntary, creating biased and non-random samples. The practice of double counting large particles produces serial correlation (Section 4.1.1.5) and bias towards large particles. Operators also introduce sampling scheme errors by sampling areas that have a systematic spatial variation in particle sizes, or by favoring easily accessed stream locations, while neglecting poorly accessible ones. Spatially non-random sampling again creates bias and non-random samples. Different sampling schemes for pebble counts are discussed in Sections 6.2 and 6.3. Operators also introduce errors into pebble counts when particles sizes are not measured correctly (Section 2.1.3.6). The use of templates largely addresses this problem.

Operator error adds to the statistical error of a sample. However, unlike statistical errors, operator errors do not improve with sample size, but become relatively more important as sample size increases (Hey and Thorne 1983).

Statistical error
Sample size and precision for number-based particle-size analysis are discussed in detail in Section 5.2. A 100-particle pebble count might determine the D_{50} to D_{84} particle sizes to within tolerable levels of precision in a moderately-well sorted gravel bed (no sand, no boulders). However, the precision of a 100-particle pebble count is usually too low to compare particle-size distributions from different sites or over time, nor does a 100-particle sample suffice in poorly sorted gravel beds comprised of sand and boulders. Generally, a fourfold increase in sample size to 400 particles is required to halve the sampling error. Much larger sample sizes are needed to accurately determine distribution parameters such as sorting, skewness and kurtosis (Sections 2.1.5.4 – 2.1.5.6). Most computations of statistical error do not include operator error, except for the statistical procedure of two-stage sampling (Section 5.2.2.1).

4.1.1.3 Operator bias against small particles

Pebble counts are widely used to determine the proportion of fine sediment on a streambed, such as the D_5 or D_{16}, or the percent fines. However, it is usually not realized that the computation of the fine part of a cumulative particle-size distribution is not only burdened with a statistical error that is more than twice as large as that for a D_{50} or D_{84}, but also with an operator error that again is larger than the operator error associated with the D_{50} or D_{84}.

The sampling component of pebble counts consists of two steps: identifying the particle to be included in the sample from among neighboring particles, and the actual lifting or retrieval of the particle from the streambed. Particle identification may be based on touch, i.e., the particle first touched by the pointed finger, eyes averted, is included in the sample. This is the method used in heel-to-toe sampling. Alternatively, particle identification can be visual, i.e., by correspondence of a particle with intersections of even-spaced marks along a measuring tape. Fingertips, or the whole hand are used for particle retrieval.

Both particle identification and retrieval may be problematic when sampling particles of fine gravel or coarse sand. Sampling in a bed of similar-sized, small particles, touching cannot discriminate between neighboring small particles, and retrieving one specific particle may be difficult. Errors in particle identification and retrieval are of negligible consequence when all neighboring particles fall into the same size category and the operator can select any one particle from a pinch of sediment taken from the streambed.

The pinch-approach is not appropriate if small particles are surrounded by neighboring coarser particles, because in the presence of particles of mixed sizes, the operator has to identify and pick one particle. Identifying a small particle amidst larger ones is difficult because the tip of the finger is more likely to touch larger neighboring particles before touching a small particle in their middle. The probability of first touching neighboring large particles increases with the size of the large particles and the tightness of interstitial spaces, and an increasing difference in particle sizes makes the touch method increasingly prone to sampling error. Similarly, the retrieval of small particles becomes more difficult as the surrounding particles become larger and more tightly spaced.

Factors exacerbating touch-identification of small particles and their retrieval

Problems of identifying small particles by touch and retrieving them can be exacerbated by many factors. Long fingernails may reduce the ability to feel the streambed with the fingertips. Not keeping the pointed finger in an exactly vertical position reduces the chance of touching a fine particle (Ramos 1996). Submergence by flow makes it more difficult for the operator to keep the pointed finger steady, which is important when identifying small particles by touch. Cold water can make the fingers numb and too clumsy to feel and pick up a small particle, and a particle just picked up can be washed out the operator's hand by the flow. The cold water problem is most pronounced in mountain streams in late fall or before the spring snow melt. Thus, to improve sampling accuracy, mountain streams should be sampled in later summer when the water is less cold. Gloves can be useful for under-water pebble counts. Simple rubber household gloves tied at the wrists with rubber bands are often a workable compromise between cold protection and retaining some feeling for small particles. Neoprene gloves are usually not suitable for retrieving fine particles from the bed.

Visual identification most useful on dry beds

On dry beds, a small particle to be included in the sample can be more accurately identified *visually* at the intersection with even-spaced marks on a measuring tape stretched across the sampling area than by *touch*. The accuracy of visual particle identification on dry beds can be further improved if the operator gets close to the tape and uses a fine pin, or an awl, to pinpoint the exact particle to be included in the sample. If the approach is followed carefully, particles as small as 2 mm can be sampled representatively. The precision of visual particle identification on a dry bed does not necessarily have to decrease as the size of surrounding larger particles increases, provided the operator looks straight (vertically) down, so that small particles are not hidden from view as they would be when viewed obliquely. Thus, whenever possible, pebble counts should be performed on dry beds where particles can be visually identified.

Visual identification becomes problematic for small particles on submerged beds. Rocks need to be placed onto the tape to hold it down on the streambed and this disrupts the bed beyond the disruption associated the actual sampling process (a lead-filled measuring tape might be appropriate). The largest problem is that the visual image becomes distorted under water, which makes it impossible to visually identify small particles, particularly in deeper or faster flows.

Sampling poorly accessible stream locations or irretrievable particles

Small particles are not only difficult to identify and retrieve, but are also often deposited in deep or otherwise poorly accessible stream locations. If the sampling objective is to collect particles from the entire reach, then those areas need to be included in the sample.

Operators, for understandable reasons, tend to avoid locations too deep for wading, or poorly accessible areas, such as under overhanging branches or behind logs (Ramos 1996). Thus, fine sediment, which is likely to be encountered in these locations, is less likely to be included in the pebble count and therefore underrepresented. The operator error arising from avoiding streambed areas of poor accessibility can be reduced if the sampling path is predetermined, such as by sampling at even-spaced marks along a measuring tape stretched across the sampling area at even distances. The size class of particles that are irretrievable or in inaccessible sampling locations must be estimated in order to maintain the randomness of the sample. The 0.5 ϕ size class of an irretrievable particle can usually be estimated, if the particle to be selected can be seen or touched. If the particle size cannot be estimated, then that location cannot be part of the sampling area.

Small particles between the low and the high-flow water line

Unless a sampling protocol clearly determines the stream width to be sampled, fine particles on the exposed bank between the low and high-flow water line may or may not be included representatively in the sample. Lack of a sampling protocol leaves the operator with no guidelines as to how far to sample the banks and may introduce a high variability in the proportion of fine sediment between samples or between operators. The decision of whether the sampling area covers the bankfull width of the stream, or remains within the low flow bed, depends on the sampling objective. A study which focuses on the supply of fine sediment, for example, should sample the bankfull width, whereas sampling for a computation of stream roughness is usually restricted to the low flow bed.

Results of operator bias: small particles underrepresented and variable

Operators are more likely to neglect small particles and instead select mid-sized, handy particles (Marcus et al. 1995). This propensity is due to the difficulty of touching small particles first before touching neighboring large particles, of seeing small particles among large ones in a bed submerged by flow, of selecting small particles off the bed, and of loosing small particles in the flow. Some operators are conscious of this problem and try to avoid bias against small particles. Other operators may even overcorrect and introduce a new bias (Marcus et al. 1995). Often, operators are not consistent in their effort to representatively include small particles in the sample, and may include small particles within fine sediment but not small particles in between large ones. Together with the tendency of small particles to accumulate in poorly accessible areas, and a poorly defined stream width to be sampled, the number of small particles tends to be underrepresented in a sample. Between operators, small particle sampling is quite variable. Bias against small particles coarsens a particle-size distribution on its fine end, whereas a variability in the number of fines leads to variability in the percentile particle-size of the D_5 and D_{16}, or the percentage fines, such as particles smaller than 4 or 16 mm.

Quantification of variability in fines due to operator error

A good quantification of operator error in pebble counts is currently not available. The magnitude of operator error for pebble counts in gravel-bed streams can be estimated by comparing the total error (operator and statistical) of heel-to-toe pebble counts with the purely statistical error of a surface sample. Ideally, the difference between the total error and the statistical error indicates the magnitude of the operator error.

The purely statistical error around the various particle-size percentiles of a surface sample can be computed using a bootstrap approach in which a computer re-samples a large sample entered into the computer. This was performed by Rice and Church (1996b) for a surface sample of more than 3500 particles collected from the gravel bed of the Mamquam River. The size distribution had a standard deviation of 1.17 ϕ and was slightly skewed towards a tail of fines, typical of particle-size distributions in coarse gravel beds. A sample size of 400 particles yielded a statistical percent error around the D_5 (in mm) of approximately ± 20%, which is roughly equivalent to an statistical absolute error of ± 0.3 ϕ for the ϕ_5 [1] (Fig. 4.2). The percent error around the D_{50}, D_{75} or the D_{84} was approximately ± 8%, which is roughly equivalent to an absolute error of ± 0.12 ϕ (see Section 5.2.2.3 for details). Note that these errors pertain to the statistical error only and that the collected particles are assumed to be statistically independent.

The combined statistical and operator error was computed for a set of 7 heel-to-toe pebble count samples obtained by the authors in several gravel and cobble-bed rivers. The samples had bed-material sorting coefficients s_I between 1.0 and 1.6, and sample sizes n between 201 and 537. The mean s_I for all samples was 1.24, and the mean sample size was 451. Thus, standard deviations and sample size were generally similar to the standard deviation and the 400-particle sample size for the sample from the Mamquam River. Each of the 7 samples was split in two: subsample *a* comprised the 1st, 3rd, 5th, … recorded particle size for each transect, whereas subsample *b* comprised the 2nd, 4th, 6th,… recorded particle size. The percent error $e_{\%Dp}$ around several percentiles in mm between the two subsamples was computed using a standard sample size equation $e_{\%Dp} = (1.96 \cdot s/\mu_p)/\sqrt{n}$ (Section 5.2.1), where μ_p is the mean of the two subsample percentiles analyzed, e.g., $(D_{5(a)} + D_{5(b)})/2$.

The mean total errors around the D_{25}, D_{50}, D_{75}, and D_{84} for the 7 heel-to-toe samples were roughly within the range of the statistical errors determined by Rice and Church (1996b) (Fig. 4.2). This indicates that the variability between samples due to operator error is of no large concern for central and high percentiles. However, the between-sample variability was quite pronounced for small percentiles. The total relative error (operator and statistical error combined) around the D_5 was ± 50% for the heel-to-toe samples, which is 2.5 times larger than the purely statistical sample error determined for the D_5 from the bootstrap approach by Rice and Church (1996b). The corresponding total

[1] *The absolute error in ϕ units is not precisely convertible to the percent error in mm because the percent error in mm is not evenly distributed around a percentile (Section 5.2.2.3, Fig. 5.8). However, this imprecision is negligible for small errors. The numerical value of an absolute error in ϕ units can be converted to the percent error in mm by the following rule of thumb: $e_{\pm\phi} \cdot 70 \approx e_{\%mm}$ or $e_{\%mm}/70 \approx e_{\pm\phi}$. For example, an absolute error of ±0.1 ϕ is approximately equal to a 7% error in mm ($e_{\pm\phi m} \cdot 70 \approx e_{\%Dm}$).*

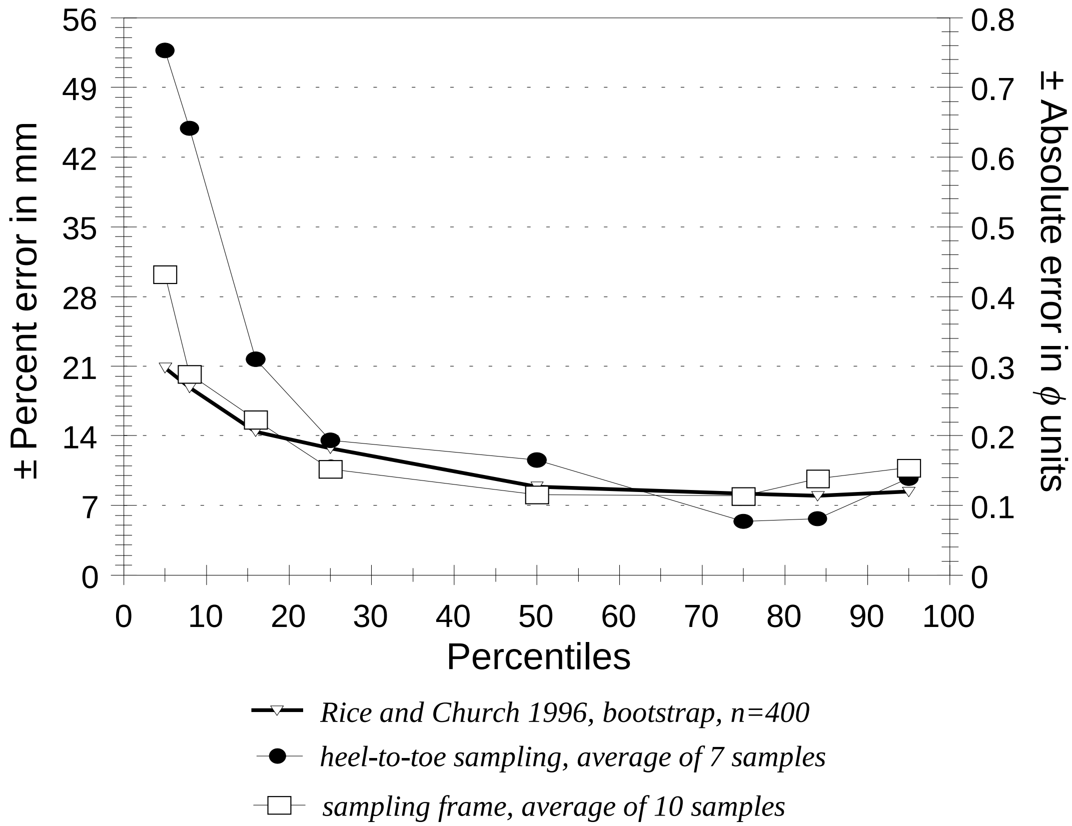

Fig. 4.2: Statistical error computed for a bed-material sample with a standard deviation of 1.17 and a sample size of 400 using a bootstrap approach (—∇—) by Rice and Church (1996b) = R&C '96 (see Section 5.2.3.3 for details). Mean percent error observed for heel-to-toe sampling (–●–), and for samples taken with the sampling frame (–□–) (Section 4.1.1.6).

absolute error around the D_5 for the heel-to-toe samples was ± 0.75 ϕ units, which is one and a half standard sieve classes. This high error for small percentiles suggests that heel-to-toe pebble counts in coarse gravel- and cobble-bed streams should only be used for determining the D_{50}, D_{75}, and D_{84} of a distribution, but not for small percentiles or for determining the percent fines.

Truncation of the underrepresented and variable fine end of size distributions

The exact particle size at which a bias against small particles in heel-to-toe sampling begins to show depends on the streambed conditions. Rice (1995), for example, found that particles finer than 8 mm are underrepresented in underwater pebble counts, whereas Fripp and Diplas (1993) suggest that particles finer than 15 mm cannot be sampled representatively in heel-to-toe pebble counts. As a statistical measure to address this problem, Rice (1995) suggested exclusion of particles finer than 8 mm from the size analysis, thus truncating the cumulative distribution curve at 8 mm. Truncation at the fine end coarsens the low percentiles of the distribution, while large percentiles are less affected. Thus, truncation at the fine end of the sample should be restricted to studies in which low percentile particle-sizes, such as the D_5 or D_{16} are of no concern.

Another, less drastic approach to deal with bias against fines is to tally all small particles in one joint particle-size class, for example, as finer than 8, or 16 mm. (Generally, pebble counts tally particles smaller than 2 mm jointly in the < 2 mm category). This approach assumes that the sampling difficulty lies in the distinction of small particles between neighboring small particle sizes, but does not address the difficulty of reliably identifying and selecting a small particle from between neighboring large particles. The advantage of joint tallying as opposed to truncation is that it does not affect the size distribution of larger particles.

If the correct characterization of small particle sizes is the study goal, Diplas and Fripp (1992) and Fripp and Diplas (1993) suggest taking areal samples (with clay as an adhesive) (Section 4.1.3.1). Note that particle-size distributions from areal samples need to be converted into the equivalent volumetric or grid-by-number distribution before they can be compared to particle-size distributions from pebble counts (Section 4.3.1 and 4.3.2).

4.1.1.4 Operator bias against and towards cobbles and boulders

Heel-to-toe walks were invented for sampling streambeds of mid-sized gravel, but not for sampling beds with cobbles and boulders or streams with bed surface-structures (e.g., clusters and wake deposits). If applied to such beds, heel-to-toe sampling may bring about bias both for and against large clasts.

Operators avoid stepping onto cobbles and boulders

One reason for operator bias against cobbles and boulders in heel-to toe samples arises from the practice of determining the sampling location by foot placement. Operators are understandably reluctant to place their feet onto an exposed and slippery cobble or boulder for risk of insecure footing and falling. Consequently, if particle identification is based on foot placement, operators (even unconsciously) tend to avoid cobbles and boulders in heel-to-toe pebble counts. An operator’s reluctance to step onto a cobble or boulder is likely to increase with increasing slipperiness, size, and protrusion of cobbles and boulders, the coldness of the water, swiftness of flow, remoteness of the site, or other factors that decrease an operator’s readiness for taking a risk. Physical shape of the operator can also play a role in the variability of sampling results between operators in heel-to-toe pebble counts. Bunte and Abt (2001) compared sampling results obtained from heel-to-toe walks in a cobble-bed stream (D_{50} = 69 mm, D_{max} > 720 mm, sorting coefficient $s_I = 1.7\ \phi$) between two operators of different size. The operator with a small boot size (Operator B) was more prone to avoiding cobbles and boulders, and produced particle-size distributions with fewer coarse particles than the operator with a large boot size (Fig. 4.3). Operator B also extended the sample further onto the banks and counted more small particles than Operator A (Section 4.1.1.3).

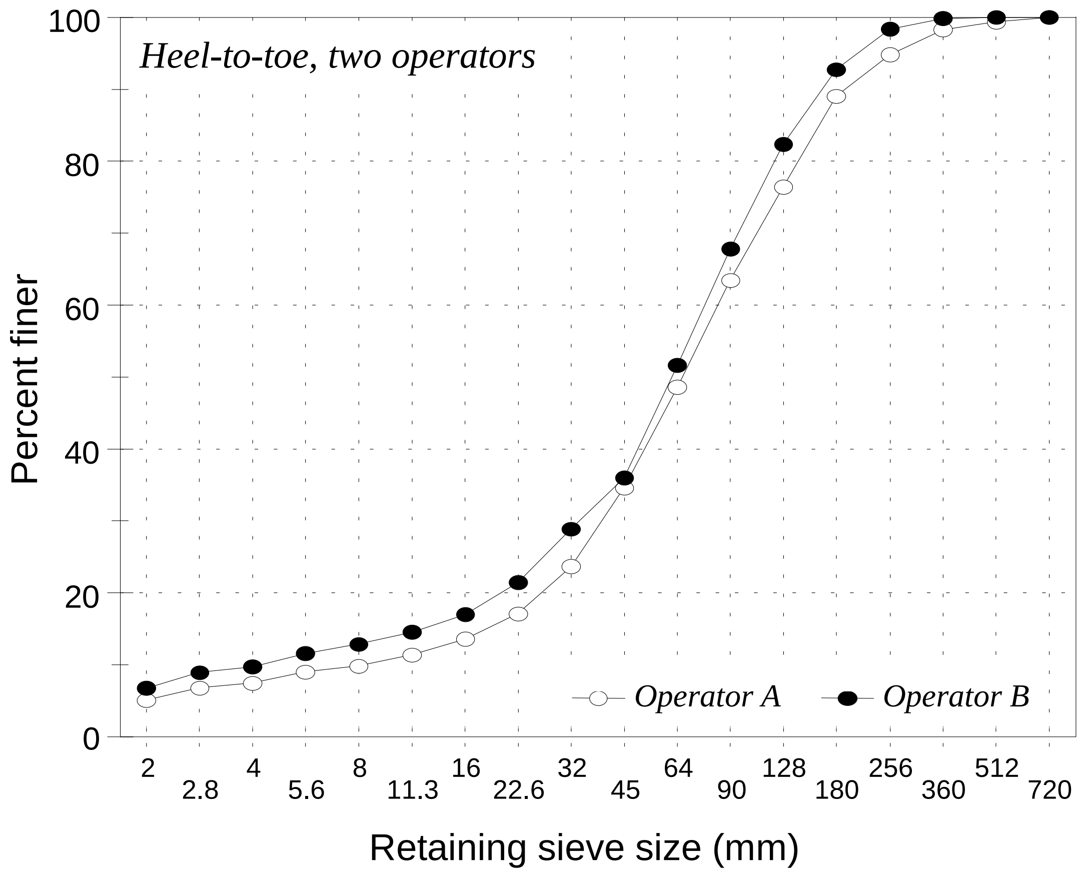

Fig. 4.3: Different cumulative frequency distributions obtained by operator A (large boot size) and operator B (small boot size) sampling with heel-to-toe steps in a cobble-bed stream.

Operators avoid cobbles and boulders in their sampling paths

Cobbles and boulders are not only risky to step upon, but also heavy, often wedged, and difficult to dislodge from the bed. Heel-to-toe walks make it easy for operators to avoid such particles; it only requires a slight change in foot position in the last one or two steps. Operators might also change their previously pursued sampling path if a streambed area lies ahead that has particularly unappealing-looking cobbles and boulders or that seems poorly accessible. Again, avoiding cobble and boulders produces a particle size-distribution that, compared to an unbiased sample, is too fine in its coarse part.

The tendency to avoid, and thus bias against cobbles and boulders can be corrected by sampling systematically, such as at even-spaced intersection along a measuring tape stretched at even increments across the sampling area. Systematic sampling along a measuring tape renders the operator's stepping position irrelevant. If an irretrievable particle is encountered, randomness of the sample can be maintained by estimating the particle-size class. The 0.5 ϕ size-class of a particle can usually be estimated to within ± one size class if the particle to be selected can be seen or touched. If the particle size-class cannot be estimated, then that location must be explicitly excluded from the sampling area.

Inherent bias versus overrepresenting coarse particles by double counting
Pebble counts have an inherent bias towards coarse particles, because sampling at even-spaced intervals gives coarse particles a larger *statistical* chance of being included in the sample than smaller particles. This inherent statistical bias makes the number frequency of a pebble-count size-distribution directly comparable to the weight frequency of a volumetric sample from the same location, provided the bed is not armored (see conversion of sample distributions, Sections 4.3.1 – 4.3.2). Inherent statistical bias should not be confused with an operator bias towards cobbles and boulders due to the practice of double counting.

Counting the size of cobbles and boulders as frequently as the preset spacing (e.g., one boot length) is statistically not correct because it produces a serially correlated sample that is not random. The step spacing of pebble counts must be wide enough to allot only one count per each cobble or boulder. Yuzyk and Winkler (1991) suggest that the spacing should be twice as large as the largest particle diameter to ensure that each particle receives only one count. Double counting due to proximity should not be confused with double counting that may result from random sampling with replacement.

Double counting of cobbles and boulders overrepresents the presence of large particles and produces particle size-distributions that are too coarse in their coarse part. The effect on the D_{50} percentile particle-size is small if double counting occurs infrequently, but the effect on the D_{95} can be quite pronounced if many large particles are counted double or multiple times. This is illustrated by the following example for a poorly sorted cobble bed (s_I = 1.7) with a D_{50} particle size of 69 mm and a D_{max} particle size class of 720-1024 mm (particle-size distribution for Operator B in Fig. 4.8). If cobbles larger than 180 mm and boulders were allotted double or multiple counts so that the total sample size increased by 1, 2, and 3% (e.g., by 5, 10, and 15 particles in a 469 particle pebble count), the D_{50} particle size would increase by 1, 3, and 4%, respectively. The D_{84} would increase by 3, 5, and 8%, and the D_{95} particle size by 4, 7, and 22%. Although double counting and cobble avoidance introduce biases in opposite directions, and their effects act towards canceling each other, one inaccurate procedure must not be used as a corrective means for another inaccurate procedure.

Another form of spatial correlation is introduced if several particles from within the coarse or fine part of bed surface-structures (Section 3.4.1) are included in the sample. A random sample series should only contain independently deposited particles, whereas the position and size of particles within a cluster or wake deposit are influenced by the size and position of neighboring particles. Thus, in order to avoid multiple counts of large particles within a cluster, or of small particles within a wake deposit, the sample point spacing needs to be larger than the diameter of bed surface-structures.

4.1.1.5 Statistical detectability of operator bias

Heel-to-toe sampling in gravel-bed streams tends to undersample both very fine gravel as well as the cobble/boulder fraction. Consequently, mid-sized, handy particles are oversampled. Double counting due to small sampling-point spacing oversamples cobbles and boulders. The bias against fines has the most pronounced effect on the cumulative particle-size distribution if the bed contains a large number of difficult-to-sample fines and thus presents a large opportunity for neglecting fines. Similarly, the tendency of avoiding cobbles and boulders has the most pronounced effect on the cumulative particle-size distribution in beds containing a large number of difficult-to-sample cobbles and boulders. Fig. 4.4 shows the expected effect of operator bias on particle-size distributions in heel-to-toe samples compared to unbiased sampling.

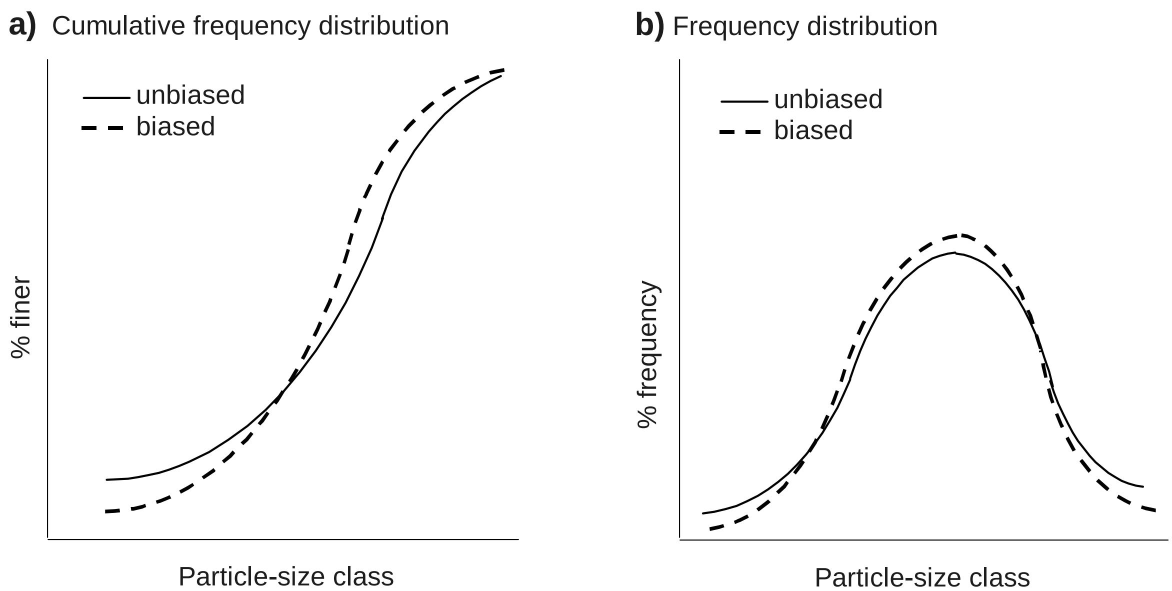

Fig. 4.4: Cumulative distribution (a) and frequency distribution (b) of an unbiased pebble count (—) and a pebble count biased against small and large particles (– –) typical of heel-to-toe sampling in gravel- and cobble-bed streams.

The bias that heel-to-toe sampling introduces against the fine gravel fraction and the cobble/boulder fraction is not detectable by standard statistical procedures, for example when samples are compared using ANOVA, or F-tests (Wohl et al. 1996). This is because each percentile is associated with a large error due to the relatively large standard deviation on poorly-sorted beds and the statistically small sample size of 100 – 400 particles. The difference between two size distributions, each with a large error, must be quite large before it becomes statistically detectable. For example, the statistical error around the mean particle size of an approximately normal distributed 100-particle pebble count with a sorting coefficient of 1.6 is ±0.32 ϕ [(2)], or approximately ±22% for particle sizes in mm[(3)]. Thus, the means of two such 100-particle pebble counts would have to

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[2] *An absolute error of $e_{\pm\phi p} = 0.32\ \phi$ was estimated for an assumed normal distribution of particle sizes in ϕ units from $e_\phi = t_{1-\alpha/2,n-1} \cdot s/n^{0.5}$. $t_{1-\alpha/2,n-1}$ was set to 1.987, α=0.05, s is the sample sorting coefficient, and n the sample size. Refer to Section 5.2.1 for further detail.*

[3] *See footnote 1 in Section 4.1.1.3.*

differ by more than 22% before their difference is statistically significant. If one pebble count had a mean of 50 mm, the other pebble-count mean would have to be larger than 61 or less than 39 mm before the difference is statistically significant. Stream studies, however, may be concerned about differences between sample means considerably smaller than 20%, or may require results with an error of much less than 20%.

The absence of a statistically significant difference between two samples from poorly sorted streambeds also gives a false sense of precision and does not mean that there is no difference. Differences between two samples can usually be better presented by simply plotting parallel samples. The user can then decide from the plots whether the observed difference between samples is acceptable for the study.

The study by Wohl et al. (1996) provides an example of inter-sample difference that is observable from plotted data, but not indicated as statistically significant by standard statistics. Wohl et al. (1996) compared samples obtained from heel-to-toe sampling and sampling along a tape on mainly dry beds of several gravel- and cobbles-bed streams. They found that both sampling methods produced statistically indistinguishable results. However, when data were plotted, the ratio of the same percentile particle-sizes between heel-to-toe samples and sampling along a tape showed a systematic decrease with bed-material particle size (Fig. 4.5) (Bunte and Abt 2001). On fine gravel beds, heel-to-toe samples had coarser D_{16}, D_{50} and D_{84} particle sizes than sampling along a tape. By contrast, heel-to-toe sampling in coarse gravel and cobbles beds had smaller D_{50} and D_{84} particle sizes than sampling along a measuring tape (Fig. 4.5). Both results correspond to the findings of observer bias.

4.1.1.6 Sampling frame for bias reduction in particle identification

A measuring tape, which is a useful sampling tool for preventing operator bias against fine and coarse particles on dry beds, is difficult to use when the streambed is submerged by flow, particularly when the flow is fast. The marks on the tape are difficult to see and relocating a large number of rocks to hold the tape down on the bed creates an extra bed disturbance beyond that induced by the actual sampling process. Operators performing pebble counts in mountain gravel-bed streams are often faced with submerged beds and swift flow, however, and need a device that overcomes the shortcomings of a measuring tape in underwater pebble counts and that mitigates the typical sampling errors associated with heel-to-toe walks. For this reason, Bunte and Abt (2001) developed a sampling frame, following a suggestion made earlier by Marcus et al. (1995).

Construction of the sampling frame

The sampling frame consists of four aluminum bars that are connected to form a square with an inside diameter of 60 by 60 cm (Fig. 4.6 a). The four aluminum bars are 0.63 cm thick (0.25 inch), 3.81 cm (1.5 inch) wide, and 65.4 cm long, cut in a miter joint and held together by corner pieces. The corner pieces have threaded pins that fit through borings at the ends of the aluminum bars. Wing nuts ensure easy set-up of the frame. The frame is sturdy and can be stepped upon to hold it down on the stream bottom in fast flow. In

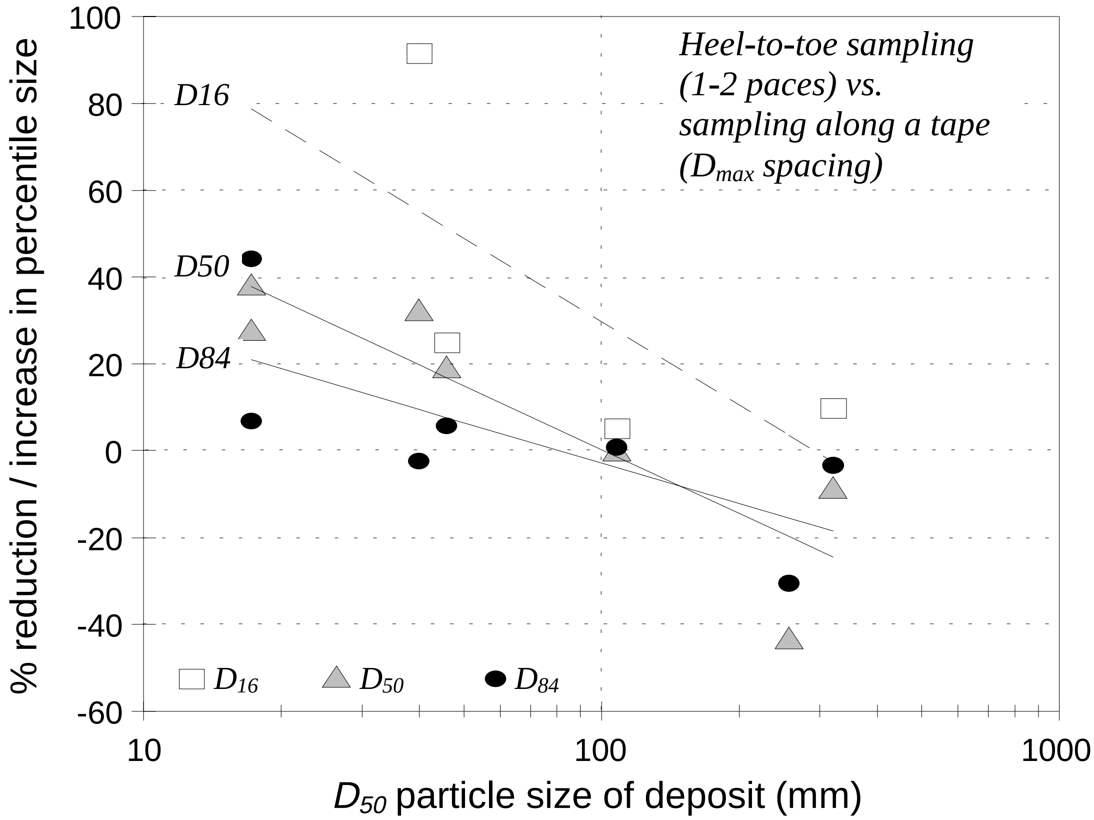


Fig. 4.5: Coarsening of the D_{16}, D_{50} and D_{84} on fine gravel beds and fining of the D_{50} and D_{84} on cobble beds for heel-to-toe sampling compared to sampling along a measuring tape with a spacing of the D_{max} particle size *b*-axis length. Stippled lines indicate best-fit regression lines. Data from Wohl et al. (1996).

order to make the frame easier to assemble and to transport, the parts can be reduced to a length of 35 cm, yielding 8 pieces that snap together with a spring and bolt mechanism (Bunte and Abt 2001) (Fig. 4.6 b).

Small slots cut in 5 cm increments along the outside edges of the frame hold thin white elastic bands in place that are stretched horizontally across the frame. Together with elastic bands stretched in a vertical direction, a grid with four or more cross-points is defined. The spacing of the grid points is adjusted to a size equal to or larger than the D_{max} particle size.

Using the sampling frame

To use the sampling frame in the stream, a tape measure is stretched from bank to bank. The sampling frame is placed onto the stream bottom so that one of the corners aligns with even-spaced marks on the tape, e.g., every three feet or one meter. Grid points derived by the elastic bands are used to visually define the particle to be selected. If the flow is deep and fast, and vision is blurred, looking at the grid intersection can help identify the particle to be included in the sample. If, for example, the grid intersection

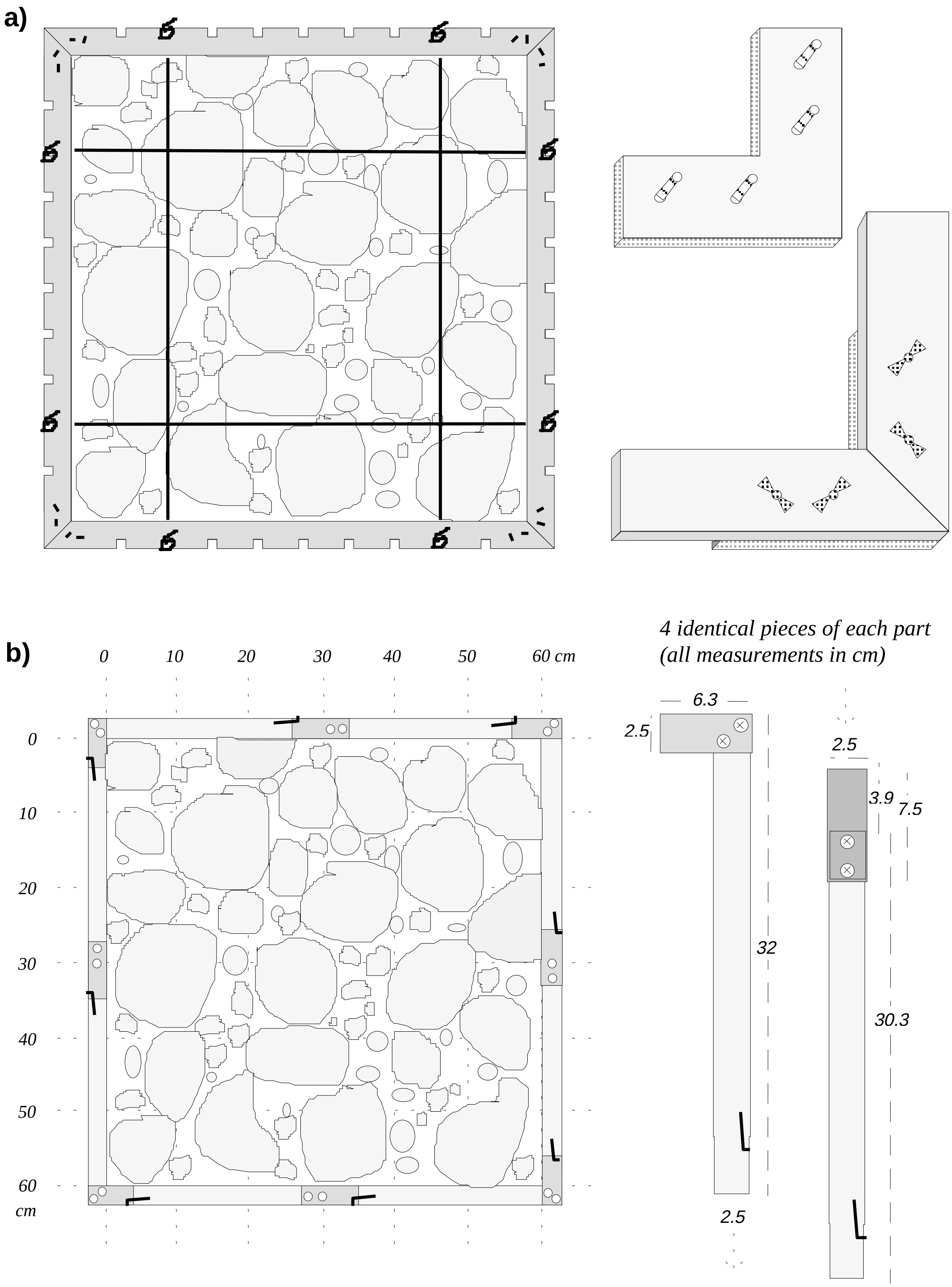


Fig. 4.6 (a): Four-piece sampling frame 60 by 60 cm with an adjustable grid of elastic bands (left). Detail of the corner piece with mounted threaded pins is shown and the joining using corner pieces and the wing nuts (right). (b): Eight-piece sampling frame modified for easy assembly and transport (left). Detail of pieces that snap together with a spring and bolt mechanism (right).

is between two cobbles, the operator knows that a small interstitial particle should be selected, but neither of the cobbles.

If flow is too deep or too fast to see the particle under the grid intersection, the particle to be included in the sample has to be identified by touch. A pointed index finger is placed in a corner of the grid intersection, and vertically lowered onto the sediment surface. The grid intersection serves as a guide for the position of the finger as it is lowered to the bed surface. Using the grid intersection as a reference point as opposed to the tip of the boot helps the operator select a particle more representatively because the operator works in a more comfortable posture when bending down to the sampling frame as opposed to bending down to the tip of the boot. The elastic bands in the sampling frame do not hinder the removal of a particle from the streambed. Particles are collected from under all four grid points, measured with a template, and placed back approximately into the same position from which they were taken. The frame is then moved to the next position along the tape. For many coarse gravel-bed rivers, a 30-cm grid within a 60 by 60 cm frame placed at 1 m, or 3 feet increments along the tape will be adequate. The sampling frame can be used on both sides of a transect. Individual transects should be 3 - 4 m apart to avoid overlap between sampled areas.

Comparison of sampling results between sampling frame and heel-to-toe walks

Particle-size distributions obtained from using the sampling frame and from sampling with heel-to-toe walks were compared in samples obtained on a poorly sorted cobble-bed stream (s = 1.7 ϕ) with a D_{50} of 69 mm (Bunte and Abt 2001). Each of two experienced operators performed two pebble counts over the same river reach, one pebble count using the sampling frame and one collecting a heel-to-toe sample. Sample size ranged between 470 and 570 particles per sample.

A comparison of the frequency distribution for both sampling methods shows that samples from the sampling frame contained a larger number of cobbles than samples from heel-to-toe walks (Fig. 4.7). The heel-to-toe samples comprised a large number of mid-sized gravel in the size class 45 and 64 mm and generally fewer cobbles. This difference clearly demonstrates an operator bias against cobbles and boulders in heel-to-toe samples, while large, handy particles were favored instead. For inexperienced operators, the difference is expected to be even more pronounced.

Sampling frame reduces variability between operators

Two operators sampling the same transect using the heel-to-toe method are very likely to produce different particle-size distributions, especially if the operators are of different stature (Fig. 4.7). Using the sampling frame largely reduced the variability between operators, because it eliminates operator decision on the selection of cobbles and boulders and equalizes the sampled stream width, as well as the number of particles sampled by both operators. Consequently, both operators who had markedly different distributions in heel-to-toe samples (Fig. 4.7), produced very similar particle-size distributions when using the sampling frame (Fig. 4.8). The percentile particle-sizes of the D_{50} to D_{95}

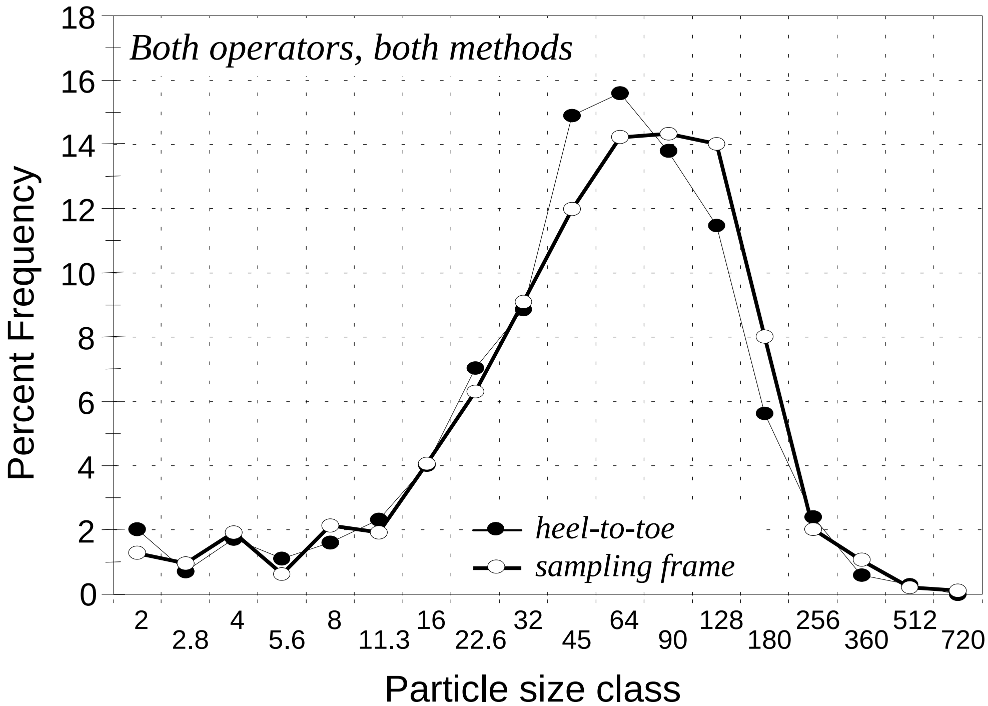


Fig. 4.7: Difference in frequency distributions obtained for heel-to-toe sampling and the sampling frame (both operators). The size class < 2 mm is not included in the analysis.

differed by less than 5% between operators, whereas the percentile difference for the D_{50} to D_{95} ranged from 7 to 22% when both operators sampled with heel-to-toe walks (Fig. 4.9).

Quantification of sample variability due to operator error

In order to estimate the magnitude of the operator error when using the sampling frame, the total error incurred in samples from the sampling frame was compared to the statistical error computed by Rice and Church (1996) for a large sample from gravel-bed river sample in Section 4.1.1.3 (Fig. 4.2). A set of 10 samples collected by the authors of this study in several gravel- and cobble-bed streams using the sampling frame was available for this comparison. The sorting coefficient s_I for the 10 samples ranged between 0.97 and 1.64, and sample sizes *n* between 309 and 469. The mean sorting coefficient of s_I = 1.26 of these 10 samples was similar to the standard deviation of the Mamquam River for which Rice and Church (1996b) computed the relation between sample size and statistical error with a bootstrap approach. Likewise, the mean sample size of 426 was similar to the sample size of 400 for which the statistical error around various percentiles is shown in Fig. 5.10 and 5.11.

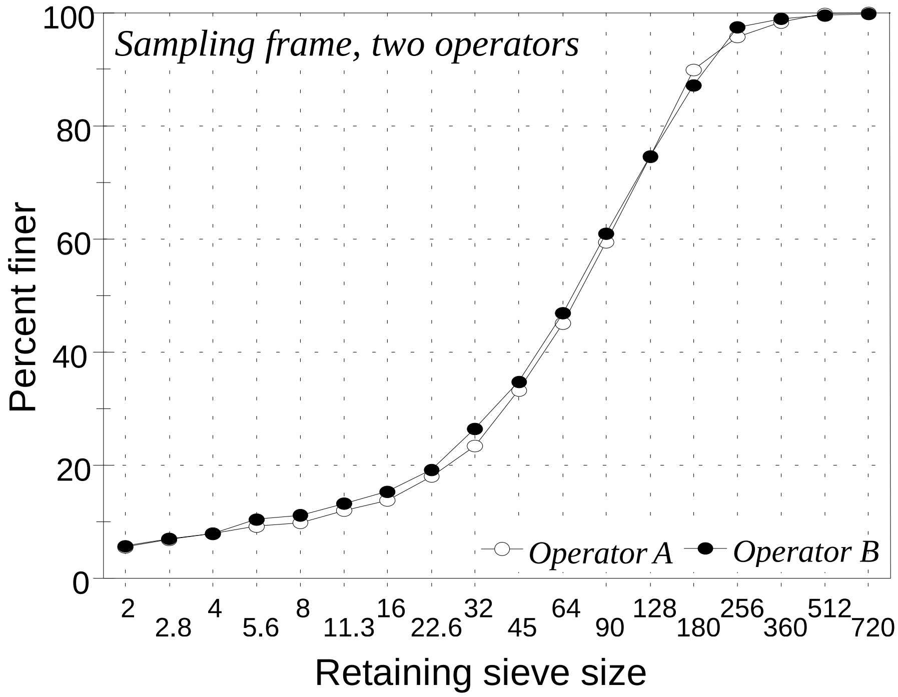


Fig. 4.8: Almost identical cumulative frequency distributions obtained by operators A and B when using the sampling frame in a cobble-bed stream.

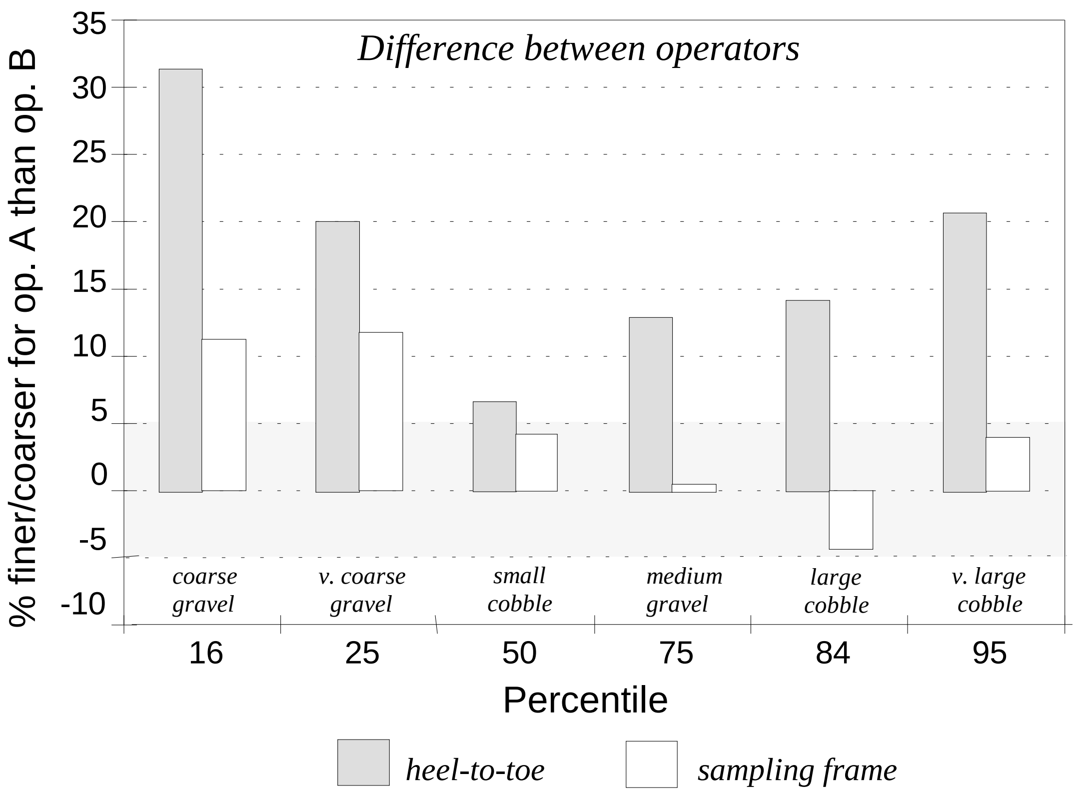


Fig. 4.9: Percentage difference in percentile particle-size obtained by operator A and by operator B. The gray band indicates the range of up to ± 5% difference.

In order to compute the operator error for each sample collected with the sampling frame, each of the 10 samples was split in two: subsample *a* comprised the 1st, 3rd, 5th, … recorded particle size for each transect, while subsample *b* comprised the 2nd, 4th, 6th, … recorded particle size. The percent error $e_{\%Dp}$ around percentiles was computed using a standard sample-size equation $e_{\%Dp} = (1.96 \cdot s/\mu)/\sqrt{n}$ (Section 5.2.1), where μ is the mean of the two subsample percentiles analyzed, e.g., $(D_{5(a)} + D_{5(b)})/2$.

Sampling with the frame yielded an average relative error around the D_5 of ± 30% between samples (Fig. 4.2). This is still higher than the statistical error of ± 20%, but a considerable improvement over the high variability of ± 50% error or more for the D_5 obtained from heel-to-toe sampling. The reduced error for the D_5 suggests that the sampling frame indeed reduces operator variability in the identification of small particles. Using the sampling frame cannot completely eliminate operator error because frame does not prevent inaccurate particle retrieval. For all other percentiles, the operator error computed for the sampling frame samples is similar to the purely statistical error computed by Rice and Church (1996b), suggesting that the sampling frame does largely eliminate operator errors and thus inter-sample variability in all but the smallest particle sizes.

4.1.1.7 Measuring, recording and analyzing pebble count data

Pebble counts are usually a two-person operation: one person selects and picks up a particle from the streambed, measures its *b*-axis, preferably with a template (Section 2.1.3.6) and places the particle back onto the streambed in the location where it was taken. The second person records the particle size in a notebook. Voice activated tape recorders may be an option for data recording if a person works alone. However, the background noise from the water flow in mountain gravel-bed streams is too loud to allow a recorder shut-off and thus causes a lengthy record.

For many purposes, particle sizes in pebble counts are best measured with a template (Section 2.1.3.6) that has a 0.5 ϕ gradation (Section 2.1.2). Smaller or larger ϕ gradations may be appropriate in some studies or stream situations. Particles finer than 2 mm are usually not differentiated in size, but tallied together as a single size-class finer than 2 mm. Some studies use a ruler or caliper to measure particle axes to the nearest mm (Section 2.1.3.7). This should only be done if the range of measured particle sizes is small, if a near-normal distribution of particle sizes in terms of ϕ units cannot be assumed, or if all particle axes are measured (Section 2.1.3.7). Measuring the particle *b*-axis with a ruler is not recommended as a substitute for template measurements. Using templates not only reduces the variability in particle-size measurements between operators, but also ensures comparability of the measurements with data obtained from using standard square-hole sieve sets.

When the measured particle sizes are recorded, the note taker should use a separate column for each transect in order to allow tracing back the approximate location of each recorded particle size (Table 4.3). This can be helpful in identifying systematic spatial variability of particle sizes. Information can be lost when recording particle sizes as tick

Table 4.3: Example of a sampling form for pebble counts

Stream: *Squaw Creek* Reach: *100-150 m downstream of Spire Rock Campground Bridge*

Date: *July 8, 1996* Person sampling: *Jack Brown* Person recording: *Jill White*

Particle size measurements: Template in *0.5* ϕ gradation; Calipers (~~yes~~/no); Ruler (~~yes~~/no)

Select one: x Largest size class (mm) through which particle cannot pass (larger than)
__ Smallest size class (mm) through which particle can pass (smaller than)

Stream morphology: *mostly plane bed, small plunge pools, some riffles and rapids*

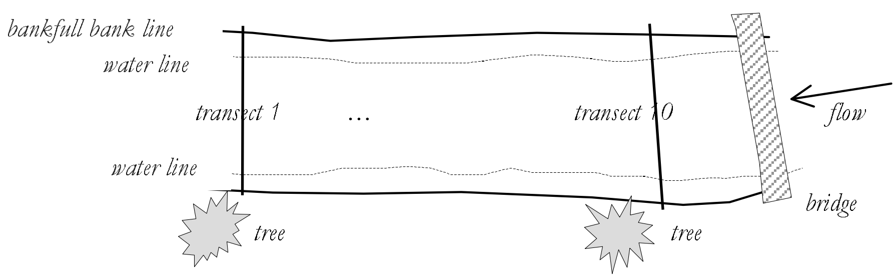
Banks within reach: *LB steep, ca. 0.5 m incised into meadow; RB gentle sloping, sandy* Bed material structure and packing: *large particles wedged, some clusters, little imbrication*

Particle shape: *mostly ellipsoid, some discs, subrounded; cobbles and boulders mostly angular*

Lithology: *70% andesite and other volcanic rocks, 20% sedimentary, 10% gneiss*

Remarks: *used sampling frame with grid spacing of 0.3 m*

Sketch of sampling site:



Location of 1st transect: *150 m downstream of bridge*

Transect number:	1	2	3	…	k
Dist. upstream from 1st transect (m):	0	5	10	…	j
Left Bank	5.6	11.3	8		4
	16	8	5.6 WL		11.3
WL = waterline	32 WL	22.6	45		16
	45	64 WL	90		128 WL
	⋮	⋮	⋮		⋮
	90	45	32		64
	16	11.3 Wl	8		22.6
	2.8	5.6	4 WL		16
	4 WL	<2	2		2.8
Right Bank	2		5.6		

marks in the respective size class of a sampling form. A sequential data record is also necessary if a sample is to be split for a statistical error analysis (Section 5.2.1 and 5.2.2). Mention of the water line and whether a particle was collected bankward or waterward from the water line is important because it facilitates the decision to either include or exclude fine particles near banks from the analysis, an option that depends on the study objective. Field forms and field books are further discussed in Section 4.5.

Particle sizes are analyzed based on the frequency-by-number of particles per size class. A cumulative percentage frequency distribution is computed from the measured particle sizes, and particle-size percentiles, such as the D_{50} or D_{84} (Sections 2.1.4.1 and 2.1.4.2), or the % fines smaller than 2, or 8 mm (Section 2.1.5.8) are determined. Particle-size parameters may be computed from the frequency distribution or from percentiles of the cumulative frequency distribution (Section 2.1.5).

4.1.2 Grid sampling

In grid sampling, particles are measured from under a *preselected number of grid points* that cover a predefined sampling area. Particles can be physically picked up from under a grid laid directly on the streambed surface, and in this case, a grid count is actually a pebble count. Pebble count procedures are described in Section 4.1.1. Another form of grid count is to take vertical photographs of the sediment surface, and measure particle sizes under a grid superimposed on the photograph. Both physical grid counts (pebble counts) and photographic grid counts can be performed at a variety of different spatial scales.

4.1.2.1 Grid sizes and spatial scale

Grid counts can cover sampling areas of any shape as long as the grid is evenly spaced. The spatial scale of grid counts is flexible. The smallest grid unit is determined by the coarsest particles on the sediment surface. Grid spaces should be at least as large as the D_{max} particle size, or even better twice the D_{max}, in order to avoid double counting and serial correlation (Section 4.1.1.2). A gravel surface with a D_{max} of 100 mm requires at least a 0.1-m grid. A grid of this size can be set up by rubber bands spanned across the sampling frame (Section 4.1.1.6, Fig. 4.6). Minimum sampling area for a sample size of 400 particles for this grid spacing is 4 m^2. A cobble surface with a D_{max} of 256 mm requires at least a 0.25-m grid, and the minimum area for sampling 400 particles is 10 m^2. At this scale, grid points can be marked by parallel transects along a measuring tape. The largest extent for a grid count is an areal overview that extends over a reach of several 100 m^2 in.

4.1.2.2 Photographic grid counts

A grid count can be performed on a photograph taken vertically over the sediment surface. The photograph is superimposed with a grid, and the projected *b*-axis length of particles under the grid points is measured with a ruler or planimetrically (Section

4.1.3.3). The measurements are converted to the natural scale of the particles by an appropriate scale factor before a particle-size analysis is done.

Scales of photographic grid counts vary with the desired resolution of the photograph, the coverage for each photograph, and the coarseness of the bed. Each scale facilitates analyzing a certain range of particle sizes. If a broad particle-size spectrum is to be analyzed, areal photographs need to be taken at various scales.

Scale, resolution, and areal coverage of the photograph

A photograph with a side ratio of 1:1.5 covers an area of approximately 0.5 m by 0.75 m = 0.35 m^2, if taken by a standing person at a distance of about 1.3 m, when using 24 by 36 mm negatives, and a standard 50-mm camera lens. The smallest distinguishable particle size of such photographs is about 2 mm (Bunte and Poesen 1993). Coverage of larger areas is desirable on coarse gravel surfaces. This can be obtained by cameras with lenses that have wider angles (e.g., 35 mm), or by creating a larger distance between camera and the ground. A 35-mm lens leads to distortion at the edges of the photograph, but is a compromise to the otherwise greater camera height required for a larger areal coverage. With a 35-mm lens, camera height equals the natural length of the longest side of the photograph. For example, to cover areas of 0.9 by 1.4 m, 1.33 by 2 m, or of 2 by 3 m on a photograph, camera height needs to be 1.4, 2, and 3 m, respectively (Ibbeken and Schleyer 1986). The smallest distinguishable particle size for a coverage of 1.33 by 2 m is approximately 10 mm, but the resolution depends on the quality of the photograph (see discussion below). Several photographic scales may have to be used to analyze all particle sizes within a reach.

For camera heights of 1.4 m or more, the camera can be mounted either to the underside of a wide legged tripod, or the underside of a pyramid-shaped frame especially designed for this purpose. The bottom part of the pyramid is connected to a rectangular frame (ground frame) that outlines exactly the area covered by the photograph. A cm scale, preferably in black and white stripes like on a surveyor's rod, is attached or painted to the bottom part of the ground frame to serve as a scale in each photograph. Each photograph requires some form of identification. An electronic or mechanical remote control is needed to operate the camera shutter if the camera is mounted out of reach and the film is advanced with an automatic winder.

If an entire stream reach is to be photographed on a scale so that each photograph covers approximately 1 m^2, consecutive photographs should not overlap, but be exactly adjacent so that particles at the edge of photos are neither excluded from the analysis nor counted twice. The correct position required for neighboring ground frames can be determined with a tape measure and small pins or flags that mark the corner positions of the ground frame.

Photography experience is essential to produce usable pictures under poor light conditions. Single-lens reflex cameras with adjustable aperture and speed tend to produce better pictures than fully automatic "point and shoot" cameras. A high speed film (400 ASA) that facilitates a short exposure time to prevent blurring in hand-held photography is not unconditionally recommended because of its graininess. 100 or 200 ASA films are less grainy, and these films are ideal for sunny weather when short exposure times of 1/125 s can be used or for mounted cameras. Photographs should be taken around mid-day to minimize shadows around large particles in which small particles could be undetectable. Dark conditions, such as under forest canopy, require long exposure times of perhaps 1/8 of a second, and a camera stand to avoid blurring. Prints should be developed with low contrast to span a large range of gray tones or color shades, and be enlarged to about 18 by 24 cm.

Grid setting

A grid may be placed directly onto the sediment surface before the photo is taken (Kellerhals and Bray 1971), but this is not recommended because the physical grid may obscure small particles from view. A better alternative is to take a slide photograph of the sediment surface and project the slide onto a screen with grid lines. Such a "screen" can be a letter-sized or larger piece of paper with grid lines printed on it. The slide is then projected onto this screen from a close distance (Bunte and Poesen 1993). The grid line spacing should match the D_{max} particle size in the selected projection scale to avoid serial correlation and double counting (Section 4.1.1.2). If, for example, the largest particle in the projection is 2 cm, then the grid spacing should be at least 2 cm as well. A letter-sized piece of paper has about 13 by 10 = 130 grid points in a 2 cm grid.

b-axes measurements on photographs

If particles lie flat with the *b*-axis plane parallel to the photographic plane, the short particle axis visible on photographs is the particle *b*-axis. The simplest way to measure *b*-axes lengths of particles under grid points is with a ruler. Ruler measurements are suitable if the number of photographs to be analyzed is relatively small. If particle sizes span a narrow range only, or if measured *b*-axes lengths are not tallied in ϕ units, *b*-axes lengths are measured to the nearest mm. If particle sizes are to be tallied in 0.5 ϕ units, ruler-measurements can be simplified if the mm equivalent of all size classes in 0.5 ϕ units (larger or smaller class sizes for some studies) is computed based on the scale of the photograph. Once the mm-equivalent for 0.5 ϕ size classes is known, ruler measurements only need to determine the 0.5 ϕ size class into which a *b*-axis length falls. Ruler measurements of *b*-axes on photographs correspond to sieve results from round-hole sieves and need to be converted before they can be compared to standard sieve results from square-hole sieves (Section 2.1.3.4 and 2.1.3.5).

A particle-size analysis from a photographic grid count produces a grid-by-number (i.e., frequency-by-number) particle-size distribution. Measuring the *b*-axes of *all* particles on the photograph constitutes an areal sample, which is a different sampling technique and results in a different particle-size distribution. Areal sampling is discussed in Section 4.1.3.3.

Errors from misreading the ruler, or from miscomputing measurements can be avoided by using an optical particle-size analyzer (Ritter and Helley 1969) to measure particle *b*-axes. This instrument projects an adjustable circle of light onto the photograph of a gravel surface. The size of the light spot is adjusted to match the apparent *b*-axis of a particle. An activated foot switch then registers the diameter of the circle in the instrument and marks the particle just analyzed. After all particles have been measured, a size distribution is computed.

Errors in *b*-axes measurements resulting from particles that are partially hidden from view, or when the *b*-axis plane is not parallel to the photographic plane can be mitigated when measuring particle *b*-axes planimetrically using computer digitizing equipment (Ibbeken and Schleyer 1987). This technique is described in Section 4.1.3.3.

Potential errors of photographic b-axes measurements

If all particle *b*-axes on the photograph are fully visible and parallel to the photographic plane, the photographic distribution is similar to the distribution obtained by physically measuring the *b*-axes of all surface particles of the deposit with a ruler. However, neither the photograph, nor the sedimentary structure is always ideal for photographic analysis, and the farther conditions are from ideal, the larger the deviation between photographic and physical *b*-axes measurements.

The particle *b*-axes lengths measured on a photograph and converted to their natural size using the appropriate scale factor tend to be smaller than *b*-axes lengths measured on the actual particles. This is due to several factors: the *b*-axes length may not be fully visible on the photograph when particles are embedded or partially hidden by other particles. The projected *b*-axis is also shorter than the natural *b*-axis if the particle does not lie flat (*b*-axis plane not parallel to photographic plane). Thus, photographic grid counts are problematic on imbricated and clustered surfaces.

The question of whether this discrepancy is dependent on particle size has been debated and probably depends on the shape and orientation of the particles on the sediment surface. Kellerhals and Bray (1971) found that the mean particle size on photographic analyses was 5 mm smaller than that obtained by sieving. This discrepancy could be corrected by adding 5 mm to all photographically determined particle sizes. A constant difference of a few mm for all particle sizes could be conceivable for a surface on which particles are bladed and lying flat.

Adams (1979) found that the discrepancy between photographic analysis and sieving with square-hole sieves becomes larger with particle size. Therefore, the correction factor to be applied for conversion of photographic *b*-axes and photographic percentiles into an equivalent sieve size should be a constant fraction of a ϕ unit. Excluding particles finer than 8 mm from both photographic and sieve analysis, Adams (1979) suggested that 0.1 ϕ should be subtracted (or 0.1 ψ be added) to make photographic grid counts comparable to results from square-hole sieves. For analysis in mm units, the correction factor is multiplication of the photographic *b*-axes lengths by a constant factor of 1.07 (Adams 1979).

In some deposits, the *a*-axis is easier to identify on photographs than the particle *b*-axis. For such surfaces, Adams (1979) suggested computing a particle-size distribution of *a*-axes lengths. This distribution is then converted into an equivalent distribution that would have been obtained had the particles been sieved using square-hole sieves by adding 0.45 ϕ units (or subtracting 0.45 ψ units) to all photographic particle-size percentiles. Such a procedure is only recommended if the axis ratio a/b is constant within and between particle-size classes.

Both manual pebble counts and small-scale photographic grid counts covering approximately 1 m^2 per photograph are prone to bias against fines. The resolution of the photograph may not be sufficient to identify particles as fine as 2 mm, and some of the small particles might be overlooked on the photograph because they are located in shadows between large particles. Both factors cause bias against fines and a particle-size distribution that is coarser, particularly at the fine end, than the true distribution. In order to avoid bias against invisible fines, it might be necessary to exclude particles finer than 10 or 20 mm from the analysis, depending on the scale and the quality of the photograph.

In summary, photographic grid counts facilitate non-destructive sampling of gravel- and cobble beds and substantially reduce field time. Thus, photographic grid counts are a good choice if field time must be short, although time is needed for analyzing the photographs. A disadvantage of photographic grid counts is that the lengths of the scale-adjusted *a*- and *b*-axes measured on the photograph tend to be smaller than the actual particle *a*- and *b*-axes, and that fines tend to be overlooked. This is due to non-horizontal particle orientation and shadows on the photograph. Numerical factors correcting for these discrepancies vary depending on the shape and orientation of particles on the sediment surface. Thus, photographic grid counts are best applied when particles are lying flat and are fully visible, when high-quality photographs can be obtained, and when the fine part of the particle-size distribution may be neglected in the study.

4.1.3 Areal sampling

Definition, sample area, sample size and number of samples

For areal surface samples, the operator collects *all* particles exposed on the surface within a *predefined* area, which is typically an area of about 0.1 - 1 m^2. Sampling *all* surface particles without including any subsurface particles can be problematic. Not only is it conceptually difficult to determine how much hiding is tolerable for a surface particle, but it is also physically difficult to retrieve all surface particles without leaving some surface particles unsampled and without starting to sample subsurface particles. This sampling problem becomes more pronounced as the range of particle sizes increases, and as the particle packing deviates from a simple side-by-side arrangement with *b*-axes planes parallel to the bed surface.

A variety of methods have been proposed for particle retrieval in areal samples:

- Manual picking, lifting, and scraping,
- Adhesives (contact and penetrating), and
- Non-destructive methods (photo sieving, visual estimate, and wax imprints).

These methods are discussed in greater detail in the following sections. Some of the techniques are more suitable for fine gravel, others are better suited for coarse gravel. Sampling results from different areal sampling procedures can vary greatly. This is because gravel bed-material usually has a coarse surface layer overlying a deposit richer in fines, and each of the areal procedures collects surface particles down to a slightly different depth. Consequently, each method includes a different percentage of small particles partially hidden between large clasts.

Areal samples typically cover an area of 0.1 – 1 m^2 per sample. The number of particles, or the sample volume obtained from areal samples of that size, may provide sufficient material for a meaningful particle-size analysis if the bed is comprised of fine gravel, but not for a bed of coarse gravel (see Section 5.3 and 5.4 for size of an individual sample). In coarse beds, areal samples should be repeated several times within an area of homogeneous bed material until a sufficiently large amount of sediment has been collected for a statistically meaningful size analysis. Note that even if one areal sample provided sufficient material for a statistically meaningful size analysis, one sample only characterizes a reach if the bed material within the reach is spatially homogeneous. This is rarely the case. Several samples are required if the bed-material size is spatially inhomogeneous. The number of samples necessary to characterize a reach increases with the degree of spatial variability of the bed-material size and may be determined using a two-stage sampling approach (Section 5.3.2)

Areal samples may be analyzed either on a weight- or as a number-based frequency. Both particle-size distributions, area-by-weight or area-by-number, are different from weight frequencies obtained in volumetric samples (volume-by-weight) or the number frequencies obtained in pebble counts (grid-by-number). To be comparable with pebble counts or volumetric samples, particle-size distributions of areal samples need to be converted to a volume-by-weight or grid-by-number sample. Conversion is also necessary to compare areal samples obtained by different methodologies, and even to compare areal samples obtained by the same methodology (Diplas 1992a). Sample conversion is discussed in Sections 4.3.1 and 4.3.2.

4.1.3.1 Manual sampling

Hand picking on coarse gravel surfaces

Hand-picking is the method of choice for areal sampling on coarse gravel beds. The operator outlines the sampling area with a frame (e.g., lawn edging) and hand-picks all surface particles within the area (Billi and Paris 1992). The smallest particles are most difficult to assign to either the surface or the subsurface sediment, particularly when small particles are difficult to see and to retrieve in between large clasts or are partially hidden.

Although small partially hidden surface particles can only be seen and retrieved after large surface particles have been removed, generally the smallest particle should be picked first. This procedure may leave some hidden surface particles unsampled, but if large particles are removed first, it is almost impossible to determine whether remaining small particles belong to the surface or whether they lay under a large particle already removed and thus belong to the subsurface. Picking the smallest particles first and then continuing with progressively larger particles ensures that only exposed surface particles are included in the sample (D. Rosgen, pers. comm.).

Lane and Carlson (1953) suggested differentiating surface from subsurface particles by marking surface particles with spray paint. Church et al. (1987), however, note that spray paint does not unequivocally identify surface particles because the paint might run down the side of rocks and infiltrate into the subsurface sediment.

The strict distinction between surface and subsurface particles becomes even more problematic when hand-picking particles in areal samples under water because one can only feel but not see the sediment surface. A bias towards large particles ensues when only undisputed, large surface particles are picked. Scraping all surface particles in an effort not to overlook the finer particles is likely to include fine subsurface particles and may cause a bias towards fines.

Surfaces with fine gravel and sand

Fine gravel and sand cannot be hand picked. Surface particles could be scraped, which is a rather indiscriminate procedure, or individual particles could be picked up with tweezers. A less tedious method is to coat surface particles with *magnetic paint* (spray paint with magnetite dust) and then lift all coated surface particles with a strong hand-held magnet (Wilcock and Stull 1989). Usually, adhesive methods are used for fine gravel.

4.1.3.2 Adhesive sampling

Adhesive methods may be used for areal samples of gravel surfaces that contain particle sizes between sand and coarse gravel. Adhesive methods are particularly recommended for surfaces that contain relatively large amounts of sand and fine gravel. The general procedure for areal adhesive sampling is that a board covered with an adhesive is pressed onto the gravel surface. The adhesive penetrates the sediment surface and touches all surface particles, both large and small. When the board is lifted off the surface, surface particles adhere to the adhesive. For a size analysis, sampled particles are separated from the adhesive, by dispersing or dissolving the adhesive, or by brushing and scraping particles off. Cured epoxy makes an inseparable bond with the particles and requires a thin section analysis.

A variety of substances have been used as adhesive, including all-purpose glue, epoxy resin, mud, clay, soap, grease, wax, putty and flour paste (e.g., Little and Mayer 1976; Gomez 1979; Ettema 1984; Diplas and Sutherland 1988; Diplas 1992a; Diplas and Fripp

1992; Gessler 1992; Marion and Fraccarollo 1997). The selection of an adhesive depends on several factors which include the depth of penetration required for a deposit of a given particle size and sorting, whether the sample is to be wet-sieved right at the stream site, whether the sample needs to remain undisturbed during transport, or whether it is to be analyzed by thin-section analysis. Most adhesives stick only to dry surfaces. Gomez (1983a) used a freeze technique whereby the surface particles froze to plastic wrap cooled by liquid nitrogen. This technique could be used on wet and slightly inundated river beds.

The requirement of areal samples to sample *all* surface particles, and to sample surface particles exclusively can lead to the following dilemma. Adhesives that barely penetrate the surface ensure that only surface particles are sampled, however, by not reaching the bed-surface plane, small intersticial surface particles are probably not sampled in their entirety and are underrepresented in the sample (Fig. 4.10, a, b and c). By contrast, adhesives that penetrate the surface sediment deeply ensure that all surface particles are sampled, but subsurface particles may falsely be included in the sample as well (Fig. 4.10, e), resulting in a semi-volumetric sample. Accurate areal samples require that the adhesive penetrates the surface to the appropriate depth (Fig. 4.10 d), which is the bed-surface plane. Deep penetration of the adhesive is required to reach the bed-surface plane in coarse and poorly sorted gravel beds, while less or slight penetration suffices in fine and well sorted beds.

Obtaining the right penetration depth for a given sediment

The appropriate penetration of the adhesive to the bed-surface plane can be obtained in two ways: by selecting an adhesive with an appropriate viscosity and plasticity, and by controlling the penetration depth through the method with which the adhesive is applied. The degree of viscosity determines the flow rate of the adhesive (that may range from thin glue to stiff pottery clay). The degree of plasticity determines how well the adhesive is pliable to the surface particles (that may range from very soft grease to putty). In order to control the depth of penetration, an operator may vary the thickness of the adhesive coating, the pressure exerted when bringing adhesive and sediment into contact, and the flexibility or rigidity of the background onto which the adhesive coating is spread.

Penetration of the adhesive can be deepened by using thin or soft adhesives, and by applying thick coatings of adhesive with moderately high pressure from a flexible background. Penetration depth can be lessened by using a somewhat less pliable adhesive, and by applying thin coatings with slight pressure from a rigid background. The same adhesive applied in the same manner to bed material of different sizes and sorting coefficients leads to different sampling results.

Fig. 4.11 combines the three variables of adhesive properties, sedimentary properties, and mode of application, and suggests how adhesives of different penetration properties can be combined with application modes that result in different penetration depths in order to achieve the right penetration depth required for accurate areal samples in deposits of different particle sizes and sorting coefficients.

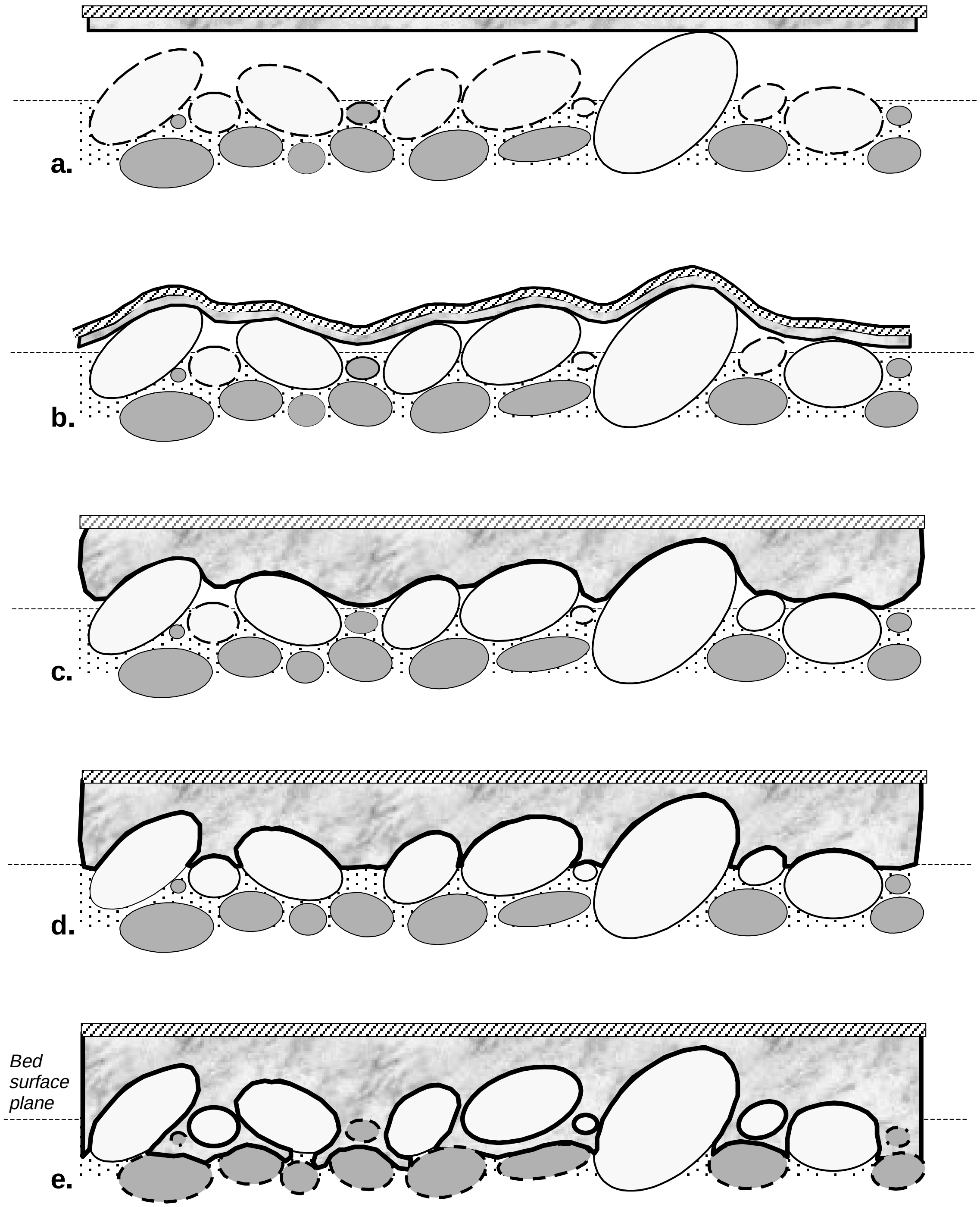


Fig. 4.10: Sampling properties of adhesives with coatings of different thickness, applied to different backgrounds, their viscosity, and different sampling properties on a poorly sorted bed that includes sand and gravel. Sampled surface particles; Wrongly unsampled surface particles; Subsurface particles; Wrongly sampled subsurface particles; Adhesive; Backing. Insufficiently thin coating of adhesive applied to a board (a) and a textile (b); Thick coating of adhesive, but too little penetration (c); appropriate penetration (d); too much penetration (e).

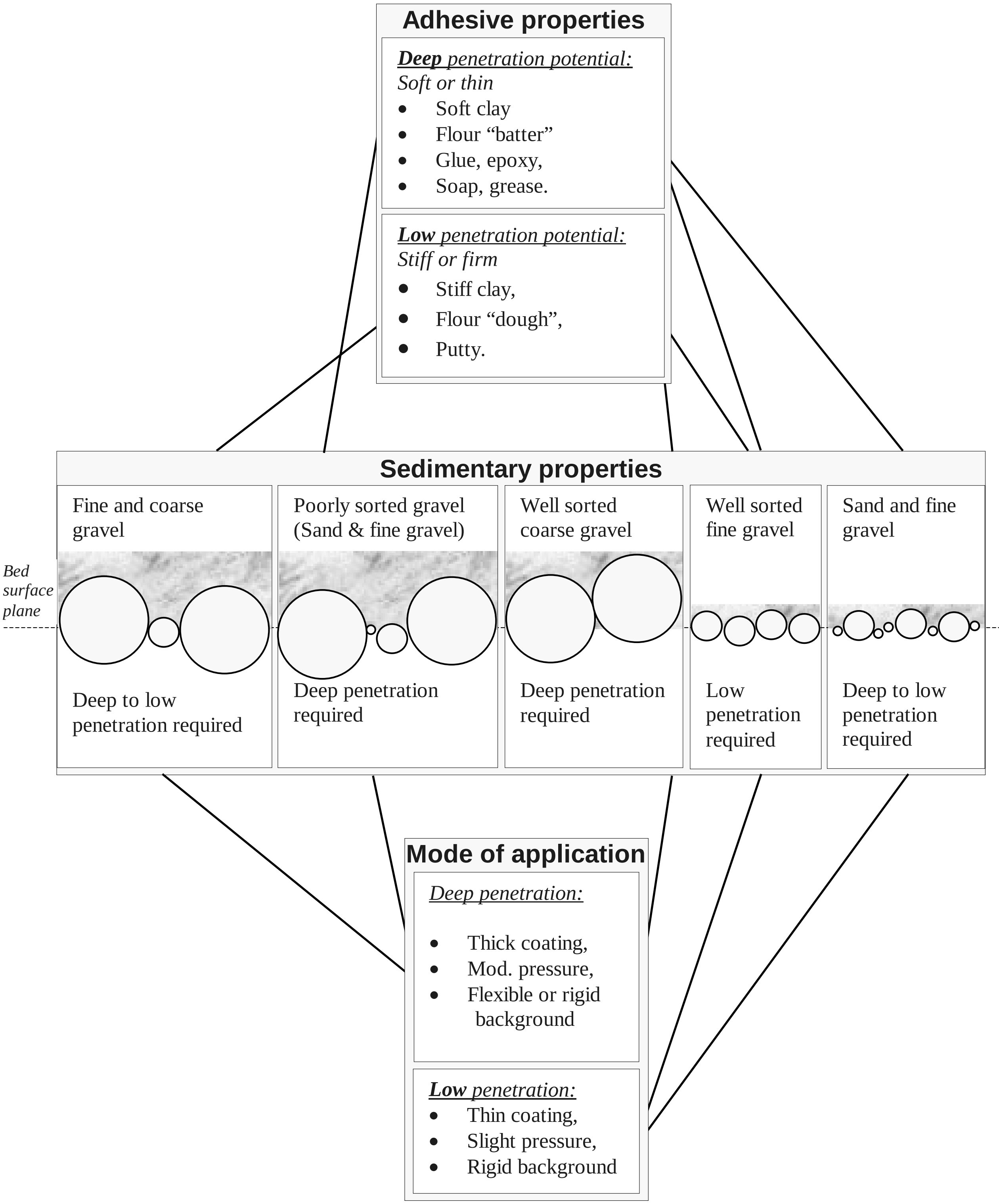


Fig. 4.11: Interrelation between adhesive properties and their potential depth of penetration, the mode of application, the resulting depth of penetration, and the sedimentary properties with their required penetration depths. Note that modifiers such as soft, stiff, deep, low, thin, and thick are relative.

Testing

The accuracy of a sampling procedure obtained from the combination of a particular adhesive and the particular mode of application should be tested before it is used for a study project. This could be accomplished by carefully coloring the surface particles with an appropriate paint. All colored particles should adhere to the adhesive, while none should remain on the streambed. The adhesive and/or the application technique should be modified until all surface particles can be accurately sampled.

A sampling error on the fine sediment end (missing surface fines or wrongly including subsurface fines) is more difficult to determine and to correct than errors that result when large particles fall off as the adhesive is lifted off the surface. When in doubt, select an adhesive and an application technique that is most suitable for sampling the fine surface particles in voids between large particles. If the sampling area contains a few disproportionately large particles or narrow voids, it might be helpful to do some preparation work. An application of adhesive material around large particles or into small voids before the adhesive is generally applied to the sample area makes small particles in voids between large particles more accessible to the adhesive.

Operator variability

Areal samples are highly prone to variability between operators, because each operator has a slightly different way of adhesive preparation, or in application technique. Thus, one operator should do all the adhesive preparation, while another operator takes all the samples. Variability between operators should be tested and minimized before multiple operators take areal samples within the same study.

Separation of sampled particles from the adhesive

Properties of the adhesives determine how sediment and adhesive are separated after the sample is taken. Adhesives may be dispersible or soluble in water, or in solvent. Adhesives may remain largely inert, harden over time, or cure. This requires different methods of separating the sampled particles from the adhesive, and different methods of particle-size analysis. An overview of these factors is presented in Table 4.4.

Soft clay, and flour batter are dispersible in water. The dispersion is discarded through a sieve with a mesh size smaller than the smallest sampled particle size. A similar procedure can be applied to water-soluble, uncured all-purpose glue and to solvent-soluble grease. If stiffer clay, and flour “dough” is used as an adhesive, sampled particles can mostly be brushed away. If a little scraping is necessary, the sample needs to be washed or wet-sieved to eliminate the clay or the flour from the sample.

The clay, or the flour dough, can be reused for another sample if a moist wrap keeps the clay or flour dough from drying. If no future use is planned for the adhesive, or if samples cannot be processed soon after the field work, the clay and flour dough adhesives can be allowed to harden. Sampled particles from hardened clay or dough are retrieved by brushing and scraping. A thin-section technique is required for particle-size analysis

Table 4.4: Adhesives and their properties, method of particle separation from the adhesive, adhesive reusability, and method of particle-size analysis

Adhesive	Adhesive Property	Method of separation	Reusability of adhesive	Method of particle-size analysis
soft clay, flour "batter", uncured glue	sticky, runny, dispersible, water soluble	disperse or dissolve adhesive in water	not intended	wet or dry sieving
grease	sticky, solvent soluble	dissolve adhesive in solvent	none	wet or dry sieving
stiffer clay*, flour "dough"*, putty, wax	firm, inert *in moist wrap	brush and scrape off sampled particles	reusable	wet or dry sieving
stiffer clay, flour "dough"	hardens without moist wrap	brush and scrape off sampled particles	not intended	wet or dry sieving
epoxy resin, all-purpose glue	curable	visual separation only	none	thin section analysis

of areal samples obtained by epoxy resin or glue that was allowed to cure. The plane of the cut should be exactly at the bed-surface plane, otherwise surface particles are wrongly excluded, or subsurface particles are wrongly included in the analysis.

Advantages of clay and flour paste as adhesive

Using clay (Diplas and Fripp 1992) or flour paste (Gessler 1992) as adhesive has several advantages besides being affordable, generally available, and non-toxic for the operator. Flour dough or batter can be mixed with water to obtain a desired degree of viscosity and plasticity. The mixing result is basically reproducible (write down exact proportions of wet and dry ingredients, and manufacturer), although the consistency may vary slightly with air humidity. Since flour dough or batter can be prepared in the field, it can be prepared to the appropriate consistency for a given deposit. Mixing clay from powder, or changing the moisture content of moist clay in order to change its viscosity and plasticity takes more time, so ready-to-use clay of different consistencies should be brought to the field site. The possibility of mixing flour dough or batter to the right consistency, or using clay of just the right consistency for a given deposit provides a good chance of producing accurate and unbiased sampling results.

Clay and flour paste are two of the few substances that adhere to wet surfaces. Clay can be used for under water sampling. For multiple use, the clay surface needs to be well scraped between samples to provide a fresh surface for the next sample. Clay and flour paste provide two options for separating the sampled particles from the adhesive. The adhesive matrix can be dissolved and the sampled particles wet-sieved, or particles can be mechanically brushed off the clay surface and collected (see above). Both methods can be performed at the field site. Dispersion has the advantage that no clay or flour batter needs to be hauled back to the lab. However, dispersed clay or flour should not be discarded into a stream as it may clog interstitial spaces and impair streambed habitat. Brushing particles from the clay or dough slab and reconstituting the adhesive surface for a new sample saves material and has the advantage that only the material for a few samples needs to be carried to the stream site. Clay or flour dough that is kept in a moist wrap can be reused for sampling at a later time. To delay or prevent flour dough from getting moldy with time, substitute water with vinegar, or freeze the dough.

4.1.3.3 Photographic areal sampling

For photographic areal sampling, a photograph is taken of a sediment surface and the size of *all* particles visible on the photograph is measured, either with a ruler or planimetrically (Section 4.1.2.2). Like manual or adhesive samples, particle-size distributions obtained from photographic areal samples need to be converted before comparison with other samples (Sections 4.3.1 and 4.3.2). Photographic techniques for analyzing particle sizes off photographs are described in Section 4.1.2.2. Three different methods of particle-size analysis can be used for photographic areal sampling:

- Measuring the *b*-axes of all particles,
- Planimetric particle-size measurements and analysis (photo sieving), and
- Empirical relation between the number of particles per photograph and a pebble count D_{50} size.

Measuring b-axes of all particles on the photograph

The techniques of *b*-axes measurements with a ruler or an optical particle-size analyzer are discussed in Section 4.1.2.2. However, in contrast to grid samples that measure the *b*-axes of particles under grid points only, *areal* samples measure the *b*-axes of *all* particles visible on the photograph. Measuring all particle *b*-axes provides an *area-by-number* distribution, i.e., the number-frequency of *all* particles contained within the sample area, and this distribution is different from the grid-by-number distribution obtained from photographic grid counts (Section 4.1.2.2). See Section 4.3 for conversion of distributions obtained by different methods of sampling and analysis.

Planimetric particle-size measurements and analysis: Photo sieving

b-axes measurements on photographs with a ruler or an optical particle-size analyzer become relatively inaccurate if particle *b*-axes are partially hidden from view or not parallel to the photographic plane (Section 4.1.2.2). Ibbeken and Schleyer (1986) largely overcame this problem by developing a photographic particle-size analysis that attempts to restore the third dimension of the particle lost in the projection from actual particle to its photographic image. Particle shapes are assumed to be generally ellipsoidal for this technique, and the best-fit ellipsoidal body is fitted into the outline of the particle shape on the digitized photograph. This procedure improves the size determination of particles partially hidden from view or with particle *b*-axes not parallel to the photographic plane.

Computed particle volumes are converted to weight. Since this photographic procedure produces a particle-size analysis in terms of frequency-by-weight similar to a sieving result, it is called photo sieving.

Photo sieving was developed for analyzing the areal surface particle-size distribution of open framework gravel with empty voids between large particles. Ibbeken and Schleyer (1986) used low contrast prints 18 by 24 cm, obtained from 24- by 36-mm negatives taken with a 35-mm camera lens from 2 m above ground. Each photograph covered an area 1.33 by 2 m, and was large enough to identify particles as small as 10 mm.

A flow chart shows the various steps involved in photo sieving (Fig. 4.12). The first step in approximating particle volume is to outline the perimeter of each particle on the photograph using a digitizer connected to a computer. A computer program fits the longest possible axis L into the outlined particle area on the photograph and computes the subaxes S_1 and S_2 that extend at right angles from both sides of L, so that the short axis on the photographed particle is $S = S_1$ and S_2 (Fig. 4.13). An ellipsoidal shape is assumed for all particles. The true particle b- and c-axes are not known, so the projected S-axis is squared. S^2 is close to the product of $b \cdot c$, because S is likely to be smaller than the particle b-axis, but larger than the c-axis. Particle mass m_p is computed from

$$m_p = V_p \cdot \rho_s = \frac{\pi}{6} L \cdot S^2 \cdot \rho_s \qquad (4.1)$$

where V_p is the particle volume, and ρ_s is the particle density.

Ibbeken and Schleyer (1986) used samples from various gravel surfaces to compare photo-sieving results to results obtained from mechanical sieving with square-hole sieves. All surface particles > 20 mm were painted or numbered in situ before a photograph was taken. All painted or numbered particles were picked off the surface before the photo was taken and sieved with a square-hole sieve set. For particles that were fully visible and had compact shapes in the Sneed and Folk form-sphericity diagram (Fig. 2.23, Section 2.2), photo sieving correctly predicted the true particle weight. Photo sieving tended to overpredict the true particle weight when particles were platy and bladed, and underpredicted the true particle weight of particles that were partially hidden on the photograph (Ibbeken and Schleyer 1986). Particles that were allotted to different size classes by photo sieving and mechanical sieving did not have different particle shapes, thus particle shape has no effect on the assigned grain-size class. Consequently, overprediction of the particle frequency of a specific size class is attributed to the effects of particle position (i.e., the angle from which a particle is seen on a photograph). Particle hiding causes an underprediction of the frequency of particle sizes in that size class. However, when analyzing an entire photograph, many of these errors cancel each other.

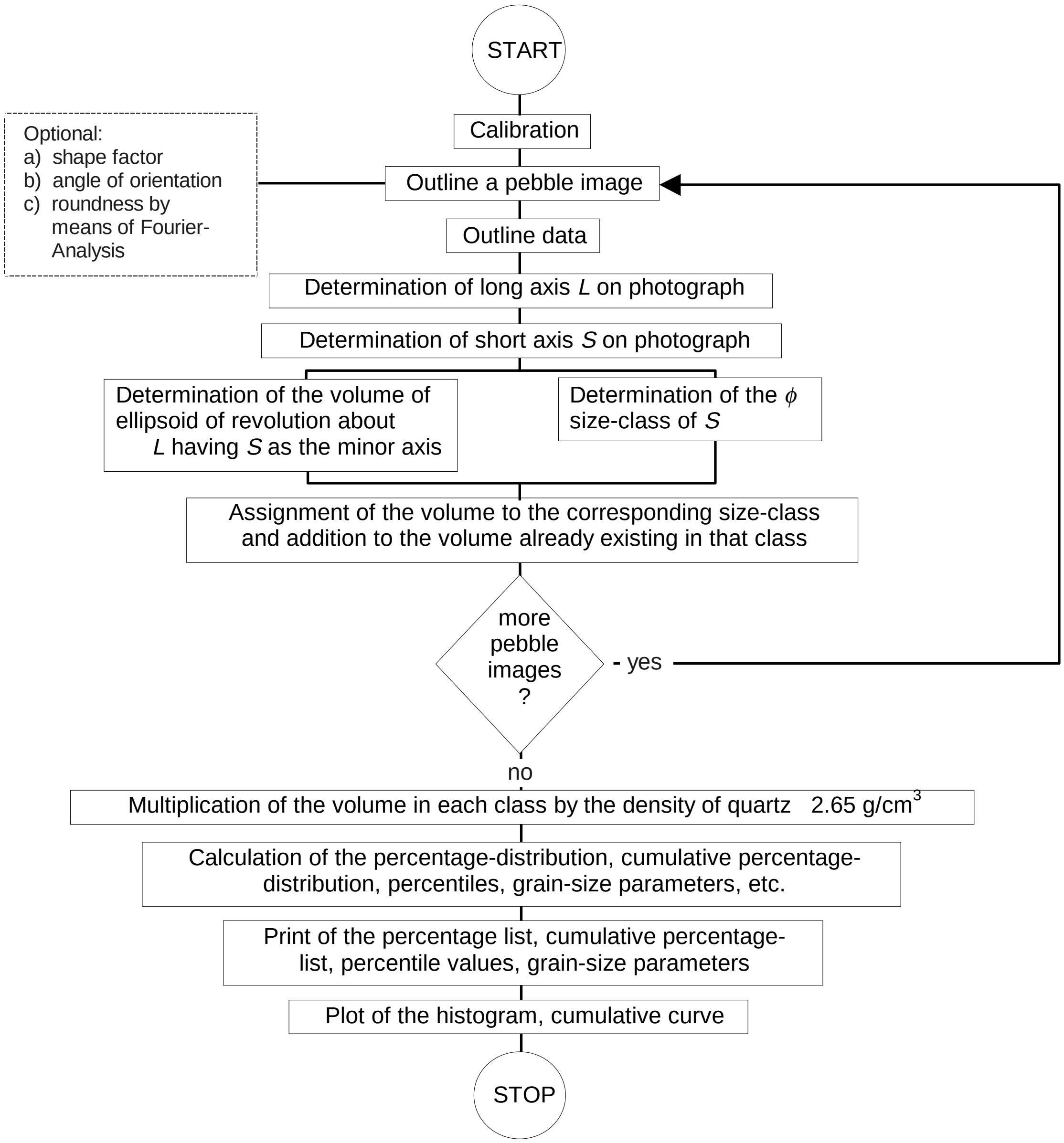


Fig. 4.12: Flow chart for photo sieving analysis. (Redrawn from Ibbeken and Schleyer (1986), by permission of John Wiley and Son. Ltd.).

Fig. 4.13: Axes L, S_1 and S_2 fitted by computer into the outlined and digitized particle shape (a); Computer-fitted ellipsoidal reference particle shape for computation of particle volume (b). (Redrawn from Ibbeken and Schleyer (1986), by permission of John Wiley and Sons, Ltd.).

A comparison between percentile particle sizes obtained from photo sieving and mechanical sieving showed a good correlation between the two sieving methods but did have a systematic bias. Percentile particle sizes obtained from photo sieving were about 0.1 ϕ units coarser than percentile particle sizes obtained from mechanical sieving (only visible particles larger than 20 mm were included in this analysis).

Over- and underprediction of particle weight or frequency per size class can be mitigated in two ways. Particle shape, position, and degree of hiding can be measured in the field and this information may then be incorporated into the algorithm that computes particle volume. Another approach is to develop an empirical factor from a regression function that relates the percentile particle size of both sampling methods to each other. This factor can then be used to fine-tune the correspondence between true particle weight and the weight predicted from photo sieving.

As photo sieving outlines the particle shape and computes particle axes lengths, the procedure can also be used to analyze particle-shape parameters such as roundness, and sphericity. Photo sieving is also suitable to analyze bed-surface structures such as clusters, as well as particle orientation within a rose diagram (Diepenbroek and De Jong 1994). Photo sieving is not well suited for fine sediment (sand and fine gravel) (Harvey 1987), unless photographs are taken from a close distance.

Photographs usable for photo sieving can be obtained from gravel beds deeply submerged by water if an underwater camera is used (Ibbeken and Schleyer 1986). However, photo sieving is not suitable for wadable streams, because taking a usable picture through the water surface is difficult due to reflections on the water surface. A glass-bottom box may be used when the water is deeper than 0.6 m and allows the investigator to photograph an area of about 0.1 m^2 with a camera having a 50-mm lens.

Compared to field sampling and sieving, photo sieving reduces field time substantially and is suitable for beds containing medium gravel, cobbles, and boulders. The effective use of field time in photo sieving allows the study to sample a large number of field sites, and the decision on sampling location and sample size can be made by an experienced person. However, a digitizer is needed for the planimetric analysis of particle shape, and special programs need to be written. Once the system is set up, digitizing the photographs is the only time consuming part of the analysis (approximately 1 hour per photograph covering 1.33 m by 2 m). Fully automated and correct particle recognition is conceivable as the techniques required for improved particle boundary identification (gray scale thresholding, edge growing and particle segmentation) are being developed (Butler et al. 2000).

Counting the number of particles per photograph and conversion to pebble count D_{50}

A simple and fast, but relatively crude way of obtaining information on the bed-material particle size from a photograph is to count the number of particles contained on the photograph. The larger the number of particles (that exceed a preset threshold size) that can be counted, the smaller the particle size of the photographed deposit. For a quantitative analysis, the number of particles on the photograph needs to be calibrated against some field determined particle-size parameter that characterizes the average surface particle size, such as a pebble count D_{50}. The calibration function is then used to predict the D_{50} particle size from the number of particles countable on the photograph.

The counting method avoids any complications posed to photographic particle-size analysis by irregular particle shapes, particle position, and partial burial. Rice (1995) applied this method when analyzing downstream change in particle size over long stream distances. For small streams in the Pacific Northwest, the best fit relationship ($r^2 = 0.99$) between the pebble count D_{50} of particles in the range of 20 - 200 mm and the number of particles n_{ph} contained within a photographed area of 0.25 m^2 was obtained by a logarithmic function:

$$D_{50} = 396 - 62 \ln (n_{ph}), \tag{4.2}$$

The parameters of the function vary with particle embeddedness and particle shape which need to be the same for all photographs. The scatter of the data decreases as particle shape and degree of hiding become more uniform. As many as 30 analyzed photographs may be needed to define the calibration function. Therefore, the counting approach only becomes economical if the study involves a large number of field sites. Results of this photographic analysis are, in principle, comparable to results of pebble counts, because the photographic analysis is calibrated against pebble counts.

4.1.3.4 Photographic (areal) analyses in other scales

Intermediate scales of about 1 m^2 bed-area per print are not the only scale used for photographic analyses. Close-up photographs covering about 0.1 m^2 can be used to analyze detailed sedimentary structures, such as particle packing or the vertical structure of bed material in a photograph of the sediment face. By contrast, areal overviews cover about 100 m^2 and may be useful for analyzing bed-surface structures as well as for streambed monitoring.

Photographic analysis of vertical sediment structure

Fraccarollo and Marion (1993) used photographic areal sampling techniques to analyze the vertical structure of the sediment, such as vertical armor development and infiltration of fines. A container deeper than the armor layer was placed into the bed of a flume and filled with the same material as the bed. It was assumed that the sedimentary structures that develop during a flow event (armoring or infiltration of fines) are the same inside as well as outside the container. After the armor layer development has started, the flow is stopped. The container is retrieved, frozen, and the sediment block is vertically broken in half. The plane of rupture is photographed for a qualitative or quantitative analysis before the two halves are reassembled, and placed back into the original channel-bed location. After the sediment is thawed, the flume experiment can continue. The container is again retrieved for sediment analysis after the armor layer development or the infiltration has progressed further. In this way it is possible to obtain information on the vertical sediment structure during various phases of the armor development during a single flume experiment.

Reach-spanning areal overview

An areal overview of a river reach can be obtained if an auto focus camera with a 32-mm lens is elevated 10 – 15 m above the riverbed surface using a crane, or a helium-filled balloon (Fig. 4.14), (Ergenzinger et al. 1999; Kozlowski and Ergenzinger 1999). The

Fig. 4.14: Areal view of a step-pool reach at the Schmiedlaine, Bavaria (FRG) taken with a 35-mm camera mounted to a tethered helium balloon. Balloon height is about 15 m. Length of surveyor's rod is 3 m. Flow direction is from upper left to lower right. (Photograph courtesy of B. Kozlowski and P. Ergenzinger, Dept. of Physical Geography, Free University of Berlin, Germany).

area covered by one photograph in the format of 1:1.5 is 110 - 160 m^2 (about 9 by 12 m to 11 by 15 m). The smallest particles distinguishable on such photographs are cobbles of about 100 mm in diameter. Besides an analysis of cobble and boulder particle sizes, and of bed surface structures, areal views provide a good opportunity to monitor change within a river reach. This can be a change in the bank line, change in patterns of scour and fill, the displacement of individually marked large particles, or change in the size of the area covered by gravel-sized and finer particles. Church et al. (1998) used elevations of about 30 m to analyze bed surface structures such as stone cells. Their photographs had a resolution of about 150 mm.

Areal overviews should be taken with ample lateral overlap to account for lateral distortion, as well as for the fact that the exact position of the photographed area cannot be determined before the photograph is taken. Unfortunately, particles submerged by flow are poorly or not at all visible, unless the water depth is very shallow, or light conditions are ideal. Thus, areal view photographs are restricted to analyses of the dry portions of the streambed.

Summary and evaluation of photographic methods

- Photographic methods facilitate non-destructive sampling of the bed.

- Photographic methods minimize field time.

- Photographic methods can be conducted at any spatial scale by changing the camera height. Close-up photographs are used to evaluate small sedimentary structures (particle packing and orientation), while photographs covering about 1 m^2 in size are used for bed-material particle-size analysis. Areal overviews that cover an entire reach are used to analyze large bed-surface structures or to monitor streambed change (4.1.3.4). This makes photographic methods a versatile tool for analysis of bed-material structures, documentation, monitoring, and historical records.

- Photographic methods can be applied to obtain information on surface particle sizes in the form of grid counts (Section 4.1.2.2), as areal samples (Section 4.1.3.3) and as a relation between the number of particles on the photograph and a pebble count D_{50}.

- Photographic analysis through the water surface is usually impossible, but underwater photography can be used when the water depth exceeds about 2 m.

- Photographic analysis often requires field calibration. Photographic measurements of particle *b*-axes tend to underestimate ruler-measured *b*-axes in the field because partially buried or hidden particle axes cannot be measured in their full length on photographs.

- The photo-sieving method (Ibbeken and Schleyer 1986) improves the accuracy of photographic particle-size measurements in deposits with partially hidden particles and when the *b*-axis plane is not parallel to the photographic plane.

- Photo sieving tends to overpredict the weight of angular, platy and bladed particles, and to underpredict the weight of partially hidden particles. Both errors tend to cancel each other when analyzing large streambed areas.

4.1.3.5 Visual particle-size estimates

The fastest way to assess the local particle-size distribution is a visual particle-size estimate. Several different techniques have been used for visual estimates.

Percentage of surface area covered by particles of various size classes

Fisheries studies often estimate the percent area covered by particles of various size classes. The size classes used for this analysis are usually larger than the 0.5 ϕ-size classes. Platts et al. (1983), for example, differentiated between larger boulders (> 610 mm), small boulders (> 305 mm), cobbles (> 76 mm), gravel (> 4.8 mm), large fines (> 0.83 mm), and small fines (< 0.83 mm). A dominant size class was assigned to each 1-foot section along a transect by visually estimating the particle-size class that covers the largest proportion within that one-foot long section. The estimation process is aided by visually arranging the particles of different size classes within the 1-foot section into strips and estimating the strip length for each size class. The dominant size classes along the transects are summed and expressed as percentages of the stream width.

Visual particle-size estimates require operator training and skill, and untrained operators can easily introduce a bias. Trained operators can be quite proficient and accurate (Shirazi and Seim 1981) in estimating bed-material sizes, particularly for bed material within the gravel range (Platts et al. 1983). By contrast, Kondolf and Li (1992) found that visual estimates as described above tend to overemphasize the frequency of fine gravel if the deposit consists mainly of fine gravel. Similarly, visual estimates overemphasize the frequency of coarse particles in deposits that consist mainly of coarse gravel. Thus, visual estimates described above seem to have their best use for reconnaissance sampling, such as when walking the stream to become familiar with the stream site, or for a delineation of streambed areas with similar bed-material size (patches) that are subsequently sampled by more stringent methods. Visual estimates are probably not the right tool for monitoring bed-material size, as that requires detecting small changes in particle size over time or space.

Estimate of particle percentile size

Visual estimates are also used for delineating areas of homogeneous particle sizes (patches or facies) when using a spatially segregated sampling scheme (Lisle and Madej 1992; Lisle and Hilton 1998, pers. comm.) (Section 6.3.2.1). For this purpose, particle sizes of one (e.g., D_{75}) or two percentiles (e.g., D_{50} and D_{90}) are visually estimated and facies types are differentiated based on the particle percentile size.

Estimate of percentage of three main particle-size classes with further specification of the major size class

Buffington and Montgomery (1999a) devised a two-level visual particle-size classification that refers to both the mean particle size and the sorting when distinguishing between different facies. The method is statistically meaningful in that deposits with statistically similar pebble counts were also visually identified as the same facies, whereas deposits with statistically different pebble counts also had different visually identified facies.

Level 1 of the visual classification procedure estimates the relative abundance of the three main constituents of a particle-size distribution. A gravel bed, for example, may be comprised of the three major constituents of sand, gravel, and cobbles. Their percentages may be 10% sand, 60% gravel, 30% cobble. This composition classifies the facies as **s**andy, **c**obbly **G**ravel, abbreviated as **scG**. Gravel is the primary constituent, cobbles the secondary, and sand the tertiary. Similarly, a bed comprising 50% **G**ravel, 30% **c**obble and 20% **b**oulders is a **b**ouldery, **c**obbly **Gr**avel facies, abbreviated to **bcG**.

The appropriate facies terminology can also be derived by plotting the frequency of the three major constituents in a triaxial diagram, or ternary. The appropriate facies terminology is obtained from the name of the field onto which data are plotted. Fig. 4.15 (top) is an example of a triaxial diagram for deposits that have sand, gravel, and cobbles as their major constituents. For facies with other major constituents, the user must rename the corner points. Copies of the spare template in Fig. 4.15 (center), or commercially available triaxial graph paper can be used for this purpose. Plotting is not necessarily required for determining the appropriate terminology of a deposit, but is recommended to aid in the grouping process. The fields outlined in Fig. 4.15 are somewhat arbitrary, and can be changed if sediment from a facies delineated in the stream plots in a cluster and falls onto the border of two neighboring facies types on the triaxial diagram. The circled group of data points in Fig. 4.15 (top), for example, plots on the border of a gsC and a sgC facies. A more appropriate characterization for this cobble facies might be a relative abundance of more than 50% cobbles, less than 30% gravel, and 15-30% sand.

A Level 2 classification further distinguishes the subsize of the major constituent that had been described in broad terms only in the Level 1 classification. For example, the composition of the cobble size in a cobble facies can be specified according to the percent frequency of very coarse (180 - 256 mm), coarse (128 - 180 mm), and medium (90 - 128 mm) cobbles. If the visual estimate determined 25% very coarse, 12% coarse, and 62% medium sized cobbles, the cobble portion of that deposit classifies as **c**oarse, **v**ery **c**oarse, **m**edium cobbles, abbreviated as C_{cvcm} (Fig. 4.15, bottom). Similarly, for a Level 2 classification of relatively fine gravel, the corner points of a triaxial diagram need to be termed very fine, fine, and medium. The unlabeled diagram can be used for this purpose.

Although not specified by the authors, the Level 2 classification could probably be applied not only to the major constituent, but to the secondary, or tertiary constituent instead, if those particle sizes were of most concern for the study.

Buffington and Montgomery (1999a) found that an increase in the number of fields per triangular diagram did not significantly improve the accuracy of the visual method. Adding the Level 2 analysis to the Level 1 analysis, however, greatly improved the ability of the visual analysis to identify statistically similar particle-size distributions.

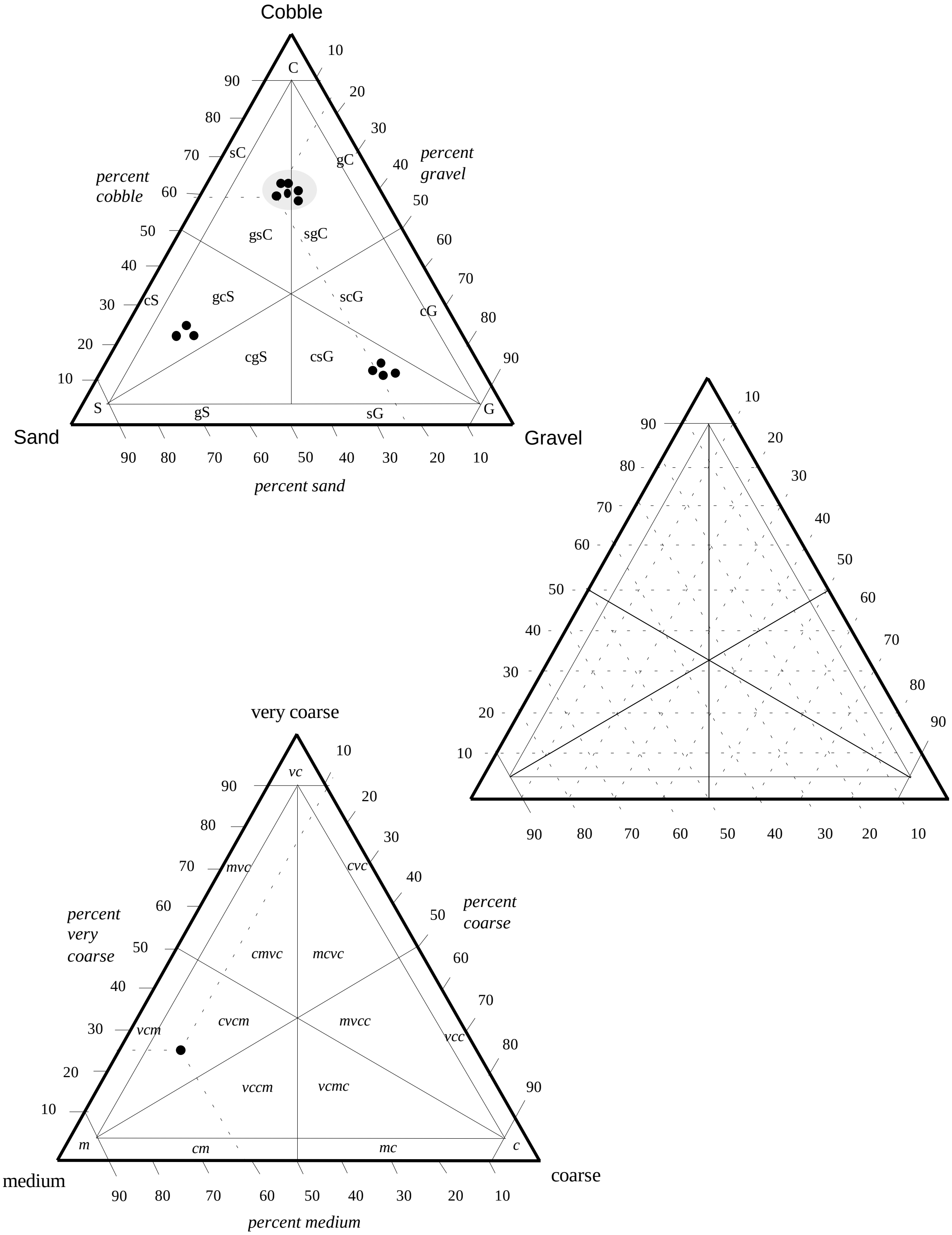


Fig. 4.15: Example triangular diagram for Level 1 classification: visually estimated percent frequency of the major three constituents of a deposit (top); Triangular diagram for user-specified use (center); Example triangular diagram for Level 2 classification: visually estimated percent frequency of the three major size breaks within a size class (bottom). (Slightly modified from Buffington and Mongomery (1999a), by permission of the American Geophysical Union).

4.2 Volumetric sampling

Volumetric samples extract a *predefined volume, or mass* of sediment from the bed. Volumetric samples are three-dimensional and may be taken from various strata of the sediment column: the armor layer, the subarmor and subsurface sediment, and the unstratified bulk sediment (Fig. 4.1). The surface sediment, which has two-dimensional properties, cannot be sampled volumetrically.

4.2.1 Armor layer

4.2.1.1 Definition and description

Several mechanisms have been proposed to explain the cause of surface coarsening and the development of an armor layer (Fig. 4.1). These include winnowing of surface fines, selective deposition of large particles, and increased availability of coarse surface particles as part of equal mobility transport (Section 3.3.1.2). A difference between the particle-size distribution of surface and subsurface layer can also be caused by an infiltration of fines into an open framework subsurface sediment (Section 3.3.1.1). Armor layers are poorly developed in streams with high sediment supply or in well sorted sediment.

Samples of the armor layer are used to characterize the streambed for many purposes including streambed monitoring and sediment transport analysis. The degree of armoring can be determined by comparing the particle-size distribution or the D_{50} of the armor layer with the D_{50} particle size of the subarmor sediment. The larger the ratio, the larger the degree of armoring. A change in the degree of armoring is used as an indication of a change in sediment supply or in flow regime.

The armor layer is three-dimensional and can only be sampled volumetrically. By contrast, an areal surface sample is two-dimensional. It collects only surface particles (Section 4.1.3), and cannot be used to describe the armor layer. In the presence of a coarse armor layer, volumetric armor-layer samples and areal surface samples describe different particle populations, and thus have different particle-size distributions. The particle-size distributions of volumetric armor-layer samples and areal surface-samples are even different in non-stratified deposits, and both distributions cannot be compared without prior application of an appropriate conversion factor (Section 4.3.1 and 4.3.2).

4.2.1.2 Thickness and sampling depth of the armor layer

The thickness of the armor layer is commonly described as extending from the bed-surface plane down to the bottom side of the largest (D_{max}) or a frequently occurring large surface particle size (D_{dom}) (Fig. 4.1). A sample of the armor layer should extend over the entire thickness of the armor layer. If the sample is not sufficiently deep, it misses the fine particles under the coarse surface particles and produces a size distribution that is too coarse. An armor-layer sample that extends too deeply into the bed includes subsurface sediment which is finer than the armor layer and thus produces a sample that is too fine.

In order to sample the strata accurately, the thickness of the armor and subarmor layer needs to be known. One possible way to obtain this information is to dig a pilot pit and examine the vertical extent of the respective strata. This approach is a labor and time intensive undertaking and is impeded by the fact that the thickness of sedimentary layers is spatially variable, which would require multiple pits. In order to avoid this procedure (which should not be completely dismissed), and considering the fact that the thickness of the armor- and subarmor-layer increases with the general coarseness of the surface sediment, several suggestions have been proposed to predict the thickness of the armor layer. All procedures are based on some characteristic of large surface particles. Armor thickness is approximated by:

- the *c*-axis of the D_{max} particle of the surface (Ettema 1984),
- the *b*-axis of the D_{max} particle size (Diplas 1992 a);
- 2 times the *b*-axis of the D_{90} surface particle size (Simons and Sentürk 1992, p.654),
- the embedded depth of the reach-average D_{dom} particle size (Winema National Forest (1998), and
- the embedded depth of the local D_{max} particle size.

The five prediction criteria listed above result in different armor-layer depths when applied to the same deposit. This is demonstrated in Fig. 4.16. Assume a deposit from a coarse gravel or cobble-bed stream with a D_{max} particle size of 200 mm, and a D_{dom} of 150 mm which is about equal to the D_{90} particle size. All particles are ellipsoidal in shape. The *a*-axis of embedded particles is inclined by an angle of 45° and particles are embedded with approximately 80% of their volume.

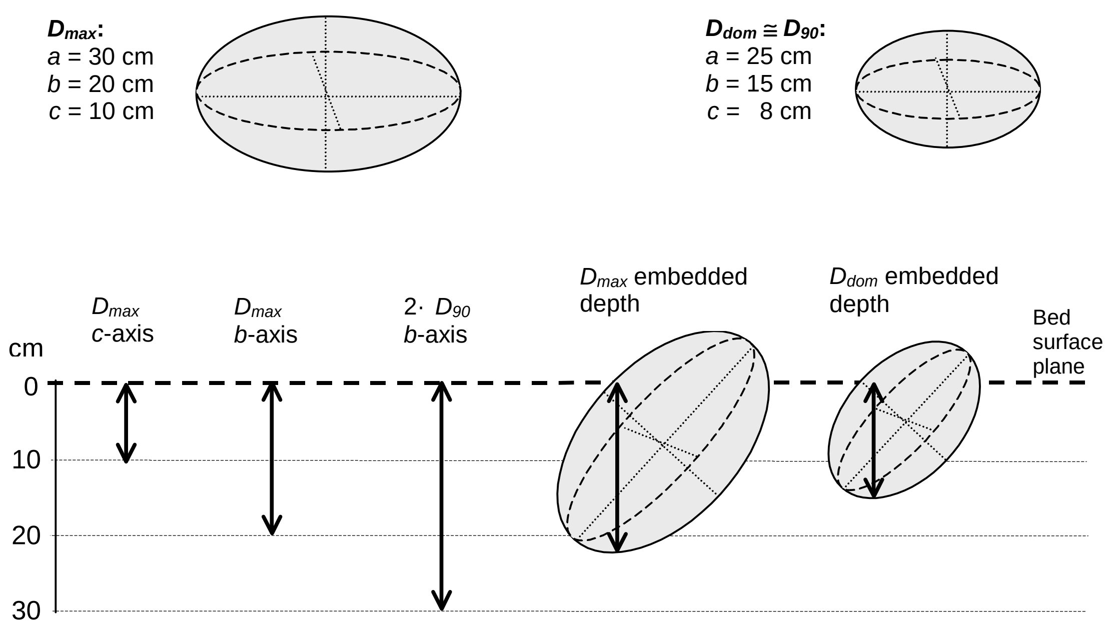


Fig. 4.16: Differences in armor-layer thickness determined for the same deposit using various prediction criteria.

The embedded depth D_e is the vertical depth to which the bottom side of a large particle (D_{max} or D_{dom}) extends downward into the channel bed (Figs. 3.21a and 4.17). Its exact extent depends on particle position and shape. A particle in a near horizontal position typical of disc-shaped particles does not extend deeply into the bed, and in this case, embedded depth is equivalent to the *c*-axis of a large particle and determines a relatively thin armor-layer sampling depth. By contrast, a particle in a vertical position extends deeply into the bed, particularly if the particle has an elongated shape. In this case, the embedded depth and the predicted armor layer thickness is equal to the particle *a*-axis.

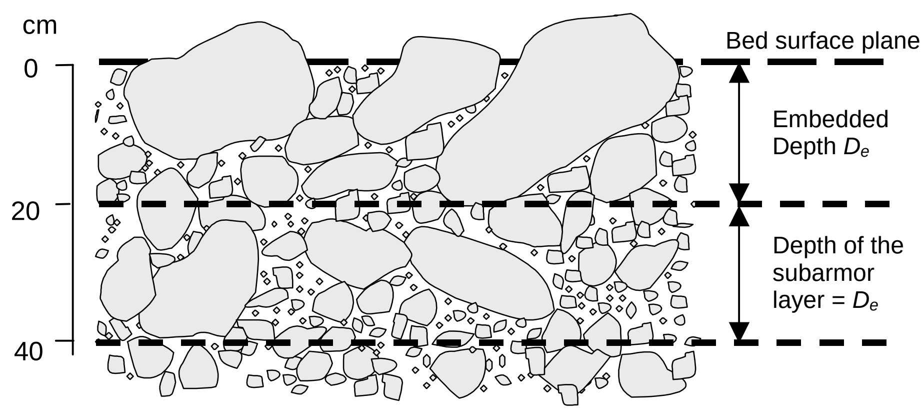


Fig. 4.17: Sampling depth of armor layer and subarmor layer adjusted to the embedded depth of a large particle (D_{max} or D_{dom}). (Figure courtesy of Winema National Forest, Klamath Falls, OR; slightly altered).

Specific stream situations and study objectives might require case-specific criteria for determining the armor-layer sampling depth. The embedded depth of the D_{max} particle is only representative of the armor layer thickness, if the D_{max} particle is involved in fluvial transport (in large but relative frequent floods). In this case, the armor layer depth may be determined based on the D_{max} particle size within the sampling area.

If D_{max} particles are too large to be involved in fluvial transport, the armor-layer depth should be predicted from large particles more representative of the reach and the bedload transporting flow regime. A possibility is the mean dominant large particle size D_{dom} which is a reach-averaged measure of large particle sizes and determined as the mean *b*- or *c*-axis measured on about 30 large, but not the largest, particles. D_{dom} could also be substituted by a large particle-size percentile, e.g., the D_{90}.

The criterion of 2 times the D_{90} particle size *b*-axis length also predicts a relatively thick armor layer. Sampling the armor layer to a large depth risks including subarmor sediment in the armor sample. Mixing armor and subarmor sediment should be avoided when comparing the sediment size of the two strata because contamination makes a difference between the armor and subarmor layer less detectable. The mean *b*-axis size of D_{dom} within the sedimentary unit of concern, or the D_{dom} embedded depth, seems to be an appropriate criterion for determining the sampling depth if armor- and subarmor layers are to be compared. Some large particles may reach farther into the bed than the embedded depth of D_{dom}. These particles should be included in the armor layer sample.

If the study objective is to characterize the armor layer within a sedimentary unit (facies), all samples within that unit should be collected to the same depth, since an equal sampling depth allows one to combine or compare individual armor-layer samples. For a comparison of armor-layer samples between sedimentary units, or to determine the area-weighted average armor-particle size for a larger reach, armor layers should be sampled to the depth appropriate for each of the sedimentary units within the reach. This discussion shows that the sampling depth for the armor layer cannot be easily expressed by a general equation. A reasonable armor-layer sampling depth must be determined for each study objective and should be identified in the field. This is best accomplished with a pit dug in a dry bed.

Surface coarsening: ratio of pebble count D_{50} to the D_{50} of a volumetric subsurface or subarmor sample

An armor-layer sample may not be required to determine the degree of armoring. The degree of armoring may be quantified by collecting a surface pebble count and a volumetric subsurface sample instead. Taking a surface pebble count instead of a volumetric armor layer sample for this analysis has several advantages. A pebble count circumvents the problems of defining and sampling the appropriate armor-layer depth. Besides, the size distribution of the armor layer and the bed surface are directly related. Another advantage is the spatial flexibly. A pebble count can be laid out to span a few m^2 or hundreds of m^2. A volumetric armor-layer sample covers a small area only and requires taking multiple samples to cover the reach. Collecting numerous volumetric samples with a sufficiently large total sample mass and the ensuing sieve analysis makes armor-layer sampling considerably more labor and time intensive than pebble counts. A caveat of this substitution is that the assumed equality between the size distribution of a pebble count and a volumetric sample may not be warranted in every situation.

4.2.2 Subsurface, subarmor, and unstratified bed material

4.2.2.1 Definition and description

Subsurface sediment is the sediment under the streambed surface, and subarmor is the sediment under the armor layer (Fig. 4.1). Subsurface and subarmor sediments are usually finer than surface or armor sediments, respectively, unless the stream is aggrading or has received a veneer of surface fines. Particle-size distributions of subsurface and subarmor sediments are basically the same, thus the term subsurface is often applied to both subsurface and subarmor sediments. The subsurface sediment size is controlled by the supply of fine sediment to the stream, by a lack of winnowing flows, and by local hydraulics that favor deposition of fines.

In order to sample subsurface or subarmor sediment, the overlying surface sediment or armor layer, respectively, first needs to be removed. This can be performed by taking an areal surface sample that exposes subsurface particles, or by a volumetric armor-layer sample that exposes the subarmor layer. The overlying sediment needs to be removed entirely in order to prevent contamination of the subsurface or subarmor sediments by surface or armor sediments. Thus, Church et al. (1987) suggest removal of the armor layer to the bottom side of the largest particle in the sample area. Thorough removal of the armor layer (Section 4.2.1.2) is an easier technique than removing all surface particles by taking an areal sample (4.1.3.1 and 4.1.3.2).

Subsurface or subarmor sediments should be sampled to at least the same thickness as the armor-layer thickness, and possibly to a somewhat larger thickness to compensate for the usually conic shape of the excavation hole. This suggestion implies that there is no lower border to the subsurface or subarmor sediment limiting the thickness. Subsurface sediment can be limited in its thickness in recently aggraded stream locations where a thin layer of sediment was deposited on top of a former surface with a different particle-size distribution.

Unstratified bed-material samples

Unstratified volumetric samples of the bed material include both armor and subarmor, or surface and subsurface sediments, respectively. Unstratified bed-material samples are useful only when the bed material is either non-stratified, i.e., non-armored and no veneer of surface fines, or when stratification is negligible or of no concern for the study result.

4.2.2.2 Sampling depth to avoid bias against large particles

The sampling depth of unstratified deposits does not usually have a lower boundary. This offers the opportunity to take a sample sufficiently deep to avoid bias against large particle sizes. The three criteria presented below can be used to compute sample depth

Cobble surfaces: 2 D_{max}

For coarse beds with a D_{max} in the cobble range, Diplas and Fripp (1992) and Simons and Sentürk (1992) suggest that volumetric sampling of unstratified sediment should extend to a minimum depth (d_{Smin}) of 2 D_{max}, e.g., to 36 cm for a D_{max} of 180 mm (Fig. 4.18).

$$d_{Smin} = 2\,D_{max} \tag{4.3}$$

Using 0.5 ϕ sieve classes, the value of 2 D_{max} (i.e., the size class of the D_{max} particle) is equal to or slightly smaller than the common multiple of the largest two sieve sizes, which are also the common multiple of all other smaller sieve sizes (Fig. 4.19). For example, the sampling depth of 2 D_{max} = 16 mm computed for a D_{max} particle size of 8 mm equals 2 · 8 mm, and is close to 3 · 5.67 mm. Similarly, 16 equals 4 · 4 mm which is close to 5 · 3.36 mm, 6 · 2.8 mm, and 7 · 2.38 mm. Thus, if an idealized deposit with a

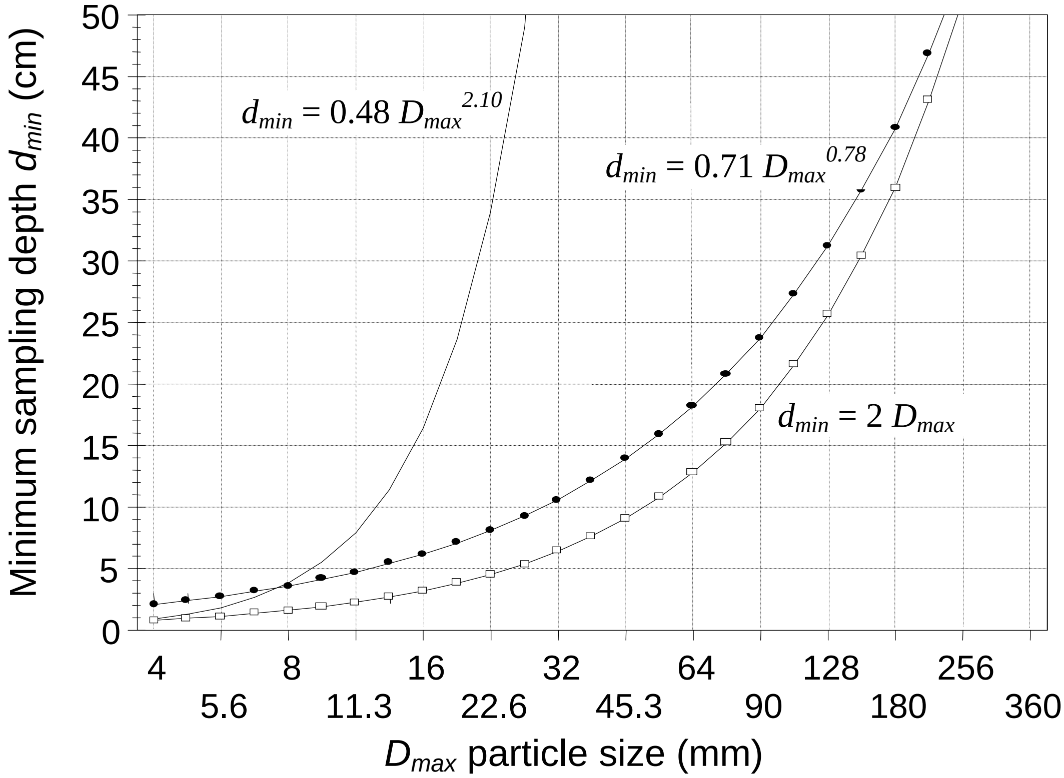


Fig. 4.18: Three functions to calculate minimum sampling depth d_{Smin} (in cm) from the D_{max} particle size (in mm).

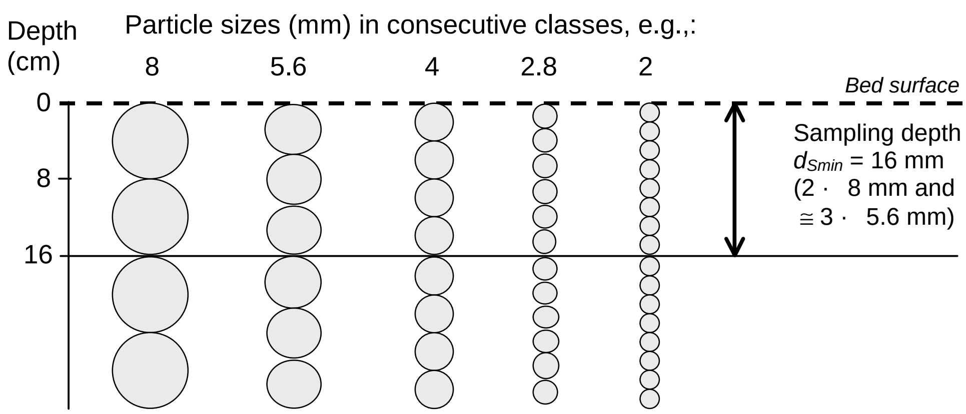


Fig. 4.19: Idealized sediment deposit showing the minimum sampling depth for volumetric samples. (Redrawn from Diplas and Fripp (1992), by permission of the American Society of Civil Engineers).

systematic packing of spheres is assumed (Fig. 4.19), a sampling depth of 2 D_{max} would representatively include large particles. However, a sampling depth of 2 D_{max} may not guarantee that large particles in natural deposits are representatively included in the sample. A bias against large particles appears as particle shapes become more elongated, and as particle orientation approaches the vertical, i.e., *a*-axes are at a right angle to the bed surface.

Lowest common multiple of the largest two sieve sizes

To avoid the bias against large particles in volumetric bulk samples, Diplas and Fripp (1991, 1992) proposed computing the minimum sampling depth as the lowest common multiple of the integer value of the largest two size classes. For example, the two sieve sizes of 4.8 and 6.7 mm (ϕ= -2.25 and ϕ=-2.75) are rounded down to 4 and 6 mm. Their lowest common multiple is computed from $4 = 2 \cdot 2$, and $6 = 2 \cdot 3$, and results in $2 \cdot 2 \cdot 3 =$ 12 mm. For the two size classes 5.67 and 4 mm, the lowest common multiple is 20, and 88 for the two size classes of 11.3 and 8 mm. The lowest common multiples increase steeply with increasing D_{max} particle size, but the data points scatter. The best fit power regression function fitted to the values expresses the relationship between minimum sampling depth d_{Smin} and D_{max} as

$$d_{Smin} = 0.48\, D_{max}^{\;2.10} \tag{4.4}$$

with d_{Smin} in cm and D_{max} in mm (Fig. 4.18). Eq. 4.4 is not designed for use in coarse gravel and cobble beds. The ratio between the computed d_{Smin} and D_{max} increases strongly with increasing D_{max} particle size. For fine gravel with a D_{max} of 4 mm, Eq. 4.4 computes a d_{Smin} of 8 mm (i.e., 2 D_{max}). For a D_{max} of 64 mm Eq. 4.4 computes a d_{Smin} of about 3 m, a sampling depth that is 47 times larger than the D_{max}.

Variable multiples of D_{max}

Sampling depths computed with Eq. 4.4 become disproportionately and unmanageably large for medium and large gravel, whereas the sampling depth for fine gravel is manageably small. In order to increase sampling depth for small particles, but maintain a feasible sampling depth for large particles, the authors suggest computing sampling depths as variable multiples of D_{max}. The depth can be set to exceed D_{max} by a factor of 2 for cobbles, such as in Eq. 4.3., but be allowed to increase for finer beds. For example, factors of 2, 3, 4, and 5 might be assigned to particle sizes of 256, 64, 16 and 4 mm. A power regression function expresses this criterion for sample depth as

$$d_{Smin} = 0.71\, D_{max}^{\;0.78} \tag{4.5}$$

with d_{Smin} in cm, and D_{max} in mm (Fig. 4.18).

4.2.3 Procedures and sampling dimensions for dry beds

Sampling bed material in dry beds has the advantage that no special sampling equipment is needed. Also, problems arising from sampling under water do not need to be considered (e.g., poor visual control, slumping walls in the sampling pit, potential for losing fines, working with your hands in cold water). Thus, bed material should generally be sampled during lowest flows when much of the bed is exposed.

However, the relative ease of volumetric bed-material sampling under dry conditions should not be abused by selecting only dry locations when sampling in partially inundated streambeds. Dry streambed areas are most likely bars, and particle sizes on bars, both surface and the subsurface, tend to be finer than bed material in other parts of the streambed. Thus, unless the study objective focuses on the investigation of bars, representative sampling for characterizing a reach requires sampling all areas of the reach, wet and dry (see sampling schemes, Sections 6.4 and 6.5).

4.2.3.1 Tools for shoveled samples

A sturdy shovel often suffices as a tool for sampling bed material on dry beds. A pick, or a pry bar can be useful to pry lose cobbles and boulders. A trowel is handy for separating armor and subarmor sediment and for working in finer gravel. A metal bowl is convenient for scooping sediment out of a narrow pit.

The sampling area should to be outlined by a frame, preferably one that is round and adjustable, e.g., lawn edging. The walls of the pit should remain as straight as possible because a conic-shaped hole has different proportions of sediment from the top and the bottom of the pit. The advantage of shoveled samples is that they do not limit the sample size, as freeze-cores or pipe samplers do (Sections 4.2.4.8 and 4.2.4.5). In addition, a shovel is relatively inexpensive and easy to use and to transport.

If samples from dry and inundated locations are to be compared, the same technique should be used for both locations to prevent a methodological bias between samples. Sampling procedures and equipment used for volumetric sampling under water (Section 4.2.4) are generally usable for dry conditions as well.

4.2.3.2 Sample dimensions for shoveled samples in unstratified bed material

Volumetric samples must have a predefined sample volume. This volume is determined from sample-mass criteria. Some of the sample mass criteria are empirically based and compute sample mass as a function of the D_{max} particle size (Section 5.4.1), whereas others are analytically based and determine sample mass on the basis of a preset precision for a sediment deposit of a given coarseness and sediment sorting (Sections 5.4.2 and 5.4.3). Sampling dry beds has the advantage that the dimensions of the sampling pit can be made sufficiently large to match the appropriate sample volume and sample depth, i.e., sampling equipment does not pose a limitation on sample size.

Minimum sample mass and volume

Sections 5.4.1 and 5.4.2 discus a variety of sample-mass equations from which the user can choose. The discussion below uses a simple function that determines sample mass for particles with a D_{max} > 32 mm by

$$m = (2.87 \cdot D_{max} - 44.8) \qquad (4.6)$$

where sample mass m is in kg and D_{max} in mm. Eq. 4.6 is plotted in Fig. 4.20 and derived from the three sample mass criteria proposed by Church et al. (1987) for bed material of different D_{max} particle sizes (Section 5.4.1.1). Sample volume is obtained by multiplying

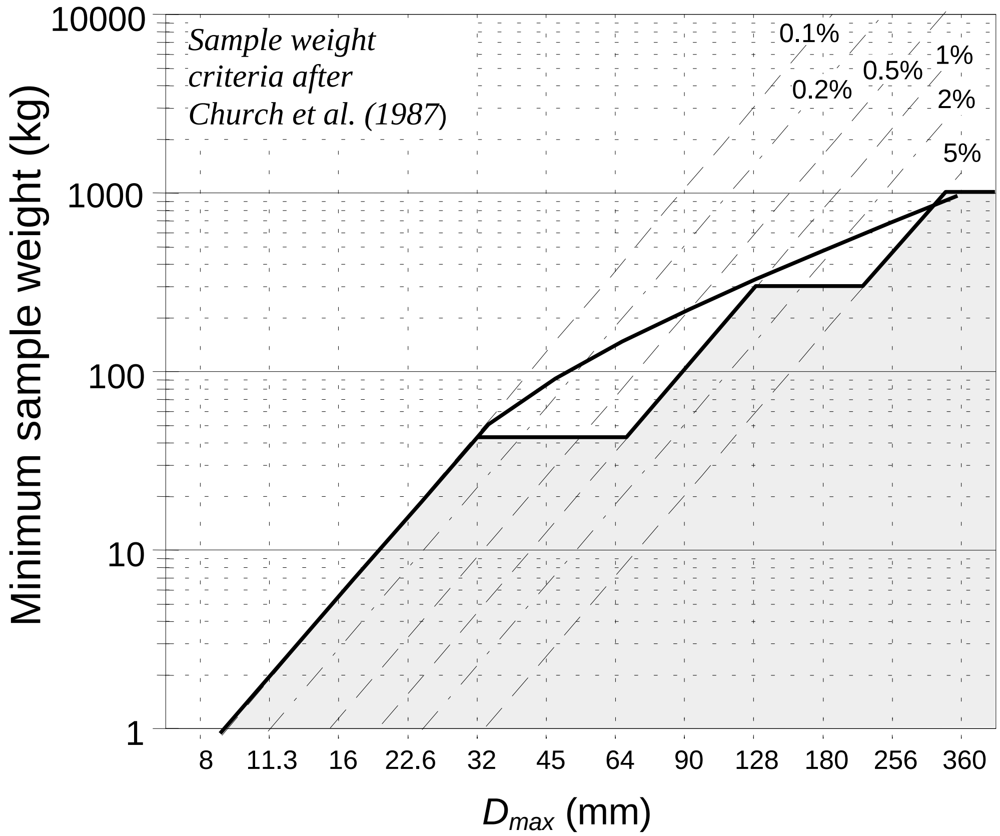


Fig. 4.20: Minimum sample weight for sediment with different D_{max} sizes (D_{max} = 0.1% m for a D_{max} <32 mm, D_{max} = 1% m for a D_{max} <128 mm, and D_{max} = 5% m for D_{max} > 128 mm) (after Church et al. 1987). The thick line represents a linear regression function fitted through the "corner points" of the stair-case function derived from the three sample-mass criteria by Church et al. (1987).

sample mass and sediment bulk density. Bulk density for shoveled gravelly sediment is approximately 1.500 kg/m^3, while *in situ* bulk density may range between 1.700 and 2.600 kg/m^3 (Section 2.4).

Minimum sample dimensions
Once minimum sample mass and volume, as well as an appropriate sampling depth (Section 4.2.2.2) are determined, the quotient of volume to depth provides an estimate of the areal extent of the sample. This area can be allotted to a circle which should have a diameter at least as large as the sampling depth to ensure representative sampling of large particles.

The example below can be used to visualize the size of the pit required for sampling in medium and coarse gravel beds.

> <u>Example 4.1:</u>
> Sample mass for a deposit with a D_{max} of 45 mm is about 84 kg (Eq. 4.6). Tightly packed, this mass is about 42,000 cm^3 or 4.2 household pails in volume if a bulk density of about 2 g/cm^3 is assumed. Sampling depth for a deposit with a D_{max} of 45 mm is 9 cm (Eq. 4.3, 2 D_{max}), or 14 cm (Eq. 4.5, variable multiples of D_{max}). Eq. 4.4 (common multiple method) is not applicable to particles larger than 22 mm because it computes unreasonably large sampling depths (Fig. 4.18). A sampling depth of 9 cm (2 D_{max}) requires a round pit with a diameter of 77 cm. For a sampling depth of 14 cm, the pit has to be 60 cm in diameter.
>
> In a coarse gravel-bed river with a D_{max} particle size of 180 mm, sampling depth is 36 cm (Eq. 4.3), or 40 cm (Eq. 4.5). Taking the average of 38 cm, the sample volume of 236,000 cm^3 (about 24 household pails) requires a pit of 89 cm in diameter. The user might consider allocating the required sample volume to several smaller pits excavated at several sampling sites (Wolcott and Church 1991; Rood and Church 1994 (Section 6.4.4).

A calculation analogous to the one above can be used to compute the areal extent for volumetric armor-layer samples.

<u>4.2.3.3 Surface pebble count on subsurface sediment</u>

Based on the equivalence of particle-size distributions determined from volume-by-weight and grid-by-number samples proposed by Kellerhals and Bray (1971) on non-stratified deposits (see Section 4.3.1), Buffington (1996) developed a technique that uses pebble counts to sample the subsurface sediment. The first step of the procedure is to remove surface particles by hand from an area of about 1 m^2 in order to expose the subsurface sediment. Sand and fine gravel particles which often accumulate just below the surface are usually not completely removed by manual picking of surface particles (Section 4.1.3.1) and would produce a sample that is biased towards fines. In order to prevent this potential bias, these fines are mixed into the subsurface sediment prior to sampling. The depth of mixing should be slightly deeper than the sampling depth that would be required for a volumetric sample, which depends on the D_{max} particle size and the number of samples taken. Mixing to the depth of one shovel blade length is a practical criterion. The necessity for mixing becomes apparent by Buffington's test analyses: without mixing, only 2 out of 5 of the subsurface pebble counts corresponded ($\alpha = 0.05$) to a volume-by-weight analysis of samples of the same sediment. The mixing procedure produced a statistical correspondence between subsurface pebble counts and volume-by-weight analyses in 4 of 5 samples.

Buffington (1996) suggested that particles included in the pebble count should be selected at random by pointing at a particle with a pencil tip, eyes averted. Bias against fines or large particles is probably not much of a concern under these circumstances (Sections 4.1.1.2 - 4.1.1.6). However, an operator kneeling or crouching besides the pit may involuntarily favor the center or some other easily reached part of the sampling area, thus introducing a spatial bias. A sampling frame that covers the 1 m^2 surface with a small-scale grid of 10 by 10 cm or smaller (Section 4.1.1.6) can be used in the absence of cobbles and ensures that particles are sampled systematically from the entire sample area.

Another concern regarding this method is that an area of 1 m^2 might not provide ample space to collect a sufficient number of particles in coarse bed material without counting some particles twice. Counting 400 particles is required to determine the particle sizes of the D_{50} and D_{95} to within about 0.1 - 0.15 ϕ-units, and the D_5 to within about 0.3 ϕ-units (Rice and Church 1996b, Section 5.2.2.3) in a deposit with a standard deviation of 1.17 ϕ. If the spacing between grid points equals the D_{max} particle size, and the D_{max} particle size is 180 mm, the sampling area needs to be 13 m^2 (400 D_{max}^2) which may be met with a square 3.6 by 3.6 m in size. A sampling area of 1 m^2 can accommodate a 100 particle count if the D_{max} particle size is 100 mm, or a 400 particle count if the D_{max} particle size is 50 mm. Thus, several pits may have to be sampled in order to obtain enough sampling points for a representative pebble count on subsurface sediment that contains cobbles.

4.2.4 Procedures and equipment for submerged conditions

Although dry gravel bars are convenient for volumetric sampling, samples need to be taken from all parts of the streambed for a reach-averaged analysis of sediment size, or from riffles for tasks such as an analysis of fish spawning habitats, or the ratio of surface to subsurface particle size. Thus, armor, subsurface, and unstratified volumetric samples frequently have to be obtained under water. Several procedures and equipment for taking volumetric samples under water are described below. These include:

- shovels, scoops and clams,
- pipe and McNeil samplers,
- barrel samplers,
- freeze-core samplers and resin cores, and
- hybrid pipe freeze-core samplers.

An extensive comparison of various sampling procedures for unstratified bed material is summarized by Ramos (1996). His literature review compares equipment needed, the sampling procedure, advantages and disadvantages, as well as a description of the accuracy and precision expected from five sampling devices: single probe, and multiprobe freeze-cores, McNeil samplers, shovels, and the hybrid pipe-freeze-core sampler. Not all samplers are equally well suited for a specified study objective. The user needs to select a sampling procedure appropriate for the particular bed-material characteristics, sample-size requirements, and the remoteness of the site.

In addition to taking samples under submerged conditions, volumetric bed-material sampling in mountain gravel-bed rivers has to overcome several other problems:

- Armoring is usually well developed, in which case many study objectives require stratification of the bed material into surface and subsurface or armor and subarmor,
- Stream-bed particle sizes that range from silt and boulders are difficult to sample with one method,
- Large sample sizes of 100 kg and more are required for representative particle-size analysis, and
- Fast flow velocities that wash away fines dislodged when the bed is disturbed by the sampling process.

Most procedures for underwater volumetric sampling employ sampling devices that have fixed sample volumes. The volume of one sample may be much smaller than what is required for the total sample mass. Because of this, several subsamples may need to be combined to obtain the required total sample mass (Sections 6.4.4; Wolcott and Church 1991; Rood and Church 1994).

4.2.4.1 Shovels

When sampling subsurface sediment under water, the operator needs to ensure that fine sediment remains in the sample and is not swept away by the flow. A shovel sample taken from the riverbed under water loses these fines and causes an unrepresentative sample that is biased against fines. The loss of fines increases with the increasing velocity of flow. Billi and Paris (1992) and Billi (1994) caution against using shovels in submerged conditions, unless the water is still, and an underwater storage box with a mesh-bag cover is available for depositing the sampled sediment.

Comparison of shovel methods with the McNeil sampler

Schuett-Hames et al. (1996) compared the results of three methods of collecting shoveled samples with results obtained with the McNeil sampler (Section 4.2.4.5), a sampler that is commonly used on beds of fine and medium gravel. The three shovel methods used were a standard shovel, a standard shovel used within a stilling well that shields the sampling site from moving flow, and a special shovel with elevated sides to minimize the loss of fine sediment over the sides of the shovel. Paired samples were taken with the McNeil sampler and one of the shovel methods at several riffles on two streams with relatively fine gravel beds. Sampling protocols were followed carefully, and the data were analyzed by several statistical tests.

At one of the streams, samples taken with a standard shovel within a stilling well and with a McNeil sampler produced similar geometric mean particle sizes and a similar percent fines (particles less than 0.85 mm). The other two shovel methods had 2.9 - 4.7 % less fines than the McNeil sampler, and geometric mean particle sizes were on average 20% larger. This suggests that a standard shovel used within a stilling well can be a suitable alternative to the McNeil sampler. Shovels and a stilling well are convenient to use in the field and have the advantage of providing a larger sample mass than the McNeil sampler.

All of the shovel methods produced a similar percent of coarse sand (0.85 - 2 mm) as did the McNeil sampler. But only the McNeil sampler collected sediment less than 0.1 mm (fine sand and silt) representatively. Material of this size is transported in suspension when the bed is disturbed during sampling. Regression functions between methods had low coefficients of determination and could not be used to predict the observed discrepancies in the percent of sediment finer than 0.85 mm or in the geometric mean particle sizes.

In the other stream, all shovel methods produced geometric means that were coarser by 9 - 18 % than the geometric means produced by the McNeil sampler, and had a slightly higher percentage of fines. Water depth and flow velocity in the two streams could not explain the difference in the results between the two streams. However, pooled data from both streams indicated a significant relation between the percentage of sediment larger than 3.35 mm and the difference in the percent fines between any shovel method and the McNeil sampler. Shovel methods produced less percent fines than the McNeil sampler in streambeds with more than 70% coarse sediment, and more percent fines than the McNeil sampler in streambeds with less than 70% coarse sediment.

Differences in the percent fines between the McNeil sampler and various shovel sampling methods appear to be the product of streambed characteristics, and further analysis of this dependency is necessary. However, sampling methods should be consistent within a study, particularly if results are to be compared over time or among locations.

4.2.4.2 Mesh-bag scoop

A mesh-bag scoop is a useful tool for sampling armor and subarmor sediment in streambeds consisting mostly of sand and fine gravel (Forest Service, Klamath Falls, OR, pers. communication). A mesh-bag scoop has a metal frame that is of the same dimensions as the back side of a 3 by 3 inch Helley-Smith bedload sampler (20.3 by 12.1 cm). The frame is constructed of V-profiles, so that a standard Helley-Smith sampling bag (0.25 mm mesh width) can be slipped into the notch of the profile. A handle is attached to the top of the metal frame (Fig. 4.21).

The mesh-bag scoop may be used in conjunction with a stilling well or a plywood shield that encloses three sides of a sampling area 0.6 by 0.6 m in size (Section 4.2.4.7). The mesh-bag scoop is especially useful when sampling armor layer and subarmor sediments in fine-grained beds. After the armor layer depth is determined, the mesh-bag scoop is pulled through the bed material along the lower border of the armor layer, scraping the armor layer sediment into the mesh bag. With the free hand, the operator ensures that dislodged armor layer particles are not pushed to the side, but enter the sampler.

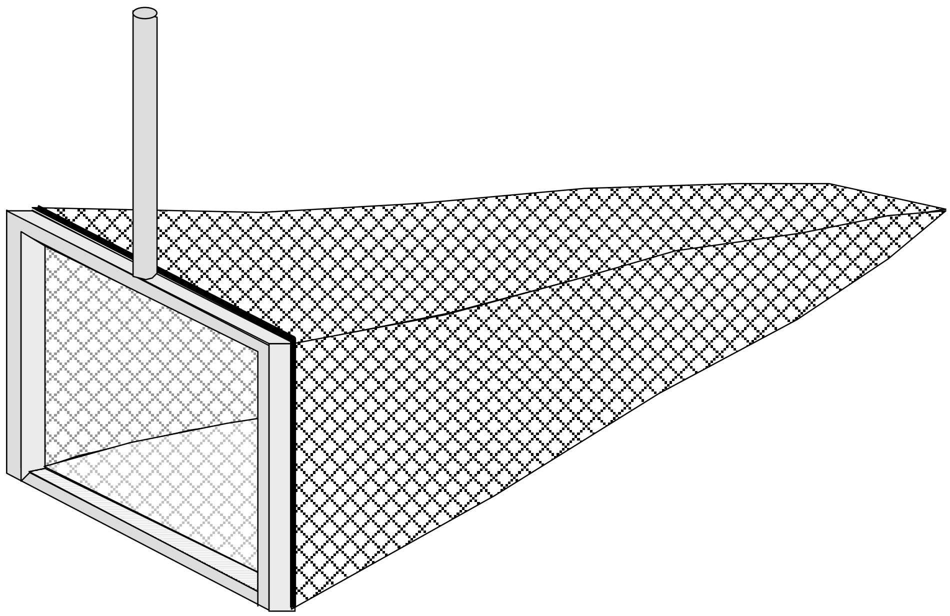


Fig. 4.21: Mesh-bag scoop with attached Helley-Smith sampling bag for sampling armor layer and subarmor sediment in fine and medium gravel-bed streams.

Sampling patterns follow parallel paths to ensure that the sampling area is sampled entirely, and that no places are sampled twice. The sampled sediment in the mesh bag is frequently emptied into a bucket. After all the armor layer sediment is removed, the mesh-bag scoop can be used to collect the subsurface sample. This sampling method works well in streambeds with predominantly fine gravel and produces about 1 - 2 household pails of armor layer sediment. However, this method has not yet been validated by peer review.

4.2.4.3 Grab samples (US RBMH-80)

A grab sampler collects as much sediment as can be held in the jaws of the sampling device. Fines are retained if the jaws close properly. Grab samplers have been developed for sand-bedded streams, but can be used in beds of fine gravel as well, provided no gravel particles become wedged in the jaws and inhibit the closing mechanism. The newest grab sampler developed by the Federal Interagency

Sedimentation Project[4] is the hand held rotary scoop sampler US RBMH-80 (Fig. 4.22). An older version of this sampler is described in Edwards and Glysson (1988). A cylindrical bucket 20 cm wide houses the rotary scoop. The bucket is mounted at the end of a rod. The total length of the sampler 1.42 m.

The sampler can be operated under water in wadable streams. To obtain a sample, the opened sampler is placed onto the streambed and firmly held down. A wire mechanism, operated by a lever, opens and closes the rotary scoop. The sampler can collect approximately 175 cm^3 of unstratified bed material, from a maximum depth of 4.5 cm. After the sample is collected, the sampler is lifted from the bed, and the sample is emptied into a bucket.

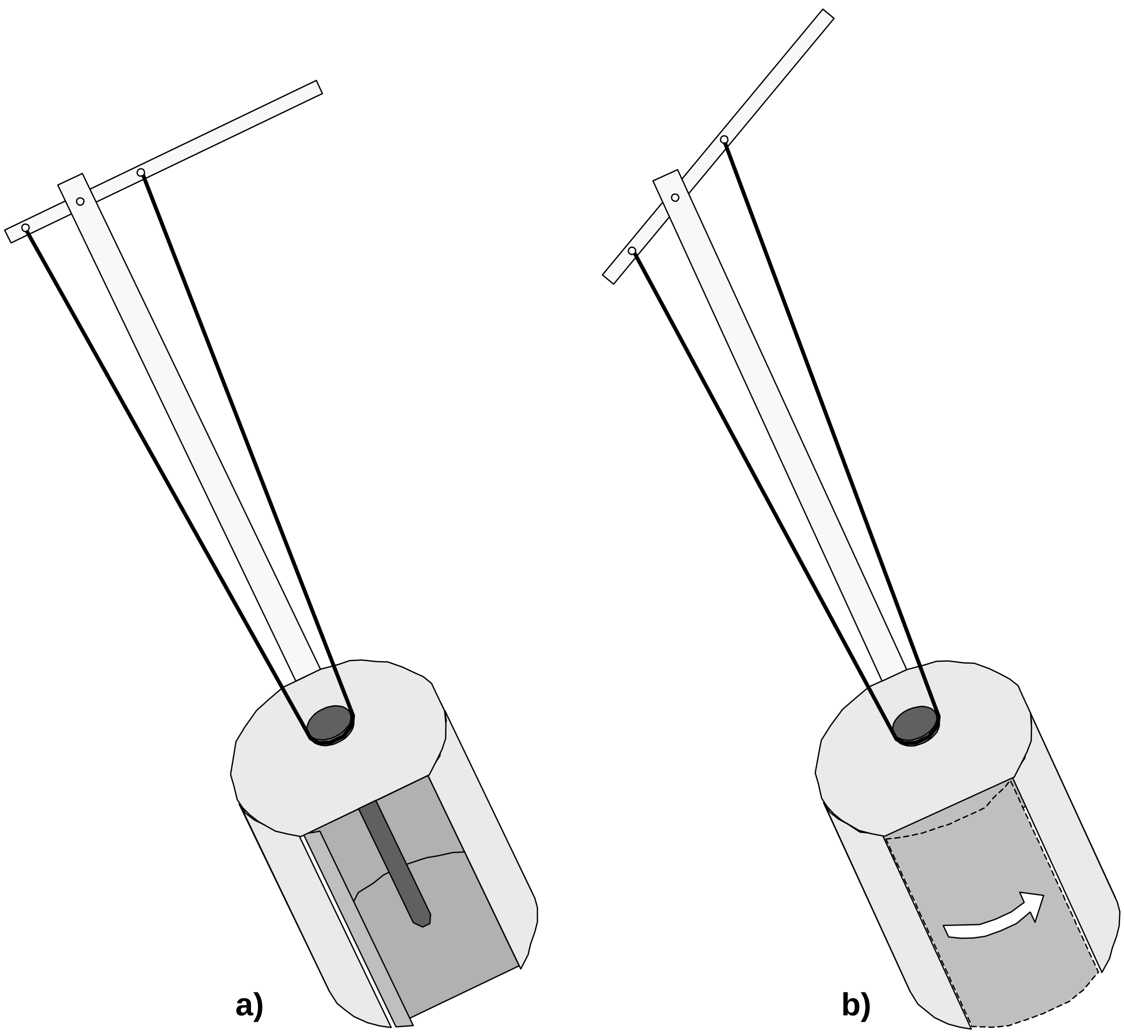


Fig. 4.22: Schematic diagram of US RBMH-80 hand-held, rotary-scoop bed material sampler developed by the Federal Interagency Sedimentation Project. a) Rotary scoop open; b) Rotary scoop closed.

[4] *The US RBMH-80 sample can be viewed and ordered from the Federal Interagency Sedimentation Project web site* *http://fisp.wes.army.mil/.*

The advantage of the rotary-scoop sampler is that a large number of samples can easily be taken over the entire sampling area, which may be a facies patch or a relatively homogeneous reach of the stream. Samples can then be commingled for a composite analysis (Sections 6.4.4; Wolcott and Church 1991; Rood and Church 1994). The disadvantage is that the sampler is not suitable for large gravel, and that the sampler may not close properly and will lose its fines if a pebble becomes lodged in the mechanism.

4.2.4.4 Backhoe

In wide alluvial gravel-bed rivers where bed material is mobilized during one or several flood events annually and tread damage is of little concern, a backhoe can be an efficient tool for sampling large amounts of unstratified sediment. However, in small and often incised mountain gravel-bed streams, backhoes may damage riparian areas and should be used with great care. Also, when digging into an inundated streambed with a backhoe, fines are likely to be washed away and will be underrepresented in the sample. However, backhoes and boom trucks parked on a bridge with the shovel (bucket) lowered to the stream can be helpful for lifting equipment and heavy sediment samples collected by other means from the streambed.

4.2.4.5 Pipe samplers and the McNeil sampler

Pipe samplers and the McNeil sampler (McNeil and Ahnell 1964) were developed for fish habitat studies primarily concerned with the amount of fine sediment in spawning gravels. Pipe and McNeil samplers have also been used to monitor the amount of fines for cumulative watershed effects analyses. Depending on the fish species of concern, or the size of fine sediment supplied to the stream from watershed disturbances, the term “fines” can refer to any particle size between fine sand (< 0.1 mm) to pea-sized gravel (< 8 mm). Therefore, the term fines needs to be specified in a given study.

Pipe and McNeil samplers consist of a stainless steel pipe 0.1 – 0.2 m in diameter that extends through the bottom of a cylinder with a diameter 2 - 3 times larger than that of the inner pipe (Fig. 4.23 a-c). Designs of pipe and McNeil samplers vary in the diameters of the inner and the outer pipe, and in the angle at which the outer pipe attaches to the inner pipe. These differences should not affect sampling performance. However, when bed-material particle sizes approach the dimensions of the sampler opening i.e., the inner pipe, the physical size of the sampler may artificially truncate the sampled particle-size distribution. Thus, the sampler opening should be large enough to easily accommodate the largest particles to be sampled. An opening size of 2 D_{max} is suggested.

Pipe and McNeil samplers are designed for wadable flows with depths of less than 0.5 m and relatively slow flow velocities. The end of the small pipe is worked into the submerged river bed, usually to a depth of about 15 cm. The sediment inside the pipe is excavated by hand and temporarily stored in the built-in storage basin. The water inside the large pipe may contain fine sediment brought into suspension during sampling. This fine sediment may be sampled by swirling the water within the sampler and taking a suspended sediment sample for lab analysis (Fig. 4.23 a and b). To retain nearly all of the fine-grained bed-material for analysis, the inside opening of the small pipe is capped before the sampler is removed from the streambed (Fig. 4.23 c). The quantity of suspended sediment can be determined directly in the field using an Imhoff cone. Failure to sample or retain the fines may significantly underestimate their presence in the substrate.

Separating surface or armor sediment from subsurface or subarmor sediment may be somewhat difficult when using pipe or McNeil samplers with small sampler openings. This is particularly true if the sampler is used underwater and the differentiation between strata has to be accomplished by feel alone. Therefore, pipe and McNeil samplers are usually used to collect an unstratified volumetric sample. The percent fines is then determined for the unstratified sample. Note that the percent fines in an unstratified sample is smaller than the percent fines in a subsurface sample. This is because the unstratified sample contains more large particles (i.e., those from the surface) than the subsurface sediment. The difference between the percent fines of the unstratified sediment and the subsurface sediment may be largely eliminated if the sample is truncated at a commonly occurring large particle size before the percent fines is computed.

Sample mass collected by McNeil samplers varies with sampler dimensions, but commonly ranges between 6 and 15 kg (Rood and Church 1994). Such sample sizes are small when the stream contains large gravel, and require taking several samples if a particle-size analysis is to be obtained for particles larger than 35 to 48 mm according to the 1% criterion by Church et al. (1987) (Section 5.4.1.1). A 0.2-m diameter McNeil sampler can be used for determining the percent fines if cobbles (coarser than 64 mm) are discarded. Discarding particles larger than some preset size is also suggested by Rice (1995) as a means to decrease the effect of large particles on the computed percent fines. Truncation improves the comparability of the percent fines between samples provided the selected truncation size is equal for all samples included in the comparison.

Pipe and McNeil samplers can be fabricated in various dimensions to best suit a particular stream-bed situation. Pipe samplers are relatively quick and easy to use, and are light enough to be transported to remote areas. However, Rood and Church (1994) caution that it takes considerable operator skill to representatively sample the fine sediment collected by the McNeil sampler. Evaluations of how representative results from McNeil samplers are with respect to fine sediment vary among studies. NCASI (1986) found that the McNeil sampler minimizes the loss of fines, but Rood and Church (1994) caution that the sampler underrepresents the fine sediment in the sample. Further information on sampling results of pipe and McNeil samplers are summarized by Ramos (1996) who compared samples of the McNeil sampler with freeze-core and other samplers. Schuett-Hames et al. (1996) compared samples from the McNeil sampler to samples obtained by various shovels (Section 4.2.4.1).

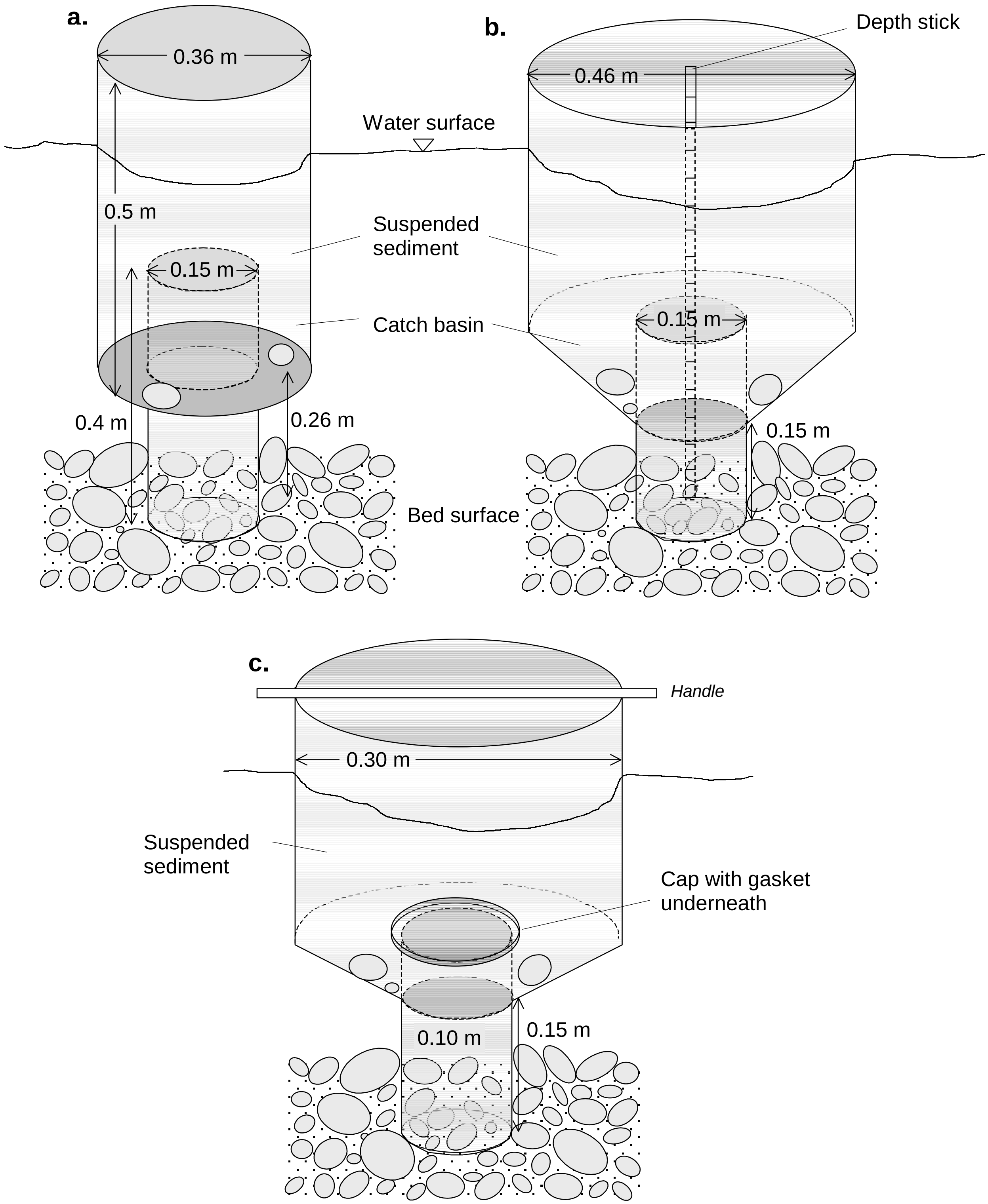


Fig. 4.23 a - c: Pipe and McNeil samplers: (a) Pipe sampler. Adapted from Yuzyk (1986); (b) McNeil sampler. Adapted from Hamilton and Bergersen (1984), source: Shepard and Graham (1983); (c) McNeil sampler. Adapted from Hogan et al. (1993), source: McNeil and Ahnell (1964).

4.2.4.6 Barrel samplers

Barrel samplers were developed specifically to accommodate the tasks and problems of collecting volumetric bed-material samples in gravel-bed rivers. Because of their large size, barrel samplers allow sampling over a wide range of particle sizes, and relatively large sample volumes. Barrel samplers retain suspended fines that can be sampled separately, and can be used under submerged conditions. Two different barrel samplers are described below.

Cookie-cutter sampler

The "cookie-cutter" or gravel-cutter sampler was developed by Klingeman and Emmett (1982) for use in coarse gravel- and cobble bed streams. The cookie-cutter sampler has an opening large enough to sample cobbles and small boulders, and facilitates large sample sizes that can better represent the percentage of gravel and cobbles than samples from the smaller pipe and McNeil samplers. The cookie-cutter sampler consists of an open 55-gallon drum that is cut in half. The resulting cylinder is about 0.4 m high and 0.5 m in diameter (Fig. 4.24). Two operators are required to use this device. The barrel is fitted with handles. Teeth are cut into the bottom of the barrel so that it can be worked a few cm into the streambed. When the sampler is used in shallow water that does not overtop the barrel, armor- and later subarmor-layer sediment is scooped out of the barrel and poured into buckets. Under submerged conditions, the sampled sediment is temporarily stored in a rectangular sample box that attaches to the barrel and is held by one of the operators. The sample box is 0.7 m long by 0.3 m high by 0.4 m wide. One end of the sample box is open, the other end has a fine mesh wire of 0.2 mm to retain

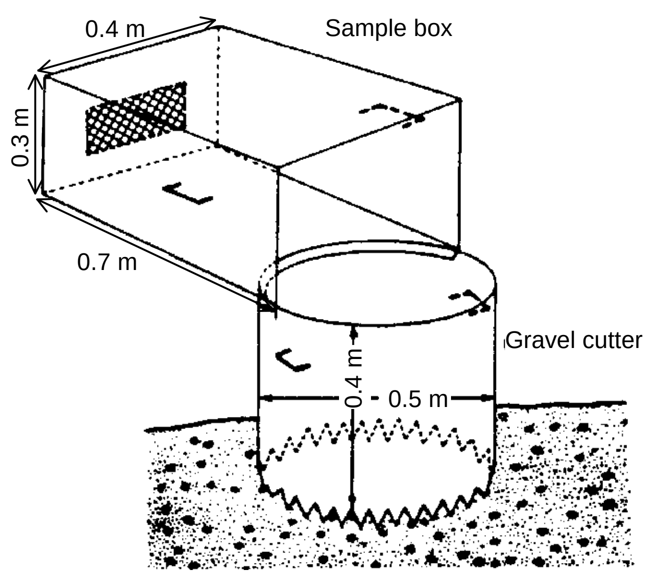


Fig. 4.24: Cookie-cutter sampler developed by Klingeman and Emmett (1982). (Reprinted from Yuzyk (1986)).

fines. The sample box is placed on the downstream side of the sampler so that the current that flows through the sample box carries the fines into the box. After sampling, the sample box is lifted out of the water and emptied. The gravel-cutter sampler can be used in deep, unwadable water if divers and a support boat are used.

CSU barrel sampler

The CSU-barrel sampler developed by Hogan et al. (1993) and Milhous et al. (1995) is a simplified alternative to the cookie-cutter sampler. To prevent the loss of suspended fines, the CSU-barrel sampler uses a taller barrel than the cookie-cutter sampler. The CSU sampler is 0.6 cm high and 0.46 m in diameter, made from a 30-gallon drum that is cut open on both ends (Fig. 4.25).

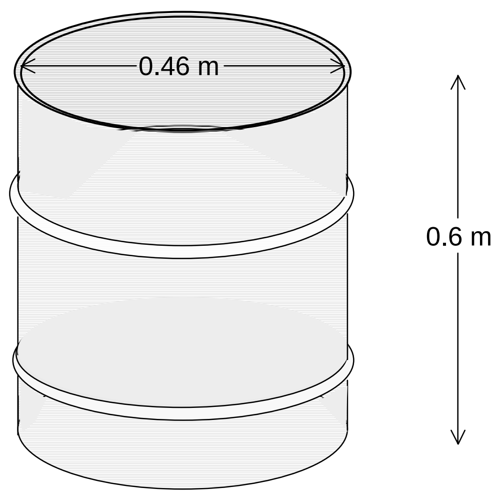


Fig. 4.25: CSU barrel sampler.

At the selected sampling location, the barrel is slightly inserted into the bed material. For a subsurface sample, surface particles must be removed first. For this task, the operator has to rely mainly on feeling the particles, because visibility on the barrel bottom is poor primarily due to suspended fines. Distinguishing between surface and subsurface particles by feel is difficult in cold water when neoprene gloves are needed. Working systematically from one side to the other helps ensure that no large surface particles are overlooked. However, small surface particles cannot be removed representatively. Also, it is not possible to distinguish between surface and armor layer when using the barrel sampler in coarse gravel beds. Particles that are under the edge of the barrel are always removed, but only included in the sample if more than half of the particle volume protrudes into the barrel. Removing surface particles from under the edge of the barrel allows the barrel to be moved deeper into the bed.

After the surface particles have been removed, the subsurface is sampled by collecting all particles within the barrel until the pit has reached a predefined depth. Particles are picked by hand, or scooped with small trowels and bowls, and put into large buckets (Fig. 4.26) that are held by an assistant who also hauls filled buckets back to the bank. An old screwdriver may be needed to pry loose large particles that are wedged in the bed.

Suspended particles (fine sand and silt) can be sampled by swirling the water around in the barrel and then taking a suspended sediment sample. To retain fines even under completely submerged conditions in chest deep water, a cloth hood can be secured over the top of the barrel. The operator wears a diving mask and a snorkel and reaches the sediment in the bottom of the barrel through a slit in the cloth.

Compared to freeze-core samplers, barrel samplers provide a low-tech method for sampling unstratified subsurface sediment under submerged conditions in gravel-bed rivers. Barrel samplers are inexpensive and relatively easy to use. The comparatively large dimension of barrel samplers provides a sample mass of about 60 - 70 kg per barrel, and makes barrel samplers suitable for cobble beds. The disadvantage of the barrel sampler is that it is difficult to carry over long distances and therefore not suitable for use at remote sites. Tall barrel samplers are also difficult to use by small persons, particularly in deep flow.

Fig. 4.26: Taking a barrel sample, South Fork Cache la Poudre Creek, Colorado. (Photograph by K. Bunte).

4.2.4.7 Three-sided plywood shield

Armor and subarmor layer in submerged conditions can be sampled more effectively and more comfortably for the operator if the sample area is enclosed by a three-sided plywood shield. The operator collects the sample from the open downstream side. The enclosure consists of three plywood sheets, each 0.6 by 0.9 m or 0.9 by 0.9 m in size, that are joined on their long sides by piano hinges. The plywood shield has a tarpaulin skirt along the outside. The tarpaulin is fastened near the bottom of the plywood sheets and extends about 0.5 m beyond the plywood (Fig. 4.27). This sampling device was developed by the Winema National Forest, Klamath Falls, OR.

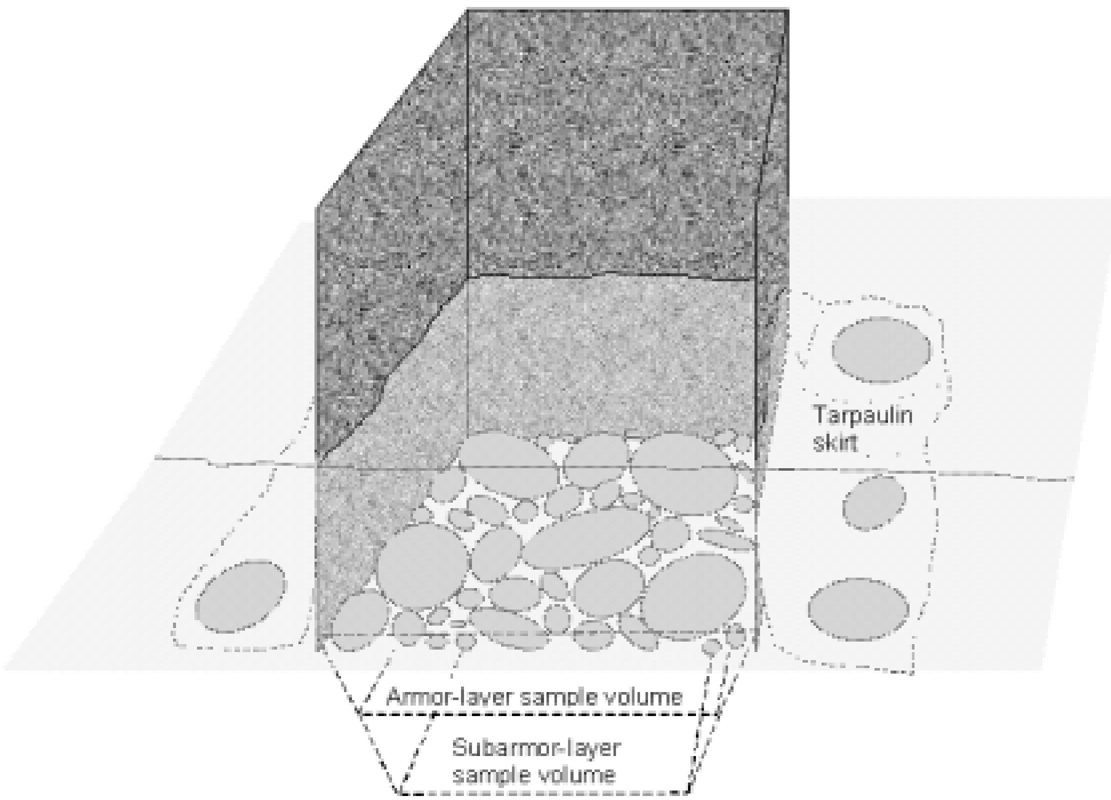


Fig. 4.27: Plywood shield to provide a three-sided enclosure of the sampling area.

Set-up of the plywood shield requires two persons. The plywood shield is unfolded and set at the appropriate location on the streambed, the open side facing downstream. The bottom side of the plywood is shoved slightly into the bed. The skirt is spread along the outside of the shield and rocks are placed along the edge of the skirt to hold it down. The set-up should be performed quickly to minimize the water flow through openings below the plywood enclosure or through the hinge area as it may scour fines from the bed. Any leaks should be minimized by squeezing rocks, rags, and plastic shopping bags into openings until the water inside the plywood shield is relatively stagnant.

The operator wears chest waders and while kneeling or crouching at the open side, removes the armor layer to a predetermined depth. In coarse gravel- and cobble-bed streams, the operator collects the armor-layer material using a trowel and a medium-sized metal bowl (approximately 1 liter capacity), and perhaps a pry bar to pry lose particles that are wedged into the bed. A mesh-bag scoop (Section 4.2.4.2) is a suitable tool for collecting armor-layer sediment in fine and medium gravel beds. The nearly stagnant water within the shielded sampling area minimizes the amount of fines swept out of the sampling area. All collected sediment is saved in buckets. After the armor layer is removed, the subarmor layer is sampled to a predetermined depth.

Working with the plywood enclosure has two advantages: it improves the access for the operator while sampling and provides a larger sampling area (0.36 – 0.81 m^2) than a barrel (0.14 – 0.20 m^2). An armor-layer sample in a coarse gravel or cobble-bed stream may yield 70 – 130 kg depending on the sampling depth. If the subarmor sample is sampled to the same thickness as the armor-layer sample, the sample mass is smaller due to the conic shape of the excavation and may yield 40 – 80 kg. Thus, if the study objective is solely the subarmor sediment, a thin armor layer should be removed in order to increase the amount of subarmor sediment that can be sampled. Even though sample mass of an individual sample from within the plywood shield is larger than that obtained with any other sampling method, several samples are needed to obtain a total sample mass that is sufficient for a statistically meaningful particle-size analysis (Section 5.4).

4.2.4.8 Freeze-cores

Freeze-core samplers collect all particles that are frozen to one or several hollow rods pounded into the streambed. The sample extends from the surface into the subsurface and leaves the stratification intact.

Freeze-core sampling was developed for aquatic habitat studies for which the distinction between surface and subsurface sediment size and the percentage of fine sediment is important. The advantage of freeze-core samples is that the bed-material stratification is visible in the sample. Also, freeze-cores can be collected in flows deeper and faster than those appropriate for McNeil and pipe samplers. Freeze-core sampling is discussed by Walcotten (1973, 1976), Adams and Beschta (1980), Everest et al. (1980), Lotspeich and Reid (1980), Carling and Reader (1981, 1982), Platts et al. (1983), Thomas and Rand (1991), Young et al. (1991), Thoms (1992), Hogan et al. (1993), Rood and Church (1994), and Milhous et al. (1995).

A single-tube freeze-core sampler consists of a pointed hollow rod with a 2 cm inside diameter. The rod is driven approximately 0.2 m into the streambed. A cooling agent, such as liquid nitrogen or liquid carbon dioxide, is injected into the rod and escapes through a series of nozzles at the lower end so that the pore water in the sediment adjacent to the rod freezes (Fig. 4.28). The size of the frozen core depends on the amount of cooling agent used, the temperature of the streambed, the velocity of the stream flow, the pore water movement, and the pore space. The frozen core is then dug out or extracted by a hoist and thawed for particle analysis. Typically, freeze-cores are 0.1 – 0.15 m in diameter and weigh about 1 - 5 kg. Sample mass can be increased to 10 - 15 kg if liquid nitrogen is used as the cooling agent (Rood and Church 1994). The sediment stratigraphy remains intact when the frozen core is retrieved, and, if the core is thawed over a slotted box (Fig. 4.29 b), the stratigraphy can be analyzed incrementally. Problems with freeze-core sampling stem from the difficulty of pounding a rod into a streambed, disruption of the bed stratification due to pounding, the extensive amount of equipment, and the cost (several thousand dollars).

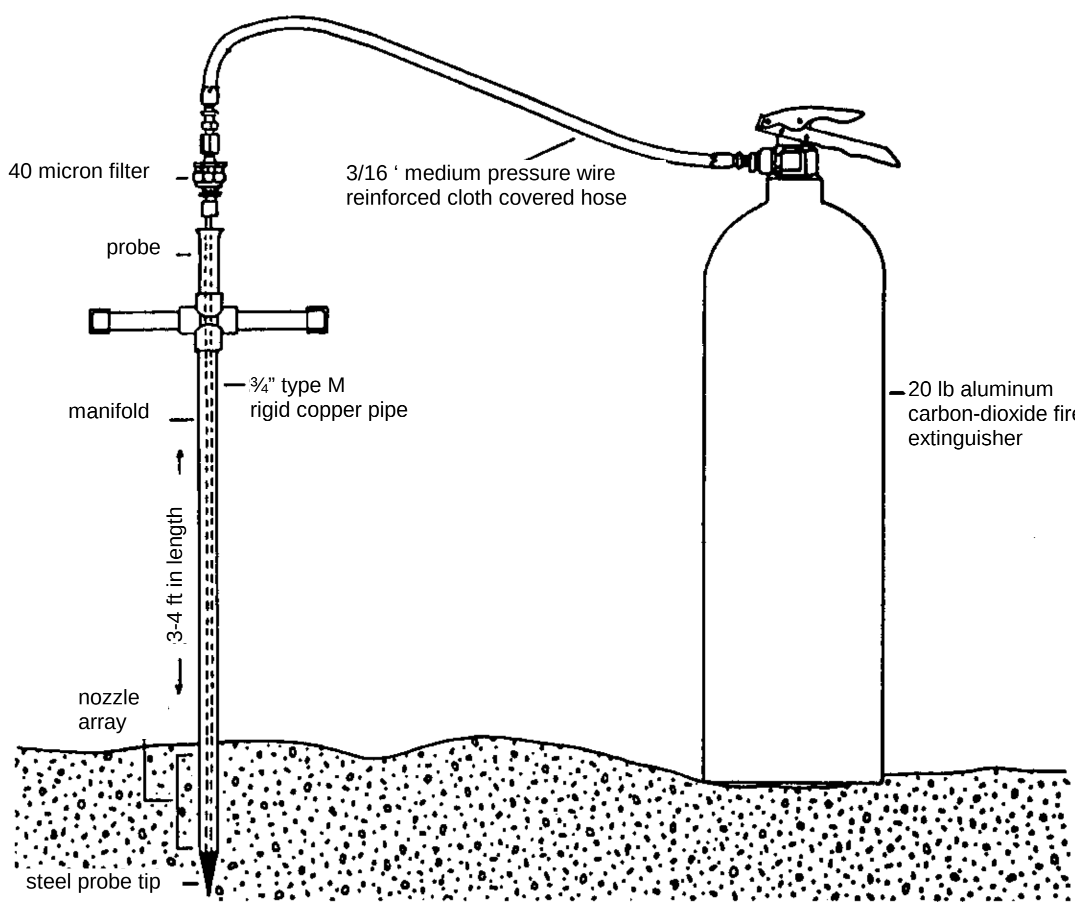


Fig. 4.28: Freeze-core samplers: Single-tube freeze-core sampler with a fire extinguisher as the source for liquid CO_2. (Reprinted from NCASI (1986), source Walcotten (1976), by permission of the National Council of the Paper Industry for Air and Stream Improvements).

In order to enlarge the freeze-core, and include larger particles in the sample, Lotspeich and Reid (1980), and Everest et al. (1980) developed the tri-tube freeze sampler. Three rods are arranged in a triangular fashion and driven into the streambed through templates at the upper end of tubes to ensure that the distance of the tubes relative to each other remains constant between 3.8 and 7.6 cm (Fig. 4.29 a). A tripod and winch are used to extract the core.

Sample mass for tri-tube samples is 10 - 20 kg (about 0.5 - 1 bucket full), which is approximately 2 - 4 times more than the mass of single-rod freeze-cores. A sample mass of 10 kg satisfies the 0.1% sample mass criterion by Church et al. (1987) for a D_{max} smaller than 20 mm (i.e., the D_{max} particle comprises 0.1% of the total sample weight,

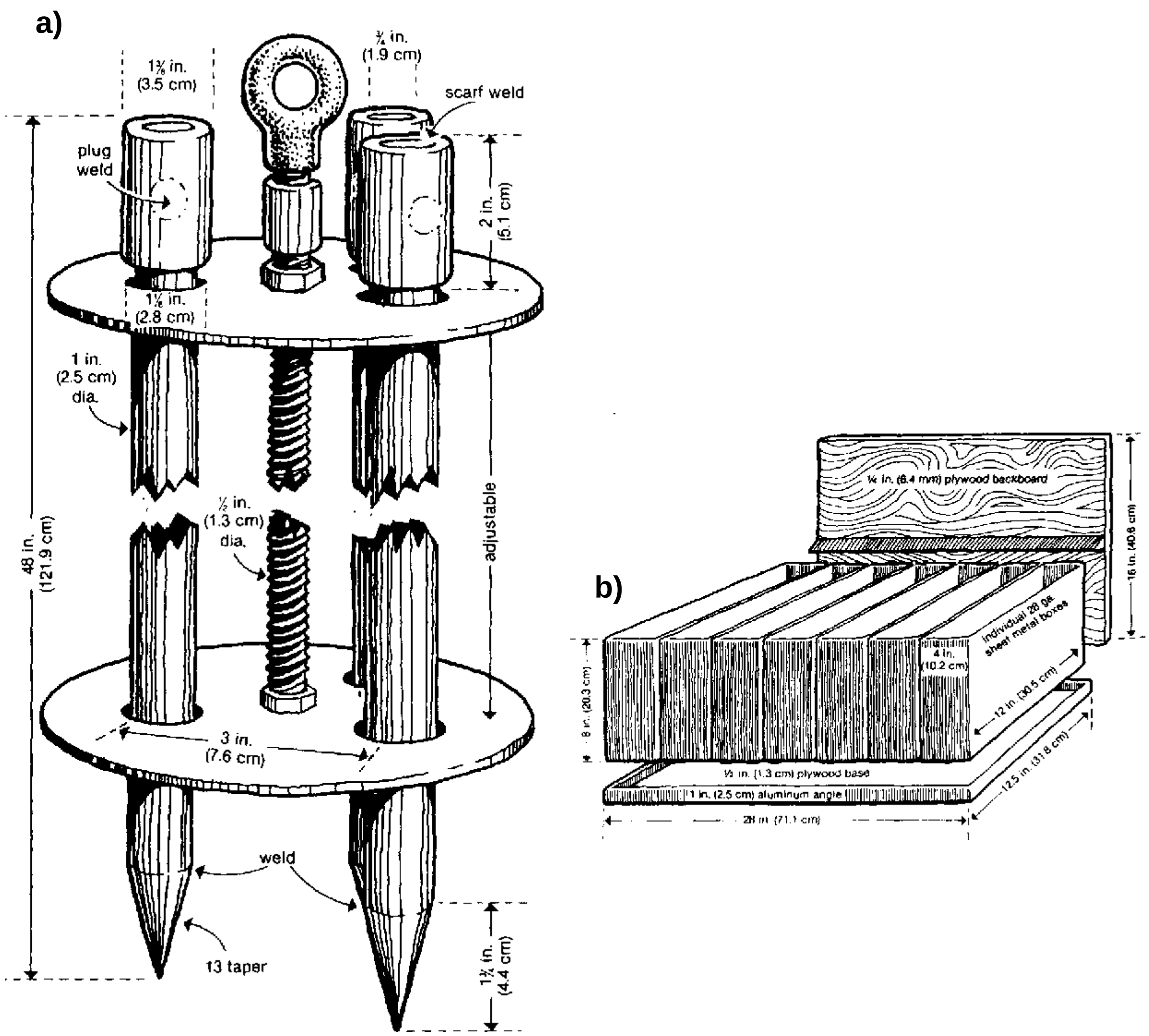


Fig. 4.29 a and b: (a) Tri-tube freeze-core sampler with templates to keep an even distance between the tubes (Reprinted from Platts et al. (1983); (b) A slotted sheet metal box for subsampling and analysis of the sediment stratigraphy (Reprinted from Platts et al. (1983)).

Section 5.4.1.1), or if the 1% criterion is applied, for particles smaller than 40 mm. Repeated samples have to be taken to analyze the size distribution of larger particles, unless the study aim justifies a truncation of the particle-size distribution, as is often necessary when determining the percent fines.

Freeze-core samples have irregular shapes that depend on how far the freezing advanced outward from the rod. Irregular core shapes can cause an unrepresentative particle-size distribution of the sample. Large particles that are only partially frozen to the core might be lost during retrieval. Because large particles occur most frequently near the bed surface, but are likely to be lost during the sample retrieval, freeze-core samples tend to underrepresent the coarse particles of the armor layer. Conversely, a few large particles frozen to the core can dominate the sample mass and underrepresent the amount of fine sediment (Rood and Church 1994). However, Thoms (1992) found that freeze-core samples are more representative of the true bed-material particle-size than grab samples. A comparative study by NCASI (1986) found that tri-tube samples underestimate the percent fines smaller 4 mm to a lesser extent than single-tube freeze-cores. Repeated tri-tube samples also have a lower variability in measured percent fines than single-tube samples. Ramos (1996) summarizes various studies comparing freeze-core samples with samples from the McNeil and other samplers.

4.2.4.9 Resin cores

Resin cores of sediment are obtained by pouring liquid resin into a small vertical hole that is created by forcing and retrieving a rod into the bed material. The hole may be approximately 1 m deep. Due to its viscosity, resin penetrates farther into the sediment when pore spaces are large, thus collecting large volumes of porous sediment layers and small volumes of tightly packed sediment layers. Resin cores can only be granulometrically analyzed by cutting the hardened core and applying thin section techniques used for sandstone or conglomerates (Adams 1979; Neumann-Mahlkau 1967). Resin cores, however, provide an excellent visual image of the bed stratigraphy.

4.2.4.10 Hybrid samplers: combined pipe and freeze-core sampler, or excavated freeze-cores

Rood and Church (1994) developed a hybrid sampler that combines the advantages of a McNeil and a freeze-core sampler: it produces a predefined sample volume contained within a pipe and a core that can be analyzed stratigraphically. The hybrid sampler has two major components: (1) a toothed pipe, or core barrel, 0.2 m in diameter with an upward extension pipe 1 m long and 0.065 m in diameter, and (2) a freeze-core probe 1.5 m long, and 0.05 m in diameter with a hardened tip (Fig. 4.30).

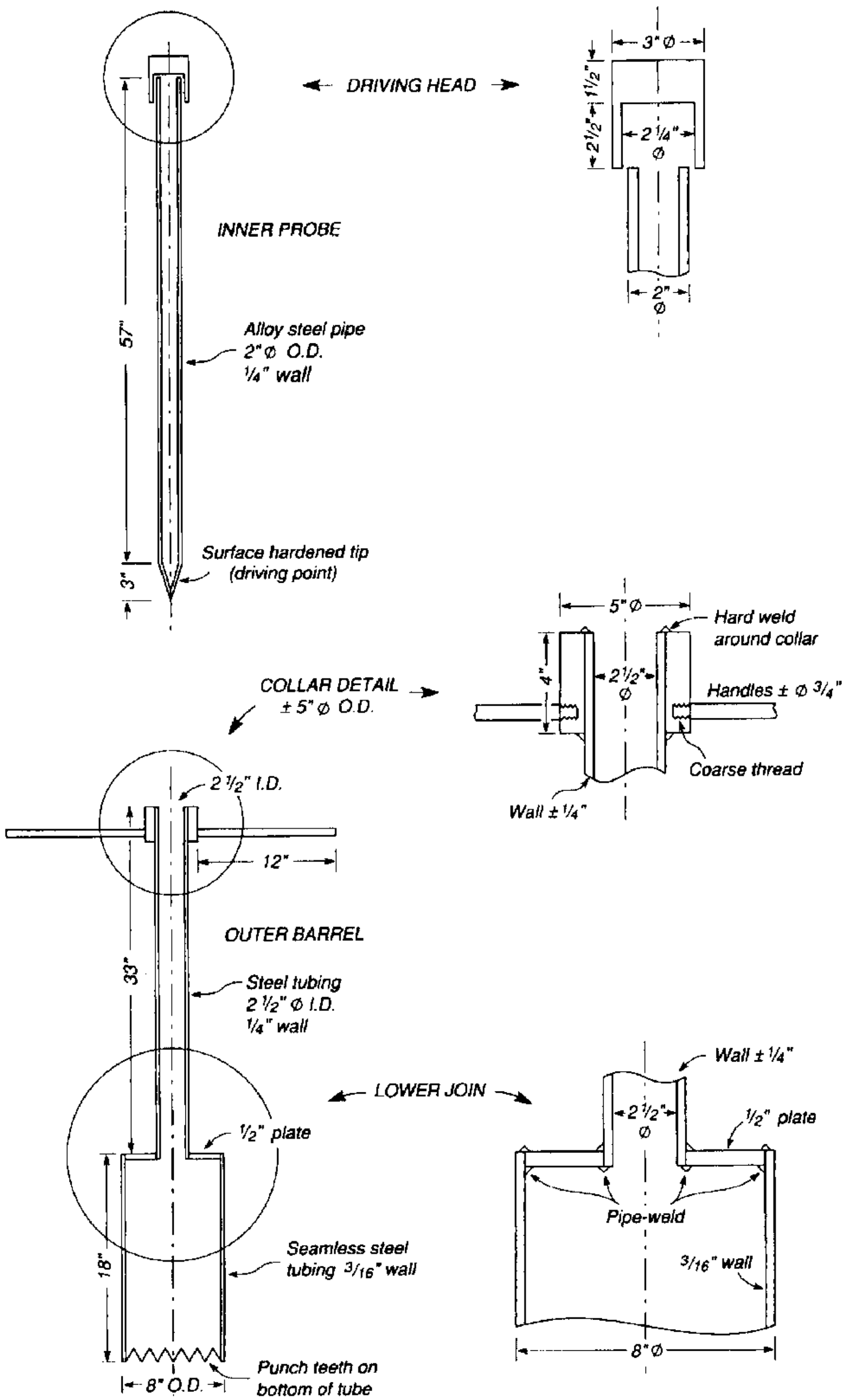


Fig. 4.30: Hybrid sampler. Manufacturing drawings for the outer barrel and the inner probe of the freeze-corer. Some lines in the drawing have been shortened for compact presentation. (Reprinted from Rood and Church (1994), by permission of the American Fisheries Society.)

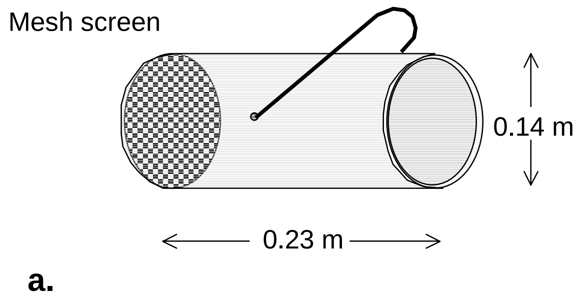
The hybrid sampler is designed for use in gravel beds and is particularly useful for analyzing spawning gravel that contain no cobbles. Two people work the core barrel into the gravel bed to a minimum depth of 0.3 m, the depth of redds built by spawning salmonid fish. The freeze-core probe is placed inside the extension pipe and driven into the bed with a sledgehammer, until the tip of the probe extends below the bottom of the core barrel. 6 - 8 liters of liquid nitrogen are poured into the freeze-core probe. After approximately 5 minutes the sample is frozen. The core barrel is twisted to break the freezing at the bottom of the core and then lifted out of the bed by one or two people. A small inflatable raft is useful for transporting the core to the bank. The frozen core is removed from the core barrel, and particles frozen to the freeze-core probe are either chipped off with a hammer or the entire sample is left to thaw. The sample can be split into several layers before bagging.

Maximum sample volume of the hybrid sampler is approximately 10 liters or the volume of a household pail. Maximum sample mass is about 13.5 kg. Repeated samples are necessary to obtain a sample mass sufficiently large to analyze a particle-size distribution that extends into the cobble range. The hybrid sampler can be used in any wadable flow, but is restricted to gravel beds with particles smaller than 128 mm. Due to the heavy equipment and the large amount of liquid nitrogen needed for repeated sampling, road access to the sampling site is desirable.

4.2.5 Volumetric sampling in deep water

If water becomes too deep for wading, bed material can either be sampled by one of the methods described in Section 4.2.4 using trained divers, or an attempt can be made to sample bed material using towed dredges (Burrows et al. 1981). Dredges are pipes or boxes with a cutting edge or teeth at the front and a mesh screen or a mesh bag at the back end (Fig. 4.31). As the dredge is pulled over the stream bottom, the cutting edge cuts a few cm into the bed material while the forward motion accumulates the sediment inside the dredge. Water moves through the dredge and out the screen at the tail end. Dredges are best used for sampling relatively fine and unstratified sediment. Hilton and Lisle (1993) and Lisle and Hilton (1999), for example, used a pipe dredge to sample fine sediment accumulated in pools (Section 6.6.2).

It is difficult to obtain representative samples with dredges in deep streams with coarse beds. Pipe dredges must be sufficiently heavy to dig into the bed and large enough to accommodate the largest bed-material particles. Towed box dredges must have a properly adjusted cable length to maintain a horizontal position. Surface and subsurface sediment is mixed in a dredged sample, so that the percent surface or subsurface sediment contained in the sample is unknown. The maximum particle size that can be sampled depends on the dredge opening. The likelihood of collecting a particle with a diameter close to that of the dredge opening is rather small. Sample volume depends on the size of the dredge, which in turn depends on whether the dredge is operated by hand or by machinery. Another drawback is that sediment collected with towed dredges can not be designated to a specific streambed location, and the rate of fill can vary as the dredge is towed.



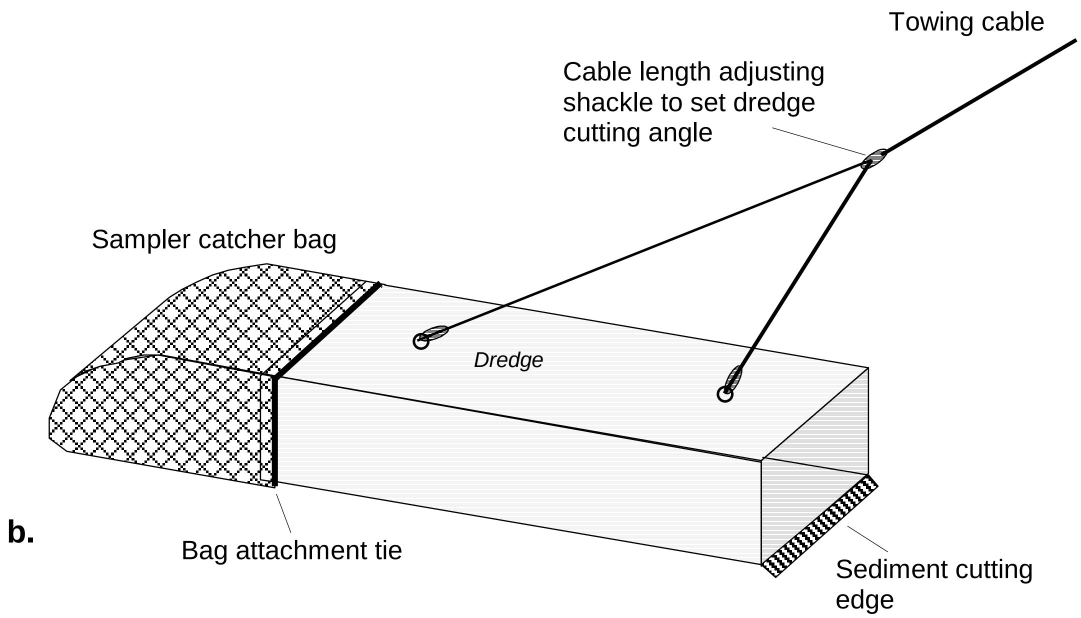


Fig. 4.31: (a) Pipe dredge for gravel sediment; (Redrawn from Yuzyk (1986). (b) Box dredge; (Redrawn from Lewis and McConchie (1994), by permission of Chapman and Hall).

If the surface sediment size is a concern in streams with coarse beds, underwater photos taken by divers and analyzed by the photo-sieving method (Section 4.1.3.3) (Ibbeken and Schleyer 1986) is an alternative to dredging. Underwater photo sieving requires clear water and a water depth of more than 2 m.

4.3 Conversion of sample distributions: grid - areal - volume, and number - weight

Bed-material samples may be obtained by three different techniques: grid samples (i.e. pebble counts) (Sections 4.1.1 and 4.1.2), areal samples (Section 4.1.3), and volumetric samples (Section 4.2.1). Particle-size distributions can be analyzed by a number frequency of particles per size class (by-number), or a frequency-by-weight (by-weight). The three methods of sampling (grid, areal, and volumetric) and two methods of particle-size analysis (by number and by weight) may be combined to six possible ways of sampling and analyzing bed-material. The terminology describing the methods of both sampling and analysis is as follows: a grid-by-number sample refers to a grid sample analyzed by a number frequency (abbreviated by g-n); an area-by-weight sample refers to an areal sample analyzed by its weight frequency (a-w). The terminology for the other combinations of sampling and analysis follows the same pattern. Analyzing a volumetric sample by a number-frequency (volume-by-number) is theoretically possible, but usually not very practical, and therefore not further discussed.

If streambeds span a wide range of particle sizes, several methods of sampling or analysis may have to be employed to representatively sample all particle sizes at one site, an approach called hybrid sampling. Boulders, for example, can only be included in a surface sample if a widely spaced pebble count is used, whereas representative sampling of fine surface sediment requires an areal sample. Another example is the comparison of surface and subsurface sediment. The surface may be sampled with an areal sample, while the subsurface is sampled volumetrically. Meta-studies that analyze bed-material samples from previous studies in a new context are likewise faced with samples taken or analyzed by different techniques.

Different methods of sampling and analysis applied to the same deposit produce different particle-size distributions. Area-by-weight samples, for example, have coarser distributions than volume-by-weight samples from the same deposit. Thus, before samples derived from different sampling methods can be combined or compared (Section 4.4), their size distributions have to be transformed into the size distribution of the same sample and analysis category.

Several methods have been proposed for conversion of particle-size distributions between different categories of sampling and analysis. Kellerhals and Bray (1971) introduced the voidless cube model as a means to explain the different particle-size distribution that may result from the five categories of sampling and analysis. They proposed factors for the conversion of a particle-size distribution obtained by one method of sampling and analysis into the distribution obtained by another method of sampling and analysis. Diplas and Fripp (1992) introduced the modified cube model to explain that differences between observed and computed conversions between areal and volumetric samples are due to sediment characteristics and the penetration depth of the adhesive used for areal sampling. Fraccarollo and Marion (1995) argued that the assumed similarity between grid-by-number and volume-by-weight samples does not hold when a more realistic model of surface particles is applied (split plane surface model). Also, because it is difficult to make the adhesive penetrate to exactly a specific depth, Marion and Fraccarollo (1997) based the conversion between areal and volumetric samples on a computed penetration depth of the adhesive.

4.3.1 Voidless cube model

Kellerhals and Bray (1971) used a model deposit comprised of a mixture of three cube sizes packed without voids (voidless cube model) (Fig. 4.32) to determine conversion factors between the various combinations of sampling method and sample analysis. The cube model represents an idealized deposit of spheres in a systematic and lose, but voidless packing. The cubes have the three sizes of $D_1 = 1$, $D_2 = 2$, and $D_3 = 4$ (any linear unit, e.g., cm). The surface area A taken up by particles with a size of D_1, D_2, and D_3 is $A = D^2$ and yields $A_1 = 1$, $A_2 = 4$, and $A_3 = 16$ (e.g., cm^2), respectively. Particle volume is computed by $V = D^3$ and yields $V_1 = 1$, $V_2 = 8$, and $V_3 = 64$ (e.g., cm^3). Cubes of each size class take up the same portion of the total volume, i.e., 33.33%. A particle density of 1 is assumed, so that volume equals weight. The number of particles of the sizes D_1, D_2, and D_3 contained in the total sediment volume is $n_1 = 4608$, $n_2 = 576$, and $n_3 = 72$. The number of surface particles $n_{surf,1} = 192$, $n_{surf,2} = 48$, $n_{surf,3} = 12$ (Table 4.5 a and b).

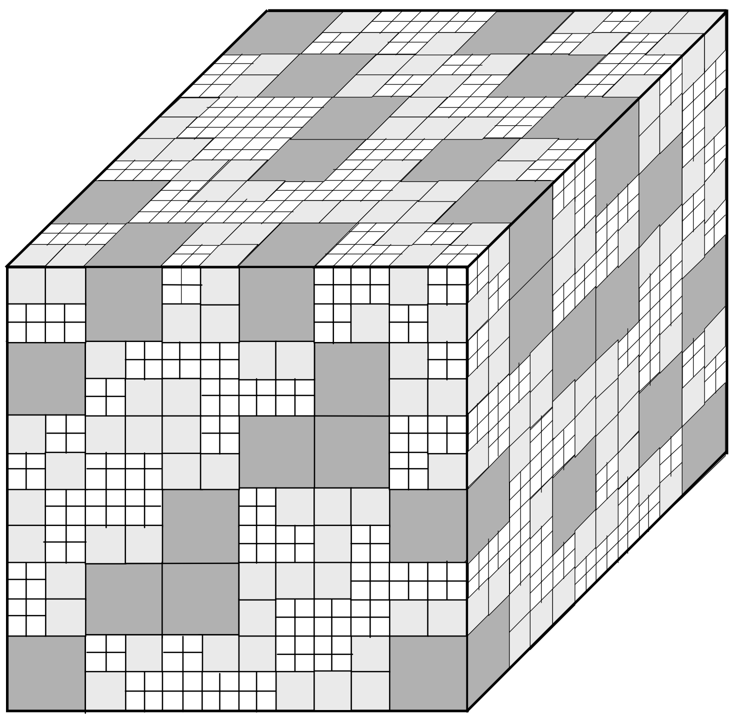


Fig. 4.32: Model of densely packed cubes (voidless cube model) developed by Kellerhals and Bray (1971). (Redrawn from Kellerhals and Bray (1971), by permission of the American Society of Civil Engineers).

Tables 4.6 a and b demonstrate the different particle-size distributions that are obtained if particles from a deposit mimicked by the voidless cube model are sampled and analyzed by different methods. The particle-size distribution of an area-by-weight sample, for example, is simulated by multiplying the number of surface particles per size class with their respective volume. The resulting values are then expressed as percent frequencies (Table 4.5 a). A grid-by-number sample is simulated by multiplying the number of surface particles per size class by their area (Table 4.5.b).

The cumulative frequency distributions obtained by sampling the voidless cube model with grid, areal, and volumetric methods analyzed by a weight and a number frequency are plotted in Fig. 4.33. The voidless cube model yields the same particle-size distribution for volume-by-weight and grid-by-number samples. Area-by-weight and grid-by-weight samples are coarser than volume-by-weight or grid-by-number samples, whereas area-by-number and volume-by-number samples are considerably finer. The D_{50} of the area-by-number sample is smaller than the D_{50} of the volume-by-weight and grid-by-number sample by a factor of 1.5, whereas the D_{50} of the area-by-weight sample is a factor of 1.5 coarser.

Table 4.5 a: Particle-size distributions obtained from collecting volumetric, areal and grid samples from the voidless cube model and analyzing the samples by a weight frequency (i.e., volume-by-weight, area-by-weight, and grid-by-weight samples).

			(vol.-by-number)	vol.-by-weight			area-by-weight		grid-by-weight	
D	$A=D^2$	$V=D^3$	n	$n \cdot V$	%	n_{surf}	$n_{surf} \cdot V$	%	$n_{surf} \cdot A \cdot V$	%
1	1	1	4608	4608	33.3	192	192	14.3	192	1.4
2	4	8	576	4608	33.3	48	384	28.6	1536	11.0
4	16	64	72	4608	33.3	12	768	57.1	12288	87.7
Σ			5256	13824	100.0	252	1344	100.0	14016	100.0

D = particle size, e.g., in cm; *A* = particle area; V = particle volume which equals weight if a particle density of 1 is assumed; *n* = number of the particles per size class; % = percent frequency; n_{surf} = number of surface particles per size class.

Table 4.5 b: Particle-size distributions derived by collecting areal and grid samples from the voidless cube model and analyzing the samples by a number frequency (i.e., area-by-number, and grid-by-number samples). The volume-by-weight sample is shown for comparison.

				vol.-by-weight		area-by-number		grid-by-number	
D	$A=D^2$	$V=D^3$	n	$n \cdot V$	%	n_{surf}	%	$n_{surf} \cdot A$	%
1	1	1	4608	4608	33.3	192	76.2	192	33.3
2	4	8	576	4608	33.3	48	19.0	192	33.3
4	16	64	72	4608	33.3	12	4.8	192	33.3
Σ			5256	13824	100.0	252	100.0	576	100.0

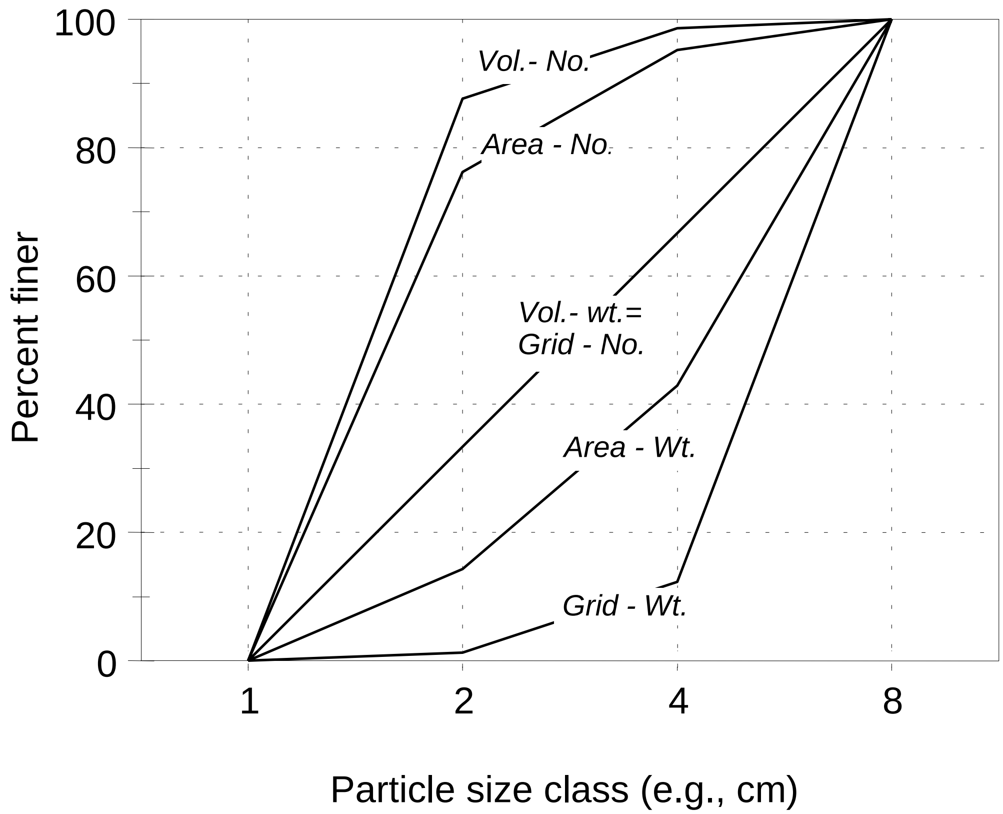


Fig. 4.33: Cumulative frequency distributions obtained for various sample and analysis methods of particles from the voidless cube model by Kellerhals and Bray (1971). Vol. - No. = volume-by-number sample, Area - wt. = area-by-weight sample; other abbreviations are likewise derived.

Conversion factors

Conversion factors consist of two parts: the conversion between methods of particle-size analyses (weight or number frequency), and the conversion between the various sampling methods (grid, areal, and volumetric). Table 4.5 a and b show that the difference between a by-number and by-weight sample is the factor V (particle volume) or D^3. Thus, converting a number frequency to a weight frequency requires multiplying the weight frequency of particles per size class by the particle size cubed (D^3). Conversely, multiplying the weight frequency of particles per size class by the reciprocal of their cubed particle size ($1/D^3$) yields the distribution in terms of frequency-by-number.

The conversion system is similar between samples that are analyzed alike, but sampled with different methods. Table 4.5 a and b show that the difference between volume and grid samples is a factor of V or D^3. Thus, a particle-size distribution of a volumetric sample yields the particle-size distribution of a grid sample when the frequency of all particle-size classes is multiplied by D^3, whereas multiplication by the factor $1/D^3$ converts a grid sample to a volumetric sample. Converting a volumetric sample to an areal sample requires multiplication by the factor D, whereas the conversion from an areal sample to a volumetric one requires multiplication by $1/D$. Finally, a factor of D^2 converts an areal sample into a grid sample, and $1/D^2$ converts a grid sample into an areal sample, assuming the same method of analysis in both cases. Table 4.6 summarizes these factors. Conversion factors assume spherical particles for which the sieve diameter D approaches the nominal diameter D_n (Eq. 2.1 in Section 2.1.2), a voidless particle packing, and the same density for all particles. In a strict sense, the conversion factors in Table 4.6 apply only to these conditions. If used for deposits with other properties, the conversion factors yield only an approximation.

Table 4.6: Conversion between samples analyzed or sampled by different methods.

Conversion from → to:	Factor
Different methods of analysis:	
weight frequency → number frequency	$1/D^3$
number frequency → weight frequency	D^3
Different sampling methods:	
volume → grid	D^3
grid → volume	$1/D^3$
volume → area	D
area → volume	$1/D$
area → grid	D^2
grid → area	$1/D^2$

The two parts of a conversion factor, one that accounts for converting sampling methods, and one that accounts for converting different methods of analysis, need to be applied together when converting particle-size distributions obtained by different methods of sampling *and* by different analysis. For example, to convert a volumetric sample analyzed on the basis of weight frequency (volume-by-weight) to an areal sample analyzed on the basis of a number frequency (area-by-number), the frequency distribution needs to be multiplied by the product of $D \cdot 1/D^3$ (D for conversion of volume → area) and $1/D^3$ for conversion of weight → number-frequency. The product $D \cdot 1/D^3$ is then simplified to $1/D^2$. Similarly, the conversion of a volume-by-weight sample to a grid-by-number sample is obtained by applying the factor $D^3 \cdot 1/D^3 = 1$, which means that both particle-size distributions are identical and do not require any conversion in order to be compared or combined. Table 4.7 lists the conversion factors used for the various combinations of sample methods and methods of analysis.

Conversion factors are also expressed in terms of the exponent that D takes in the conversion factor. A conversion factor of $1/D^2 = D^{-2}$ is then referred to as using an exponent of -2 for the conversion.

Table 4.7: Conversion factors for samples collected by various methods (from Kellerhals and Bray 1971). Numbers in the gray bars express the conversion factor as the exponent of *D*.

Conversion **from** \ Conversion **to**	Volume-by-weight	Grid-by number	Grid-by weight	Area-by number	Area-by weight
Volume-by-weight	1	1	D^3	$1/D^2$	D
	0	*0*	*3*	*-2*	*1*
Grid-by number	1	1	D^3	$1/D^2$	D
	0	*0*	*3*	*-2*	*1*
Grid-by weight	$1/D^3$	$1/D^3$	1	$1/D^5$	$1/D^2$
	-3	*-3*	*0*	*-5*	*-2*
Area-by number	D^2	D^2	D^5	1	D^3
	2	*2*	*5*	*0*	*3*
Area-by weight	**$1/D$**	$1/D$	D^2	$1/D^3$	1
	-1	*-1*	*2*	*-3*	*0*

Converting a particle-size distribution

Table 4.8 shows how a particle-size distribution is transformed, using the example of an area-by-weight sample that is converted to a grid-by-number sample. To apply the conversion factors (Table 4.7) to a particle-size distribution (Table 4.8), particle size *D* is

Table 4.8: Conversion of an areal sample expressed as weight frequency (area-by-weight) to a surface grid sample expressed as number frequency (grid-by-number) (slightly modified from Kellerhals and Bray 1971).

	area-by-weight				grid-by-number	
Size class D_i (mm)	Freq. (%)	Cum freq. (%)	Center of class D_{ic} (mm)	Freq.· **$1/D_{ic}$**	adj. to 100% Freq. (%)	Cum. Freq. (%)
2.8	2	0	3.3	0.60	11.7	0.0
4	1	2	4.8	0.21	4.1	11.7
5.67	2	3	6.7	0.30	5.8	15.8
8	5	5	9.5	0.53	10.3	21.6
11.3	13	10	13.4	0.97	18.9	31.9
16	17	23	19.0	0.89	17.5	50.8
22.6	19	40	26.9	0.71	13.8	68.3
32	22	59	38.1	0.58	11.3	82.1
45.3	16	81	53.8	0.30	5.8	93.4
64	3	97	76.1	0.04	0.8	99.2
90.6	0	100	0.0			100.0
total:	100			5.11	100.0	

expressed by the center of class D_{ic} which is computed from the geometric mean particle size (Section 2.1.5.3) of the size fraction (equal to the logarithmic mean of particle sizes in mm, or arithmetic mean of particle sizes in ϕ-units). The cumulative frequency distributions of the area-by-weight sample converted into a grid-by-number sample are shown in Fig. 4.34.

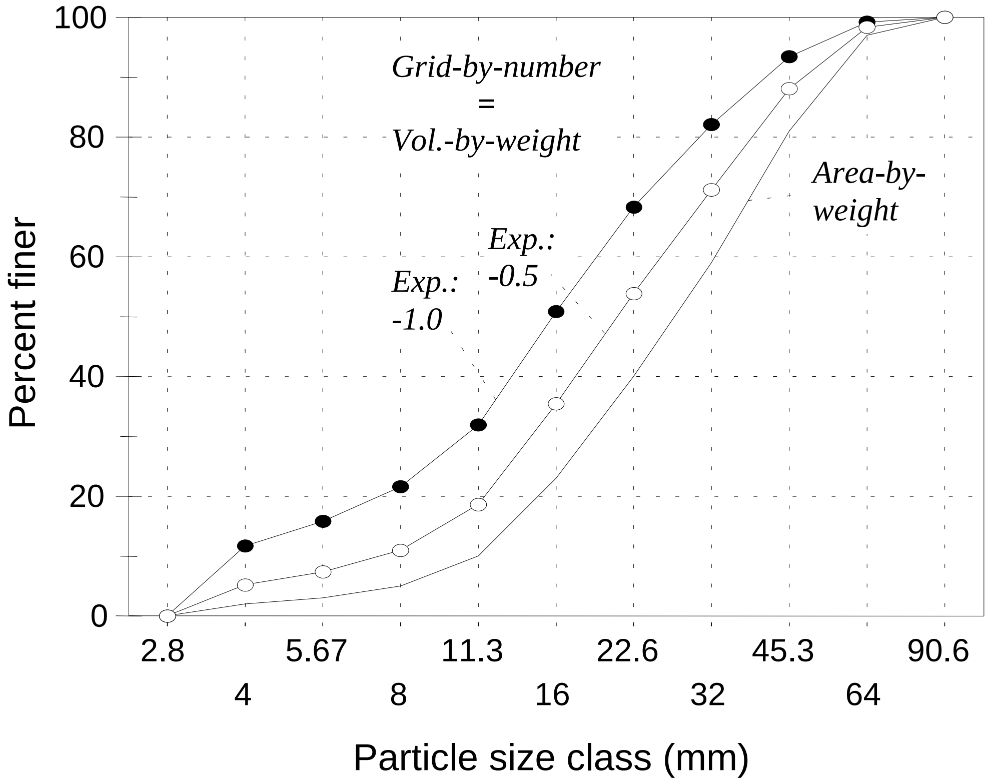


Fig. 4.34: Particle-size distribution of the area-by-weight sample in Table 4.8 converted into a grid-by-number sample (or volume-by-weight sample) using a conversion factor of 1/*D* (= -1.0) (after Kellerhals and Bray 1971) and using a conversion factor of - 0.5 as proposed by Parker (1987). D_{50} particle sizes are 27.6 mm for the area-by-weight sample, 15.7 mm for the grid-by-number and volume-by-weight samples using a conversion factor of -1.0, and 20.6 mm for a conversion factor of -0.5.

The geometrically-based conversion factors obtained from the voidless cube model yielded perfect results in the mutual conversion of a grid-by-weight to a grid-by-number frequency and confirmed earlier results by Sahu (1964) and Leopold (1970). Kellerhals and Bray (1971) concluded that their conversion factors should be applicable to any sediment and that grid-by-number and volume-by-weight analysis should yield identical results when applied to non-stratified gravel beds. The convertibility of the two methods was confirmed by Church et. al. (1987) who used different sampling methods on a gravel mixture that was shaken in a closed box to form a random, non-stratified, homogeneous deposit. Even when tested on bed material taken from various Alberta streams, the conversion factors yielded acceptable results. Note, however, that most gravel-bed rivers, and especially mountain streams, are vertically stratified (Section 3.2); surface sediment is coarser than subsurface sediment. Consequently, surface pebble counts correctly indicate a coarser particle size-distribution than the volumetric sample of the subsurface sediment.

Controversies about conversion factors

Several studies have observed that the conversion factors proposed by Kellerhals and Bray (1971), particularly the conversion between areal and volumetric samples, do not apply under all circumstances. The observed incompatibility has been attributed to the over-simplified description of bed-material surfaces by the voidless cube model.

4.3.2 Modified cube model

The voidless cube model by Kellerhals and Bray (1971) indicates a factor of $1/D$ (i.e., an exponent of D of -1) for converting an area-by-weight sample into a volume-by-weight sample for homogeneous material. However, when applied to gravels from stratified and armored deposits, researchers found that the conversion factor exponent of -1 yielded grain-size distributions that are too fine (Ettema 1984). Gomez (1983), Anastasi (1984), Parker (1987), Diplas and Sutherland (1988), and Diplas (1989) proposed substituting the exponent with a value of approximately -0.4 to -0.5. An exponent of -0.5 refers to a conversion factor of $1/D^{-0.5}$. Fig. 4.34 shows that a conversion factor of $1/D^{-0.5}$ (i.e., and exponent of -0.5) provides a less fine distribution of the area-by-weight sample converted to volume-by-weight or grid-by-number sample than an exponent of -1.

The necessity of raising the exponent from -1 to approximately -0.5 is a result of an opposing sampling bias for fine sediment in surface grid counts and areal samples. Surface grid samples or pebble counts easily neglect fine particles in voids, whereas in areal samples a deep penetration of the adhesive into subsurface sediment may collect more fines than present in the surface layer. The inclusion of surface fines by adhesive areal samples produces a finer surface-size distribution than surface grid samples. Based on this observation, Diplas and Sutherland (1988) developed the hypothesis that the exponent needed in the conversion factor of area-by-weight to volume-by-weight depends on the depth to which surface particles are actually included into the areal sample. To illustrate their point, they modified the voidless cube model used by Kellerhals and Bray (1971) (Fig. 4.32) into a void-containing cube model, in which voids take the same size and volume as the size and volume of the smallest particle-size class. This resulted in a cube model with 33% porosity, a value typical of fluvial deposits.

An adhesive areal sample of a deposit with surface voids is likely to include small particles from the next layer under a surface void. These small particles would not have been extracted by a sampling method such as adhesive tape that is truly restricted to surface particles only. Modeling adhesive areal samples from the modified porous cube model, Diplas and Sutherland (1988) and Diplas (1989) obtained finer particle-size distributions for an areal sample than predicted by the voidless cube model of Kellerhals and Bray (1971). Diplas and Sutherland (1988) and Diplas (1989) determined that an exponent of -0.42 was an appropriate conversion factor for areal samples obtained using adhesives. The general validity of a conversion exponent of -0.4 to -0.5 was confirmed in subsequent laboratory experiments.

Effect of porosity, sediment size, sorting, and sampling depth on the conversion exponent

Based on previous findings which suggested that the exponent might shift from -1.0 to -0.5 for sediment that is more porous, finer in particle size, and better sorted, Diplas and Fripp (1991) conducted a study to specifically address these issues. The void-containing cube model determined a pronounced decrease of conversion exponents from 0 to - 0.5 for very-well sorted deposits with a ratio of D_{90}/D_{10} smaller than 2.5, whereas poorly sorted deposits with a ratio of D_{90}/D_{10} larger than 8 required conversion factors of -0.8 to -0.9. However, the dependency on sediment sorting was less pronounced in laboratory experiments.

A series of experiments by Diplas and Fripp (1992) showed that the depth (and thus the conversion factor) at which an areal sample becomes volumetric depends on several factors of the particle-size distribution for the sediment used in the experiments. Areal wax samples were taken from different mixtures of framework-supported (sand content < 20 or 25%) and matrix-supported gravels (sand content > 30%) (see Fig. 3.14 a and 3.14 d). The abundance of fine sediment in matrix-supported gravels prevented the deep penetration of the wax, rendering the sample a true surface sample for which the conversion factor exponent of -1, established by Kellerhals and Bray (1971), is generally valid. Similarly, if an adhesive tape that only picks up true surface particles was used for sampling, the conversion exponent should be -1, as predicted by Kellerhals and Bray (1971). Laboratory experiments confirmed these results with exponents ranging from -0.9 to -1.19.

For framework-supported gravels, the penetration of wax was generally deeper, but depended on the overall particle size of the mixture. In coarse framework-supported sediment mixtures, areal wax samples required a conversion factor exponent of -0.5, while for generally fine framework-supported gravels, the conversion factor exponent varied between -0.5 and +0.5, with an average of 0.

An exponent of -1 should be appropriate for converting area-by-weight particle-size distribution produced from photo-sieving into a grid-by-number (e.g., for comparison with pebble counts) or volume-by-weight distribution. Particles smaller than 10 mm, which could potentially be part of the subsurface and require a conversion factor larger than -1.0 (i.e., towards -0.5) are explicitly excluded from a photo sieving analysis. Table 4.9 summarizes the results of the findings.

Table 4.9: Approximate value of the conversion factor exponent required for converting the particle-size distribution of an area-by-weight sample into a volume-by-weight sample in deposits of different characteristics, based on results of several studies.

Approximate value of the conversion factor exponent		
-1.0	-0.5	$\rightarrow$ 0
Determined from voidless cube model (Kellerhals and Bray 1971)	Determined from void-containing cube model (Diplas and Sutherland 1988)	
Coarse and fine matrix-supported gravel with high sand content	Frame-work supported gravel, esp. coarse gravel deposits	Fine frame-work gravels
Deposits of low porosity	Deposits of high porosity	
Coarse gravel deposits	Deposits of fine gravel and sand	
No depth penetration of adhesive e.g., adhesive tape	Deep penetration of adhesive into subsurface sediment	
Poorly sorted gravel deposits	Well-sorted gravel deposits	Very-well sorted gravel
Photo-sieving		

4.3.3 Conversion based on computed penetration depth

Many applications require a particle-size distribution in terms of volume-by-weight, but surface sediment can only be sampled by a surface grid sample (i.e., pebble count) (fine - coarse gravel) or an areal sample (sand - fine gravel). Conversion of an area-by-weight to a volume-by-weight particle-size distribution is problematic, because the exponents for the conversion vary with the adhesive penetration depth which in turn depends on factors such as sorting, particle-size, porosity, and on the adhesive viscosity (Section 4.3.2). The combination of these factors makes it difficult to control the exact penetration depth.

To avoid these problems, Marion and Fraccarollo (1997) developed a conversion procedure in which the exact depth of penetration is irrelevant. The conversion algorithm computes the adhesive penetration depth d_p which is then used to compute the particle-size distribution of the corresponding volume-by-weight distribution for each size class ($p_{i,0}$). The algorithm is applicable over a range of penetration depths and can account for the case in which the adhesive penetrates so deeply that the presumed areal sample is in fact volumetric. In this case, the conversion procedure does not produce a different distribution.

The penetration depth d_p of the adhesive is computed from

$$m_{tot} = \sum_{j=1}^{k} m_j = \frac{\rho_s A_s (1 - p_{v,0})}{\sum_{j=1} p_{j;a\text{-}w}/(d_p + D_i/2)} \quad (4.7)$$

m_{tot} is the total weight of the sample, k is the number of size classes, m_j is the weight of the $_j$th size class, ρ_s is sediment density, A_s is the sampling area covered by the areal sample, $p_{v,0}$ is the porosity and set to a value within the range 0.3 – 0.4, $p_{j,a\text{-}w}$ is the weight fraction of the jth size class for the area-by-weight sample (m_j/m_{tot}), d_p is the adhesive penetration depth, and D_i is the particle size of the ith size class.

Eq. 4.7 is solved iteratively, using the size of the D_{50} particle as a starting value for d_p. The denominator is solved for all size classes and summed. The numerator is solved next and is constant for all size classes. The total weight of the sample m_{tot} computed from Eq. 4.7 is compared with the actual measured sample weight. d_p is then adjusted until the computed m_{tot} matches the measured m_{tot}. The resulting value of d_p is the penetration depth and usually corresponds to a particle size between the D_{20} and the D_{80}. The percentage of total volume occupied by particles of the ith size fraction, $p_{i,0}$ is computed from Eq. 4.8.

$$p_{i,0} = \frac{p_{i;a\text{-}w} (1 - p_{v,0})}{(d_p + D_i/2) \sum_{j=1}^{k} p_{j;a\text{-}w}/(d_p + D_i/2)} \quad (4.8)$$

An example computation is provided in Table 4.10. The three particle-size distributions of the original area-by-weight sample, the converted volume-by-weight sample, and an actual volume-by-weight sample taken from the deposit (last column of Table 4.10) are plotted in Fig. 4.35.

4.3.4 Split plane surface model

The voidless cube model used by Kellerhals and Bray (1971) for conversion between different methods of sampling and analysis determined that grid-by-number and volume-by weight samples of unstratified deposits have the same distribution and are therefore directly comparable. However, Fraccarollo and Marion (1995) caution that a voidless cube model is a poor representation of a real sediment deposit and not generally applicable. They proposed that if voids were properly accounted for both in a modeled sediment surface as well as in the sampling process, grid-by-number samples would have finer distributions than volume-by-weight samples. Consequently, the correspondence between grid-by-number and volume-by-weight samples may be considered a sampling artifact, caused by neglecting the presence of voids in the voidless cube model, as well as by neglecting to sample particles in voids when doing pebble counts.

Table 4.10: Example computation of the adhesive penetration depth d_p and the particle-size distribution of the converted volume-by-weight sample $p_{i,0}$, using the parameter listed below.

ρ_s (g/mm²):	0.00265	d_p (mm) comp., (start with D_{50}):	4.0
A_s (mm²):	14,000	m_{tot} (computed from Eq. 4.7) (g):	146.2
$p_{v,0}$ (-):	0.32		

	Area-by-weight sample				Converted vol.-by-weight sample			Vol. sample
D_i (mm)	m_i (g)	$p_{i,a\text{-}w}$ (-)	$p_{i,a\text{-}w}$ (%finer)	$p_{j,a\text{-}w}/(d_p+D_i/2)$ (Eq. 4.7, denominator) (1/mm)	$p_{i,0}$ (Eq. 4.8) (-)	$p_{i,0}$ (%)	$p_{i,0}$ (%finer)	$p_{i,v\text{-}w}$ (for comparison) (%finer)
0.18	5.8	0.040	0.0	0.010	0.037	5.7	0.0	0.0
0.25	4.4	0.030	4.0	0.007	0.027	4.2	5.7	5.0
0.35	3.0	0.020	7.0	0.005	0.018	2.8	9.9	10.0
0.5	3.0	0.020	9.0	0.005	0.018	2.8	12.7	14.0
0.7	2.9	0.020	11.0	0.005	0.017	2.7	15.4	17.5
1	2.2	0.015	13.1	0.003	0.013	2.0	18.1	20.0
1.4	5.1	0.035	14.6	0.007	0.028	4.3	20.1	22.5
2	6.6	0.045	18.1	0.009	0.034	5.2	24.4	26.0
2.8	28.5	0.019	22.6	0.036	0.136	21.0	29.7	33.0
4	39.4	0.027	42.1	0.044	0.169	26.1	50.6	54.0
5.6	21.9	0.150	69.1	0.022	0.082	12.8	76.7	78.5
8	13.1	0.090	84.1	0.011	0.042	6.5	89.4	90.0
11.3	8.7	0.059	93.1	0.006	0.023	3.6	95.9	94.0
16	1.5	0.010	99.0	0.001	0.003	0.5	99.5	98.0
22.6	0.0	0.000	100.0	0.000	0.000	0.0	100.0	100.0
total:	146.1	1.000		0.673	0.650	100.0		

Fraccarollo and Marion (1995) suggest that a more realistic model of a sediment surface is obtained by a sediment model consisting of a block of sediment with irregularly-shaped particles of various sizes that is split apart along a plane (imagine a split block of frozen sediment). In the model of the split plane, particles on the split line are assigned to that part of the split block in which their center of gravity is located (Fig. 4.36). The area under a large particle that was assigned to the other part of the block is likely to contain particles that are smaller than the large particle that was lost to the other side, especially in matrix-supported gravel. Sampling such a split surface by a grid-by-number sample includes a larger proportion of fines than a volume-by-weight sample and makes the grid-by-number sample similar to an area-by-number distribution of particle sizes.

The model of surface-particle sizes proposed by Fraccarollo and Marion (1995) has fine surface particles in very exposed positions directly at the surface. This particle arrangement is not representative of armored beds in which fine surface particles are generally scarce and are not found exposed, but hidden between large particles. The model proposed by Fraccarollo and Marion (1995) is more likely to represent surfaces in aggrading streams with ample fines between large particles. In such streams, surface grid-by-number counts may be finer than volume-by-weight samples. The proposed finer distributions of grid-by-number than volume-by-weight samples are also contingent upon

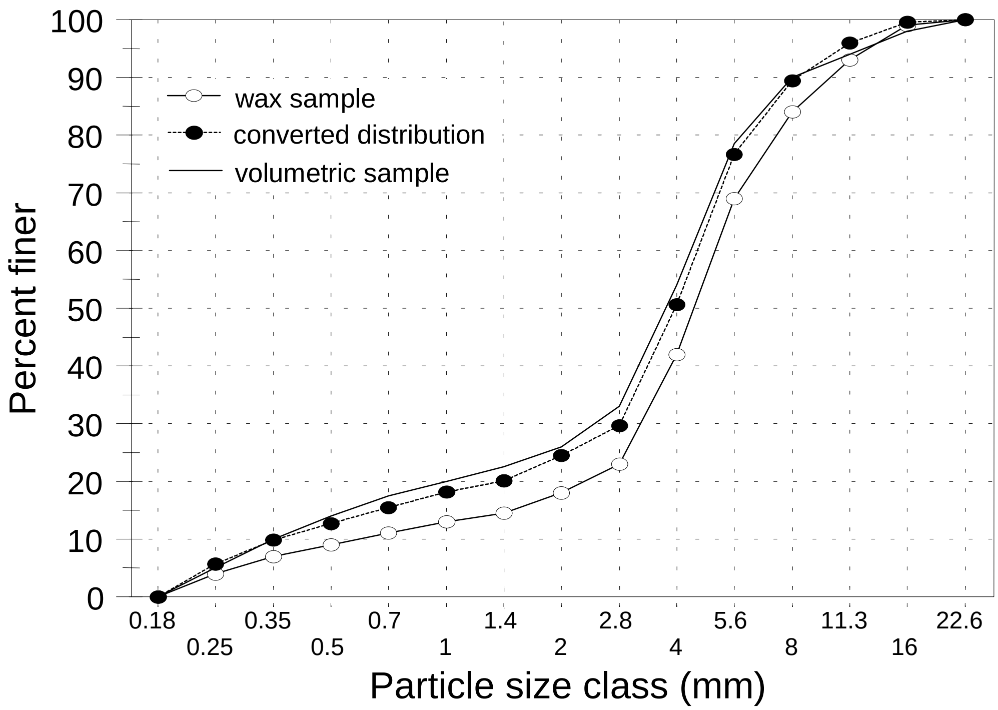


Fig. 4.35: Particle-size distribution of an area-by-weight sample collected from a surface comprised of sand and fine gravel ($D_{50} \approx 4$ mm), and its conversion to a volume-by-weight equivalent. The distribution of a volume-by-weight sample is shown for comparison (based on data by Marion and Fraccarollo 1997).

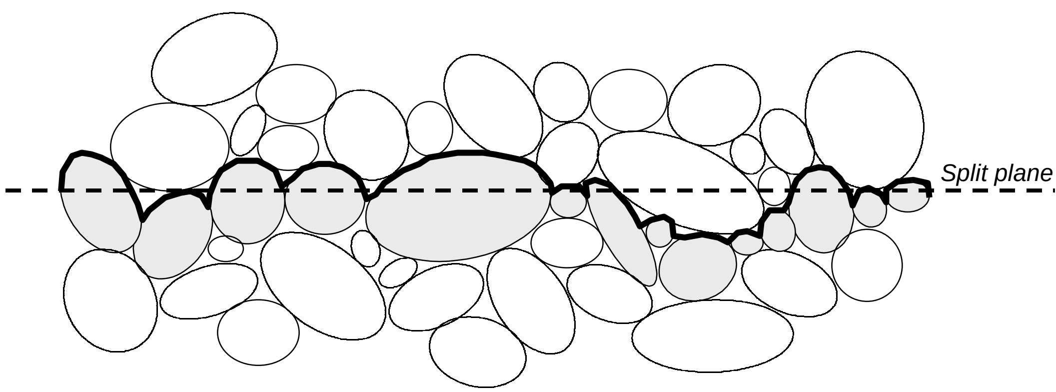


Fig. 4.36: Schematic of surface (gray particles) generated by split plane; Bold line indicates surface profile. (Redrawn from Fraccarollo and Marion (1995), by permission of the American Society of Civil Engineers.

accurate sampling of fine particles in interstitial voids. However, pebble counts on armored coarse gravel or cobble beds can not practically include interstitial fines to their full extent, especially not when the sample must be collected under water or under adverse conditions (Section 4.1.1.3). Thus, fines are underrepresented due to practical restrictions of pebble counts or grid samples, and it seems that this underrepresentation brings grid-by-number samples into a relatively close correspondence with volume-by-weight distributions.

4.4 Combination of two particle-size distributions

Fluvial deposits with wide particle-size distributions ranging from sand to boulders often require several sampling methods in order to sample all particle sizes present in the reach. Most sampling methods, however, sample only a portion of the bed-material particle-size distribution in a representative way. A surface pebble count (Section 4.1.1), for example, can representatively sample particle sizes between medium gravel and small boulders. However, pebble counts may not accurately characterize the sediment finer than 8, or 2 mm, depending on the sampling conditions. Areal samples, on the other hand, can accurately determine the fine part smaller than 40 mm of a sample, particularly if clay is used as an adhesive to collect the sample (Section 4.1.3.2). However, coarse gravels and cobbles cannot be sampled by areal methods. Thus, in order to characterize the entire bed-material surface distribution within a reach, a grid-by-number pebble count and several areal samples, which have been converted to equivalent distributions of grid-by-number samples before, (Section 4.3) need to be combined.

Several methods are available for combining two particle-size distributions:

- Rigid combination,
- Flexible combination, and
- Adjustment of frequency distributions.

4.4.1 Rigid combination

If the coarse portion of a pebble count size-distribution is considered representative for a reach, only the fine part of a pebble count needs to be adjusted to the fine part of an areal sample (converted to a grid-by-number sample beforehand) to obtain a distribution representative of all particle sizes. The rigid combination method presented by Anastasi (1984) and Fehr (1987) facilitates this adjustment. The method uses the percentile ratio between an areal sample and a pebble count at the lower and upper border of one selected particle-size class to create a new cumulative frequency distribution for the fine part for the pebble count.

Within the range of particle sizes common in both samples, one particle-size class is sought in which the ratios between the lower and an upper percentiles of the areal sample, $p_{A\ low}$ and $p_{A\ up}$, and the lower and upper percentiles of the pebble count, $p_{P\ low}$ and $p_{P\ up}$, are as similar as possible (see Eq. 4.9 and gray bars in Fig. 4.37 a - c). Note that all percentiles are used as decimals (e.g., 0.23 instead of 23 % finer).

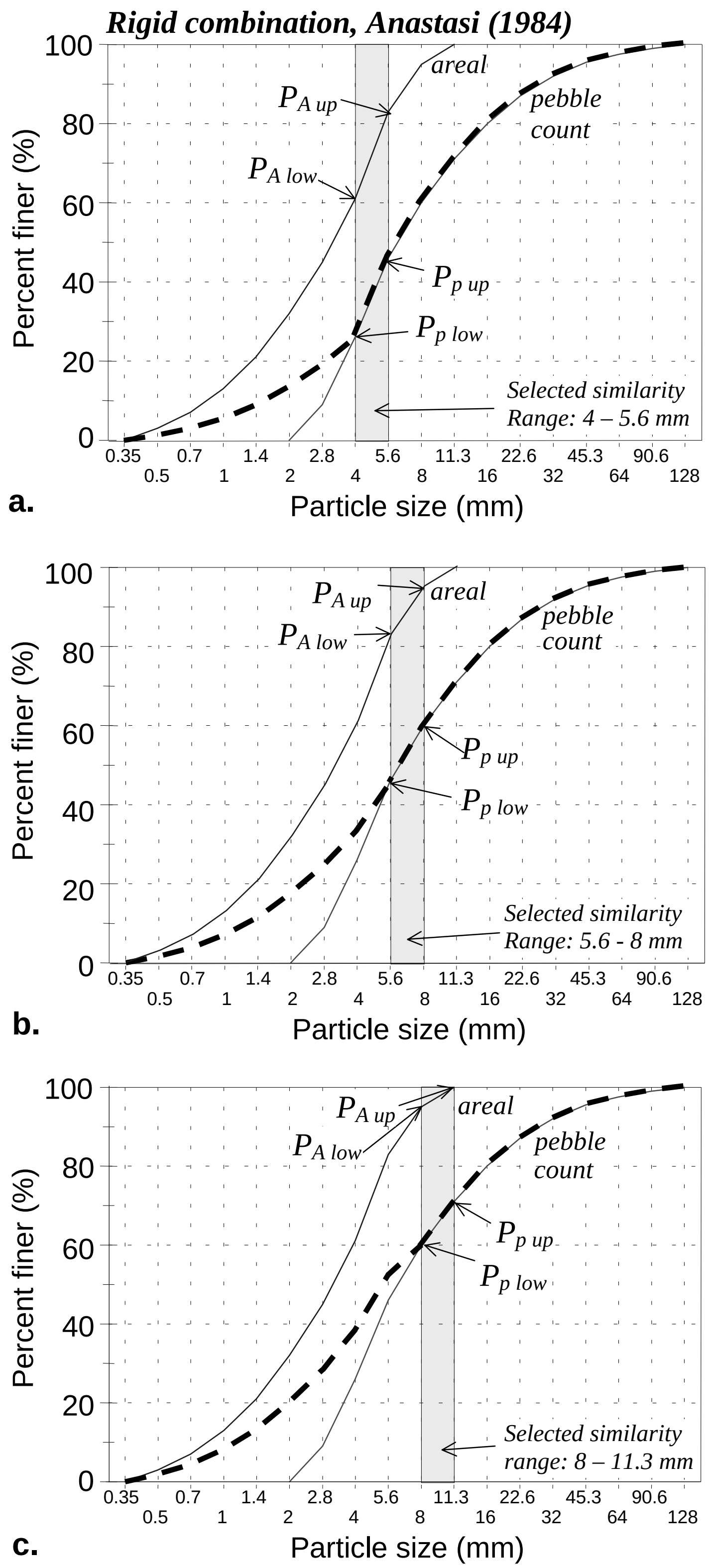


Fig. 4.37: Rigid combination (– –) between an areal sample and a pebble count to form a new fine part of the pebble count size distribution, using three different particle-size ranges of similarity (gray bars): 4 – 5.6 mm (a), 5.6 – 8 mm (b), and 8 – 11.3 mm (c). The cumulative percent finer was computed as decimals, but plotted as percentage.

$$\frac{p_{A\,low}}{p_{A\,up}} \approx \frac{p_{P\,low}}{p_{P\,up}} \quad (4.9)$$

The rigid combination methods computes the percentiles $p_{r\,i}$ (subscript r for rigid) for each particle size D_i of the fine part of the combined pebble count size-distribution from:

$$p_{r\,i} = p_{A\,i} \cdot \frac{p_{P\,low}}{p_{A\,low}} \quad (4.10)$$

Example 4.2:
Table 4.11 provides an example computation for a rigid combination of two particle-size distributions. The particle-size range 5.6 – 8 mm was considered to be similar for the areal sample and the pebble count. The percentiles of the areal sample and the pebble count at the upper and lower border of the selected similarity range, i.e., at 5.6 and 8 mm, were read as $p_{P\,up} = 0.60$, $p_{P\,low} = 0.46$, $p_{A\,up} = 0.95$, and $p_{A\,low} = 0.83$. The similarity ratio in

Table 4.11: Computation of a rigid combination between an areal sample and a pebble count. The selected particle-size range of similarity is between 5.6 and. 8 mm.

	Cumulative size distribution $\Sigma_{n\%i}$		
D_i (mm)	Areal sample $= p_{Ai}$ (Σ)	Pebble count $= p_{Pi}$ (Σ)	Rigid combination $= p_{ri}$ (Σ%)
0.35	0.00		0.000
0.5	0.03		0.017
0.7	0.07		0.039
1.0	0.13		0.072
1.4	0.21		0.116
2.0	0.32	0.00	0.177
2.8	0.45	0.09	0.249
4.0	0.61	0.260	0.338
5.6	0.83 $= p_{A\,low}$	0.**46** $= p_{P\,low}$	$=$ **0.460**
8.0	0.95 $= p_{A\,up}$	0.60 $= p_{P\,up}$	
11.3	1.00	0.71	
16.0		0.80	
22.6		0.87	
32.0		0.92	
45.3		0.955	
64.0		0.975	
90.6		0.99	
128.0		1.00	

Eq. 4.9 is 0.77 ≈ 0.87. For the particle size D_i = 2.8 mm, for example, the percentiles of the adjusted fine part of the pebble count are computed as $p_{r\,2.8}$ = 0.45 · 0.554 = 0.249 = 24.9% (Eq. 4.10)

Results of the rigid combination vary depending on the particle-size range that is selected for similarity. Fig. 4.37 shows rigid combinations that adjust the fine (unrepresentative) portion of a pebble count to an areal sample for three different particle-size ranges selected for similarity. Only the selected range of similarity in Fig. 4.37 b yields a smooth adjustment. This variability makes it necessary to repeat computations for several similar size ranges and to select a result that best fits the study objective.

4.4.2 Flexible combination

A flexible combination (Anastasi 1984; Fehr 1987) generates a completely new particle-size distribution, combined from the distribution of a pebble count and an areal sample (converted to a grid-by-number sampler beforehand) (Fig. 4.38). The distribution obtained from a flexible combination resembles a hand-drawn adjustment curve that extends from the coarse end of the pebble count distribution to the fine end of the areal sample.

Following the same approach as with the rigid combination in Section 4.4.1 (Eq. 4.9), a particle-size class is sought for which the frequency is similar in both samples (similarity range), so that

$$\frac{p_{A\,low}}{p_{A\,up}} \approx \frac{p_{P\,low}}{p_{P\,up}} \qquad \text{(see Eq. 4.9)}$$

$p_{A\,low}$ and $p_{A\,up}$ are the lower and an upper percentiles of the areal sample, and $p_{P\,low}$ and $p_{P\,up}$ are the lower and upper percentiles of the pebble count. All percentiles are used as decimals. The fine part of the new distribution below $p_{f\,low}$ (subscript *f* for flexible) and the coarse part above $p_{f\,up}$ are each generated using a different equation. The fine portion of $p_{f\,i(fine)}$ is computed from

$$p_{f\,i(fine)} = p_{A\,i} \cdot \frac{p_{f\,low}}{p_{A\,low}} \qquad (4.11)$$

$p_{A\,i}$ is the percentile of the areal distribution for the *i*th size class. $p_{f\,low}$ is the percentile of the flexible combination at the lower border of the similarity range and is computed from

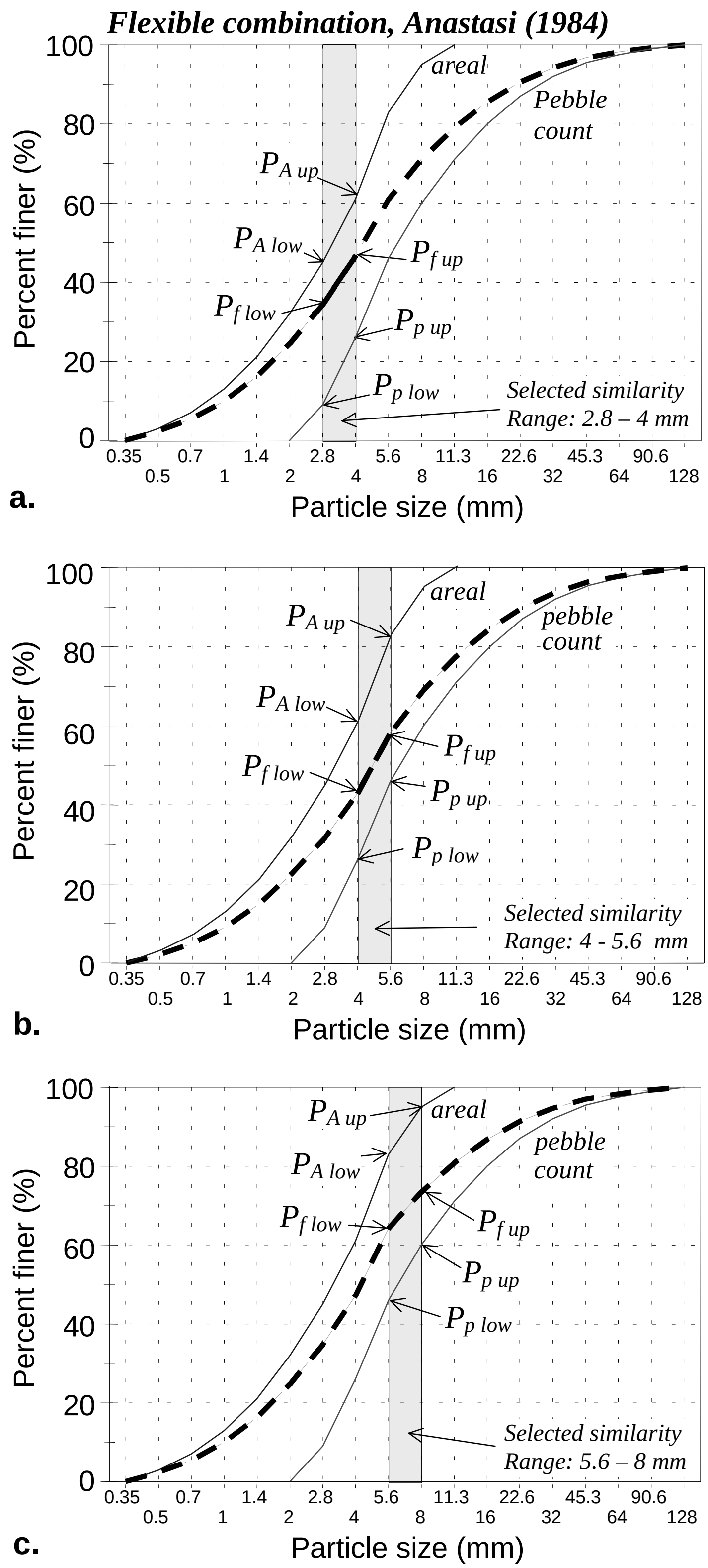


Fig. 4.38: Flexible combination (– –) between an areal sample and a pebble count, for three different particle-size ranges of similarity (gray bars): 2.8 – 4 mm (a), 4 – 5.6 mm (b), and 5.6 – 8 mm (c). Results show minimal variations between different selected ranges of similarity.

$$p_{f\ low} = \frac{(1 - p_{P\ low}) - (1 - p_{P\ up})}{\frac{p_{A\ up}}{p_{A\ low}} \cdot (1 - p_{P\ low}) - (1 - p_{P\ up})} \tag{4.12}$$

$p_{p\ low}$ and $p_{p\ up}$ are the percentiles of the pebble count at the lower and upper border of the similarity range. The coarse portion of $p_{f\ i(coarse)}$ above the upper border of the similarity range $p_{f\ up}$ is computed from

$$p_{f\ i(coarse)} = \frac{1 - p_{p\ i}}{1 - p_{p\ low}} \cdot (p_{f\ low} - 1) + 1 \tag{4.13}$$

The percentile of the flexible combination $p_{f\ up}$ at the upper border of the similarity range is

$$p_{f\ up} = p_{f\ low} \cdot \frac{p_{A\ up}}{p_{A\ low}} \tag{4.14}$$

<u>Example 4.3:</u>
Table 4.12 provides an example computation for the flexible combination of two particle-size distributions. The particle-size range of 4 – 5.6 mm was considered to be similar for the areal sample and the pebble count (grid sample).

The percentile of the flexible combination at the lower border of the similarity range at 4 mm is (Eq. 4.12):

$$p_{f\ low} = \frac{(1-0.26) - (1-0.46)}{(0.83/0.61) \cdot (1-0.26) - (1-0.46)}$$

$$= \frac{0.2}{(1.36 \cdot 0.74) - 0.54} = \frac{0.2}{0.467} = 0.428 \text{ or } 42.8\%$$

The percentiles of the areal sample and the pebble count at the upper and lower border of the similar range, i.e., at 4 and 5.6 mm, were read as $p_{A\ low} = 0.61$, $p_{A\ up} = 0.83$, $p_{P\ low} = 0.26$, and $p_{P\ up} = 0.46$. The similarity ratios in Eq. 4.9 were 0.61/0.83 = 0.57 and 0.26/0.76 = 0.73.

Table 4.12: Computation of a flexible combination between an areal sample and a pebble count. The selected particle-size range of similarity is between 4 and 5.6 mm (see gray band).

	Cumulative size distribution $\Sigma_{n\%i}$						
	Areal sample		Pebble count		Flexible combination		
D_i (mm)	p_{Ai} (Σ)		p_{Pi} (Σ)		$p_{fi\,(fine)}$ (Σ)	$p_{fi\,(coarse)}$ (Σ)	
0.35	0.00				0.000		
0.5	0.03				0.021		
0.7	0.07				0.049		
1.0	0.13				0.091		
1.4	0.21				0.147		
2.0	0.32		0.00		0.225		
2.8	0.45		0.09		0.316		
4.0	0.61	$= p_{A\,low}$	0.26	$= p_{P\,low}$	**0.428** =	**0.428**	$= p_{f\,low}$
5.6	0.83	$= p_{A\,up}$	0.46	$= p_{P\,up}$	**0.583** =	**0.583**	$= p_{f\,up}$
8.0	0.95		0.60			0.691	
11.3	1.00		0.71			0.776	
16.0			0.80			0.846	
22.6			0.870			0.900	
32.0			0.920			0.938	
45.3			0.955			0.965	
64.0			0.975			0.981	
90.6			0.990			0.992	
128.0			1.000			1.000	

The percentile of the flexible combination at the upper border of the similarity range at 5.6 mm is (Eq. 4.14):

$$p_{f\ up} = \frac{0.428 \cdot \ 0.83}{0.61} = 0.583 \text{ or } 58.3\%.$$

For the particle-size class of D_i = 2.8 mm, the adjusted fine part of the size distribution has a percentile of $p_{f2.8} = 0.45 \cdot \ 0.43/0.26 =$ 0.691 or 69.1% (Eq. 4.11). For the particle size class of D_i = 8 mm, the adjusted coarse part of size distribution has a percentile of $p_{f8} = (1\text{-}0.60)/(1\text{-}0.26) \cdot \ (0.43\text{-}1)+1 = 0.691$ or 69.1% (Eq. 4.13).

Flexible combinations were computed for three selected size ranges of similarity: 2.8 – 4 mm (a), 4 – 5.6 mm (b), and 5.6 – 8 mm (c) (Fig. 4.38). Computations of the flexible combination vary only moderately between different selected ranges of similarity, if the two original distributions (areal sample and pebble count) have only a few particle-size classes in common, which is the case in Fig. 4.38. However, the combined distribution curves become more varied between different similarity ranges as the two original distributions share a larger range of common particle-size classes and span a wider range of particle sizes.

4.4.3 Adjusting frequency distributions

Fripp and Diplas (1993) present a method for combining two frequency distributions that is computationally different from the flexible combination in Section 4.4.2, but yields the same result. The combination method by Fripp and Diplas (1993) uses two original percent frequency distributions (e.g., from an areal sample that has been converted to a grid-by-number distribution beforehand and from a pebble count). The number-frequency distributions of both samples are adjusted to create a new, combined frequency distribution. An example computation is provided in Table 4.13.

Table 4.13: Combining frequency distributions of two samples to yield a combined sample. The percent frequency of the particle-size class 4 – 5.6 mm (bold print) is selected as the similar size class for both samples (after Fripp and Diplas 1993)

	Areal sample		Original Pebble count		Adjusted Pebble count	Combined Areal sample + pebble count		
D_i (mm) (1)	$n_{\%Ai}$ (%) (2)	$\Sigma n_{\%Ai}$ (Σ%) (3)	$n_{\%Pi}$ (%) (4)	$\Sigma n_{\%Pi}$ (Σ%) (5)	n_{Padji} (-) (6)	n_{ci} (-) (7)	$n_{\%ci}$ (%) (8)	$\Sigma n_{\%ci}$ (Σ%) (9)
0.35	0.0	0.0	-	-	-	0.0	0.0	0.0
0.5	3.0	3.0	-	-	-	3.0	2.3	2.3
0.7	4.0	7.0	-	-	-	4.0	3.1	5.4
1.0	6.0	13.0	-	-	-	6.0	4.6	10.0
1.4	8.0	21.0	-	-	-	8.0	6.1	16.1
2.0	11.0	32.0	0.0	0.0	0.0	11.0	8.4	24.5
2.8	13.0	45.0	8.0	9.0	7.5	13.0	10.0	34.4
4.0	**16.0**	61.0	**17.0**	26.0	16.0	16.0	12.2	46.7
5.6	22.0	83.0	20.0	46.0	18.8	18.8	14.4	61.1
8.0	12.0	95.0	14.0	60.0	13.2	13.2	10.1	71.2
11.3	4.0	100.0	11.0	71.0	10.4	10.4	7.9	79.1
16.0	0.0	-	9.0	80.0	8.5	8.5	6.5	85.6
22.6	-	-	7.0	87.0	6.6	6.6	5.0	90.6
32.0	-	-	5.0	92.0	4.7	4.7	3.6	94.2
45.3	-	-	3.5	95.5	3.3	3.3	2.5	96.8
64.0	-	-	2.0	97.5	1.9	1.9	1.4	98.2
90.6	-	-	1.5	99.0	1.4	1.4	1.1	99.3
128.0	-	-	1.0	100.0	0.9	0.9	0.7	100.0
	100.0		100.0			142.4	100.0	

For all particle size classes D_i (column 1 in Table 4.13) the percent frequency (by number) is listed for the converted areal sample $n_{\%Ai}$ (column 2) and the pebble count $n_{\%Pi}$ (column 4). From the size classes D_i present in both samples, one size class is selected for which the percent frequencies are most similar for the areal sample $n_{\%A}$ and the pebble count $n_{\%P}$ ("the common size class"). These were the frequencies of 16 and

17% for the size class 4 – 5.6 mm in Table 4.13 (bold print in column 2 and 4). A scaling factor F is then computed that makes it possible to equate the percent frequencies of both samples for the one selected (common) size class i so that

$$n_{\%Pi} = n_{\%Ai} + (F \cdot n_{\%Pi}) \tag{4.15}$$

Solving for F yields

$$F = \frac{n_{\%Pi} - n_{\%Ai}}{n_{\%Pi}} \tag{4.16}$$

F is expressed as a percentage $F_{\%}$ and subtracted from the percent frequency of the original pebble count $n_{\%pi}$ for all size classes below the size class selected as similar for both samples to yield $n_{Padj\ i}$ (column 6).

$$n_{Padj\ i} = n_{\%pi} - F_{\%} \tag{4.17}$$

The frequency of one size class, $n_{\%padj,4}$ in this example, is now identical for the areal sample and the adjusted pebble count. The adjusted pebble count frequencies $n_{Padj\ i}$ for all size classes $D_i \leq 4$ mm (shaded part of column 6) and the percent frequency of the areal sample $n_{\%Ai}$ for all size classes $D_i > 4$ mm (shaded part of column 2) are presented in column 7 and summed. The sum of column 7 does not add to 100 and is readjusted to 100% by dividing each value in column 7 by the sum of column 7 (i.e., 142.4) and multiplying by 100 (column 8). The cumulative frequency distribution in column 9 is the new particle-size distribution for the combined sample.

Histograms of the original areal sample and the pebble count are shown in Fig. 4.39. The two samples have similar particle-size frequencies for three size classes: 4 – 5.6 mm, 5.6 – 8 mm, and 8 – 11.3 mm (i.e., three "common size classes"). Using one of these three particle-size frequencies at a time, three combined particle-size distributions were computed and produced the three combined curves in Fig. 4.40. Results vary slightly between the three computations (see also Fig. 4.38). However, variability of the result increases as the difference in (common) particle-size frequency for the areal and the grid sample increases. Thus, computations should be repeated using several similar percent frequencies (i.e., common size classes), and the combined distribution that best fits the study objective should be selected.

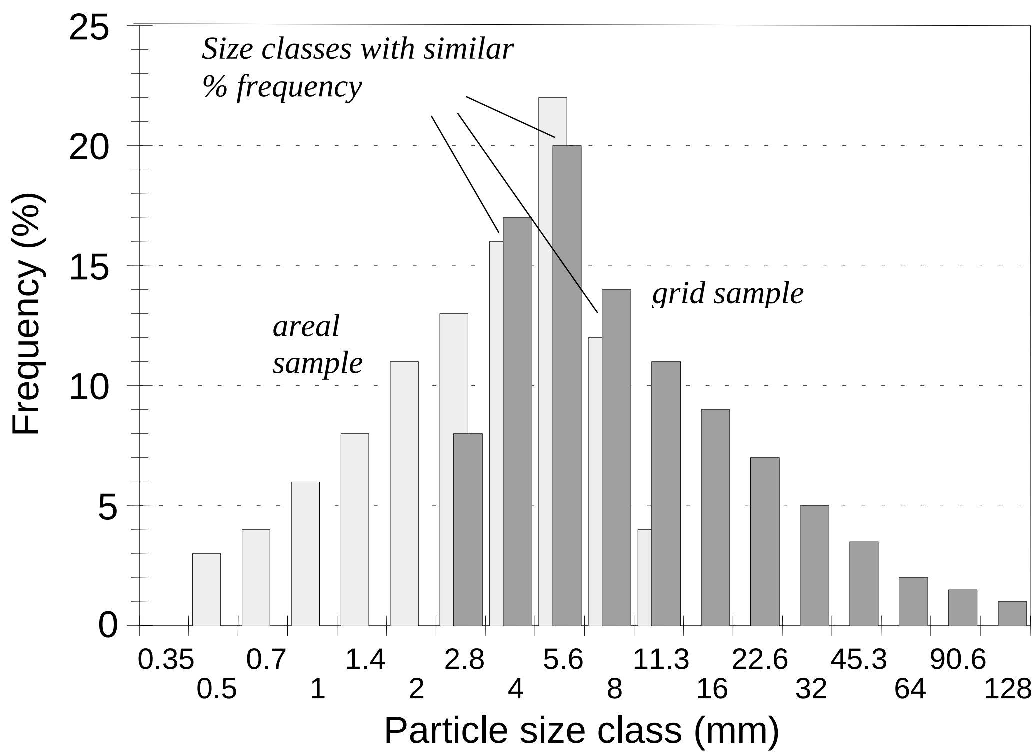


Fig. 4.39: Histogram of an areal sample and a pebble-count

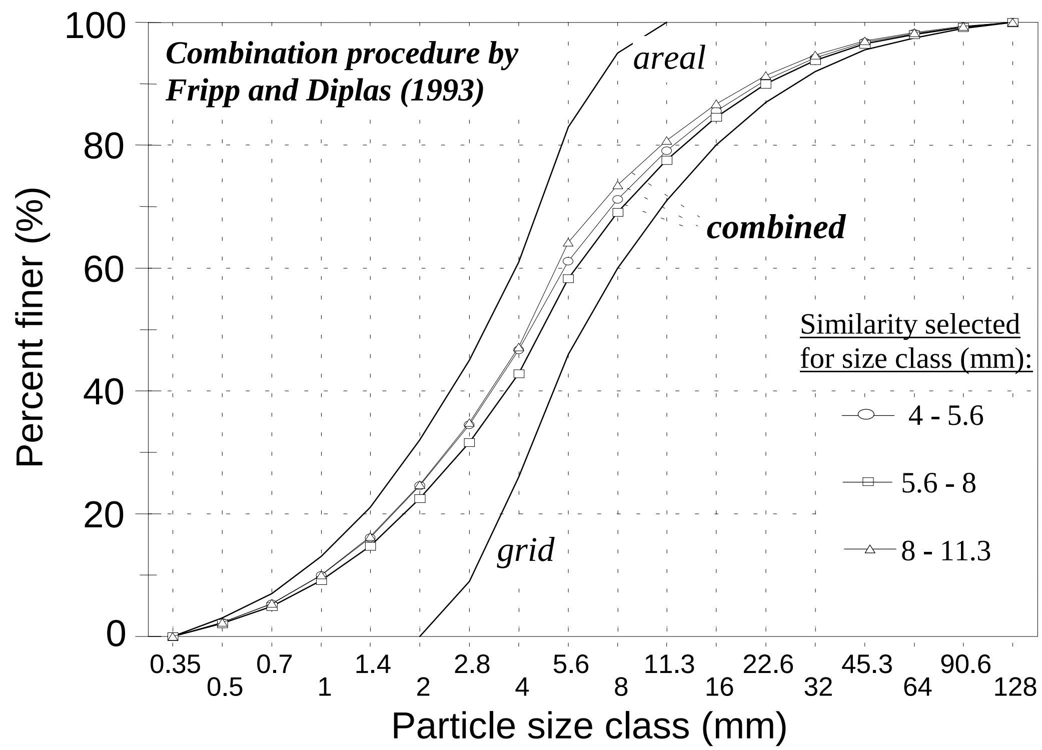


Fig. 4.40: Cumulative frequency distributions of an areal sample and a pebble-count, and the three combined samples obtained from using the percent frequencies of different particle-size classes.

4.5 Recording field results

Sampling results need to be recorded in the field. Either a field book or sampling forms developed prior to the field work may be used for this purpose. Both methods have advantages and disadvantages. Ready-made forms are useful when sampling yields information that is similar for all sites. Sampling forms are also useful to maintain a preset standard of data recording if different people are involved in the field work. One of the greatest advantages of using sampling forms is that the process of developing the forms requires visualizing and anticipating the sampling process. This "homework" helps to organize the field work as it prompts the form developer to consider all the information to be recorded, the order of measurements, all the equipment needed, and other information useful to record. Thus, developing sampling forms may be time well spent, even if the field forms are ultimately not used.

The disadvantage is that forms used during field work get dirty, become illegible when wet, and tend to get lost. Single forms are prone to being swept away by the current or the wind, or to becoming buried in the equipment. A rain-proof field book used for one site or for one study only tends to better "weather" the field season and is more suitable when different kinds of observations are recorded. A compromise between a field book and sampling forms is to print field forms on water-resistant paper, and assemble them with a spiral binding, a plastic cover, and a hard back. Personal choice and the type of field work ultimately determine whether to use a field book or field forms, or a combination of both. Both the field book and sampling forms should be photocopied frequently between days of field work, and copies should be stored in a safe place.