6. Spatial sampling schemes

Spatial sampling schemes refer to the spatial patterns by which individual particles (in pebble counts) or groups of particles (in areal or volumetric samples) are gathered from the streambed to provide a sample. Sampling schemes affect the outcome of a sample and different sampling schemes may produce different results when used in the same stream reach (Mosley and Tindale 1985). No sampling scheme is genuinely superior to others. The appropriateness is case-specific and depends on several factors including:

- *spatial scale* of the investigation, that is, whether sampling is to represent bed material from a long reach (ca. 20 stream widths), a single riffle-pool unit, an individual geomorphological or sedimentary unit, or a small-scale location;
- degree of spatial *homogeneity or heterogeneity* of particle-size patterns within the reach of concern,
- desired sampling *precision* or tolerable *error*;
- restrictions imposed by keeping the sampled volume *manageable*;
- necessity to keep streambed *destruction at a minimum*; and
- the *specifics* of a given study.

Information presented in this section is designed to assist the reader to understand sampling schemes and select an appropriate sampling scheme for a specific situation.

Three main spatial sampling schemes are discussed in this document:

1. ***Spatially integrated*** = ***unstratified sampling***	Covers the entire reach with the same sampling pattern, and ignores sedimentary[1] or geomorphological units[2]. A reach-averaged bed-material size is obtained (Sections 6.2 and 6.4);
2. ***Spatially segregated*** = ***stratified sampling***	Distinguishes between geomorphological or sedimentary units and may use a separate sampling pattern for each unit (Sections 6.3 and 6.5);
3. ***Spatially focused sampling***	Focuses on a small area of interest, such as near a hydraulic structure, or fines deposited in a pool (Section 6.6).

[1] **Sedimentary units** *are streambed areas with uniform particle-size distributions. A sedimentary unit may comprise part of one or several geomorphological units. Sedimentary units are also referred to as textural units, facies, or as patches, when areas of similar particle-size distributions appear to be "patchy". A coarse facies, for example, may cover the upstream part of a bar and extend into the adjacent riffle upstream.*

[2] **Geomorphological units** *are areas within the streambed that are part of the same geomorphological feature, such as a riffle, pool, bar, rapid, run, or glide (see Section 3.2.1 for descriptions of stream morphology). Particle-size distributions can vary greatly within a geomorphological unit. Bars, for example, display downbar and landward fining.*

Statistical analyses of bed-material samples assume that samples are collected at random locations. Randomization of sampling locations is obtained by several sampling patterns:

- Complete random – samples are collected at random locations within the sampling area;
- Systematic grid – samples are collected at the intersections of a systematic grid with a random starting point;
- Overlapping grid systems – subsamples are collected each at a separate grid system, overlaying the other ones,
- Random within systematic cells – samples are collected at random locations within grid cells that have a random starting point.

Combining these four sampling patterns with integrated (unstratified) or segregated (stratified) sampling yields eight different sampling schemes that are commonly applied to gravel-bed streams. An overview of these eight sampling schemes is presented in Fig. 6.1. The terms “strata” and “stratified” in this document refer to sedimentary or geomorpholo-gical units. This terminology departs from some texts on sampling schemes where *strata* and *stratified* refer to a segregation of the sampling area into artificial equally-sized strata, which are referred to as cells in this document.

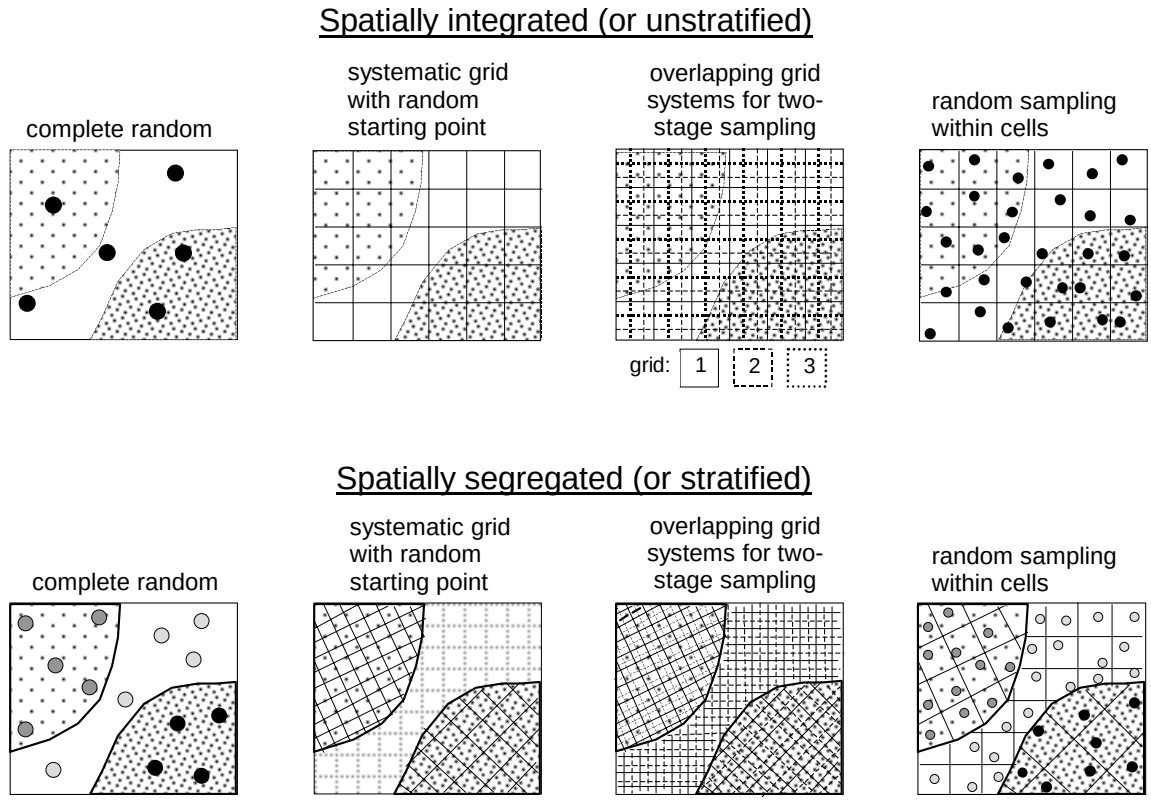

Fig. 6.1: Sampling schemes commonly used for bed-material sampling in gravel-bed streams.
Bed unit 1, Bed unit 2, and Bed unit 3.

These sampling schemes can be applied to all sampling procedures, such as surface pebble counts, volumetric sampling, and areal sampling. The various sampling procedures have been presented in Sections 4.1 and 4.2.

6.1 Terminology and sampling principles

Before various aspects of spatial sampling schemes are discussed, some terms regarding stream types, stream morphology, reach length, as well as spatial homogeneity and heterogeneity, should be clarified. Furthermore, this introductory section addresses pilot studies and briefly recalls important aspects of pebble counts and volumetric samples.

6.1.1 Stream types and stream morphology

Stream types and stream morphology refer to the stream type classification by Rosgen (1994, 1996), and the stream morphologies as classified by Montgomery and Buffington (1993, 1997). Both classification schemes are discussed in Sections 1.3.1 - 1.3.3.

6.1.2 Length of the sampling reach

The length of the sampling reach is determined by the spatial extent of the sampling goal. For local studies, a sampling reach often comprises the length of one sequence of recurring elements of stream morphology. In C-type streams (Rosgen 1994, 1996) with riffle-pool morphology (Montgomery and Buffington 1993, 1997), this sequence may include a riffle and a pool and extend over approximately 5-7 times the bankfull stream width. In meandering streams, a riffle-pool sequence covers one meander bend. In B-type streams with rather featureless plane-bed morphology, the sampling reach may be one in which there are no visible changes in the streambed composition. In A-type streams with step-pool morphology, a reach could be one, or a few, similar-looking step-pool units.

For a more general characterization of the streambed material, Rosgen (1996) proposes sampling a stream section consisting of at least four consecutive riffle-pool sequences, equaling four meander bends (= two meander wavelengths), or a reach length of 20-30 bankfull stream widths. Bevenger and King (1995) extend the length of the reach sampled by a zigzag pebble count over several hundred meters, covering a reach length on the order of 100 stream widths (Section 6.2.2). Long sampling reaches of 20 stream widths or more in length are especially important for spatially segregated sampling when particle sizes of groups of sedimentary units are combined for a reach-average value (Lisle and Hilton, personal comm.). Similarly, for a comparison of particle sizes of geomorphological units, such as riffles and pools, sampling should extend over several riffle-pool units to average any local effects. In this document, the term *reach* usually refers to the stream length of one riffle-pool sequence or about 5 - 7 stream widths, unless otherwise specified.

6.1.3 Homogeneous versus heterogeneous gravel deposits

Gravel surfaces are *homogeneous* when they consist of a mixture of particle sizes, but have no spatial variability in the composition of the particle mixture. Particle-size distributions are then similar in all stream locations. Entire reaches of truly homogeneous gravel beds are rare.

Near-homogeneity of gravel-beds may be found in large lowland gravel-bed rivers, or in mountain B-type streams with cobble and gravel beds. B-type streams have a plane-bed morphology with long, rather featureless stream sections characterized as runs. Infrequent pools, typically forced by channel obstructions (LWD, boulders, or bank projections) may occur in these channels and are interrupted by infrequent rapids (Section 6.2.2). The classification of a reach as *near*-homogeneous as opposed to heterogeneous is subjective, since there are no standards defining the degree of spatial homogeneity or heterogeneity in fluvial deposits.

Many mountain gravel-bed rivers have *heterogeneous* bed material in which the composition of the gravel bed varies between different locations of the reach. In C-type streams gravel- and cobble beds are composed of sequences of geomorphological units encompassing bars, riffles, pools, rapids, runs, and glides. Those geomorphological units often have a characteristic spatial variability of particle sizes, such as downbar and landward fining on bars (Section 3.2.2). In the longitudinal direction, bed-material size is commonly finer in pools (particularly when fine sediment deposits in pools) and coarser on riffles. Graphic examples of spatial variability of bed-material size in C-type streams are provided by the detailed field measurements of Lisle and Madej (1992) (Fig. 3.10). A-type streams with a step-pool morphology have steps composed of cobbles and boulders that are only mobile during very large floods. Smaller cobbles or gravel that are annually mobile can be deposited in pools, or occasionally on midstream deposits, while fine gravel and sand are primarily found near the banks. Streams containing large woody debris often have heterogeneous beds because the debris causes spatially varied flow hydraulics with local scour in one location and deposition in the next. An example of a heterogeneous bed in the presence of large woody debris is presented in Fig. 3.12.

6.1.4 Pilot studies

A pilot study prior to the main sampling project is useful for several reasons (Sections 2.1.5.4, 4.2.3 and 4.2.4). It allows the investigator to become familiar with the sampling reach, to determine the length of the sampling reach, and to assess the degree of spatial variability of bed-material size. The categorization of the reach into homogeneous or heterogeneous is required for selecting an appropriate sampling scheme. Pilot studies may involve collecting actual samples. Information on a particular particle-size percentile and the sediment sorting coefficient derived from a pilot sample, or the variability between pilot samples, can be used to estimate the sample size needed for a desired precision of the study. The pilot study should include a sketch map of the reach and its delineated geomorphological or sedimentary units. This sketch map, based on quick visual

assessments, should also include bed surface parameters such as the mean and maximum particle size, the percent fines, bed surface structures, the presence of large woody debris, or any other parameters of concern.

6.1.5 Spatial aspects of pebble counts

Sampling procedures for pebble counts and number-based sample size recommendations, are discussed extensively in Sections 4.1.1 and 5.2. However, reiteration of the spatial aspects of the various sampling procedures, sample-size recommendations, as well as particle measurements and data recording seems useful.

6.1.5.1 Minimum sampling point spacing

Sampling points of pebble counts should be spaced at least the length of the D_{max} particle size, or twice the D_{max} particle size, in order to avoid serial correlation due to double-counting large particles. Serial correlation and overrepresentation of large particles also occurs when the sampling path coincides with the longitudinal direction of clusters or transverse ribs (Section 4.1.1.2). A large spacing between sampling points can prevent this overrepresentation.

6.1.5.2 Number of sampling points

The number of particles that should be sampled is largely determined by statistical considerations. Spatial factors considered in sample-size determinations are minimum sampling point spacing and the size of the stream reach to be covered by one pebble count. A detailed analysis of sample size needed to define the D_{50} and other percentiles within a specified precision for a given standard deviation or sediment sorting is presented in Section 5.2.2 - 5.2.4. Major findings are summarized below.

Although traditionally 100 particles were counted in a pebble count, recent analysis of sample size indicates that it is advisable to count at least 400 particles (Rice and Church 1996b, Diplas and Lohani 1997). The gravel deposit for which Rice and Church (1996b) provided a detailed analysis of the relationship between sample size and precision can be considered representative for many gravel beds. Sediment sizes ranged from sand to large cobbles, and size frequencies were not exactly, but approximately normally distributed (in terms of ϕ-units), with a slight skewness towards a tail of fine particles, and a standard deviation of 1.2 ϕ[3]. A 400-particle sample estimated the D_{50} to within ±0.15 ϕ[4], which is approximately equivalent to an error of ±10 % in terms of mm-units. Such a precision is often desirable in particle-size assessments, although an acceptable level of precision needs to be selected for each study individually.

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[3] *This value is on the low side for mountain gravel-bed streams that tend to have standard deviations (or sorting coefficients (Inman 1952)) of 1.5 or higher if the particle-size distribution comprises large boulders. A sorting coefficient of 1.2 - 1.5 may be obtained if large boulders not transportable by frequently occurring floods are excluded from the analysis.*

[4] *See Section 2.1.2.2 for conversion between mm and ϕ-units.*

The sample size needed to estimate the tails of the distribution (e.g., the D_5 or the D_{95}) to within ±0.15 ϕ is larger than the sample size needed to estimate the D_{50} to the same precision. If the underlying distribution of the bed material is symmetrical and normal, and has a sorting coefficient of 1.2 ϕ, the sample size for estimating the D_5 and D_{95} is a factor of approximately 2.6 larger than the sample size needed for the D_{50} (Fig. 5.10). Thus, if 400 particles are required to estimate the D_{50} to within ±0.15 ϕ, more than 1,000 particles are needed to estimate the D_5 or D_{95} with the same precision.

Many gravel deposits are not symmetrical and normal, but have particle-size distributions (in ϕ-units) that are skewed towards a fine tail. This deviation from a standard normal distribution does not significantly alter the required sample size for the D_{50} particle-size estimate. However, the sample size needed to estimate the D_5 particle size is more than 4 times larger than the one for the D_{50} particle size. Thus, if 400 particles were needed to estimate the D_{50} to within ±0.15 ϕ, 1,600 particles would be needed to estimate the D_5 to the same precision in distributions skewed towards a fine tail. No pronounced increase in sample size is necessary to estimate the D_{95} to within the same precision as the D_{50} particle size (Fig. 5.11).

Sample sizes larger than indicated in the paragraph above are needed if precision criteria become more stringent, and if particle-size distributions become less well sorted. Note that these sample-size considerations do not account for spatial heterogeneity, but are only valid for homogeneous sampling reaches, such as sedimentary units. For heterogeneous reaches, sample sizes are likely to be larger. A two-stage approach should be used to determine the relation between sample size and precision (Sections 5.2.3.1, 6.3.1.2 and 6.4.4.4). Heterogeneous reaches can be sampled most efficiently if the reach is delineated into sedimentary (homogeneous) units that are sampled separately (Section 6.3.2).

6.1.5.3 Minimum sampling area

For a sample size of 400 particles, a pebble count (Section 6.2 and 6.3) requires a minimum sampling area of 400 times the square of the relevant D_{max} particle size. The necessary sampling area increases rapidly with the D_{max} particle size. For D_{max} particle sizes of 64 and 360 mm, the minimum sampling areas are 1.6 and 52 m^2, respectively (see also Table 6.4). For a more generous particle spacing of 2 D_{max}, minimum sampling area increases fourfold to 6.6 and 207 m^2, respectively.

6.1.5.4 Measurement of particle sizes in pebble counts

The sizes of particles picked up from the streambed during a pebble count are usually measured in half ϕ-units using a template and recorded in 0.5 ϕ-unit particle-size classes (e.g., 22.6 - <32 mm). Binning into ϕ classes is useful when comparing pebble count data with sieve data, and using a template reduces errors in particle size measurements. However, binning into ϕ classes assumes an underlying normal distribution of particle sizes, an assumption which may be useful in many, but not in all cases.

If particle sizes in a sampling area are obviously not normally or Gaussian distributed (in ϕ-units), particle axes should be measured with a caliper and recorded in mm, which allows more possibilities for later particle-size analysis. However, caliper or ruler measurements are subject to operator error and not directly comparable to sieve data (see Section 2.1.3.2 for comparison between ruler and template measurements).

6.1.5.5 Recording pebble count data

Particle sizes from pebble counts should always be recorded in a systematic manner, so that the approximate location of each counted particle can be traced. To achieve this, all transects should start on the same side of the stream, beginning at the downstream end of the reach and working upstream. All particle-size data from one transect should be recorded sequentially in one column (or row). Additional information to be recorded are distance from downstream end of the sampling reach, major geomorphological features of the transects (e.g., riffle, run, pool-bar), and the water line position (Table 4.3, Section 4.1.1.7). The same applies to zigzag pebble counts (Section 6.2.2) which can be considered as diagonal transects.

A spatially systematic particle-size record has several advantages. It permits the user to analyze whether particle sizes vary in a longitudinal direction by comparing individual transects, or sets of adjacent transects. Lateral particle-size variability can be estimated from moving averages over 5 to 9 consecutively counted particle sizes. Spatial patterns in particle size determined from the record may not have been obvious prior to sampling. A spatially systematic particle size record can also be used to delineate sedimentary or even geomorphological units retroactively. The delineation can be made visually (looking at the numbers) or by applying a *moving window* technique for a statistical delineation (Crowder and Diplas 1997) (Section 6.3.2.3). Particle-size data can then be consolidated for each sedimentary unit (Section 6.3.2.1). Thus, a crude spatially segregated bed-material size analysis can be obtained after the fact from a spatially integrated sampling scheme.

6.1.6 Spatial aspects of volumetric sampling

Spatial aspects of sampling schemes for volumetric samples are literally multi-layered and more complex than those for pebble counts.

6.1.6.1 Layers to be sampled

Gravel beds are often vertically stratified. Stratification of gravel beds is described in Section 3.3, and sedimentary layers are described in Fig. 4.1, Section 4, and Section 4.2. Volumetric samples can be obtained from different layers that have different particle sizes. The exact delineation of the sampled layer is crucial to the sampling success. Layers or strata that can be sampled by volumetric samples are:

- the coarse *armor* layer (1-2 times the *b*- or *c*-axis of the D_{max} particle thick),
- the finer *subarmor* layer,
- the *subsurface* layer below the particles immediately exposed on the bed surface, and
- the *unstratified* bed material.

The surface sediment, i.e., particles exposed to the surface, cannot be sampled volumetrically because conceptually, there is no thickness associated with the sediment surface.

Volumetric sampling of the armor layer in coarse gravel and cobble beds has several problems: (1) A stringent criterion defining the depth of the armor layer is not available, and each study needs to define its own criteria. (2) Taking a volumetric armor-layer sample down to a specified depth is feasible in bed material of fine gravel where the armor-layer sediment can be scraped off the subarmor sediment, but becomes difficult in coarse gravel and cobble beds. (3) For practical reasons, an armor-layer sample is limited in areal extent to approximately 0.1 - 1 m^2. The sediment mass contained in such armor-layer samples is often too small to be accurate (Section 5.4) and requires taking several subsamples. (4) Volumetric armor-layer samples and surface pebble-counts yield different particle-size distributions in armored gravel-bed rivers because volumetric armor-layer samples contain fine subsurface sediment that is not part of the surface sediment and not sampled by pebble counts.

The subsurface (surface layer removed) and the subarmor layer (armor layer removed) are conceptually similar in particle size, and both are usually finer than the armor layer sediment. This document uses the term *subsurface* sediment for the sediment from both below the surface and below the armor layer unless a specification is necessary.

6.1.6.2 Relation between surface and subsurface sediment size

The spatial variability of the surface sediment is visible, and a sampling scheme can be selected that is appropriate for the specified degree of spatial variability and the study objectives. Subsurface or subarmor sediment is hidden from view and only inferences about its spatial variability are possible based on principles of the relation between surface and subsurface sediment. Buffington and Montgomery (1999a and b), and Lisle (pers. comm.) found a linear relation between percentiles of the surface and subsurface sediment-size distribution for a sediment patch (facies)[5]. Although the subsurface sediment is often finer than the surface sediment, the exact relation varies between facies. Thus, the spatial variability of the surface sediment may be used as a first approximation of the spatial variability of the subsurface sediment, and an appropriate sampling scheme may be selected accordingly (also see Section 6.5.2).

However, the surface sediment size is not always an indication of the subsurface sediment size. For example, a veneer of fine sediment or a lobe of coarse sediment may be

[5] *Facies or patches are homogeneous streambed areas with no systematic spatial variation of bed-material size.*

deposited on the surface after the subsurface sediment was formed during the last flood event. In this case, the spatial variability of facies units on the surface is likewise not indicative of the subsurface facies and a sampling scheme selected on the basis of the surfaces facies may be inappropriate for sampling the subsurface sediment.

6.1.6.3 Feasibility and the statistical relationship between mass of subsamples, total sample mass, and number of sampling locations

An individual volumetric sample describes the bed material at a specified sampling location. Several volumetric samples need to be obtained at various locations to characterize the bed-material size within a reach. Sampling schemes for volumetric samples need to consider three factors:

1. number and mass of individual samples,
2. total sample mass, and
3. spatial allocation of sampling locations within the sampling area of concern.

In moderately sorted fine gravel beds, the three factors can be considered statistically interdependent. A preset sampling precision determines the total sample mass from a sample mass - error relation (Fig. 5.22 a - c), or from a two-step approach (Section 5.4.2.1). Sample mass for individual volumetric samples can be estimated from sample mass equations for bias avoidance (Section 5.4.3.1), or empirically from the percentage mass of the D_{max} particle size (Sections 5.4.1 and 5.4.1.2). Total sample mass divided by the mass necessary for bias avoidance in individual samples yields the number of sampling locations that need to be allocated in a strict or randomized grid pattern over the reach or sampling area of concern.

A strict statistical approach is not feasible in coarse gravel-bed mountain streams because allotting several hundreds of samples over a reach leads to sample masses of several hundreds or thousands of kg. The coarseness of the bed material and the sampling objectives determine the sampling equipment and the mass of individual samples, although several subsamples can be combined to form an individual sample. Pipe samplers (Section 4.2.4.5) appropriate for fine gravel-bed rivers collect a few kg of sediment. Barrel samplers (Section 4.2.4.6) and plywood sheets (Section 4.2.4.7) are more appropriate for coarse gravel- and cobble-bed rivers and collect about 50 kg per sample.

When using a spatially integrated sampling scheme to sample the reach (Sections 6.4.1. and 6.4.2), the number of samples needed depends on the size of the reach and how spatially variable particle-size distributions are within the reach. When sampling is spatially segregated (Section 6.5), the size of a sedimentary or geomorphological unit determines the number of samples that can reasonably be collected from the sampling area. Collecting 100 barrel samples of 50 kg each may satisfy a preset sampling precision, but doing so on a riffle 10 m by 10 m in size destroys the site. Two to four barrel samples may be justifiable from an ecological standpoint. If a pipe sampler is used in a fine gravel bed, ten or more samples may be appropriate for a 100 m^2 riffle.

The selection of a sampling scheme and the total sample mass for volumetric sampling are often governed by practicality, particularly in coarse mountain gravel-bed streams. Both sampling scheme and sample mass may be a compromise between desired sample precision, the specifics of a given study goal, the particulars of a sampling site, funding, and logistics. The *reasonable* number of sampling locations in a small reach or on a sedimentary unit in mountain gravel-bed rivers may not suffice to cover the spatial variability, and the precision obtained from a small total sample mass may not allow more than a rough estimate of the D_{50} particle size. However, thoughtful planning of the statistical analysis and the field work may assist obtaining the maximum information possible out of a restricted sampling condition (Section 5.4.1.4, 6.4.3 and 6.4.4).

6.2 Spatially integrated or unstratified pebble counts (reach-averaged sampling)

Spatially integrated pebble counts cover the reach evenly with a preset sampling pattern. The resulting particle-size information is reach-averaged, unless a spatially distinct record permits spatial segregation of the data at a later time (Sections 6.1.5.5 and 6.3.2.3). Reach-averaged information on bed-material particle size may be used for a variety of purposes which include the computation of reach-averaged bedload transport rates, a comparison of bed-material sizes between reaches, or to detect a change over time when sediment supply to the reach has been altered (Lisle et al. 1993). A comparison of the reach-averaged surface D_{50} size with the D_{50} particle size of bedload (Lisle 1995), of the subsurface D_{50} (Dietrich et al. 1989), or the D_{50} size that the stream is competent to transport (Buffington and Montgomery 1999c) may be used to evaluate whether transport is supply or transport limited.

Sampling patterns for different degrees of reach homogeneity or heterogeneity

The tightness of sampling patterns used in spatially integrated sampling schemes should reflect the degree of spatial variability of bed-material size, i.e., the degree of reach homogeneity or heterogeneity. For streambeds with moderate spatial variability in bed-material size, i.e., relatively homogeneous beds, widely-spaced sampling patterns are appropriate. As the degree of spatial variability of particle sizes over the reach increases or becomes more complex, the sampling patterns covering the reach must become more tightly spaced in order to sample all sedimentary units of the reach in a representative manner (Table 6.1).

Sampling patterns for different ease of wadability and particle retrieval

The regularity of the sampling patterns should be selected considering how well all streambed locations are accessible to the wading person and the ease of particle identification and retrieval. Easily wadable and well-sorted gravel beds may be sampled by paced transects or unplanned zigzag courses. Both sampling schemes allow the operator some latitude in deciding the sampling path. Regular and pre-determined sampling

schemes, such as parallel transects along measuring tapes or sampling at grid points are required in beds in which wading and particle retrieval are difficult. Operators may be tempted to avoid sampling in deep spots or behind obstacles and to avoid retrieving interstitial fines and wedged particles (Sections 4.1.1.1 - 4.1.1.4).

The ideal sampling scheme for a reach should reflect both the degree of homogeneity/ heterogeneity and the ease of sampling, i.e., the ease of wadability, particle selection and particle retrieval. If homogeneity of the reach is paired with well sorted gravel beds and easy wadability, sampling may use a pattern that is widely-spaced and completely random or unsystematic. Examples are widely-spaced paced transects and unplanned zigzag walks (Table 6.1). If heterogeneity of the reach is paired with poor sediment sorting and difficult particle retrieval, a tightly-spaced grid pattern should be used.

Table 6.1: Suggested spatially integrative sampling schemes for surface samples in reaches with different degrees of spatial variability of particle sizes, ease of wadability and particle retrieval

Spatial variability of particle sizes	→	Sampling scheme Tightness / Regularity	←	Ease of wadability and particle retrieval
Near-homogeneous Some B-type streams with plane beds, or sections of large streams	→	Widely-spaced / Random or irregular - paced transects - unplanned zigzag walk	←	Bed easily wadable, well sorted gravel, easy particle retrieval;
Heterogeneous e.g., C-type streams with pool-riffle sequences, complex bars	→	Tightly-spaced / Regular - transects along a tape - grid over entire reach	←	Bed poorly wadable, poorly sorted gravel, difficult particle retrieval;

6.2.1 Near-homogeneous reaches: paced transects, transects along measuring tapes, and an unplanned zigzag course

Easily wadable and well-sorted gravel beds in near-homogeneous reaches are most likely to occur on sections of large dry gravel bars. Beds in such reaches can be sampled by picking up particles from paced transects (Wolman 1954) or by following an unplanned upstream zigzag course across the reach. However, these two sampling schemes are not suitable if deep water, obstacles, mud, rapids, fast flow or protruding rocks affect the sampling path of the pacing person, and if interstitial fines and wedging make particles difficult to retrieve from the bed. Difficult wading and particle retrieval may tempt the operator to consciously or unconsciously avoid sampling at those locations, thus creating a bias against particles in poorly accessible locations (Sections 4.1.1.3 and 4.1.1.4). Parallel transects (Leopold 1970) placed along measuring tapes, or sampling in a premeditated zigzag course allows sampling the reach in a more systematic pattern and reduces the possibility for operator subjectivity. The most even coverage of an

approximately homogeneous reach is attained by performing pebble counts in a systematic grid pattern established by transects along a measuring tape.

The reach-averaged particle-size distribution in a homogeneous reach is estimated from a combined sample of all particles sampled within the reach. No information is obtained on the spatial variability of the particle sizes.

6.2.2 Long and relatively homogeneous stream sections: planned zigzag course

B-type streams with plane-bed morphology are representative of streams with relatively homogeneous beds. Long runs with a few pools forced by large rocks or large woody debris are separated from each other by occasional rapids. Paced transects and *unplanned* zigzag walks may be appropriate here. However, these sampling patterns are not appropriate where pools, rapids or large woody debris causes spatial variability in particle size and where poorly sorted gravel beds make wading and particle retrieval difficult. The unpremeditated sampling paths of both sampling patterns are guided by convenience and caution and cause irreproducible sampling results (Kondolf 1997 b). In order to avoid operator bias in selecting sampling locations and particle retrieval, the sampling pattern should become more systematic and provide less opportunity for operator subjectivity. Zigzag pebble counts with a p*remeditated*, *systematic* course, and parallel transects along a measuring tape are often suitable in B-type streams with plane-bed morphology.

Systematic zigzag sampling path

A planned, symmetric, bank-to-bank zigzag course may be viewed as a sequence of diagonal transects that integrate over both lateral and longitudinal bed-material variability. When a long stretch of river is sampled by a zigzag course, it is important that the sampling path is premeditated and based on stream dimensions and intended sample size (Fig. 6.2). Bank contact points must be spaced *evenly* and *independent* of any stream features to ensure statistical reliability of the sample. Unpremeditated sampling paths are subjective and do not provide statistical reliability in non-homogeneous stream reaches. “Eye-balled” zigzag sampling paths should be reserved for quick reconnaissance sampling. Bevenger and King (1995) proposed that the ratio of thalweg length to the length of the zigzag course walked by the operator should be about 0.9. This value is obtained when bank contact points for zigzag sampling are spaced at intervals of two stream widths. However, a tighter or wider zigzag course may be needed to obtain the necessary number of sample points (i.e., sample size) and to obtain the necessary sample point spacing within the reach of interest.

Recall that sample size should be at least 400 particles to determine the D_{50} to within approximately ± 0.15 ϕ or 10 - 11% in poorly sorted ($s \approx 1.5\ \phi$) bed material. The sample size should be larger when percentiles at the distribution tails, particularly at the fine tail, are to be determined (see Section 5.2 for discussion of sample size).

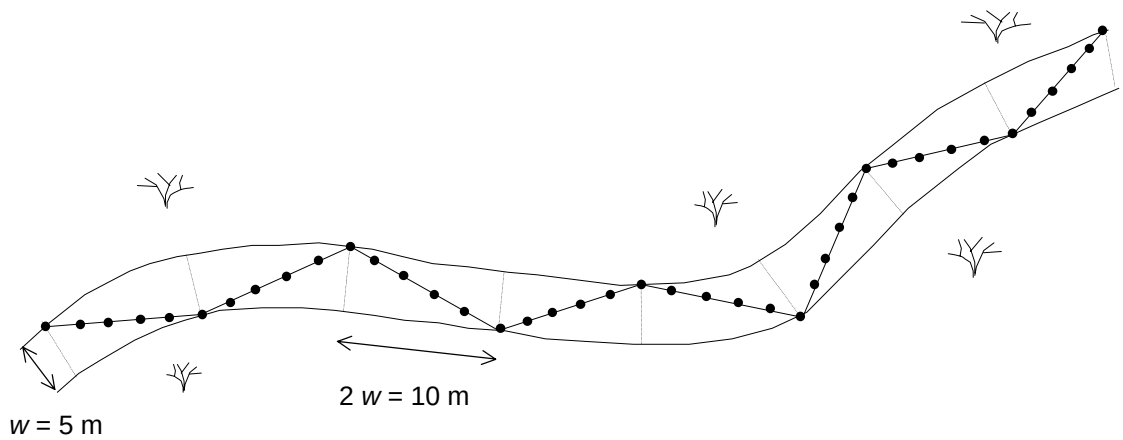

Fig. 6.2: Systematic zigzag sampling scheme with bank contact points evenly spaced at two stream widths. The ratio of thalweg length to length of the zigzag course is 0.9.

Minimum spacing for avoiding serial correlation in pebble counts is 1 - 2 D_{max} diameters, i.e., 0.3 – 0.5 m in many mountain gravel-bed streams. In a stream 5 m wide, a zigzag course that collects 400 particles at 0.3 m intervals and touches the banks at intervals of two stream widths covers a total stream length of 107 m, or 21 stream widths (Table 6.2). This is equivalent to the length of a sampling reach recommended by Rosgen (1996). If the sampling objective is to detect a change in particle-size distribution over time within a stream section, the reach should extend over roughly 100 stream widths in order to average-out local effects caused by sediment deposits at the mouths of small tributaries, rockfall, or in backwater areas. Thus, the spacing between sampling points increases accordingly. Using the same scenario with bank contact points every 10 m in a 5 m wide stream and a 400-particle sample size, a zigzag pebble count with a 2.2 m spacing covers 800 m of stream length, or 160 stream widths (Table 6.2).

Table 6.2: Longitudinal extent of a 400-particle zigzag count with bank contact points every 2 stream widths in streams 5 m and 10 m wide.

	Stream width (w):			
	5 m		10 m	
	Sample point spacing:			
	2.2 m	0.3 m	2.1 m	0.3 m
Particles per diagonal, n_d	5	37	11	73
Number of sections, $n_S = 400/n_d$	80	11	36	5.5
Thalweg length covered, $L_T = n_S \cdot 2w$	800 m	107 m	727 m	109 m
Number of stream widths covered, $n_w = L_T/w$	160 w	21 w	73 w	11 w
Zigzag course length, $L_Z = n_S \cdot \sqrt{w^2 + (2w)^2}$	894 m	120 m	805 m	122 m
L_t/L_z	0.9	0.9	0.9	0.9

The spacing L_p between particles for zigzag pebble counts can be computed from

$$L_p = \frac{\sqrt{w^2 + 2\,w^2} \cdot \; L_t}{n_s \cdot \; 2\,w} \tag{6.1}$$

where w is the stream width, L_t is the thalweg stream length, and n_s is the number of particles to be sampled.

6.2.3 Heterogeneous reaches and complex streambeds

Sampling the surface of a heterogeneous reach with a spatially integrated sampling scheme has advantages and disadvantages that should be weighed before starting the sampling project. One aspect is time. Spatially integrated sampling is often faster than spatially segregated sampling because delineation or surveying of the various geomorphological or sedimentary units is not necessary (Sections 6.3.2.1-6.3.2.3). Another aspect is the degree of spatial heterogeneity within the reach. Information obtained from spatially integrated reach-averaged sampling may be suitable in a mountain B3-type stream with little sediment supply and a gradual transition of areas with finer and coarser sediment. However, a low gradient C-type stream with ample sediment supply is likely to have areas of distinctly different surface sediment and, in this case, reach-averaged information on surface sediment is not very informative. An increase in the amount of sand delivered to the stream, for example, could produce sand patches, but their presence might not significantly affect the reach-averaged D_{10} or D_{50} particle sizes. The presence of sand patches could be better accounted for using spatially segregated sampling (Section 6.3.1). Another aspect to consider when selecting a sampling scheme is the sample size required for a preset precision. In reaches with pronounced spatial variability of particle sizes, sample standard deviation varies between sampling locations and one-step sample-size equations (Section 5.2.1) are not applicable to the reach as a whole. Sample size either needs to be computed for individual sediment units, or a two-stage sampling approach is necessary in which samples are taken from several grid systems overlaying the reach, each slightly shifted against the other (Section 5.2.3.1) (Fig. 6.3). This may result in a large sampling effort.

6.2.3.1 Grid sampling and lay-out of the grid

If spatially integrated sampling is the selected sampling scheme for a heterogeneous reach, a *tightly*-spaced systematic grid pattern that evenly covers the entire sampling reach is required for reach-averaged particle-size information (Diplas and Lohani 1997). Entire coverage implies that particles from *all* possible sampling locations are included in the sample (Fig. 6.4). If this is physically impossible because a potential sampling location is inaccessible or a particle is unretrievable, it is statistically more accurate to make an educated guess about the size class of such particles than to exclude those locations from the sample altogether.

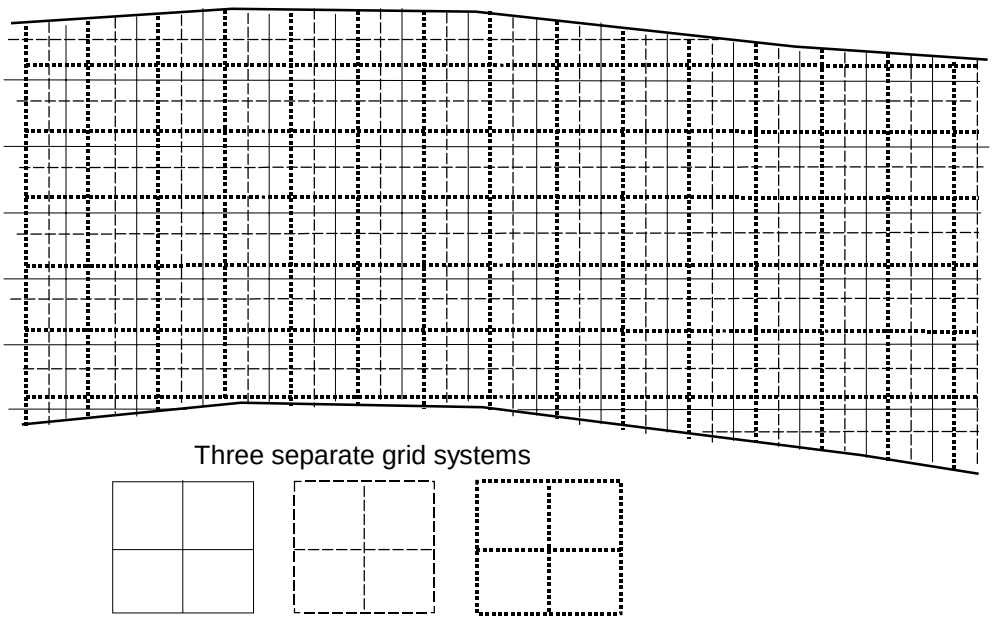

Fig. 6.3: A reach covered by three grid systems each slightly shifted relative to each other.

The grid orientation should be rectangular so that each grid point represents a streambed section of the same size. In a slightly sinuous reach, a grid of tightly-spaced transects perpendicular to the low flow streambed are widely-spaced at the outside bends, and

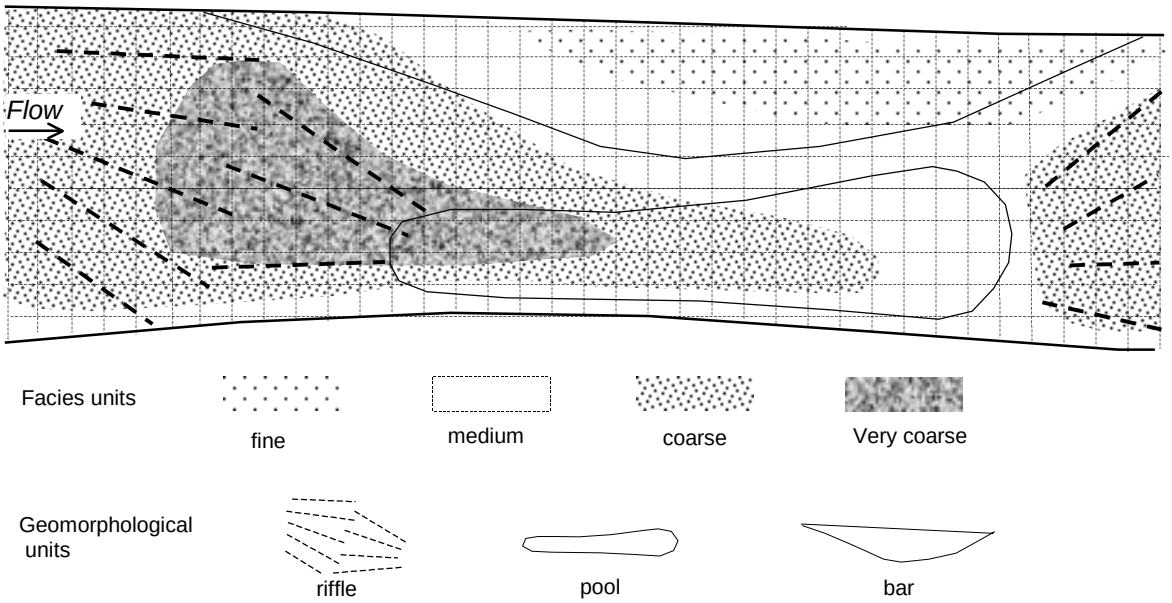

Fig. 6.4: Sketch map of a reach with its facies units, the underlying geomorphological units, and a sampling grid (sampling points at grid intersections).

tightly-spaced at the inside bend. This uneven sampling pattern underrepresents particle sizes at the outside bends, and overrepresents particle sizes at the inside bends, potentially causing samples that are biased against coarse particles. In moderately sinuous reaches, this bias can be mitigated by adjusting transects to the high flow bed which is usually less sinuous than the low flow bed. In highly meandering streams, a reach consisting of several meander bends should be sampled by a rectangular grid unconnected to stream morphology, if a reach-averaged bed-material particle size is to be obtained from a joint particle-size analysis of all sampled particles. Laterally, transects or grids should extend over the entire bankfull width when the sampling objective is to provide a reach-averaged estimate of channel bed conditions.

6.2.3.2 Grid spacing and areal extent of the sampling grid

The grid spacing used for spatially integrated sampling is determined by three factors: (1) The sample size needed for a tolerable error given the sorting of the bed material, (2) the minimum grid spacing required to avoid serial correlation due to double counting of an individual clast within a particle cluster, and (3) the areal extent of the sampling reach. Recall that pebble counts of 400 particles provide an precision of about ±0.15 ϕ, or ±10 - 11% for the D_{50} particle size for gravel bed-material with a typical sorting coefficient (Inman 1952) of approximately 1.2 (Sections 5.2.3.4 and 6.1.5.2). The error is larger for more poorly sorted bed material or for the tails of the distribution (Sections 5.2.1. and 5.2.2).

For gravel- and cobble-bed streams with a D_{max} particle size of small boulders, minimum sampling-point spacing should be 0.3 - 0.5 m. This means that a stream width of 5 m can hold 10 - 17 sampling points per transect, but considerably less if the grid spacing is to accommodate large boulders. If the streambed area to be sampled is small, e.g., a stream section of 1 - 2 stream widths, it is best to select a square sampling grid which facilitates the densest sampling point spacing possible.

Representative spatially integrated sampling of a morphologically or sedimentologically diverse sampling reach must ensure that a sufficient number of sampling points falls onto each unit to ensure a fair representation of that part of the reach. A grid system with about 20 transects is required to cover the morphological and sedimentary units within a riffle-pool section (from one riffle to the next riffle) in sufficient detail (Fig. 6.5). The actual number of transects needed in a particular stream reach can be calculated based on the following considerations:

The stream reach to be sampled is a riffle-pool sequence 5 m wide and 30 m long (i.e., 6 *w*). The D_{max} is 0.3 m. A grid spacing of 0.3 m yields 17 sampling points per transect. 20 transects yield 340 sampling points, which is less than a sample size of 400 required in poorly sorted gravel beds. 408 sampling points are obtained by sampling 24 transects each spaced 1.25 m apart. If a grid spacing of 0.5 m was selected, with 10 sampling points per transect, the reach would be covered by 40 transects each spaced 0.75 m apart.

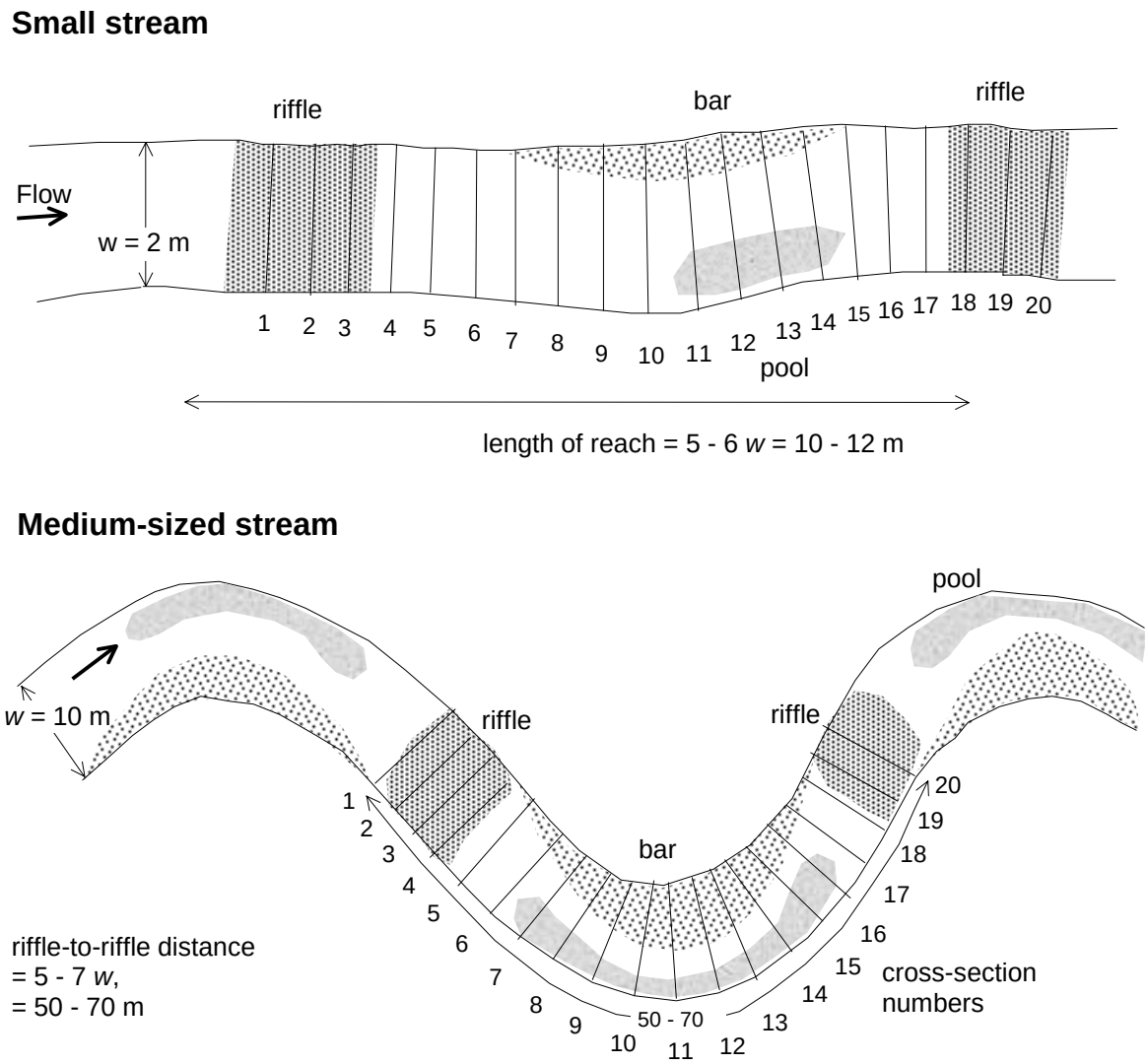

Fig. 6.5: Sampling grid with 20 cross-sections covering the entire reach in a small (top) and medium-sized (bottom) stream.

The widest spacing between individual sampling points is obtained by a distance of 0.625 m between sampling points on a transect, which allows 8 sampling points per transect. 50 transects each spaced 0.6 m apart yield a total of 400 sampling points.

Small cobble-bed streams less than 2 m wide are difficult to sample with a pebble count because a reach 12 m long may have only 200 grid points, even if the grid spacing is set to the minimal value of the D_{max} particle size. In this case, either a lower criterion for

sampling precision should be accepted, or sampling should be extended over a stream reach long enough to provide a sufficient number of grid points.

6.3 Spatially segregated pebble counts (sampling each unit individually)

Whereas spatially integrative sampling ignores geomorphological or sedimentary units and the associated patterns of spatial variability in bed-material size and sorting within a reach, spatially segregated sampling distinguishes between individual streambed areas that have particle-size distributions different from neighboring areas. Depending on the study objective, a heterogeneous sampling reach can be delineated according to geomorphological, or sedimentary criteria, and sampling can either encompass all units or be restricted to one or a few.

6.3.1 Geomorphologically stratified sampling

Geomorphologically stratified sampling delineates all *geomorphological*[6] units within a reach, such as riffles or pools, and samples each unit individually (Kondolf 1997a). The results of geomorphologically stratified sampling provide insight into the patterns of spatial variability of bed-material size and permit comparison of particle sizes among different geomorphological units (e.g., riffles and pools, or bar head and riffle). Alternatively, the same geomorphological units can be compared between different stream reaches or over time. The differences in particle sizes between units can provide insight into whether sediment transport is supply limited or transport limited. A reduction in sediment supply, for example, can be analyzed by comparing the dominant large particle size D_{dom} at the upstream end of bars with the riffle particle size distribution (Riffle Stability Index, RSI, Kappesser 1995). D_{dom} approaches the riffle D_{max}-particle size in aggrading streams, but is closer to the riffle D_{50} size in degrading streams. This is because when sediment supply is reduced, riffles respond by coarsening, whereas the size of dominant large particles at the upstream end of bars remains unaffected for some time.

An input of sand and fine gravel into a stream reach is not necessarily shown by fining on riffles. Introduced fine sediment is more likely to be accumulated in depositional areas, such as pools, backwaters, wakes, and along banks. Thus, a comparison of the volume of fine sediment stored in pools over time or between reaches can be used for monitoring fine sediment supply to streams (Section 6.6.2)1(Lisle and Hilton 1992; 1996; 1999).

Similarly, a comparison of particle sizes from the same geomorphological units over time, space, or between streams is useful for monitoring the effects of changes in water and sediment supply. Such changes may not be detectable when monitoring reach-averaged particle-sizes.

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[6] *See footnote 2 in Section 6.*

6.3.1.1 Characterization and delineation of geomorphological units

The first step in geomorphologically stratified sampling is to carefully delineate the various geomorphological units. This is performed visually based on recognition of streambed topography, flow patterns, and patterns of spatial bed-material variability. The delineation of geomorphological units may be difficult, particularly for inexperienced operators (Poole et al. 1997). Delineation requires training and the results are affected by the stage of flow. The frequent lack of well-defined boundaries between geomorphological units, and the deviation of geomorphological units from textbook descriptions, make delineation difficult and introduce subjectivity. Even trained geomorphologists may be inconsistent in their delineation of geomorphological units in different stream types. A description of the characteristics of geomorphological units is provided in Section 3.2.

6.3.1.2 Grid sampling on individual geomorphological units

Delineated geomorphological units and their spatial patterns of bed-material size should be shown in a sketch map of the reach to help design the optimum sampling scheme for each unit. Closely-spaced parallel transects or a square grid within a geomorphological unit ensures representative sampling in most cases. The grid spacing should not be smaller than the largest particle size to be included in the sample in order to avoid counting a large particle multiple times. Counting a large particle more than once introduces serial correlation into the sample and is not recommended. To do so overemphasizes the presence of large particles in small samples and disturbs the relation between sample size and error because sample-size statistics assume random, non-correlated sample points.

A geomorphological unit often has spatial variability in particle size distributions, and sample-size recommendations provided in Section 5.2 are not applicable because they refer only to homogeneous streambed areas. In order to establish a relation between sample size and error on heterogeneous units, a two-stage sampling approach (Section 5.2.3.1) may be used. The heterogeneous unit is sampled multiple times using a systematic grid that covers the entire unit. The grid is slightly shifted for each subsample (Fig. 6.6). The two-stage approach then determines how many subsamples are needed in order to obtain a desired precision for the sampling result.

Usually, a total sampling effort has a higher statistical validity if the total large sample is broken up into several subsamples that are each collected with a slightly shifted grid. Grid spacing may need to be tailored to each geomorphological unit within a reach since the patterns and the degree of spatial particle-size variability vary among geomorphological units.

Small geomorphological units

Geomorphological units in small streams may be too small to provide a sufficient sample size for the smallest grid spacing usable for a given D_{max} particle size, and even when

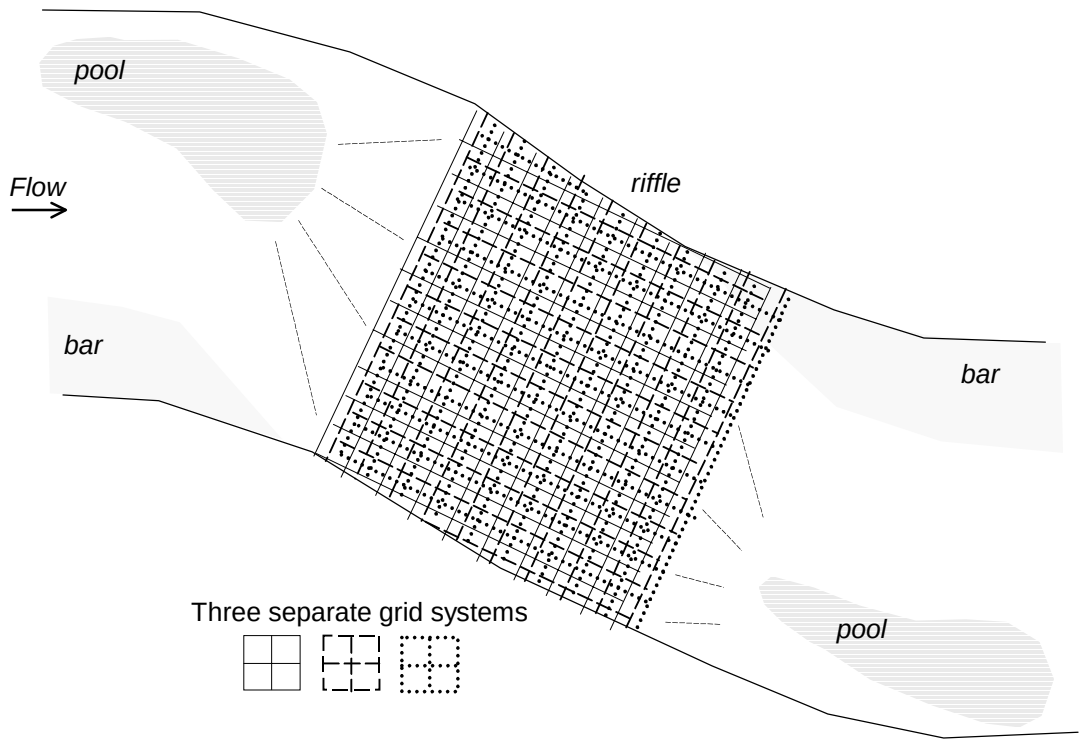


Fig. 6.6: Three replicate samples of a riffle using three grid systems, each slightly shifted relative to each other.

multiple shifted grids are used. If the precision resulting from a small sample size is not acceptable, the user may combine samples from several adjacent geomorphological units of a kind, e.g., samples from several riffles or from several bars. If the study objective focuses on one particular riffle or bar, the problem of a small sampling area may be circumvented by taking one or several areal samples (Section 4.1.3). Areal samples include *all* particles within the delineated area. Thus, the sampled area can be much smaller than required for grid samples. For small areas, areal sampling increases the potential sample size and precision. However, the conversion necessary to compare areal samples with grid samples may be difficult (Section 4.3).

6.3.1.3 Sampling on riffles only

Bed-material sampling is sometimes limited to riffles because the cross-sectional channel shape and flow hydraulics in a reach tend to be most uniform on riffles. In addition, riffles are commonly the shallowest areas in an inundated streambed and have comparatively low spatial variability in particle size and little sand in the surface layer. Thus, riffles are the most convenient stream location for pebble counts.

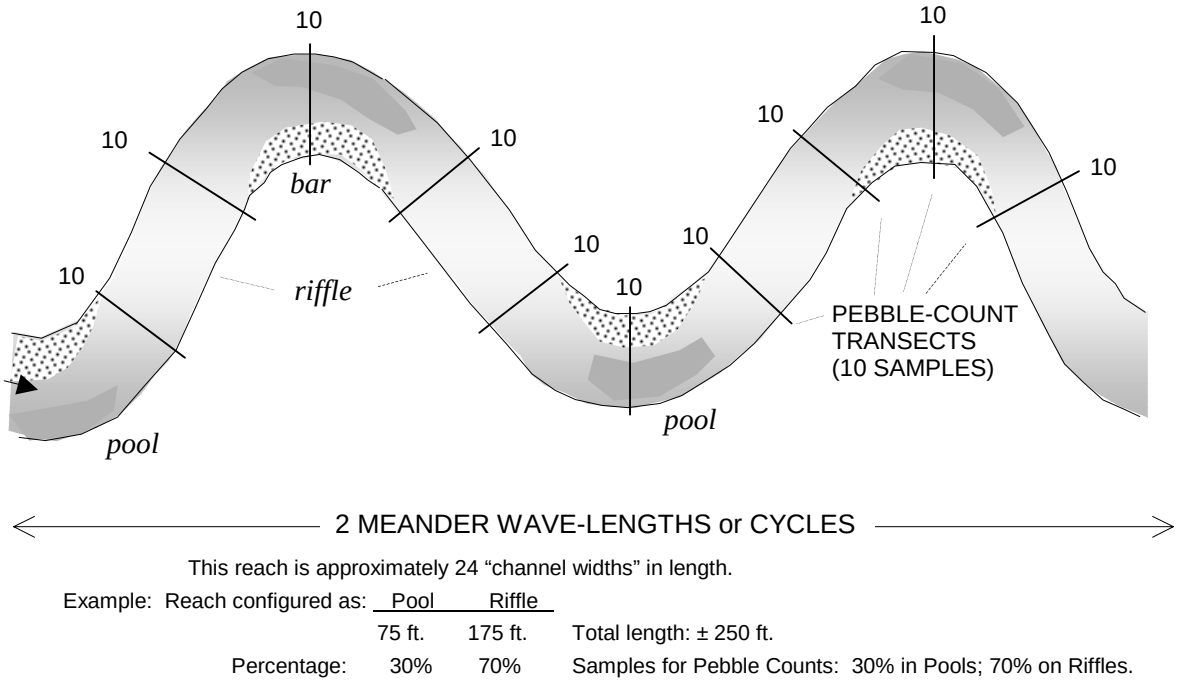
However, the analyst must keep in mind that sampling on a riffle does not provide a reach-averaged particle-size distribution. Often, but not always, riffles have coarser bed material than the reach because finer sediment is eroded off the riffle surface. Also, if boulders are supplied to the reach from rock falls or debris flows, riffles may be finer than the reach average. Riffles may be the location with the steepest local gradient, but are not necessarily coarser than the reach average (Clifford 1993). The reason for this is that riffles may be stabilized by structural elements, such as clusters, particle interlocking, and imbrication (Sear 1996) (Fig. 3.9).

While riffle particle-sizes are not necessarily indicative of the reach as a whole, the *ratio* of riffle sediment size to the sediment size of other geomorphological units is frequently used to determine whether bedload transport is supply or transport limited (Section 6.3.1). Riffle surface sediment size could also be monitored over time or compared between different sites.

Bed-material sampling for bedload-transport computations is often limited to riffles. The argument for this practice is that bedload is often computed for a riffle cross-section only, and that all stream sediment is transported through a specified cross-section. However, bed material may be entrained or deposited at many stream locations within a reach. Thus, bed material from the entire reach affects bedload transport and using the reach-averaged bed-material size distribution for bedload-transport modeling within a given cross-section seems more appropriate.

6.3.1.4 Proportional sampling on long reaches

If the study aim is to estimate the average particle-size distribution over a long meandering reach and to obtain information on the different particle sizes in riffles and pools, Rosgen (1996) proposes a proportional procedure that samples riffles and pools in proportion to their occurrence along the reach. Reach length for this approach extends over two complete meander wave-lengths, which comprise four individual meander bends and thus four riffle-pool sequences. With a riffle spacing of 5 - 7 stream widths, a reach covers a stream length of 20 - 30 stream widths. While walking the reach, the stream length occupied by pools and riffles is measured. Riffle-like features such as rapids, runs, and glides (Section 3.2.2.2) are included into the riffle category. Once the percentage stream length occupied by riffles and pools is determined, transects are placed so the percentage of samples taken on riffles is equal to the percentage of channel reach length delineated as a riffle. For example, if 70% of the reach length was classified as riffle-dominated, 70% of all transects would be placed into riffle-dominated sections (Fig. 6.7). Rosgen (1996) suggested using 10 transects per reach, so the number of transects allocated to riffles and pools can be easily determined. On each transect, 10 particles are sampled with even spacing, resulting in a total sample size of 100. Since particles were sampled on a proportional basis, data from riffles and pools may be combined for a joint particle-size analysis to obtain a reach-averaged particle-size distribution.



This reach is approximately 24 "channel widths" in length.

	Pool	Riffle	
Example: Reach configured as:			
	75 ft.	175 ft.	Total length: ± 250 ft.
Percentage:	30%	70%	Samples for Pebble Counts: 30% in Pools; 70% on Riffles.

Fig. 6.7: Allocation of transects in a reach of consecutive riffle-pool sequences on a proportional basis. (Redrawn from Rosgen (1996), by permission of Wildland Hydrology).

The proportional procedure described in this section can be a quick estimate of the median particle size over a long reach if there is little spatial variability within each geomorphological unit. However, geomorphological units are often spatially non-homogeneous. When the proportional procedure with 10-transects per reach is applied to reaches where particle sizes vary between riffles and pools, and where particle sizes vary between consecutive riffles or consecutive pools, sampling is unrepresentative and unsystematic. An increase in the number of transects per reach increases sample representativeness and statistical accuracy by avoiding: (1) a misfit between the number of transects and the number of riffles and pools per reach, (2) operator arbitrariness, and (3) an unrepresentative, small sample size.

If a reach comprises four riffle-pool units, and 70% of the reach length is identified as riffle, 30% as pool, and each reach is sampled by 10 transects, then seven transects need to be allocated onto four riffles and three transects onto four pools. Consequently, one of the riffles is sampled with only one transect, and one of the pools is not sampled at all. Such a misfit could be avoided if the same number of transects is allocated to each of the riffles and the pools. The percentage stream length occupied by riffles or pools (e.g., the 70% riffles, 30% pools) may then be proportionally sampled by placing 7 transects onto each riffle and 3 transects onto each pool. This apportioning yields 40 transects per reach, 28 on riffles, and 12 on pools. Sampling 10 particles per transects yields a total of 400 particles. This sample size is more in line with recommendations suggested by other

sources and may provide an precision for the D_{50} particle size (in mm) of about ±10% (Rice and Church 1996b) (Section 5.2.3.4).

Another reason why a larger number of transects for each riffle and pool is recommended is because it decreases the emphasis placed on an individual transect and its placement within the riffle or the pool. Although some systemization can be attempted by alternately placing transects at the upstream, center, and downstream sections of riffles and pools, transect placement largely depends on operator discretion.

6.3.2 Sedimentary stratified sampling

If the purpose of the study is to characterize spatial heterogeneity of surface grains rather than compare geomorphological units, sampling should be stratified by sedimentary units. Sedimentary units are homogeneous streambed areas with no systematic spatial variation of bed-material size, and are sometimes termed *facies* or *patches*. The size of a patch or sedimentary unit is not fixed, but depends on the degree of spatial heterogeneity of the streambed, and the number of different facies that the study wants to distinguish. Most studies differentiate between 3 or 4 different facies, so that facies units are visually distinguishable. Fig. 3.10 provides an example of a heterogeneous stream reach with several facies units in an aggraded C-type stream. A heterogeneous streambed with four facies due to a heavy loading of large woody debris is shown in Fig. 3.12.

There are two basic methods of delineating a heterogeneous streambed into homogeneous sedimentary units: visual (Section 6.3.2.1 and 6.3.2.2) and statistical methods (6.3.2.3). Examples of both are presented below. After the various sedimentary units have been delineated, a sampling scheme needs to be established that is appropriate for the patch size and the degree of homogeneity. Various sampling schemes for spatially segregated sampling are explained in Section 6.3.2.4.

6.3.2.1 Visual delineation of sedimentary units (facies or patches) based on estimates of percentile particle sizes

Experienced operators can become proficient in visually estimating particle-sizes (Shirazi and Seim 1981; Platts et al. 1983), and thus in the distinction between areas of different particle-size composition. However, the facies delineation process remains to some degree subjective (Kondolf and Li 1992) because segregation of sedimentary units from a heterogeneous surface reduces, but not eliminates heterogeneity. In addition, there are no standards defining a meaningful degree of spatial variability within sedimentary units. For best delineation results, it is important to spend some time walking the streambed to become familiar with the particle sizes present on the bed and their spatial distribution. Based on these insights, the user can devise criteria for delineation of sedimentary units. The reach length covered by the study should be sufficiently enough (20 stream widths or more) so that each type of sedimentary unit occurs several times within the reach.

Estimating the particle size of one or two percentiles

Criteria for delineation of sedimentary units in gravel-bed rivers may be based on the particle size of specified percentiles. The size of one large percentile, e.g., the D_{75}, may be sufficient in some deposits (Lisle and Madej 1992), but in poorly sorted bed material, different facies can be better discriminated on the basis of the size of several percentiles, e.g., the D_{50} and the D_{90} (Hilton and Lisle, pers. comm.,1998). Each study needs to define its own delineation criteria in correspondence with the site characteristics and the study aim. Example criteria for delineation of sedimentary units (patches, facies) are provided in Table 6.3.

Table 6.3: Example criteria for delineation of sedimentary units (patches, facies).

Lisle and Madej (1992)		Hilton and Lisle, pers. comm., 1998		
D_{75} (mm)	Sedimentary unit (facies)	D_{50} (mm)	D_{90} (mm)	Sedimentary unit (facies)
< 22	fine pebbles	<16	<45	fine pebbles
22 - 64	coarse pebbles	<16	>45	sand and pebbles
> 64	cobbles	16-45	any	coarse pebbles
sand>25%	bimodal	>45	any	cobbles

For field application, the procedure of visual delineation and the subsequent segregated sampling can be segmented into several steps:

1. Walk the reach and familiarize yourself with the different compositions of surface sediments.

2. Determine the different facies and define delineation criteria appropriate to the site and the study aim.

3. Apply the delineation criteria to distinguish between sedimentary units and mark the boundaries with surveyors' flags.

4. Conduct pebble counts covering the entire sedimentary unit or only parts of it, depending on the size of the sedimentary unit (see explanations below).

5. Survey the boundaries of all sedimentary units.

6. Prepare maps from the survey data.

7. Determine the areal extent of each sedimentary unit.

8. Determine the percent area of each facies type.

9. Compute the reach-averaged particle size distribution by adding the area-weighted particle-size distributions from each facies (Section 6.3.2.5).

The size of a sedimentary unit, or of the patches that comprise a unit, needs to be sufficiently large to accommodate a pebble count. The minimum area needed for a pebble count depends on the product of sample size and grid spacing. Grid spacing for pebble counts should be at least as large as the D_{max} particle size, about 0.3 - 0.5 m in gravel-bed rivers comprised of small boulders. Sample size depends on the desired precision and the sediment sorting. Recall that a sample of about 400 particles from a homogeneous unit determines the D_{50} to within ±0.12 to ±0.15 ϕ (Section 5.2.2.3), or to within approximately 10% in terms of mm-units in poorly sorted sediment. A 100-particle sample nearly doubles this error. If a facies unit is too small or too fine in bed-material size for a pebble count, areal samples should be used.

6.3.2.2 Visual delineation based on a two-level characterization of particle sizes

Buffington and Montgomery (1999a) devised a two-level visual particle-size classification based on the relative abundance of the major size classes (sand, gravel, and cobble) and on the subsizes of the dominant size class. The delineation procedure is described in detail in Section 4.1.3.5, but summarized below for convenience. In a Level 1 delineation, the operator visually estimates the relative abundance of the main three constituents of a particle-size distribution. For example, a deposit with 10% sand, 60% gravel, 30% cobble classifies as a **s**andy, **c**obbly **G**ravel facies (**scG**). In Level 2, the operator characterizes the size of the major constituent (i.e., gravel in this example) more precisely and estimates the percentage of three out of the five classifiers: very fine, fine, medium, coarse and very coarse. The percentages of 20% fine, 50% medium, and 30% coarse gravel, for example, classify the gravel part as fine-coarse-medium. The approach provides statistically significant distinctions between particle-size distributions of facies and has the advantage of being generally applicable to all facies.

Visual delineation and sampling procedure for spatially segregated sampling on heterogeneous surfaces can be broken down into the following steps:

1. Conduct a preliminary reconnaissance of the stream reach, visually identifying the facies (sedimentary units) according to the Level 1 and 2 classifications presented by Buffington and Mongomery (1999a) (Section 4.1.3.5).

2. Do pebble counts in each facies type, using an appropriate grid spacing and sample size for the desired precision. This may be performed with one sufficiently large, facies-spanning pebble count per unit. Use areal sampling (Section 4.1.3.1 - 4.1.3.4) for facies areas too small or too fine for a pebble count of adequate extent.

3. Plot the percent frequency of the three major constituents of each facies on a triaxial diagram (Fig. 4.15 in Section 4.1.3.5). Redefine facies criteria if clusters of data points plotted in the diagrams fail to distinguish between facies.

4. Construct a textural map by surveying.

5. Compute the reach-averaged particle-size distribution by adding the area-weighted particle-size distributions from each facies (Section 6.3.2.5)

6.3.2.3 Statistical delineation from systematic grid data

Visual delineation of sedimentary units can be problematic, particularly when the streambed is submerged. In order to alleviate this problem, Crowder (1996) and Crowder and Diplas (1997) suggest a four-step delineation procedure, whereby visual delineation is augmented by a statistical delineation method in which hypothesis testing of sample similarity or difference is applied incrementally over the reach by a moving window technique. The steps involved in hypothesis testing and the moving window technique are:

1. Walk the reach to become familiar with the various sedimentary units and select the subsample area and the number of particles collected in each subsample. The subsample area (cell size) depends on the degree of heterogeneity of the bed and on the D_{max} particle size. For example, a D_{max} particle size of 0.3 m requires a minimum grid spacing of 0.3 m. Crowder and Diplas (1997) suggest starting with a sample size of 20 – 30 per cell, or of 25 - 36 if a square cell-size is selected. Sampling 25 particles from a 0.3 by 0.3 m grid requires a grid cell-size of 1.5 by 1.5 m. Sampling 36 particles with a grid spacing of 0.5 m requires a grid cell size of 3 by 3 m.

2. Spread a systematic grid of cells over the entire stream reach disregarding sedimentary units. For example, the reach may be covered by a 1.5 by 1.5 m grid, and subsamples of 25 particles are collected from each grid cell (Fig. 6.8). Do not use less than about 25 particles per subsample.

3. Compute the arithmetic mean particle size D_m (in mm; Eq. 2.39, Section 2.1.5.3) as well as the arithmetic standard deviation (variance s^2 (Eq. 2.56, Section 2.1.5.4) for each cell. The values of D_m and s^2 for each cell are plotted into a sketch map of the reach (Fig. 6.8).

4. Check whether the selected sample size and the computed sample variance s^2 per grid cell allow detection of a difference in the mean particle size between all adjacent grid cells 1 and 2 using Fig. 6.9. The curve for $s_1^2 + s_2^2 = 100$ in Fig. 6.9 indicates that 6 mm is the smallest difference detectable between two neighboring D_m with a subsample size of 30. Similarly, a 6 mm difference between two neighboring D_m requires a sample size of 800 if the summed variance is $s_1^2 + s_2^2 = 3000$. If the sample size per grid cell is too low, more particles need to be sampled in each grid cell.

5. Determine the boundaries between sedimentary units by performing statistical hypothesis testing and the moving windows procedure explained below.

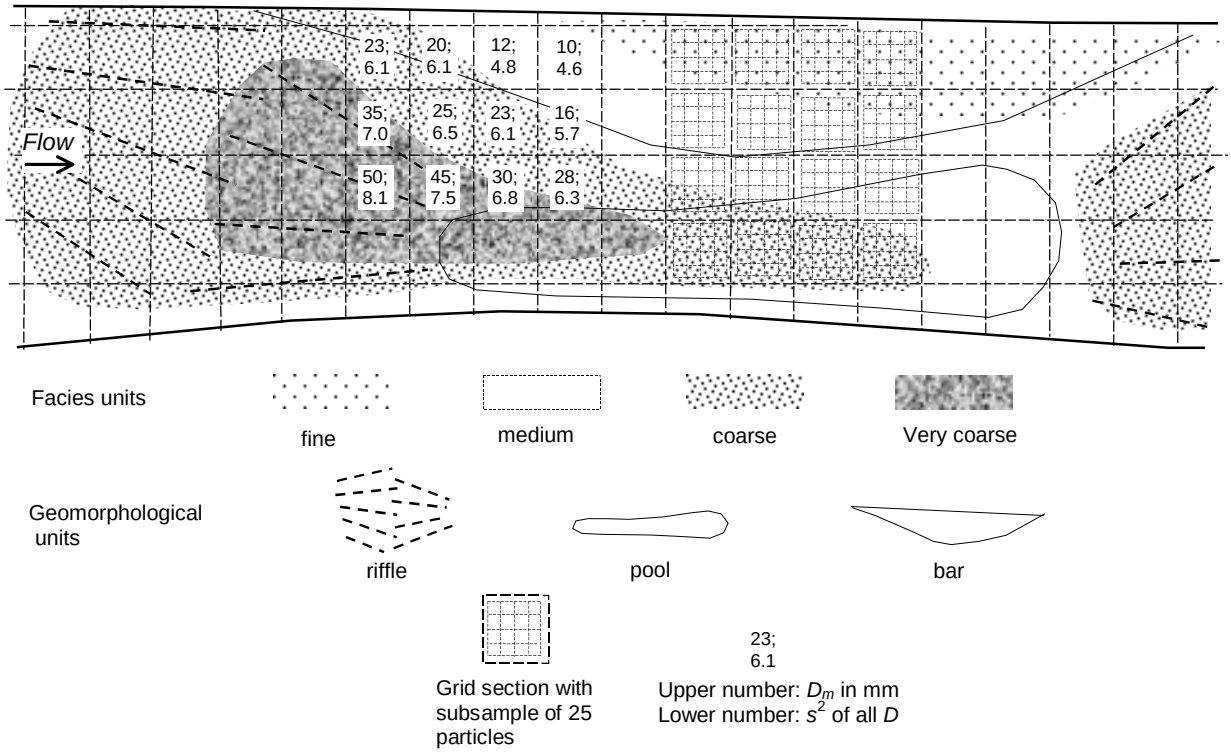


Fig. 6.8: A grid is superimposed on the sampling reach, extending over facies boundaries. The upper number in each grid section is the arithmetic mean particle size in mm, the lower number is the particle-size variance s^2 obtained from a 25-particle pebble count collected in each grid section (here shown for 16 of the grid sections).

6. Once the boundaries of sedimentary units are determined, combine all subsample particles within the delineated sedimentary unit and do a particle-size analysis to characterize the specified sedimentary unit.

<u>Example 6.1:</u>
Two subsamples with a sample size of n = 25 were collected in neighboring grid cells. Subsample 1 had a D_{m1} = 6 mm, and a s_1 = 4.7. Subsample 2 had a D_m = 14 mm, and a s_1 = 8.8. $s_1^2 + s_2^2$ = 99.5. $\Delta D_m = |D_{m1} - D_{m2}|$ = 14 - 6 = 8 mm. The line for $s_1^2 + s_2^2$ = 100 on Fig. 6.8 b indicates that a sample size of 25 is sufficient to detect a difference of 6 mm and thus adequate to detect an 8 mm difference between D_{m1} and D_{m2}.

Statistical discrimination
One method of determining a sedimentary boundary is to test whether the mean particle sizes of two neighboring subsamples are statistically different. The neighboring D_{m1} and D_{m2} are different with a 90% confidence if the value for Z_{12} determined from

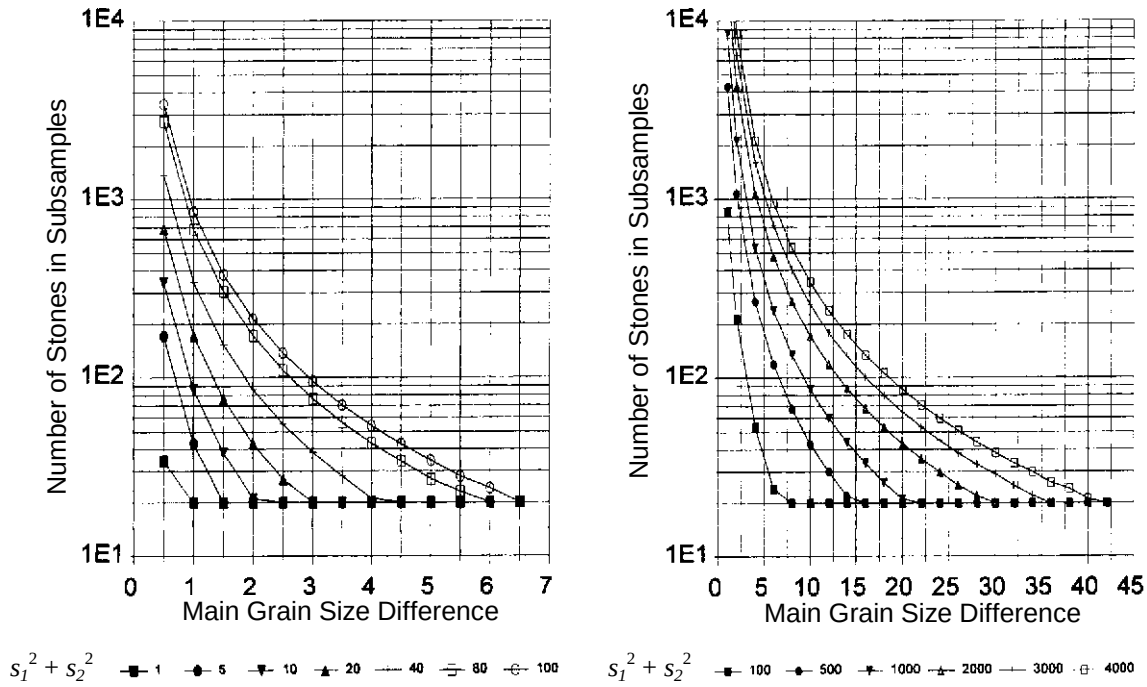


Fig. 6.9: Minimum subsample size necessary to locate a specified difference in the arithmetic mean particle size (mm); legend indicates lines of constant sums of variances $s_1^2 + s_2^2$ ranging from 1 - 100 (left), and 100 - 4000 (right). (Reprinted from Crowder and Diplas (1997), by permission of the American Society of Civil Engineers).

$$Z_{12} = \frac{|D_{m1} - D_{m2}|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{6.2}$$

exceeds the value of 1.645 or is less than - 1.645. s_1 and s_2 are the arithmetic standard deviations of subsample 1 and 2 and n is the subsample size which is usually the same for n_1 and n_2. For a 95% probability, Z_{12} is increased to 1.96 (See Table 5.1 for values of Z for various probabilities). A statistical difference between neighboring D_m confirms the presence of a sedimentary boundary. The Z-statistic in Eq. 6.2 could be replaced by a t-statistic with $n_1 + n_2$ -2 degrees of freedom if the user wants to acknowledge the effect of a small samples size. t-statistics for a 95% confidence limit are listed in Table 5.2. t-statistics for other confidence levels can be found in general statistics books.

<u>Example 6.2:</u>
Two neighboring grid cells with a sample size of n = 25 have a D_{m1} = 6 mm, s_1 = 4.7, and D_{m2} = 20 mm, and s_2 = 8.8. Solving Eq. 6.2 yields:

$$Z_{12} = \frac{|6 - 20|}{\sqrt{\frac{4.7^2}{25} + \frac{8.8^2}{25}}} = \frac{14}{\sqrt{0.88 + 3.10}} = \frac{14}{1.99} = 7.02$$

which is larger than 1.96 (and larger than 2.00 if *t*-statistics are used) and indicates a statistically significant difference in the D_m between the neighboring grid cells. Thus, subsamples 1 and 2 belong to different sedimentary units.

Eq. 6.2 could be applied systematically to all neighboring grid cells to locate sedimentary boundaries. However, this discrimination procedure defines a sedimentary boundary along the grid-cell margins, even if the true sedimentary boundary goes through the middle of the grid cell. In order to facilitate a more accurate detection of the true boundary location, Crowder and Diplas (1997) devised the moving windows procedure.

Moving window technique

To apply the moving window technique (Fig. 6.10), the area of sample 1 is covered by two adjacent windows A and B which are incrementally moved towards the area of sample 2 over the area in which the boundary is expected. For each step, the difference between the mean particle sizes D_{mA} and D_{mB} is computed. The boundary between sample 1 and 2 is located where the difference between D_{mA} and D_{mB} reaches a maximum value.

The statistical delineation procedure confirms that sampled sedimentary units are sufficiently homogeneous. Since each sedimentary unit may be of different size, a reach-averaged size distribution is computed from an area-weighted average (Section 6.3.2.5).

6.3.2.4 Strategies for sampling within delineated facies units

Segregated sampling schemes may be applied to sample the surface sediment of a reach delineated into different facies units. Four basic sampling types can be distinguished:

1. Reach spanning grid that covers all facies with the same grid patterns;

2. Different grid pattern to cover each facies unit;

3. Different sampling procedures on different facies (e.g., taking areal adhesive samples in facies with particle sizes too small for pebble count or photographs in facies areas too small for a pebble count (= hybrid sampling));

4. Different sampling procedures on one facies (e.g., taking a pebble count to sample coarse gravel and areal adhesive samples for a representative sample of fine gravel);

5. Large reach with large facies units: sample extends only over a small part of large facies units and is collected at a representative location.

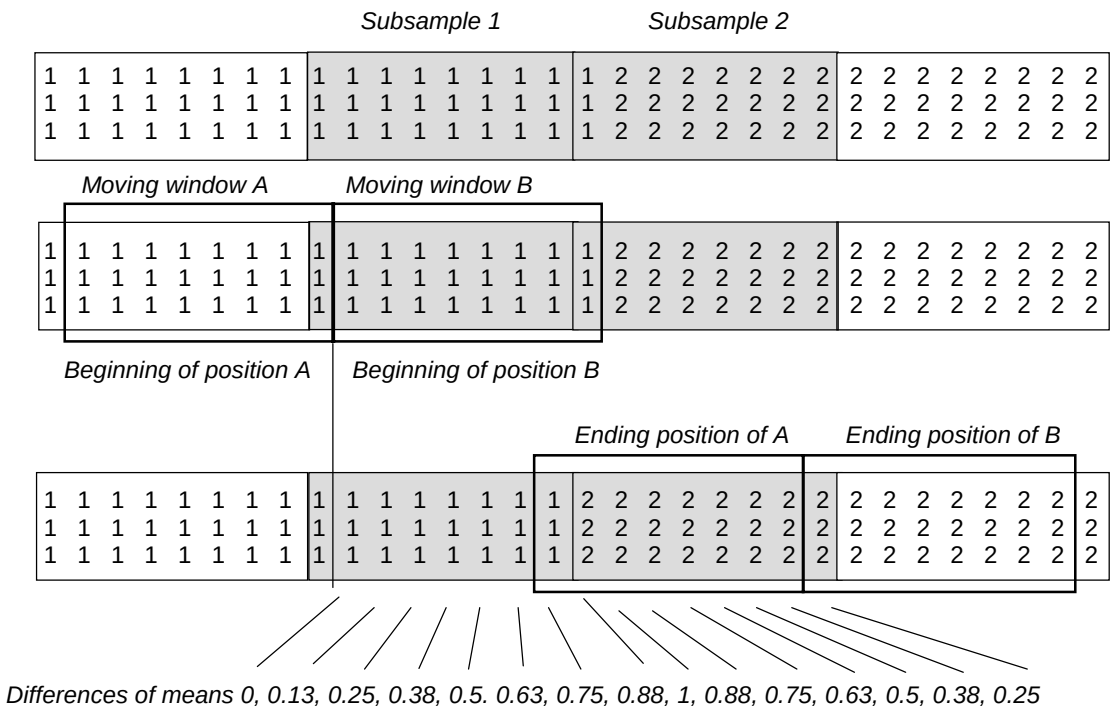


Fig. 6.10: Moving window technique: Two subsamples that are statistically different and surrounding material (top); Moving windows A and B in their starting position (center); Ending positions of moving windows A and B and differences in their mean particle sizes at each increment between beginning and ending position of windows. (Redrawn from Crowder and Diplas (1997), by permission of the American Society of Civil Engineers).

These five methods of spatially segregated sampling are explained below. Selection of one of the five methods depends on the characteristics of the facies units such as the D_{max} particle size, the sediment sorting, the size and orientation of facies units, and how clearly distinguishable facies units are from each other.

1. Reach spanning systematic grid and allocation of sampled particle to respective facies

The easiest method of spatially segregated sampling is to cover the entire reach with one grid system and segregate the particles into the various facies unit during the sampling process (Fig. 6.11) (Kondolf and Li (1992), and Kondolf (1997a). This method requires that all facies may be covered by the same grid, which means that the grid size necessary for the coarsest facies provides a sufficient number of grid points in each facies. It also requires that the various facies units are easily distinguishable by eye.

If spatially segregated sampling with a reach-spanning grid is possible, the operator traverses the reach along transects that may span several facies units. Particles collected along each transect are categorized according to their sedimentary unit, which means

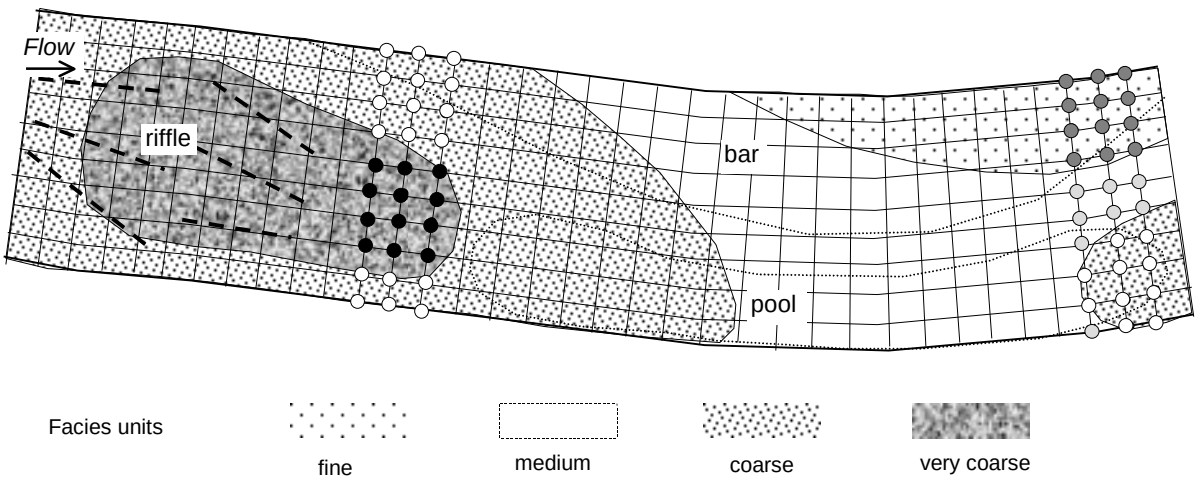


Fig. 6.11: Spatially segregated sampling using a systematic reach-spanning grid. All facies units are covered by the same grid. Examples of allocating sampling points to facies units is given for some of the transects. Equal shading of the circles indicates allocation to the same facies.

particles collected while the transect traverses the "very coarse" facies are allotted to the very coarse facies, whereas particles collected while the transect passes over the " coarse", "medium" or "fine" facies are listed under the category "coarse facies", "medium facies" or "fine facies".

2. A separate grid system covers each facies unit

When sampling a reach delineated into sedimentary units, it may be necessary to select a separate grid pattern that varies in grid size and orientation for each unit (Fig. 6.12). The coarse facies, for example, may require a wider grid spacing than the fine facies, or the

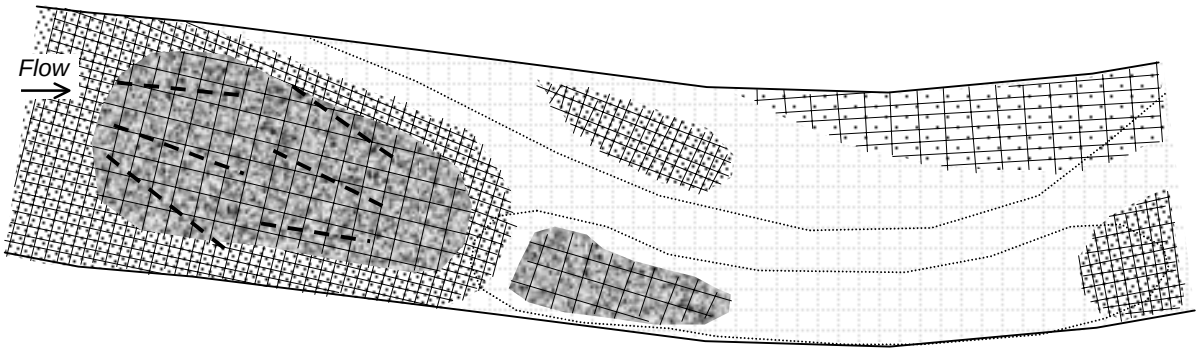


Fig. 6.12: Spatially segregated sampling using a different grid for each facies unit (same legend as Fig. 6.11).

poor sorting of particle sizes in one facies may require a larger sample size to attain a specified precision than a facies with well sorted sediment. Directional orientation of facies units may warrant still another grid orientation.

3. Small sedimentary units: pebble counts or areal samples

Some delineated units may be substantially smaller than the area needed for pebble counts. In this case, the user may either collect pebble counts using several grids, each slightly shifted relative to each other (Section 6.3.1.2), or use areal samples (Fig. 6.13). Areal samples, and specifically adhesive sampling (Section 4.1.3.2) may be useful if the surface sediment is mostly finer than about 15 mm, and the user wants to know an exact frequency distribution of the fine gravel and sand. A small, but coarse facies unit may be analyzed by photo sieving (Section 4.1.3.3) using photographs that cover the entire facies unit.

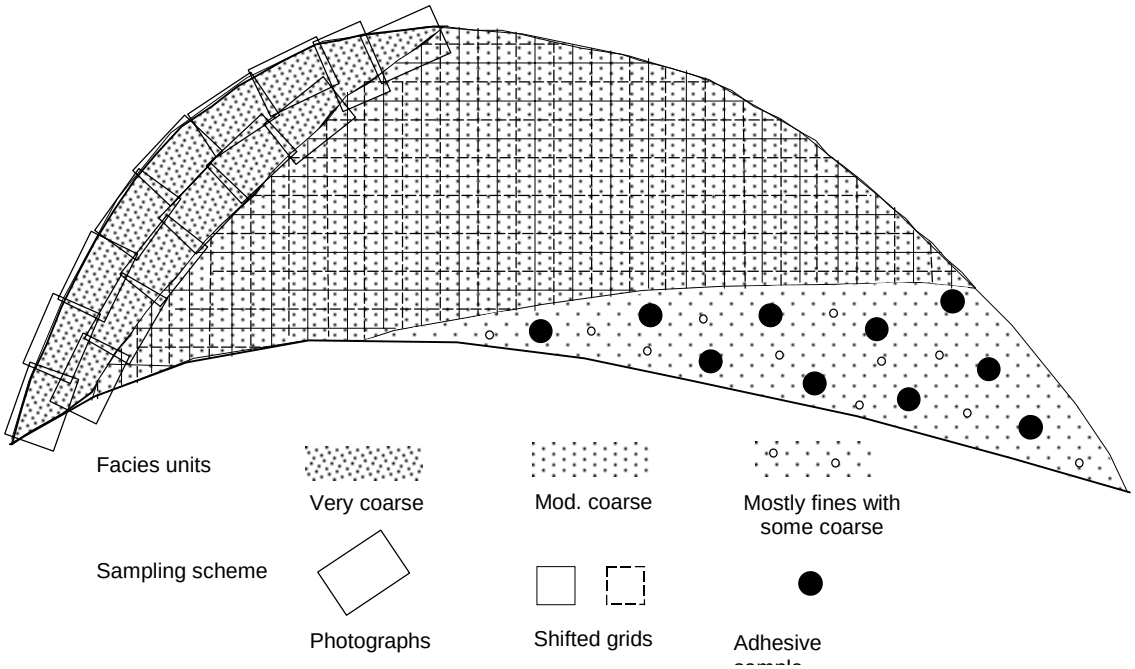


Fig. 6.13: Small sedimentary units: shifted grids, photographs, or adhesive samples are applicable.

Recall that particle-size distributions of areal samples need to be converted into equivalent grid-by-number particle-size distributions before comparison with pebble count data (Section 4.3). After the statistical conversion of areal samples into equivalent grid-by-number samples, particle-size distributions from each facies are area-weighted and summed to yield a reach-averaged particle-size distribution (Section 6.3.2.5).

4. Poorly sorted facies units containing fine and coarse gravel: hybrid sampling

If a sedimentary unit has a wide particle-size spectrum with both a large amount of fine gavel and also coarse gravel and cobbles, both adhesive areal samples and a pebble count may need to be collected to representatively sample that facies (hybrid sampling, Diplas 1992) (Fig. 6.14). An adhesive sample (Section 4.1.3.2) can representatively sample fine gravel and sand and provide a more accurate analysis of fine gravel and sand than pebble counts, whereas the pebble count can characterize the coarse part of the distribution better than an areal sample. The particle-size distribution for the entire facies unit is obtained from a sample combination procedure (Section 4.4).

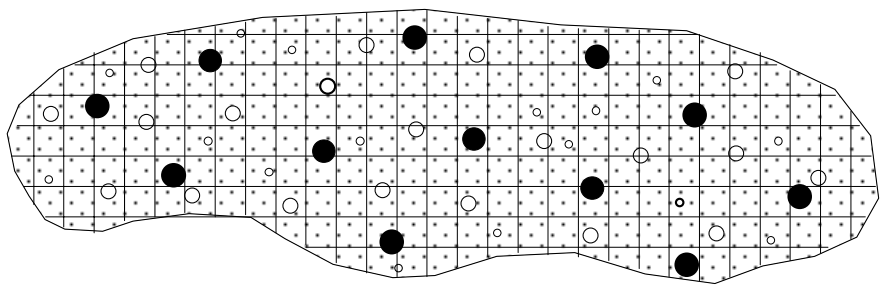


Fig. 6.14: Hybrid sampling on a poorly sorted facies unit with mostly fine but also some coarse gravel: Grid sample for a representative sample of the coarse gravel, and areal (adhesive) samples ( ) for ● representative samples of the fine gravel and sand.

5. Long reach with large and reoccurring facies units: sample extends only over a small part of large facies units

A sampling project may have to be conducted in a large stream about 100 m wide and over a long reach where 20 or more channel widths (4 riffle-pool sequences) result in a reach length of 2000 m. The total streambed area is 200,000 m^2. If the stream has four facies with areas of 20,000, 40,000, 60,000 and 80,000 m^2, and each facies occurs 4 - 6 times, then the size of individual facies may range between 4,000 (40 by 100 m) and 30,000 m^2 (150 by 200 m). It may still be feasible to collect a 400-particle pebble count from a 4000 m^2 unit, covering the entire facies unit with 20 transects and sampling in 2.5 m step spacing, but total coverage becomes inconvenient for large facies units. In this case, it seems reasonable to restrict a pebble count to a relatively small area (e.g., 20 by 20 m) and to select a representative area within each or almost each of the facies units (Fig. 6.15) for the pebble count (some judgement is required). Facies A, for example, may occur four times in the reach, and a 100-particle pebble count may be collected from each of the four areas of facies A, yielding a total sample size of 400 for facies A. Pebble count data from all four areas of that unit are eventually combined into one sample. However, each pebble count may be analyzed separately in order to evaluate the similarity between the four units. The same process is repeated for the facies units B, C, and D.

If a certain facies occurs numerous times, it may not be necessary to collect a sample from each unit belonging to that facies. A few units most representative of that facies type are

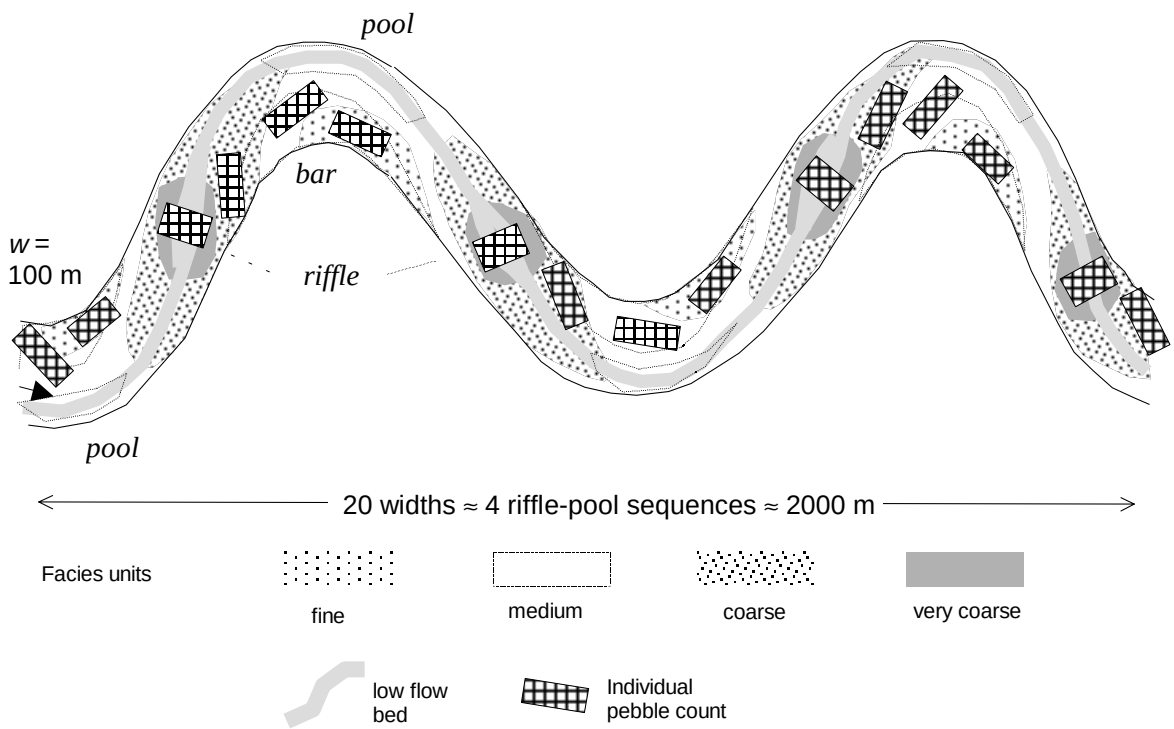


Fig. 6.15: Spatially segregated sampling in a long reach with large and reoccurring facies units: each pebble count covers only part of a facies unit.

then selected for sampling. Also, some units might be so large that they cannot be covered by one large grid count. In that case, several smaller grid counts may be used, each grid covering only a fraction of the total sedimentary unit (Lisle and Madej 1992). The total number of pebble counts to be performed on a sedimentary unit of a specific type should correspond roughly to the percentage area covered by that facies type. If, for example, the cobble, coarse gravel, and fine gravel facies comprise 30, 50, and 20% of the total reach area, then 30, 50, and 20% of all pebble counts are collected from cobble, coarse gravel, and fines gravel facies, respectively. The reach-averaged particle-size distribution is computed from area-weighted particle-size number or percentage frequencies of each unit (Section 6.3.2.5).

<u>Example 6.3:</u>
For a D_{max} or D_{95} particle size of 0.3 m, and a sample-size requirement of 400 particles, the minimum sampling area is 400 x 0.3 m^2 = 36 m^2 (size of a small classroom). Table 6.4 provides minimum sampling areas of sedimentary units for various sample sizes and D_{max} particle sizes, anticipated absolute errors in particle size ϕ-units (see Table 5.6), and relative errors as percentage based on mm-units (based on Fig. 5.8).

If the facies area is too small to accommodate grid spacing for a particular D_{max} particle size, and sample size required for a specified precision, grid spacing and sample size can be reduced, but either reduction decreases sampling precision.

Table 6.4: Minimum sampling area for various D_{max} and sample size, and sampling errors in ϕ and % mm.

D_{max} (m)					
0.1	0.3	1.0			
Minimum sampling area			Sample size	error in terms of	
m^2	m^2	m^2	n	ϕ-units	% mm
1	9	100	100	± 0.30	± 17
4	36	400	400	± 0.12	± 10
10	90	1,000	1,000	± 0.07	± 4

6.3.2.5 Area-weighted reach-averaged particle-size distribution from stratified sampling

To compute the reach-averaged bed-material size distribution from a stratified sampling scheme, each sedimentary (or geomorphological) unit (Section 6.3.2) (e.g., *A*, *B*, and *C*) should be surveyed and mapped. The fraction of the total area for each of the units is then computed ($A_{\%} + B_{\%} + C_{\%} = 1$). After the particle-size frequency distributions f_A, f_B, and f_C are established for each unit, the reach-average size distribution $f_{i,m}$ for the *i*th size class is obtained by multiplying the frequency of particles of the *i*th size class $f_{i,A}$ from unit *A* by the percent total area $A_{\%}$ comprised in unit *A*. This multiplication is repeated for all geomorphological (or sedimentary) units and frequencies are added to obtain the area-weighted reach-average number frequency $f_{i,m}$.

$$f_{i,m} = f_{i,A} \cdot A_{\%} + f_{i,B} \cdot B_{\%} + f_{i,C} \cdot C_{\%} \tag{6.3}$$

The process is then repeated for all size classes to obtain the area-weighted particle-number frequency distribution. The percentage frequency distribution $f_{\%,m}$, and the cumulative frequency distribution $\Sigma f_{\%,m}$ are then computed (Table 6.5). Alternatively, area-weighting can be deferred and applied to the percentage frequencies $f_{\%,i}$ from all units to obtain area-weighted percentage frequencies $f_{\%,m,i}$.

$$f_{\%,m,i} = f_{\%,i} \cdot A_{\%} + f_{\%,i} \cdot B_{\%} + f_{\%,i} \cdot C_{\%} \tag{6.4}$$

The computations are repeated for all size classes and $f_{\%,m,i}$ is summed to obtained a cumulative frequency distribution $\Sigma f_{\%,m,Di}$. Both methods provide almost identical

cumulative frequency distributions (compare the two shaded columns $\Sigma f_{\%,m,i}$ in the example computation in Table 6.5).

Table 6.5: Original frequency distributions f_i of pebble counts in geomorphological or sedimentary units *A* (57%), *B* (27%) and *C* (16% of total streambed area), and difference between cumulative frequency distribution derived from area-weighted number-frequencies $\Sigma f_{\%,m,i}$ and area-weighted percentage frequencies $\Sigma f_{\%,m,i}$. All values larger than 10 are rounded to the nearest integer value.

				area-weighted			reach-average			area-weighted			reach-average	
D_i	f_i			f_{awi}			$f_{m,i}$	$f_{\%,m,i}$	$\Sigma f_{\%,m,i}$	$f_{\%awi}$			$f_{\%,m\,i}$	$\Sigma f_{\%\,m\,i}$
(mm)	*A*	*B*	*C*	*A*	*B*	*C*				*A*	*B*	*C*		
<2	30	25	10	17	6.8	1.6	26	6.0	6.0	4.0	1.6	0.4	5.9	5.9
2	1	1	1	0.6	0.3	0.2	1.0	0.2	6.2	0.1	0.1	0.0	0.2	6.2
2.8	2	0	0	1.1	0.0	0.0	1.1	0.3	6.5	0.3	0.0	0.0	0.3	6.4
4	6	4	1	3.4	1.1	0.2	4.7	1.1	7.6	0.8	0.3	0.0	1.1	7.5
5.6	7	5	1	4.0	1.4	0.2	5.5	1.3	8.9	0.9	0.3	0.0	1.3	8.8
8	8	6	3	4.6	1.6	0.5	6.7	1.6	10	1.1	0.4	0.1	1.6	10
11.3	13	9	6	7.4	2.4	1.0	11	2.5	13	1.7	0.6	0.2	2.5	13
16	25	15	9	14	4.1	1.4	20	4.6	18	3.3	0.9	0.4	4.6	18
22.6	65	27	15	37	7.3	2.4	47	11	29	8.6	1.7	0.6	11	28
32	87	62	35	50	17	5.6	72	17	45	12	3.9	1.4	17	45
45	91	95	57	52	26	9.1	87	20	66	12	5.9	2.3	20	65
64	53	83	81	30	22	13	66	15	81	7.0	5.2	3.2	15	81
90	23	57	96	13	15	15	44	10	91	3.0	3.6	3.8	10	91
128	9	26	49	5.1	7.0	7.8	20	4.7	96	1.2	1.6	1.9	4.8	96
180	7	10	20	4.0	2.7	3.2	9.9	2.3	98	0.9	0.6	0.8	2.3	98
256	2	5	10	1.1	1.4	1.6	4.1	1.0	99	0.3	0.3	0.4	1.0	99
360	1	1	8	0.6	0.3	1.3	2.1	0.5	100	0.1	0.1	0.3	0.5	100
512	0	1	3	0.0	0.3	0.5	0.8	0.2	100	0.0	0.1	0.1	0.2	100
total:	430	432	405	245	117	65	427	100		57	27	16	100	

6.4 Spatially integrated volumetric sampling (reach-averaged)

A reach-averaged mass-based particle-size distribution may be obtained by sampling an entire reach with a spatially integrated methodology or by delineating the reach into its sedimentary units which are then sampled separately (spatially segregated). Spatially integrated sampling means that sampling integrates over all sedimentary units (or any other distinguishable streambed units such as geomorphological units or habitat units) instead of sampling each unit separately (i.e., spatially segregated). Whether spatially integrated sampling is preferable to spatially segregated sampling must be determined for each stream and study situation. Criteria for making this decision will be outlined.

Spatially integrated or segregated sampling for a reach-averaged particle-size distribution?

Spatially integrated volumetric sampling is best used for computing the reach-averaged particle size of relatively homogeneous reaches in which the number of sampling locations is relatively low. If heterogeneous reaches are sampled spatially integrated, the number of samples needed to cover the reach is relatively high which leads to a large total sample mass. Heterogeneous reaches are therefore better sampled using a spatially segregated approach (Section 6.5.2.2). Within the delineated sedimentary unit, bed material is comparatively homogeneous. This leads to a relatively small number of samples for each unit and to a relatively small mass for each sample. Therefore, the total mass required for each sedimentary unit remains rather small.

Note, however, that the process of delineating the reach into its sedimentary units and the survey to measure the areal extent of each unit is labor intensive as well, particularly if the reach is comprised of a large number of relatively small sedimentary units (patches). The increased work effort from delineation and surveying offsets some of the work effort rendered unnecessary by the reduced sample mass of spatially segregated sampling. Thus, on moderately heterogeneous reaches or patchy reaches comprising numerous small facies units, the total work effort may actually be similar for spatially integrated and spatially segregated techniques. Finally, spatially integrated sampling is also used when the presence of facies units is irrelevant for the study.

Volumetric samples may refer to sediment from the armor layer, the subarmor, the subsurface, or the vertically unstratified bulk sediment (Fig. 4.1). Because spatially integrated sampling is used for reaches that are relatively homogeneous, or that have small patches, the user needs to evaluate the degree of spatial heterogeneity within the reach. When sampling the armor layer or the vertically unstratified bulk sediment, the surface portion of the sediment to be sampled is visible to the observer. However, when the sampling target is the subarmor or subsurface sediment, its degree of spatial variability can only be inferred from the degree of spatial variability of the surface sediment. Inference is possible based on the observations by Lisle and Hilton (pers. comm. 1998) and Buffington and Montgomery (1999 a and b) that surface and subsurface particle-size distributions are often related in a positive, linear way (Section 6.1.6.2). Fine surface sediment is likely to have fine subsurface sediment beneath, whereas coarse surface sediment is likely to have coarse subsurface sediment. The degree of subsurface homogeneity or heterogeneity, and thus the subsurface sampling scheme cannot be inferred from the surface sediment if a post-flood surface deposit (usually of fines) alters the flood-generated relation between surface and subsurface sediment size.

The following sections explain sampling schemes for spatially integrated volumetric sampling. Sampling schemes should be discussed together with sample-mass requirements because the precision obtained from a given sample mass may differ depending on the sampling scheme applied. Thus, the topic of sample size recurs throughout Sections 6.4 and 6.5.

6.4.1 Sampling a truly homogeneous reach

A truly homogeneous sediment deposit has very little or no variability between samples collected at various locations within the reach. Thus, all sampling schemes lead to the same sampling result. The most practical approach to sample a truly homogeneous reach is to collect one or a few unbiased samples that suffice for a predetermined precision requirement at random location(s) within the reach.

Total sample mass required for a homogeneous reach depends on a preset precision requirement, and may be determined from a relation between sample mass and error (e.g., Ferguson and Paola (1997), Fig. 5.22 or Eqs. 5.62 and 5.63 in Section 5.4.3.2). For an assumed normal distribution in terms of ϕ, sample mass for a specified precision depends on the general coarseness of the sediment, the percentile of interest, and most markedly on sediment sorting (Section 5.4.3). Estimates of the ϕ_{50} and the bed material sorting (i.e., the ϕ_{16} and ϕ_{84}) are obtained from a pilot study. If no particular underlying distribution type can be assumed for the parent distribution, sample mass may be computed from the empirical and mathematically simple recommendations by Church et al. (1987) that are based on the D_{max} particle size (Section 5.4.1.1). The 0.1% criterion, for example, determines total sample mass m_{tot} as 1000 times the mass m_{Dmax} of the D_{max} particle. A pilot study then only needs to determine the D_{max} particle size for the reach. When applied to a normal distribution, the 0.1% criterion provides a precision of at least $\pm 0.4\phi$ for all percentiles up to the D_{95}, even for poorly sorted sediment with $s \leq 2$. Sample mass can easily amount to hundreds or thousands of kg or more in coarse gravel-bed streams, even if the less stringent 1% criterion of $m_{tot} = 100\ m_{Dmax}$ is applied.

6.4.2 Sampling schemes for spatially integrated sampling of heterogeneous reaches

The statistical precision, as well as the work effort of a sampling study is affected by the spatial patterns with which samples are collected within a reach (Smartt and Grainger 1974). The sampling pattern used for spatially integrated volumetric sampling include: (1) random locations for volumetric samples, (2) volumetric samples at systematic grid points, (3) volumetric samples at random locations within systematic grid cells, and (4) volumetric samples at the grid points of several grid systems overlaying each other (two-step approach) (Fig. 6.1). Application of these sampling schemes to heterogeneous reaches in coarse gravel-bed streams are discussed below.

6.4.2.1 Random sampling locations

Random sampling is appropriate for homogeneous streambed areas in which the location of sampling does not influence the outcome of the sampling result. However, spatial homogeneity is rare in mountain gravel-bed streams. Sampling at random locations is not recommended for heterogeneous reaches. One reason is that the irregular spacing of random sampling may fail to include all stream locations in a representative way. Small facies areas, in particular, are likely to remain unsampled. Thus, random sampling tends to

require more samples than systematic sampling to arrive at the point where further sampling leads only to minor improvements in precision. Analyzing volumetric samples collected on a spatially heterogeneous large gravel bar, Wolcott and Church (1991) found that random sampling resulted in a different particle-size distribution than systematic sampling and required five times more samples for the same sampling precision.

Another reason why random sampling is not recommended in coarse gravel- and cobble-bed streams is that random sampling is not as versatile as systematic sampling. Samples taken at random locations cannot be used for a retroactive delineation of the streambed area into facies units, nor can random samples collected from heterogeneous beds be combined for joint analysis in one large sample (Section 6.4.4.3 and 6.4.4.5). A joint analysis of subsamples in one aggregate sample requires that all samples represent an identical portion of the streambed area. Random samples collected from heterogeneous beds are also not usable to assess the sampling precision in a two-stage approach (see below).

6.4.2.2 Sampling the reach at systematic grid points

When applying a spatially integrated sampling scheme to a heterogeneous reach, a good strategy is to cover the reach by a systematic grid and to collect volumetric samples at each grid intersection. Fig. 6.16 shows an example of a systematic grid that covers the reach with 360 grid points. Sampling a heterogeneous reach at systematic grid points ensures that all areas in the reach are representatively included in the sample.

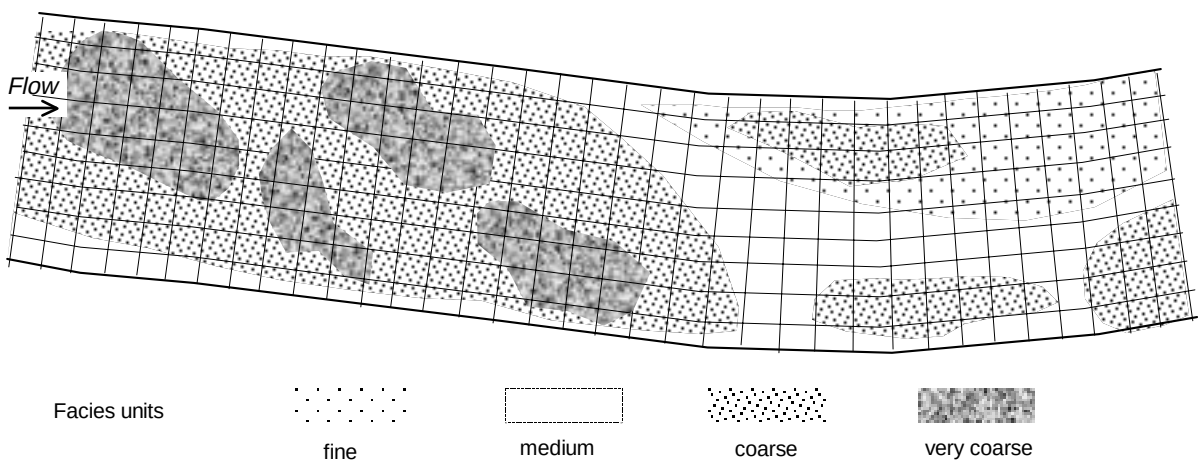


Fig. 6.16: Spatially integrated volumetric sampling (reach-averaged sampling) of a heterogeneous reach with small sedimentary units at grid points. A grid with 360 points or 324 grid cells covers the reach.

However, systematic sampling may not correctly represent sediment from units that are smaller than the grid size. Small sediment units are underrepresented if no grid points falls into that area and overrepresented if a grid point happens to fall within the area.

Misrepresentation can be avoided by choosing a grid spacing to match the smallest sampling units on the bed.

6.4.2.3 Random placement of sampling locations within grid cells

In a stream reach with linear structural streambed elements, such as transverse ribs, berms, or sand-filled micro-channels, some randomization in sample placement is preferable to a strict placement at grid points. Randomization avoids sample locations that align with linear bed elements. A moderate randomization of sampling locations can be achieved by sampling at a random location within the area outlined by regularly-shaped and even-sized cells (Fig. 6.17) (Wolcott and Church 1991). The outline of cells does not need to correspond to the boundaries of sedimentary or geomorphological units. Random placement of sampling locations into very large grid cells approaches the outcome of random sampling (Section 6.4.2.1). Thus, the cell size should not be too large. It is also possible to introduce more regularity into the sample point location by using algorithms. An example is to place the sample locations of the first row of cells at an equal distance x_1 from the left boundary of all cells in row 1. Likewise, all sampling locations for the second row of cells are placed at an equal distance x_2 from the left cell borders. The y-coordinate of the sampling locations is determined accordingly. All sampling locations in the first column of cells are placed at an equal distance y_1 from the top of the cells, and at an equal distance y_2 from the top for all cells in the second column (Smartt and Grainger 1974).

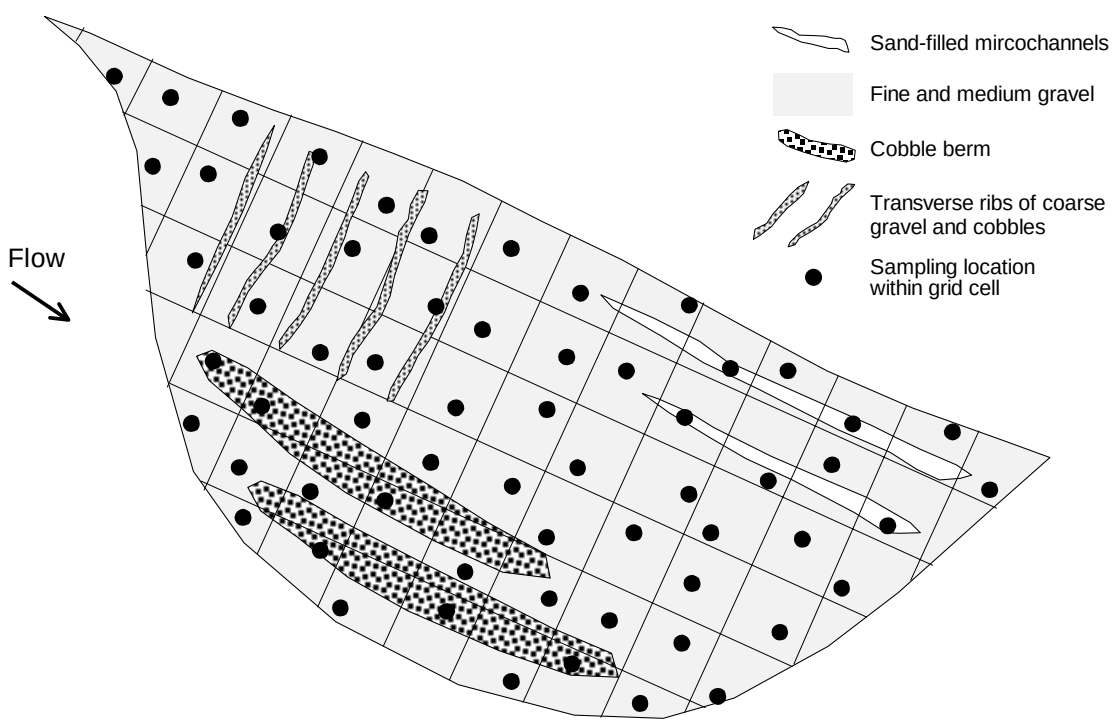


Fig. 6.17: Sampling at random locations within systematic grid cells.

If linear bed features are absent, Wolcott and Church (1991) found that sampling at systematic grid points and sampling at random locations within the same number of systematic cells produced similar reach-averaged particle-size distributions with similar sampling precision.

6.4.2.4 Two-stage sampling using overlaying grid systems or a small grid pattern

Two-stage sampling is used to compute the statistical difference or precision between repetitive samples collected from the same population (Sections 5.4.2.1 and 6.4.4.4). For spatially integrated sampling on a heterogeneous bed, the requirement that all samples come from the same population means that each sample should represent the same degree of spatial variability. This demand is best achieved by sampling the reach using several grid systems, each with the same size and spacing, but each slightly shifted in position against the other grids. The sample grid systems may be laid out and sampled sequentially until a desired sampling precision has been attained. A more efficient alternative may be to use a pilot study to estimate the number of repeated samples needed to obtain a preset precision. If, for example, the pilot study suggested that each volumetric sample collected from 200 grid points should be repeated about 5 times, repetitions can be performed by laying out a small grid pattern of 1,000 points from the start. Individual samples are then allocated either randomly or systematically into one of five sets. Care must be taken to avoid any systematic difference between subsamples, which may occur when a streambed shows fining or coarsening towards one bank or in a downstream direction.

6.4.3 Number of sampling points for systematic samples of heterogeneous reaches

After the patterns for spatially integrated sampling have been determined, the user needs to determine four factors that relate to sample mass:

1. Number of sampling points in the reach (Sections 6.4.3.1 and 6.4.3.2) ,
2. Mass of sediment to be collected at each sampling locatior } Sections 6.4.4.1 - 6.4.4.3)
3. Total mass of sediment to be collected in the reach, and
4. Number of replications of the total sample (Section 6.4.4.4).

The number of samples required for an accurate characterization of the particle-size distribution in the reach depends on the degree of spatial variability within the reach. Purely statistical criteria may be applied to compute this number when sampling a large area in a dry streambed (e.g., 160 m by 1,000 m or 400 m by 400 m) where the resulting number of sampling locations may amount to 100 or more. Geometrical and ecological criteria need to be considered in smaller streams. When sampling in a mountain stream 10 m wide with most of the bed inundated by flow, sampling space becomes not only restricted from a geometrical standpoint, but also from an ecological one.

6.4.3.1 Large streams, no space limitation

Based on their study on a large and heterogeneous gravel bar of approximately 160,000 m^2, Wolcott and Church (1991) suggested that 100 to 300 samples collected from even-spaced sampling points may be appropriate for an unbiased particle-size estimate of reach-averaged subsurface sediment in many gravel-bed rivers. The number of sampling locations can be determined for a specified reach by collecting a number of subsamples. The standard deviation of the subsample mean s_{Dm} is then computed for an increasing number of subsamples (n_2 to n_{tot}) and plotted. As the number of subsamples increases, the standard deviation of the subsample means decreases. Ideally, the plotted relation of standard deviation versus sample size follows the function $s_{Dm} = f\,(1/\sqrt{n})$. The graph of this curve decreases steeply for small sample sizes and flattens for larger sample sizes (Fig. 6.18 and Section 5.4.2.2; Figs. 5.10 and 5.11 in Section 5.2.3.4). At some position along the curve there is a point at which a further increase in the number of samples does not significantly improve the sampling precision. This point defines the number of samples n_{opt} needed to characterize the reach as the optimum trade off between sampling effort and sampling precision.

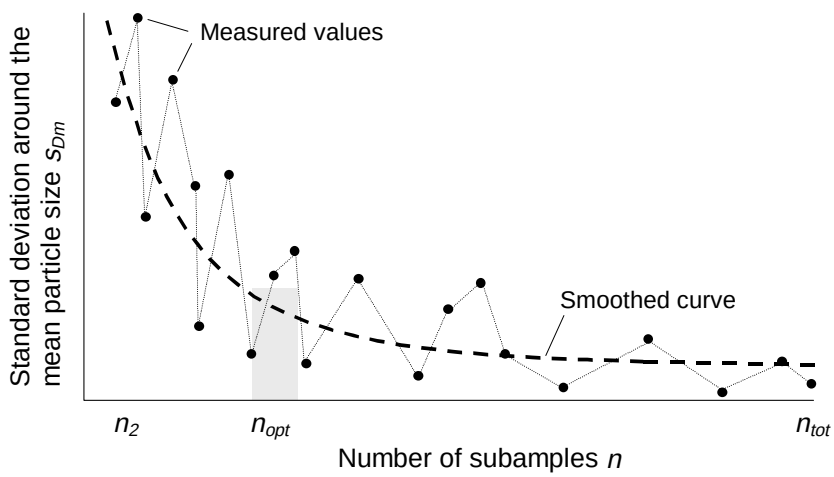


Fig. 6.18: Decrease of the standard deviation of the mean particle size s_{Dm} for subsamples increasing in number from n_2 to n_{tot}. n_{opt} is the sample size at which a further increase in sample size does not lead to a further significant increase in sampling precision and the optimal sample size in the trade-off between precision and work effort.

When performing an analysis with only one data set, the resulting curve is likely to be jagged (Fig. 6.18). A smooth curve is only obtained if the standard deviation for each subsample size is computed for a large number (approximately 50 - 200) of repeated subsamples. This number of repetitions is only practical with computer sampling. When using only one data set, the user might want to fit a regression curve through the data points to better visualize the optimal number of samples for a reach (Section 5.4.2.2). However, the smoothed curve indicates an unduly high precision.

6.4.3.2 Small streams, space limitation for sampling

Another aspect to consider when determining the grid size for spatially integrated sampling is the areal extent of each volumetric sample in relation to the size of the reach. Assume a mountain stream with most of the streambed inundated by flow and that volumetric samples are collected with the plywood shield (Section 4.2.4.7). Each sample then covers (and disturbs) a streambed area of approximately 0.5 m^2. If such samples were spaced 5 m apart in a stream 10 m wide, and the reach was 50 m long, 20 samples could be collected per reach. The combined area of all samples is 2% of the reach (10 m^2 of 500 m^2). With respect to statistical precision, 20 samples may be low. From an ecological standpoint, the damage caused by 20 samples may be high. The user must decide where to place the emphasis.

6.4.4 Subsample mass at each grid location and total sample mass within the reach

The mass of individual samples taken within the reach may be computed using either an empirical or an analytical approach. The empirical approach presented by Wolcott and Church (1991) makes no assumptions regarding the bed-material distribution-type and is based on the sample mass criteria by Church et al. (1987) (Fig. 5.14 in Section 5.4.1.1). Ferguson and Paola (1997) present an analytical approach that assumes that the bed material follows a normal distribution in terms of ϕ-units. The analytical approach allows computing sample mass for a specified level of precision around a given percentile (Fig. 5.22 or Eq. 5.62), but requires prior knowledge of at least one percentile of the distribution and the sorting coefficient of the bed through a pilot study.

6.4.4.1 Full sample at each grid location in well sorted, fine to medium gravel beds

One means for determining the sample mass needed for an unbiased sample (Fig. 5.14) or for a preset precision requirement (Fig. 5.22) is to select a stream location that best represents the average particle-size distribution of the bed. Sample mass that satisfies a predetermined precision is then computed for that location and collected at each of the 100 or so grid locations within the reach. Collection of “full” samples at all grid points may be feasible in streams with fine gravel where a kg of sediment is adequate for a specified precision, but not for poorly sorted gravel-bed streams.

6.4.4.2 Reduction of sample mass at each grid location in poorly sorted gravel- and cobble beds

When sampling in poorly sorted, coarse gravel- or cobble-bed streams, the mass required for a single sample alone can amount to hundreds or thousands of kg (Fig. 5.14 or Fig. 5 22). If such a sample is collected at each of the 100 or so grid points per reach, the total mass of sediment collected in a reach approaches several tens or hundreds of tons, a mass

that is usually impossible to collect, particularly in mountain gravel-bed streams. In order to facilitate collection of a manageable sediment sample, the sample mass needs to be reduced. To the extent possible, the reduction needs to be carried out such that the total sample mass collected remains statistically meaningful. Reducing the number of grid points is not recommended because this may lead to unrepresentative samples of the various facies in the reach. A better approach is to reduce the sample mass collected at each sampling point. Several approaches may be used.

1. Exclusion of the largest particle sizes from the analysis (truncation at the coarse end, Section 5.4.1.4, acceptable and even recommended by some if the study focuses on fines),
2. Acceptance of a larger error (see discussion of sample size, e.g., Fig. 5.22 in Section 5.4.3.2),
3. Limitation of the analysis to the D_{50} particle-size for which fewer sample are requirement than for higher or lower percentiles; see Fig. 5.22 in Section 5.4.3.2), and
4. Collection of individually small samples (grab samples) that are combined to one composite sample that is then statistically unbiased and "accurate".

Approaches 1 - 3 have been already been discussed. The mass of the individually small samples (Approach 4) can be computed based on either empirical sample-mass recommendations (Section 6.4.4.3) or analytically (6.4.4.5). Both approaches may yield a different grab sample mass.

6.4.4.3 Individually biased grab samples, empirical approach

Instead of collecting large and statistically valid samples at each grid location, Wolcott and Church (1991) proposed collection of individually small grab samples while maintaining the number of sampling locations. The reduction of sample mass at each grid location is justified on the basis of two arguments. (1) If the entire reach is sampled at regular grid points (Section 6.4.2.2) or at random locations within regular grid cells (Section 6.4.2.3), each sample represents the same fraction of the total sampling area. Since all samples represent an area of the same size, all particles collected in a reach may be combined into one large sample for joint sieving to obtain a reach-averaged particle-size. (2) If all volumetric samples are reduced by an equal amount, the sample mass per grid point may be substantially reduced to the size of a grab sample and still remain unbiased with respect to total sample mass. Based on the empirical 1%-criterion by Church et al. (1987), that makes no assumptions about the underlying distribution type, Wolcott and Church (1991) recommend the following two sample mass criteria for determining the grab sample mass:

1. Each grab sample must encompass at least 1% of the total sample mass required for an unbiased sample of the entire reach.

2. Each grab sample must be at least as large as the mass of the largest particle present in the reach (D_{max}) to ensure a potentially equal mass of all grab samples. The sampling device used must not hinder collecting a particle of near D_{max} size.

Example 6.4:
A pilot study has estimated a subsurface D_{max} particle size to be 256 mm, which is approximately the D_{99} particle size of a sediment with a D_{50} of 22.6 mm and a sorting of s = 1.5. A spherical or ellipsoidal quartz (ρ_s = 2.65 g/cm^3) particle with a b-axis length of 256 mm has a mass m_p of approximately 23 kg ($m_p = \pi/6 \cdot b^3 \cdot \rho_s$).

Each grab sample should have a mass of at least 23 kg, the mass of the D_{max} particle in order to give each grab sample the chance to contain at least one D_{max} particle. 23 kg of sediment fills a heaping household pail.

If the D_{max} particle mass is not to exceed 1% of the total sample mass (1% criterion for coarse gravel beds, Section 5.4.1.1), total sample mass allotted to a 100-point grid system is 100 · 23 kg = 2,300 kg (≈ 1.2 m^3 or 12 cubic feet). If 200 samples are needed to cover the spatial variability of the reach, total sample mass is 200 · 23 kg = 4,600 kg.

Assume, a two-stage approach (see next heading) determined that the 200 grab samples need to be repeated 5 times to arrive at an acceptable level of precision, total sample mass for the reach is 5 · 4,600 kg = 23,000 kg. Results of these computations are presented for three D_{99} particle sizes in Table 6.6.

Table 6.6: Grab sample mass m_{ss} (kg) suggested by Wolcott and Church (1991) according to the 1% criterion by Church et al. (1987): $m_{ss} = m_{Dmax}$. 200 grab samples are collected in the reach, amounting to a sample size of 200 m_{ss}. Five repetitions yield a total sample mass of m_{tot} = 1,000 m_{ss} for the reach.

Particles size of D_{max} or D_{99} (mm)	Grab sample mass m_{ss} (kg)	Combined mass for 200 grid points (200 m_{ss}) (kg)	Total sample mass for 5· 200 grid points (1,000 m_{ss}) (kg)
114	2.0	412	2,060
225	23	4,600	23,000
572	260	52,000	260,000

The sample mass required for one grab sample may exceed the capacity of the sampling device which is a few kg for a pipe sampler (Section 4.2.4.5), and nearly 50 kg for a barrel sampler (Section 4.2.4.6). In this case, a larger sampling device should be used, such as the plywood shields (Section 4.2.4.7). If several physical samples must be combined to obtain one grab sample, care must be taken that the device facilitates collecting a particle of D_{max} size. Truncation of the sample at a certain large particle size (Section 5.4.1.4) may be unavoidable.

6.4.4.4 Determining sampling precision from two-stage sampling with overlaying grid systems

When taking individually small grab samples, information on sampling precision is obtained from a two-stage sampling procedure that compares several repetitions of the combined sample from the reach (Sections 5.4.2.1, 5.4.2.2 and 6.4.2.4).

Example 6.5:
The study objective is to determine the D_{50} particle size to a precision of ± 20%. The number of sampling locations was estimated at 50. Five sets of 50 grab samples of 40 kg each were collected and jointly sieved. The five values of the D_{50} particle size are 60, 70, 80, 90, and 100, mm with a mean D_{50m} of 80 mm, and a standard deviation s_{D84} of 15.8 mm. The precision of those 5 samples may be computed either with the general sample size equation (Eq. 5.13 for absolute error) or with the equation given below for relative error. The *t*-value for n = 5 is 2.78 (Table 5.2).

$$n = \left(\frac{t_{1-\alpha/2;n-1} \cdot CV}{e_{\%}}\right)^2 = \left(\frac{t_{1-\alpha/2;n-1} \cdot s_{50}}{e_{\%} \cdot D_{50m}}\right)^2$$

$$= \left(\frac{2.78 \cdot 15.8}{0.2 \cdot 80}\right)^2 = 7.5 \cong 8$$

Since the computed sample size of 7.5 is smaller than 5, the computation is repeated with a *t*-value for 6 =2.57, yielding n = 6.4. Another iteration is not necessary, because even if a *t*-value for 6.2 was used and yielded a result close to n = 6.2, sample size is usually rounded up to the next integer value, which is 7. Total grab sample mass necessary to estimate the D_{50} particle size to a precision of ± 20% amounts to 7 · 50 · 40 kg = 14 metric tons, or ca. 7 m^3.

6.4.4.5 Individually unbiased subsamples for assumed normal distributions

The sample mass for individual grab samples determined in Section 6.4.4.3 and Example 6.4 ($m_{ss} = m_{Dmax}$, and $m_{ss} = m_{tot}$ /100) was geared towards creating a total sample that is unbiased towards the D_{max} or D_{99} particle size. This sample-mass computation is free of any assumptions of an underlying distribution type. Table 6.6 illustrates that the total sample mass amounts to tons and hundreds of tons when the D_{max} particle size is in the boulder range. The sample mass for grab samples can be smaller than computed in Table 6.6 and Example 6.4, if the sampling objective requires an accurate determination of the D_{50} particle sizes only, and if a pilot study revealed that a normal distribution of particle sizes in ϕ units might be assumed.

For underlying normal distributions, Ferguson and Paola (1997) provide a sample mass equation that provides bias avoidance for specified percentiles. If the study objective is to determine the D_{50} size, bias only needs to be avoided in the D_{50} particles size and the subsample mass can be accordingly small. By contrast, if the reach-averaged D_{95} is of interest, each subsample should be sufficiently large to satisfy the criterion for an unbiased D_{95} particle size. The subsample mass for bias avoidance and the total sample mass required for the reach is computed in Table 6.7 for three particle-size distributions. Each of the distributions has a D_{50} of 22.6 mm, but the sorting coefficients are 1, 1.5, and 2 ϕ, so that the D_{84}, D_{95}, and D_{99} particle sizes are different for each of the three distributions. Collecting individually unbiased samples has the advantage that samples may be compared among themselves and may be used for retroactively delineating facies units (Crowder and Diplas 1997, Section 6.3.2.3).

Table 6.7: Three normal particle-size distributions (in ϕ) with equal D_{50} particle sizes of 22.6 mm, but sorting coefficients of s = 1, 1.5 and 2. Total sample mass (m_{tot}, kg) required for a tolerable absolute error of ± 0.3 ϕ for the D_{50}, D_{84}, D_{95}, and D_{99} particle size as well as the subsample mass necessary for bias avoidance in the D_{50}, D_{84}, D_{95}, and D_{99}. Number of sampling points is computed from the ratio m_{tot}/m_{ss}.

Per-cen-tile	Particle size (mm)*			Total sample mass m_{tot} (kg) for acceptable absolute error ± 0.3 ϕ#			Subsample mass m_{ss} (kg) required for bias avoidance§			Number of sampling points m_{tot}/m_{ss} for		
	s =1	s = 1.5	s = 2	s =1	s = 1.5	s = 2	s = 1	s = 1.5	s = 2	s = 1	s = 1.5	s = 2
D_{50}	22.6	22.6	22.6	18	99	336	0.32	0.48	0.64	58	207	525
D_{84}	45	64	90	146	2.24 t	19.2 t	2.6	10.4	38	57	215	526
D_{95}	71	125	221	528	17.6 t	304 t	9.9	80.0	592	54	220	513
D_{99}	114	255	572	2.24 t	136 t	5,100 t	40	670	9.9 t	56	203	515

* Computed from Eq. 5.58 in Sect. 5.4.3. # Values read off and determined from Fig. 5.22 b in Section 5.4.3.2. § Values read off and determined from Fig. 5.20 and Eq. 5.60 in Section 5.4.3.1.

6.4.4.6 Comparison of subsample masses and total sample mass computed with two different approaches

The grab-sample mass computed by Wolcott and Church (1991) (Table 6.6) for bias avoidance of the D_{99} particle size of the total sample is sufficient to avoid bias in the D_{90} particle size when applied to subsamples from normally distributed deposits (Table 6.7). The total sample mass computed by Wolcott and Church (1991) (Table 6.6) which assumed the necessity of 200 grid points and 5 repetitions of the 200-grid (a total of 1,000 grid points) suffices for a ± 0.3 ϕ precision of approximately the D_{95} particle size. Thus, both approaches yield comparable results for high percentiles in the D_{90} to D_{95} region.

The approach by Ferguson and Paola (1997) determines a much smaller subsample mass when central percentiles are the focus of the study. If the D_{50} or the D_{84} are the only percentiles of interest, subsample mass may be reduced to 0.6 or 38 kg (Table 6.7), if a deposit sorting of s = 2 and a normal distribution are assumed. This is a substantial

reduction of sample mass compared to a subsample mass of 260 kg for a deposit with a D_{max} particle size of 572 mm (Table 6.6).

6.4.4.7 Retroactive computation of the number of sampling points

In the approach by Ferguson and Paola (1997) shown in Table 6.7, the number of sampling points per reach may be computed retroactively from the ratio of the total sample mass m_{tot} required for a sampling precision of 0.3 ϕ around a specified percentile and the subsample mass for bias avoidance m_{ss}. The ratio of the two independently determined parameters m_{tot}/m_{ss} ranges from approximately 55 for a sorting coefficient of s = 1, to 210 for s = 1.5, and to approximately 520 for s = 2. These values are similar to the sampling point numbers of 100 - 300 suggested by Wolcott and Church (1991). While the approach by Wolcott and Church (1991) points out that the number of sampling locations depends on the degree of spatial heterogeneity of the reach, results by Ferguson and Paola (1997) point out that the number of grid points strongly increases with the degree of bed-material sorting.

6.4.4.8 Problems with collecting large samples in coarse gravel and cobble-bed streams

The total mass of all volumetric samples per reach can become very large. One reason for this is that heterogeneous beds require many samples to characterize a reach (Table 6.6 and 6.7). Other reasons are that individual samples become large due to a large percentile of interest, poor sorting of the bed, or a large D_{50} size. Sampling large masses not only requires heavy equipment, but is also restricted to large streams where gravel extraction of this magnitude does not result in severe environmental damage. When sampling in mountain gravel-bed streams, collecting large sample masses is often neither feasible, nor ecologically responsible. Statistical measures (e.g., truncation at the coarse end, acceptance of a larger error, limitation of analysis to the D_{50} size) help to reduce the huge sample mass. Logistical measures (e.g., sieving and analyzing the coarse portion of the sediment in the field, splitting the sample (preferably in the field) and retaining only a fraction of the medium and fine gravel and sand for laboratory analysis) improve the manageability of large sample masses (Section 2.1.3.8 - 2.1.3.10).

6.4.4.9 Computation of the reach-averaged particle-size distribution

To compute the reach-averaged particle-size distribution, each subsample is sieved individually and a particle-size distribution is computed. The reach-averaged particle-size distribution is obtained from the arithmetic mean weight frequencies or percentage frequencies per particle-size class of all individual samples. This approach is mathematically identical to lumping all individual samples together for joint sieving. However, joint sieving looses all information on spatial variability. The computation of a reach-averaged percentile particle size from the mean percentile particle-size of all individual samples is not recommended and is only an option if all individual samples are

sufficiently large to be unbiased. Areal weighting is not required because each subsample represents an equal fraction of the streambed area.

6.5 Spatially segregated volumetric sampling (sampling each unit individually)

For spatially segregated volumetric sampling, the reach is delineated into geomorphological units (e.g., bars, riffles, pools) (Section 6.3.1), sedimentary units (e.g., fine, medium and coarse facies) (Section 6.3.2), aquatic habitat units (e.g., areas with particular flow conditions and/or substrate), or any other stream units of interest. Depending on the study objective, sampling may be restricted to one unit that is of specific concern, to all units of a certain type, to some representative units of a type, or to all units within a reach.

Spatially segregated volumetric sampling may be applied for sampling the armor layer, the subsurface, or the vertically unstratified bulk sediment. Determining appropriate sampling schemes and sample masses has been previously discussed.

6.5.1 Geomorphologically stratified sampling

Geomorphologically stratified sampling is usually used to characterize the particle-size distribution of a geomorphological unit. The geomorphological unit most commonly sampled by volumetric samples is the riffle. Samples collected from bars or pools usually focus on a particular location within the unit (e.g., the bar head), or on a particular kind of sediment (e.g., fine sediment only, or coarsest clasts only) (Sections 6.6.1 and 6.6.2).

Geomorphologically stratified sampling is not a recommended strategy for characterizing the reach-averaged bed-material size because the number and mass of subsamples required is much larger than would be the case when sampling the reach stratified into sedimentary units. This aspect is discussed in more detail in Section 6.5.2.1.

6.5.1.1 Sampling on riffles only

Information on subarmor or subsurface sediment size on riffles is important for a variety of studies. The percentage of subsurface fines, for example, is part of the evaluation of fish spawning habitat because subsurface fines can decrease the spawning success of salmonid fish (Bjornn and Reiser 1991). Watershed monitoring studies use changes in the percentage of riffle subsurface fines over time as an indication of changes in land use practices and sediment production.

Riffles that are sampled in such studies should be representative of the reach. Riffles that are considerably coarser than the reach should be avoided. Coarse riffles may result from large rockfall particles being incorporated in the riffle but not in the remainder of the

reach. Riffles that are unusually fine should also be avoided. Fine riffles can result when imbrication and particle interlocking provide the stability that would otherwise be provided by the presence of large particles (Sections 6.3.1.3, 3.2.2.2 and 3.2.2.3). Sampling should be repeated over several riffles in order to average out local effects.

Note that neither the riffle subsurface sediment, nor the armor layer, nor the vertically unstratified bulk sediment is automatically representative of the average subsurface particle-size distribution of the reach. For example, fine sediment entering the reach is not necessarily stored in the subsurface of the riffle if the stream reach contains backwater areas or pools that are more likely to be storage places for fines. If typical storage features are absent, more fines may be stored in the riffle subsurface sediment than would be if backwater areas and pools were available for storing fine sediment. Thus, the riffle subsurface sediment is not necessarily representative of the fine sediment supply to the reach. The supply of fine sediment is better determined from collecting subsurface sediment from the entire reach (Section 6.5.2.1) or from spatially focused sampling of fine sediment in pools (Section 6.6.2).

6.5.1.2 Sampling patterns and sample mass for riffle samples

If the study objective focuses on an analysis of the riffle subsurface (or armor, or bulk) sediment, volumetric samples should be collected from the entire riffle either in a grid pattern (Section 6.4.2.2) or from random locations within even-spaced and even-sized cells (Section 6.4.2.3). The number of samples to be collected on the riffle depends on the spatial variability of the riffle subsurface sediment which is unknown but assumed to be similar to the spatial variability of the surface sediment (Section 6.4). The mass for each individual sample depends on the sorting of the subsurface riffle sediment, the percentile in question, and the particulars of the sampling goal (Section 6.4.4).

The user has a choice between collecting full samples, grab samples, or individually unbiased samples at each grid point. The first option may yield a large total sediment mass and is only feasible if either the number of samples is small, or when the sediment on the riffle is fine to medium gravel (Section 6.4.4.1). Grab samples are obtained in coarse gravel-beds when no particular type of particle-size distribution is assumed, and if obtaining an unbiased sample for the riffle sediment in general is the study objective (Section 6.4.4.3). The number of sampling points for grab samples should be determined from a precision analysis similar to that in Fig. 6.18 (Section 6.4.3.1). A two-stage sampling approach may be used to compute the sampling precision (Section 6.4.4.4). If, for example, a barrel sampler provides a sample mass of approximately 50 kg each, the user may begin by collecting 3 - 5 samples on the riffle. The samples are repeated 3 - 4 times at slightly shifted locations to yield a total of 9 to 20 samples weighing a total of 450 - 1000 kg. Rood and Church (1994) used a hybrid sampler (Section 4.2.4.10) that collects about 13 kg per sample. They found that about 30 - 50 samples were necessary to detect a 10% change in the percent subsurface fines on an individual riffle if particles larger than 32 mm were present. A sample mass of approximately 1 ton may be logistically or ecologically unfeasible. The user needs to either accept a higher tolerable error for

detecting a change in subsurface fines, or the samples collected must be truncated at some large particle size in order to reduce the mass of individual samples (Section 5.4.1.4).

If the particle-size distribution in the bed can be assumed to be normal, and the sediment sorting is known from a pilot study, the user may collect samples that are individually unbiased (Section 6.4.4.5). Individually unbiased samples tend to produce a higher total sample mass than the grab-sample approach if the sample is unbiased with respect of the D_{95} and higher percentiles. The total mass of individually unbiased subsamples is lower if central percentiles are of concern and sample size only needs to avoid bias in particle sizes between the D_{50} and the D_{84} (Tables 6.6 and 6.7). The total sample mass required for the reach is determined for a specified precision around a specified percentile. The number of samples per reach is the ratio between the mass of the total sample and an individual sample (Section 6.4.4.7). The number increases with the sorting of the bed material.

6.5.2 Sedimentary stratified sampling

Sedimentary stratified volumetric sampling is used to describe the reach-averaged particle size-distribution of the armor, the subarmor (or subsurface) and the unstratified bulk sediment (Section 6.5.2.1). Another use of sedimentary stratified volumetric sampling is to determine the reach-averaged subsurface D_{50} size (Section 6.5.2.2). The ratio of surface sediment size to the size of subsurface sediment (D_{50surf}/D_{50sub}) is an important tool for watershed monitoring and sediment transport analysis.

The ratio of the surface sediment size to the size of the fine mode of bedload, or to the size of pool fines, is also used for analysis. These ratios may be used to determine whether bedload transport is supply- or transport limited (Dietrich et al. 1989; 1993; Lisle et al. 1993; Lisle 1995; Lisle and Hilton 1992, 1996, 1999; Buffington and Montgomery 1999 a, b, and c). A value close to 1 for the ratio D_{50surf}/D_{50sub} indicates high sediment supply, while values larger than 1 indicate low sediment supply. Subsurface sediment size is also used as an estimate of the particle-size distribution for bedload transport. Subsurface is similar in size to bedload in aggrading streams, but in degrading streams, subsurface sediment is coarser than bedload (Lisle 1995). Surface and subsurface sediment are often related in size, such that coarse surfaces have coarse subsurface sediment. In reaches where this relation is true, it is possible to segregate the reach for subsurface sampling based on the sedimentary textures visible on the surface (Section 6.4).

6.5.2.1 Reach-averaged information on subsurface, armor, or bulk sediment size

Sedimentary stratified sampling is recommended for computing the reach-averaged bed-material size in heterogeneous reaches because sedimentary units are more homogeneous and better sorted than either geomorphological units or the reach as a whole. Consequently, each sedimentary unit requires a smaller total sample mass for a specified precision than does sampling from a geomorphological unit, or the reach as a whole.

Sampling schemes for spatially segregated sampling on sedimentary units
Several sampling schemes may be applied for spatially segregated sampling of sedimentary units. The patterns with which volumetric samples are collected depend on the size of both the reach and its sedimentary units, and on how dispersed the sedimentary units are within the reach (patchiness). The sampling patterns are summarized in Table 6.8.

Table 6.8: Approaches for spatially segregated sampling of sedimentary units for reach-averaged information on sediment size.

Sampling situation	Sampling approach
1. Small reach, few sedimentary units	An appropriate number of sampling locations is distributed evenly over each of the units.
2. Large units within large reaches	Samples are collected from representative locations within each of the sedimentary units.
3. Each sedimentary unit occurs multiple times (patchiness)	Samples are collected from a few patches that are representative for a given facies type.
4. Study objective restricted to surface and subsurface D_{50} particle size	Samples are collected at locations at which the local surface D_{50} is equal to the reach-averaged surface D_{50} particle size (Section 6.5.2.2).

Situation 1: A reach that has only a few sedimentary units that are mostly contiguous and of approximately equal size may be sampled by collecting several subsamples from all sedimentary units either at grid points or from within grid cells (Fig. 6.19). This situation is most likely encountered in small B- and C-type (mountain) gravel-bed streams with plane-bed and riffle-pool morphology (Sections 1.3.1. and 1.3.2).

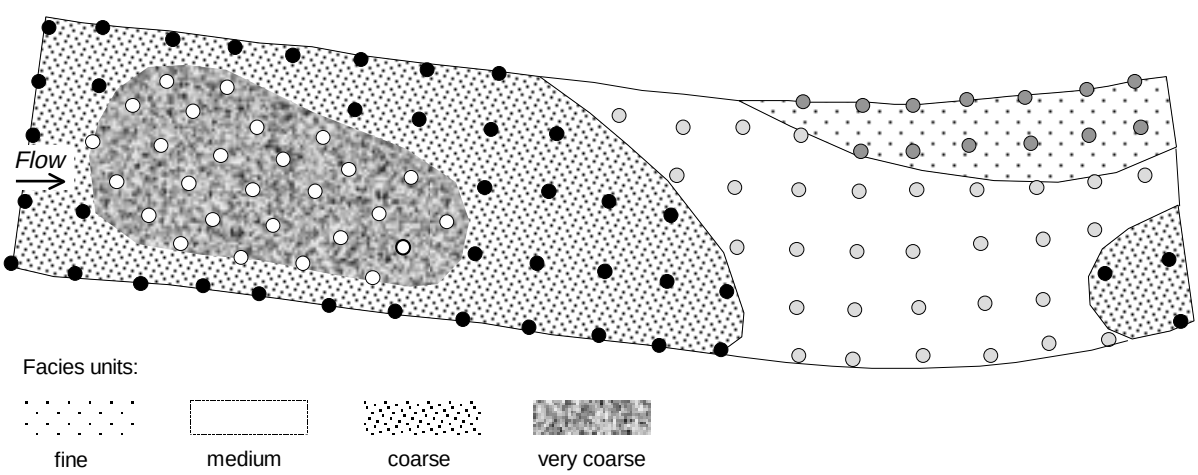


Fig. 6.19: Sampling a reach with only a few and mostly contiguous sedimentary units of approximately equal size by collecting samples from all sedimentary units using reach-spanning grid points.

Situation 2: If the sedimentary units are large and in large streams, samples may be collected from a few representative locations within each unit (Fig. 6.20). The selection of representative units for sampling allows the user to avoid an obviously unrepresentative location simply because it happens to lie under a grid point. This approach is termed *judgement sampling* (e.g., Gilbert 1987). Judgement sampling can improve the sampling results. However, note that sound judgement requires extensive experience, and that judgement may vary between operators, particularly if operators have different backgrounds or levels of training.

Situation 3: Judgement in selection of sampling locations is also required when the reach is comprised of numerous small sedimentary units so that each facies occurs multiple times (patchiness). The number of units may be too large to sample each unit individually. In this case, the user should select a few units that are representative of a specific facies and collect samples only from those units (Fig. 6.20). Situation 2 and 3 may occur together, particularly in braided streams or in gravel-bed streams that carry a large amount of sand and fine gravel.

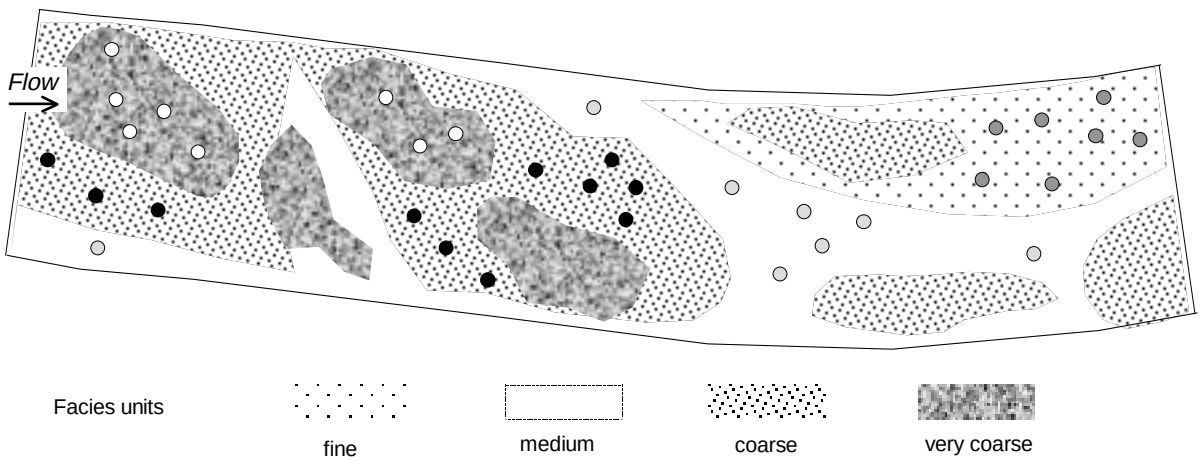


Fig. 6.20: For a reach in which a specified facies type occurs multiple times, samples are not collected from all facies of a kind, but from a few representative locations within the sedimentary units. Obviously unrepresentative locations are avoided.

Situation 4: Sampling from only one selected unit that is representative of the reach-averaged D_{50} surface or subsurface particle entire reach is discussed in Section 6.5.2.2.

Sample mass for spatially segregated sampling and comparison with spatially integrated sampling

The mass of each individual sample should be sufficiently large to qualify as a grab sample when no assumption about the underlying particle-size distribution is made (Section

6.4.4.3). If the distribution in ϕ-units can be assumed to be near-normal, sample mass needs to be large enough to avoid bias with respect to a specified percentile (Section 6.4.4.5). The total sample mass is determined by the optimum number of grab samples in excess of which further sampling does not significantly improve the sampling precision (Fig. 6.18, Section 6.4.3.1). When sampling individually unbiased subsamples, total sample mass for each sedimentary unit is determined for a predetermined acceptable percentile error from Figs. 5.22 a-c. The number of individually unbiased subsamples per unit is the quotient of total sample mass to the mass of individually unbiased subsamples.

Example 6.6 demonstrates how sedimentary stratified sampling of a reach can substantially decrease the sample mass compared to the sample mass needed for spatially integrative sampling.

Example 6.6:
Assume a reach had three sedimentary units A, B, and C each with a sorting coefficient of s = 1, and a D_{50} particle size of 16, 22.6, and 32 mm, respectively. Sample mass for characterizing each unit with an acceptable error of ±0.3 ϕ units is 6.6 kg, 18 kg, and 52 kg (Table 6.9) and sums to 77 kg for the entire reach (upper, shaded part of last column).

Table 6.9: Sample mass (kg) for bias avoidance around the D_{50}, D_{84}, and D_{95} in individual samples and total sample mass for a tolerable absolute error of ± 0.3 ϕ for subsurface bed material from three sedimentary units with D_{50} particle sizes of 16, 22.6, and 32 mm, respectively. Computations are done for sorting coefficients of s = 1 and s = 2. Sample mass for bias avoidance computed from Fig. 5.20; Total sample mass computed from Fig. 5.22 b (Section 5.4.3).

Percentile of interest	Bias avoidance in individual samples for a D_{50} of (mm)			Total mass for absolute error of ± 0.3 ϕ for D_{50} of (mm)			
	16 Unit A	22.6 Unit B	32 Unit C	16 Unit A	22.6 Unit B	32 Unit C	22.6 all units
s = 1							
D_{50}	0.12	0.3	0.9	6.6	18	52	77
D_{84}	0.9	2.6	7.3	52	146	414	612
D_{95}	3.5	9.8	27	188	528	1502	2,218
s = 2							
D_{50}	0.2	0.6	1.8	120	336	956	1,412
D_{84}	13.7	38	109	6,800	19,200	54,600	80,000
D_{95}	211	592	1684	96,900	304,000	773,500	1,142,000

If the reach-averaged D_{50} particle size was 22.6 mm, and the reach-averaged sorting coefficient was 2, a sample mass of 336 kg is required to estimate the D_{50} to an precision of ±0.3 ϕ units when

using a spatially integrated sampling scheme (Table 6.10, lower, shaded part of column for total sample mass for D_{50} = 22.6 mm). This is more than 4 times the sample mass accrued from spatially segregated sampling of that reach. The difference between spatially segregated and spatially integrated becomes larger if the study objective shifts from the D_{50} particle size to higher percentiles. Spatially integrated sampling would require more than 30 times the sediment mass of spatially segregated sampling to correctly sample the D_{84} particle size (Table 6.9, compare the two shaded columns). The factor by which spatially segregated sampling reduces the total sample mass over spatially integrated sampling also depends on how well the reach can be delineated into homogeneous sedimentary units.

The reach-averaged particle-size distribution is computed by areal weighting of the frequency or percent frequency of the particle-size frequency distribution from each of the sedimentary units (Section 6.3.2.5).

6.5.2.2 Sampling location for reach-averaged subsurface D_{50} size

Spatially segregated sampling is particularly useful for determining the reach-averaged subsurface D_{50} particle size, because sampling may be focused on a few sampling locations. The ability to focus sampling is based on two factors: (1) The ratio between the surface and subsurface particle size is such that locations with a coarse surface tend to have coarse subsurface sediment (Section 6.5.2). (2) There is a spatial relationship between the ratios of the local and reach-averaged D_{50} subsurface size and the ratios of the local and reach-averaged D_{50} surface size (Lisle and Hilton 1998 pers. communication):

$$\frac{D_{50sub;loc}}{D_{50sub;r\text{-}avg}} \approx \frac{D_{50sur;loc}}{D_{50sur;r\text{-}avg}} \tag{6.5}$$

The proportionality expressed in Eq. 6.5 is also valid for other percentiles and has been verified in several gravel-bed rivers. Thus, the sedimentary unit at which the local surface D_{50} equals the reach-averaged surface D_{50} is the ideal location for sampling to obtain the representative reach-averaged subsurface D_{50} particle size. This focus of sampling locations to representative locations provides statistically valid samples that describe the subsurface bed material relatively accurately with a relative small sample size. Stratified subsurface sampling becomes particularly important when a long (and large) spatially heterogeneous reach is to be characterized.

The procedure for identifying representative locations for subsurface bed-material sampling depends on the degree of spatial heterogeneity of the reach and on the relative size of the reach. A familiarity with the bed-surface particle sizes within the reach of

concern is therefore very important. The approach outlined below assumes that sedimentary units (e.g., fine gravel, sand and gravel, coarse gravel, cobbles), each larger than a few m^2, are visually distinguishable within a spatially heterogeneous bed. The approach can be divided into the following steps[7]:

1. Walk the stream, look at the spatial variation in surface particle sizes and define different sedimentary units (facies or patches) based on surface particle sizes within the entire reach. Visual estimates of the D_{50} and the D_{90} particle sizes are helpful, but other criteria may be used for delineating facies units as well (Section 6.3.2.1). Determine the degree of spatial heterogeneity of the reach. Particle sizes on the streambed may have a complex appearance in which patches of similar bed-material size are intermingled with other facies types. This is common in large or aggrading streams (case A), (e.g., Fig. 6.16). In riffle-pool streams, bed-material particle size may show simple systematic lateral and longitudinal variability (case B) (e.g., Fig. 6.11).

(Case A) ***Patchy, and intermingled sedimentary units: select a long sampling reach of ca. 20 stream widths***

2. Identify the length of the study reach. The reach must be sufficiently long to ensure that the proportion of the area in each mapped facies is stable. That is, if you sampled further up- or downstream, the percentage of the area allotted to each facies would be stable. A reach length on the order of 20 stream widths is usually required.

3. Flag the boundaries of the sedimentary units, survey the boundaries, and prepare a map of the various sedimentary units within the study reach. Determine the area of each patch or sedimentary unit.

4. Perform a surface pebble count on each type of sedimentary unit. If sedimentary units are patchy, i.e., small and interspersed, and there are many patches of a common facies type, select a few patches that seem most representative and cover each patch with an individual pebble count (Situation 3, Section 6.5.2.1). Sample enough patches to determine the variance within a type of sedimentary unit. If sedimentary units are few, comparatively less patchy, less intermingled and larger in size, cover the entire unit with a pebble count (Situation 1, Section 6.5.2.1). If sedimentary units extend over large areas, perform localized pebble counts at random locations within the unit (Situation 2, Section 6.5.2.1).

5. Compute the average surface sediment-size distribution for each type of sedimentary unit. The reach-averaged surface bed-material size is obtained by weighting the average surface-size distribution for each type by its percentage area of the reach (Section 6.3.2.5).

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[7] *Step 1 - 5 are similar to the procedure listed for spatially segregated pebble counts and visual delineation of the reach in Section 6.3.2.2. For completeness and convenience for the user, the entire procedure is repeated here.*

6. Determine subsurface bed-material sampling locations. Samples that best represent the reach-averaged subsurface sediment size can either be obtained at one or several locations at which surface particle-size distributions are similar to the reach-averaged surface distribution. Alternatively, random volumetric samples can be collected from the one sedimentary unit that best represents the reach-averaged particle size. If that sedimentary unit is coarser or finer than the reach average, a few volumetric samples from a finer, or coarser type of sedimentary unit are needed to better represent the reach-averaged subsurface particle-size distribution.

7. Alternatively, establish the ratio D_{50surf}/D_{50sub} for the sampling reach. Take several randomly placed subsurface samples from each facies type. Calculate the average subsurface D_{50} for each type of sedimentary unit and the reach-averaged subsurface D_{50} as a area-weighted mean, as above. The surface D_{50} size of the various sedimentary units is known, and a relation can be established between the ratios of the surface D_{50} of the particular facies type over the reach-averaged surface D_{50} (i.e., Eq. 6.5). Plotted graphs of this relation intersect close to the point where abscissa and ordinate both have the values of 1, but the slopes of the graphs are different for various stream types (Lisle and Hilton 1998, pers. comm.). Because it is expected that sedimentary units with particle-size distributions in the medium size range best represent the reach-average particle size, sampling should be concentrated on those units.

(Case B) ***Simple systematic lateral and longitudinal variability in bed-material size: a short reach may be sufficient***

If there is negligible patchiness in surface bed-material size, and only simple systematic lateral and longitudinal variability as expected in coarse-bedded riffle-pool streams with a relatively small supply of sandy and gravelly sediment, sampling may be limited to a shorter reach of a single riffle-pool sequence. However, a longer reach of about 20 stream widths provides additional representative samples, unless the study is focussed on a particular riffle-pool section.

Sampling the subsurface bed material at the location within the reach where the surface sediment is most similar to the reach-average usually provides a reasonable estimate of the reach-averaged subsurface distribution. Sampling errors can only be estimated if several samples are obtained at each sedimentary unit. The adjustment process described in Step 7 is difficult to perform in reaches with few sedimentary units, particularly if none of them has a surface D_{50} that closely matches the reach-average surface D_{50}. In this case, it is difficult to identify a facies unit with a subsurface D_{50} that is likely to represent the reach-averaged subsurface D_{50}.

6.6 Spatially focused sampling

Spatially focused sampling collects a sample from a small and isolated location within the streambed area. This area may be in close vicinity of an object of concern, such as zones

of scour and deposition around bridge piers, or near fish habitat structures. Spatially focused sampling uses small-scale grids, areal samples, photo sieving and volumetric sampling. Spatially focused sampling is either used to evaluate the hydraulic and sedimentary response at a certain locally confined stream location, or to sample sediment in stream locations that are indicative of reach-averaged conditions of sediment supply.

6.6.1 Sampling large particles on bar heads for stream competence analysis

Stream competence analysis evaluates the largest particle size transportable by a specific stream flow, such as the annual high flow, bankfull flow or the 100-year flood. In order to measure particle sizes transportable by such flows, stream locations need to be found in which such particles are deposited.

Coarse particles that are mobile during frequent floods are commonly deposited at the upstream end of bars. Free-formed bars, such as mid-channel and diagonal bars (Fig. 3.4 in Section 3.2.1), have the most direct interaction with the free-flowing stream and are most indicative of the general flow hydraulics. This makes the upstream end of mid-channel and diagonal bars ideal sampling sites for stream competence analysis (Fig. 6.21). Next in a hierarchy of sampling sites are point bars, followed by lateral bars.

Particles deposited during infrequent large floods may be found in overbank deposits away from the main channel or in cobble and boulder berms along the channel.

6.6.2 Sampling fines in pools for analysis of fine sediment supply

Local deposits of fine sediment may also be indicative of reach-averaged conditions of sediment supply. A moderate supply of fine sediment may not be detectable in the main channel bed or on riffles. Fine sediment should be visible, though, in locations conducive to local deposits of fines, such as backwater areas, the wake of stream obstructions (e.g., a log), as well as in pools. Repeated monitoring of such locations may indicate whether the quantity of fines transported by the stream changes over time.

Lisle and Hilton (1992; 1999) and Hilton and Lisle (1993) developed a field analysis for monitoring the deposition of fine sediment in pools. Fine sediment (comprising mostly sand and fine gravel) is transported in gravel-bed streams long after a high flow during subsequent moderate and low flows. The fines are eventually trapped in pools and build deposits of measurable thickness along zones of low shear stress near the sides or in backwater areas of pools. The parameter V^* quantifies the ratio of the fine sediment volume in pools V_{fines} to pool volume V_{pool} and is computed from

$$V^* = \frac{V_{fines}}{V_{pool} + V_{fines}} \tag{6.6}$$

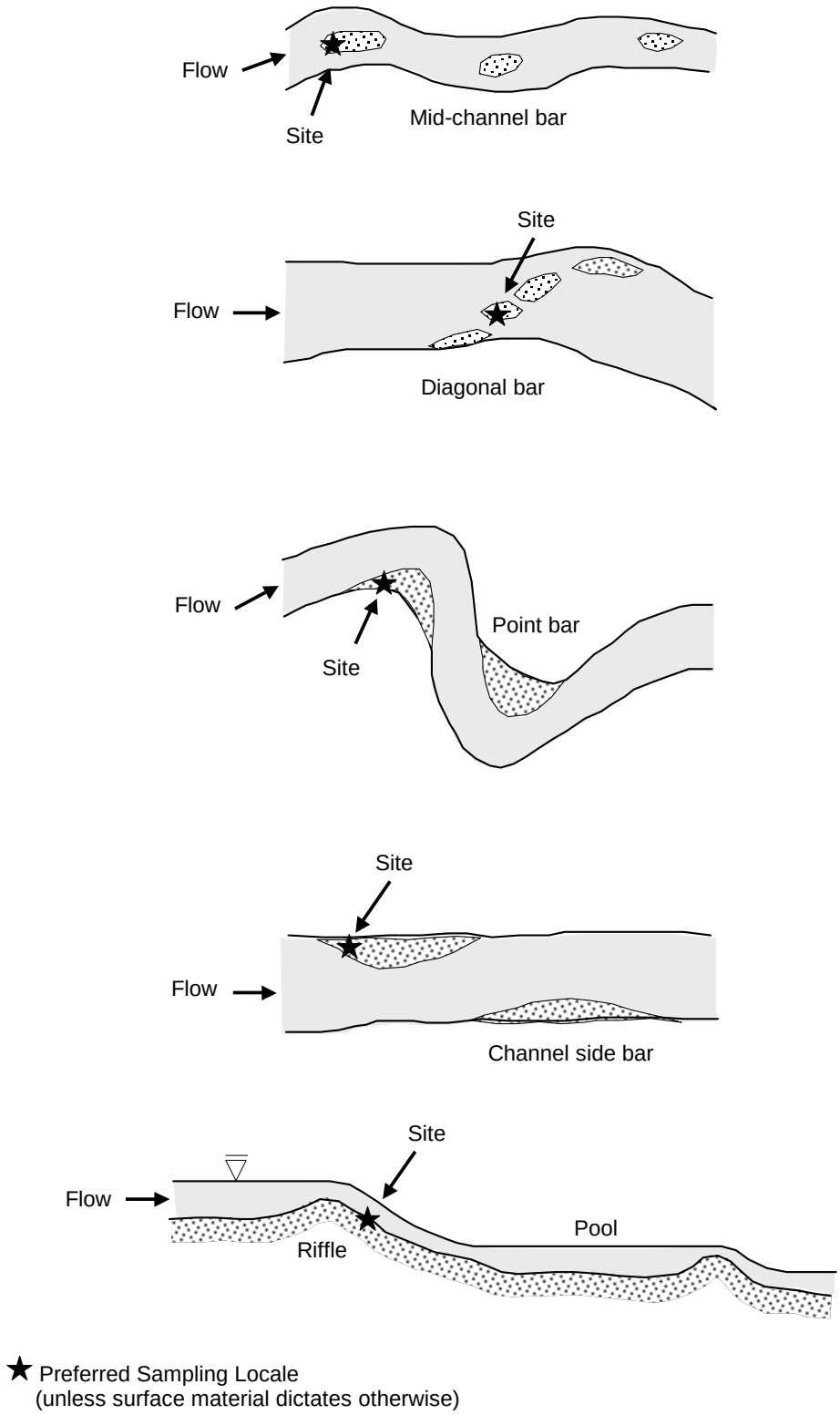

Fig. 6.21: Gravel-bar sampling sites for stream competence analysis (Redrawn from Yuzuk 1986).

To compute V^*, the water depth and the thickness of the fine sediment deposit is measured along a grid system spanned over the pool. The thickness of the fine sediment deposit is measured by probing with a steel rod that has a cm gradation (Fig. 6.22).

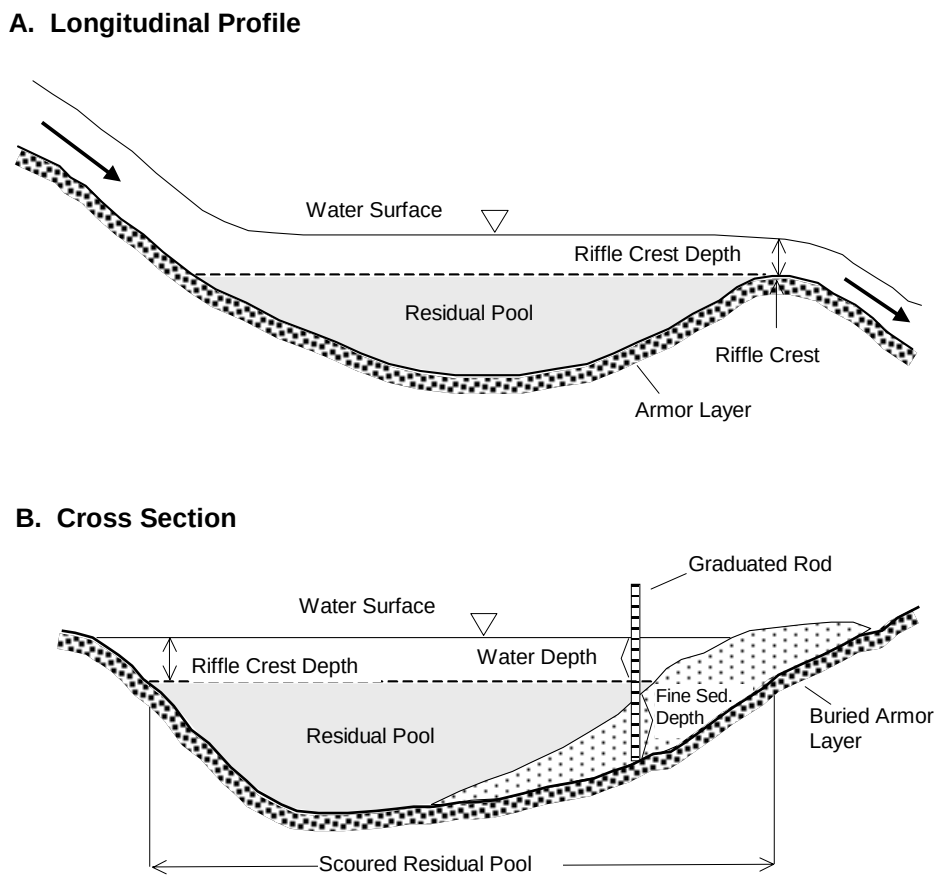

Fig. 6.22: (A) Longitudinal profile of a pool, showing the riffle crest and the area included in the residual pool volume. (B) Cross-section of a pool, showing measurement of water and fine sediment depth and volume of water and fine sediment in the scoured residual pool (Redrawn from Hilton and Lisle (1993)).

Tap the rod with a hammer to penetrate the fine sediment until a resistance is felt at the boundary with the coarse armor layer beneath. In order to measure water depth independent of a current flow depth, water depth is measured up to the residual pool volume, i.e., the minimum water depth at which water would just overflow the downstream riffle. Volumes of pool and fine sediment are computed by multiplying the cross-sectional areas of pools and fines by the distance between cross-sections.

Values of V^* can range from 0 (for no fines) to 1 if the pool is completely filled by fines. V^* is computed for about 10 - 15 pools (more if V^* varies heavily between pools) and

averaged. A change in V^* can be used as a measure to monitor spatial or temporal changes in fine sediment yield.

Volumetric samples of pool fines may be obtained using a pipe dredge (Section 4.2.4, Fig. 4.30a). Lisle and Hilton (1999) compared the particle-size distribution of pool fines to the fine mode of bedload sediment and to the subsurface sediment in order to analyze whether sediment transport is supply- or transport limited.