1. Introduction

1.1 Gravel- and cobble-bed streams: distinctions from other streams

Gravel-and cobble-bed streams are principally distinguished from sand- and boulder-bed streams by their particle-size distributions. Gravel-bed streams have a mean particle size in the range of 2 - 64 mm, and cobble-bed streams in the range of 64 - 256 mm (Table 1.1). By contrast, sand-bedded streams contain bed-material that is mostly less than 2 mm, and boulder-bed streams are comprised of mostly boulders and have a mean particle size larger than 256 mm.

Table 1.1: Stream classification based on the median bed-material particle size.

Stream type	Range of median bed-material particle size (mm)
Sand-bed stream	0.063 - 2
Gravel-bed stream	2 - 64
Cobble-bed stream	64 - 256
Boulder-bed stream	256 - 4096

Gravel- and cobble beds usually contain some sand, typically less than 10% in mountainous areas, and maximally up to about 50%. In mountain areas, gravel- and cobble bed streams may also contain large boulders. Thus, the entire range of bed-material particle size can span five orders of magnitude (i.e., from fine sand of 0.06 mm to boulders of 4000 mm). This wide range causes complex interactions between particles of different sizes during erosion, transport, deposition, and causes spatially heterogeneous beds that complicate bed-material sampling.

Gravel- and cobble-bed streams differ from sand- and boulder-bed streams not only by particle size, but also with respect to the appearance of the stream (morphology) and the environment in which the stream occurs (topographic setting). Sand-bed streams often have low gradients and occur in valleys or on broad plains, whereas most boulder-bed streams have are steep gradients and are found in mountain environments, although exceptions exist for both. Gravel-and cobble-bed streams are commonly found in moderately steep mountain valleys and where streams enter plains near mountains. The distinction between sand-, gravel-, cobble-, and boulder-bed streams is included in the stream classification by Rosgen (1994) that is discussed in Section 1.3.2.

1.2 Bed-material sampling and guidelines

1.2.1 Purpose of bed-material sampling

The majority of bed-material sampling work is undertaken in order to obtain information on the particle-size distribution of the riverbed. Information on bed-material particle size is needed for a variety of purposes that can be grouped into three major areas:

1) Streambed monitoring for detecting watershed impacts, analyzing stream habitat, and evaluating the success of mitigation efforts,
2) Computations of flow hydraulics, bedload transport rates transport capacity and flow competence to analyze and predict stream behavior, and
3) Advancement in the understanding of stream processes.

Information on particle shape is also needed for predicting bed stability and the onset of scour by balancing entraining versus resisting forces, as well as for analyzing the source and travel distance of sediment.

1.2.1 Aspects of bed-material sampling in gravel- and cobble-bed streams

Stream studies quantify bed-material particle size by analyzing the frequency distribution of particle sizes contained within a bed-material sample. However, sampling bed-material in gravel- and cobble-bed streams is different from sampling in sand- and boulder-bed streams. Sand-bedded streams may be sampled by taking about a cup-full of sediment from several locations distributed more or less systematically over the streambed. Differentiation between surface and subsurface sediment is usually not necessary, and a shovel is often sufficient as a sampling device. Thus sampling bed-material in sand-bedded streams is a relatively straight-forward task. Ashmore et al. (1988) provide detailed guidelines for bed-material sampling in sand-bedded streams.

Sampling bed-material in gravel- and cobble-bed streams is a more complicated enterprise and forces the user to make a number of informed decisions on the study methods that depend on the study objective and the stream condition. Prior to sampling, the user needs to decide where in the stream samples are to be taken. Sampling may need to cover a large area of the streambed about 5-7 channel widths long, or concentrates on a downstream sequence of riffles or pools.

Gravel- and cobble-bed streams usually have surface sediment that is coarser than the sediment below the surface. The degree of difference between surface and subsurface sediment is tied to the flow regime and upstream sediment supply. The user needs to identify the appropriate bed-material strata (i.e., layer) to be sampled for a given study objective. Some objectives require sampling particles exposed to the surface, other studies sample the armor layer that extends from the surface down to a depth of 1 or 2 large particles. Still other studies sample the subsurface sediment below the surface, or compare sediment from different layers (strata) within the bed.

Particles on the surface, in the subsurface, and in the armor layer are sampled by different techniques. For example, particles may be picked off the stream surface (pebble count), or the subsurface sediment may be dug up after surface particles or the armor layer has been removed. There are a number of sub-procedures for sampling each strata; surface particles may be collected along a grid, or all particles within a small area may be collected (areal sample, or the streambed surface may be analyzed from photographs. Equipment and techniques that may be used for sampling subsurface sediment depend on the sampling objective, the size of the bed material in the stream, and on whether the streambed is dry or inundated.

Gravel- and cobble-bed streams may have a relatively uniform particle-size distribution over distances several stream widths long (homogeneous bed). Alternatively, the streambed may be composed of many areas with different particle-size distributions, or of areas in which particle-size distributions change from coarse to fine (heterogeneous bed). It may be difficult to find areas that are both spatially homogeneous and large enough for collecting a surface sample. In any case, the user needs to select a spatial sampling strategy (sampling scheme) that matches study objectives and stream conditions. This requires deciding on the areal extent of the streambed to sample, and the spatial pattern with which particles are selected. Sampling may extend in some systematic patterns over the entire area (spatially integrated), or the user may choose to sample in locations representative for a particular streambed area or sample spatially focused on streambed areas of concern. Alternatively, the stream reach may be segregated into sub-areas that are then sampled individually (spatially segregated).

Bed-material sampling should also provide information on the statistical precision of the sampling result. Ideally, a desired level of precision is selected before the study begins. Different relations between sample size and precision may be consulted to determine how large the sample needs to be in terms of particle numbers, of sediment weight, or how many parallel samples need to be taken. Investigators are frequently surprised by the large sample sizes necessary. Several hundred particles may have to be collected for one pebble count, while the mass of volumetric samples needed may be several hundred kg or more.

The physical act of collecting representative samples in gravel-and cobble-bed streams may be challenging. Individual fine particles located between large clasts on the bed may be difficult to pick up, while cobbles and boulders may be too heavy or too wedged in the bed surface to dislodge. Cold water makes it difficult to work bare-handed in mountain streams, and the flow may be fast or deep. The sample mass needed for statistical accuracy is usually large, and sampling sites may not have vehicle access.

After all the samples are taken, the final part of bed-material sampling is performing a particle-size analysis. This involves sieving the sample as well as selecting particle-size parameters and statistical analyses suitable for demonstrating sampling results.

1.2.2 Interdependency between sampling methods and study objectives

Bed-material strata, the sampling procedures and equipment, the sampling scheme, the sampling precision and ensuing sample size, and the particle-size analysis used in the study must be thoughtfully selected to provide useful information. For the most part, their selection depends on study objectives and on the streambed conditions encountered.

There is a dependency between study methods and study aim. A study performed in a given streambed may yield different results if different methodological approaches are used. Consequently, studies with similar objectives that use different methods generally fail to produce comparable results. Since results from bed-material sampling projects are method specific, the user needs to describe the methods used clearly, so that a comparable study can be done at a different location or time. Similarly, a clear description of sampling and analysis methods is essential for readers to assess the meaning and reliability of published results.

1.2.3 Deficiencies in existing guidelines

There is an abundance of literature that demonstrates sampling equipment, compares and suggests sampling procedures, recommends sample sizes, proposes sampling schemes, presents alternative particle-size parameters or computational methods, and describes findings of specific bed-material studies. This methodological diversity, and the ongoing debates on the general appropriateness of methods or their applicability in specific situations, leave the field person with an abundance of techniques from which to choose. However, there is little guidance for deciding if a particular method is suitable for a given study and a given stream.

Faced with this diversity, stream studies tend to resort to so-called “standard methods”. For example, the 100-particle Wolman (1954) pebble-count is often considered a standard method for surface particles, or the McNeil and Ahnell (1964) sampler is commonly used for volumetric bed-material samples in submerged conditions. These methods have attained “standard” status, and are described and applied on numerous occasions, primarily because they are relatively quick and easy to perform. However, presumed standard methods, although desirable, are not generally applicable.

Current guidelines on stream studies include the description of a few widely-used methods but are not a comprehensive source of information on bed-material sampling in general. Some guidelines focus on specific fluvial environments, such as large alluvial gravel-bed rivers (Yuzyk and Winkler 1991), or on specific sampling aims, such as the evaluation of aquatic habitat (Platts et al. 1883; Hamilton and Bergersen 1984). The paper by Church et al. (1987) and the guidelines by Ramos (1996) provide perhaps the widest coverage of bed-material sampling to date.

None of the current guidelines for bed-material sampling and analysis (Platts et al. 1883; Williams et al. 1988; Edwards and Glysson 1998; ISO 1992; Yuzyk and Winkler 1991;

Hamilton and Bergersen 1984; Church et al. 1987; Ramos 1996), and few published papers provide specific information on bed-material sampling in small mountain streams with coarse beds. Sampling these environments is particularly difficult because bed-material particle sizes extend over a wide range - from sand to boulders. Streambeds are often perennially inundated, and scour and deposition around large woody debris leads to a spatially diversified streambed.

1.2.4 What these guidelines are intended to do

These guidelines explain the various aspects of bed-material sampling in gravel- and cobble-bed streams and discuss the proper application, scope, and limitations of sampling methods. This includes the explanation of bed-material strata, the procedures and equipment used for sampling, a discussion of the spatial scheme to be employed, the relation between sample size and precision, and methods of particle-size analysis. These guidelines are meant to provide the user with a wide range information from which to select methods and approaches suitable for a given study in a given fluvial setting. Information used to compile these guidelines was mostly found in published papers, government documents, monographs, and the authors' field studies.

1.2.5 Guidelines are no substitute for experience

The physical processes acting in mountain streams are quite complex. Stream morphology and spatial variability of bed-material size are not only affected by fluvial processes, but also by near-stream and off-stream sedimentary processes. Such complex, multi-process environments require professional experience for meaningful field work. Unfortunately, government agencies and consulting companies frequently desire simple guidelines that advocate methods requiring little field time and that can be followed by inexperienced field personnel.

For quality results, field work needs to be performed or closely guided by experienced personnel. An inexperienced crew cannot determine sampling locations and sample size if these decisions depend on recognizing geomorphic, hydraulic, and sedimentary processes of various scales and magnitude. Such assessments require knowledge and familiarity with fluvial processes.

Operator training is extremely important. When selecting particles from a predefined streambed location, or even when measuring particle sizes in a preselected sample of rocks, there is less variability between the results of experienced operators than between those obtained by novices. Field personnel need to be trained to perform procedures accurately, to avoid bias, and to use equipment that reduces operator induced error.
No guidelines, these included, can substitute for operator experience and training.

1.3 Classification of gravel- and cobble-bed streams

Gravel-and cobble-bed rivers have different appearances because stream gradients, bed-material particle-size distributions, large woody debris content, the cross-sectional channel shape, and stream morphology[1] may be different between streams. The diversity of resulting stream forms makes it useful to classify streams.

Stream classifications are educational in and of themselves. They make the user aware of different cross-sectional shapes of the stream and the flood plain, of the different morphological parts of a stream, the specifics of the interactions between flow and sedimentation, and the resulting stream types. This knowledge leads to an understanding that stream morphometry[2], stream morphology, flow hydraulics and sedimentation processes respond to controlling agents such as flow regime, quantity and size of sediment supplied, and channel gradient. Besides an understanding of stream behavior, a familiarity with the terminology used in stream classifications helps clarify communication.

From the variety of stream classifications available, two recent stream classification systems, Montgomery and Buffington (1993, 1997, 1998), and Rosgen (1994, 1996) are explained below. These two classification systems are currently used most often in the U.S. Readers are encouraged to become acquainted with them, not only because their terminology will be used in this document, but also to acquire an understanding for the variety of stream types and processes common in gravel- and cobble-bed streams.

1.3.1 The Montgomery-Buffington stream classification

Montgomery and Buffington (1993, 1997) developed a stream classification to describe streams found in the Pacific Northwest. The steep mountain ranges and the short distance to the Pacific coast result in a sequence of predominant landforms: steep valleys and hillslopes in the upper watersheds, gentler valleys in the middle watersheds, and low gradient valleys at the end of the watershed. In accordance with those landforms, the classification system differentiates between five stream types: *cascades, step-pool, plane-bed*, *pool-riffle*, and *dune-ripple* streams, listed in the order of decreasing stream gradient (Table 1.2). Those streams have a distinctly different morphology because the interaction between flow hydraulics and sedimentary processes, particularly the amount of energy dissipated by the turbulence of flow, differs in each of the stream types. Although bed-material size generally decreases from cascades to dune-ripple streams, it is not a discriminating feature of the classification. Longitudinal and planform illustrations of the five stream types are shown in Fig. 1.1.

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[1] *Morphology characterizes a (fluvial) object through a descriptive term, e.g., a riffle and a pool.*

[2] *Morphometry describes the physical dimensions of a (fluvial) object through measurements, e.g., the width and depth of a streambed.*

Table 1.2: Stream classification by Montgomery and Buffington (after Montgomery and Buffington 1997, 1998)

Stream gradient, range and mode (m/m)	Stream type	Typical bed material	Dominant sediment source	Dominant sediment storage	Typical pool spacing*
0.03 - 0.20 (0.08 - 0.20)	Cascades	Cobble-boulder	Fluvial, hillslopes, debris flows	Around flow obstructions	< 1
0.02 - 0.09 (0.04 - 0.08)	Step-pool	Cobble-boulder	Fluvial, hillslopes, debris flows	Bedforms	1 - 4
<0.02 - 0.05 (0.02 - 0.04)	Plane-bed, forced pools	Gravel-cobble	Fluvial, bank failure, debris flows	Overbank	None
<0.001- 0.03 (0.01)	Pool-riffle	Gravel	Fluvial, bank failure	Overbank, bedforms	5 - 7
< 0.001	Dune-ripple	Sand	Fluvial, bank failure bedforms	Overbank,	5 - 7

*Values in parentheses are the modes of the observed stream gradient distribution; * in terms of channel widths*

1.3.2 The Rosgen stream classification

The Rosgen classification (1994, 1996) uses an alphanumeric code to classify streams based on five morphometric parameters of the stream channel and its flood plain:

- entrenchment ratio, i.e., ratio of the width of the flood-prone area inundated by flows having twice the maximum depth of bankfull flow to the width of the bankfull channel (i.e., a measure of flood plain width),
- width-depth ratio at bankfull flow,
- sinuosity, i.e., stream length to valley length,
- stream gradient, and
- median bed-surface particle size.

The five parameters are used to distinguish seven main stream types identified by capital letters A to G. Each main stream type has a number assigned that reflects the bed-material particle size. Streams with boulder-, cobble- and gravel beds have the numbers 2, 3, and 4, respectively and are the only stream types referred to in the context of these guidelines. Uncapitalized letters a, b and c are used to specify stream gradients outside the typical range for a main stream type. For example, a stream classified as Bc3 is a B-type stream (B), with a cobble bed (3) but a gradient within the range of 0.001 - 0.02 more typical of C-type streams (c). Morphological characteristics of the mayor stream types in the Rosgen classification are presented in Table 1.3. Fig. 1.2 shows the stream types in longitudinal, cross-sectional and plan views and provides bed-material sizes and morphometric criteria for the 41 delineated stream types.

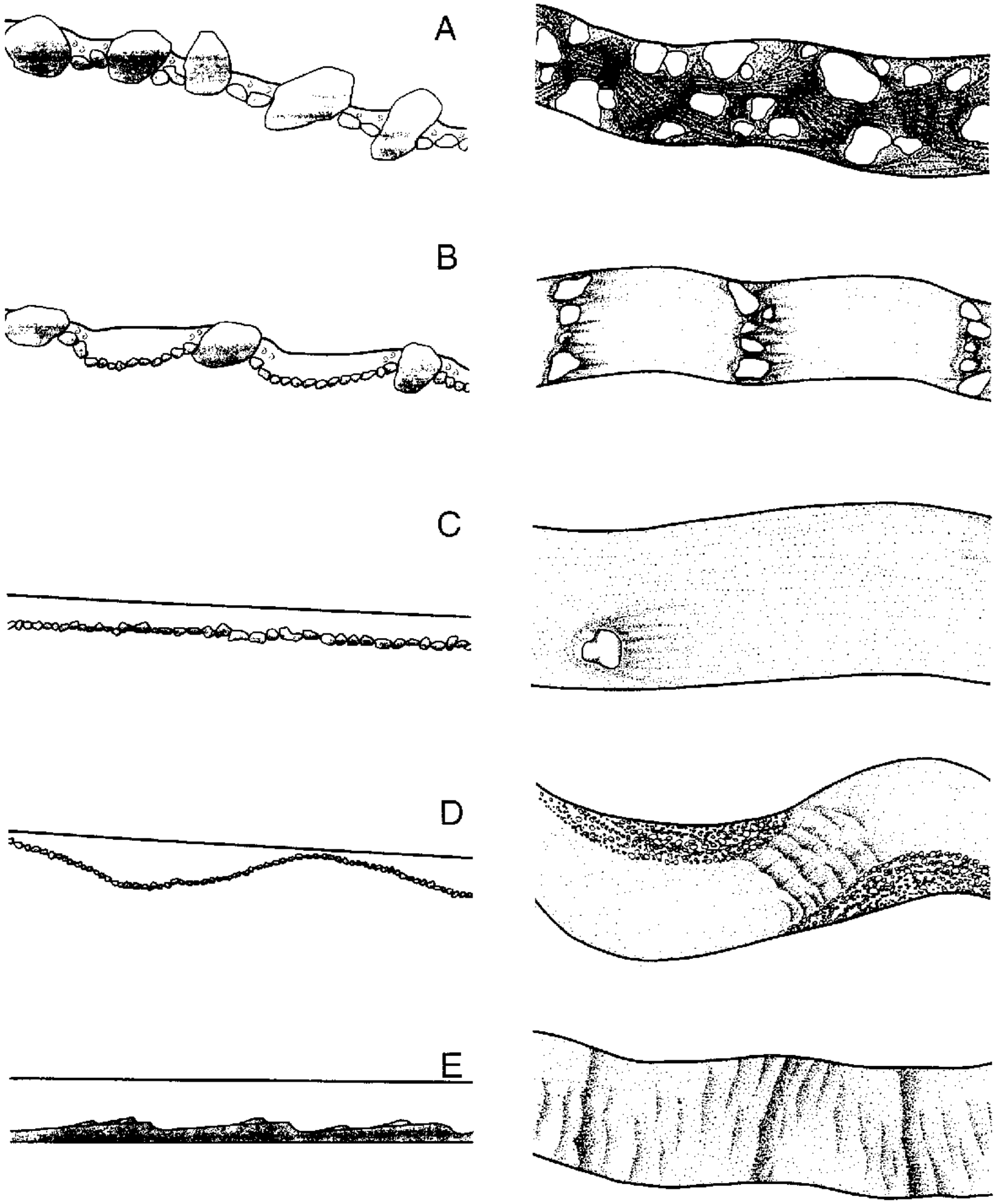

Fig. 1.1: Schematic longitudinal (left) and planform (right) illustration of the five stream types at low flow: (A) **Cascade** with nearly continuous highly turbulent flow around large particles; (B) **Step-pool** channel with sequential highly turbulent flow over steps and more tranquil flows through intervening pools; (C) **Plane-bed** channel with an isolated boulder protruding through otherwise uniform flow; (D) **Pool-riffle** channel with exposed bars, highly turbulent flow over riffles, and more tranquil flow through pools; and (E) **Dune-ripple** channel with dune-ripple bedforms. (Slightly altered and reprinted from Montgomery and Buffington (1997), by permission of the Geological Society of America).

Table 1.3: Morphological characteristics of the major Rosgen stream types

Stream Type	Morphological characteristics
A	**Step-pool, or cascading**: plunge and scour pools, high energy, low sediment storage, stable;
B	**Riffles and rapids**: some scour pools, bars rare, stable;
C	**Pool-riffle sequences**: meandering, point bars, well developed floodplain, banks stable or unstable;
D	**Braided**: multiple channels, shifting bars, scour, deposition, high sediment supply, eroding banks;
DA	**Anastomosing**: multiple channels, pool-riffle, vegetated floodplain, adjcnt. wetlands, stable banks;
E	**Meadow meanders**: well-developed floodplain, riffle-pool, relative high sediment conveyance;
F	**Valley meanders**: incised into valleys, poor floodplain, pool-riffle, banks stable or unstable;
G	**Gullies**: incised into hillslopes and meadows, high sediment supply, unstable banks, step-pool.

1.3.3 Differences between the Rosgen and the Montgomery-Buffington classifications

The Rosgen and the Montgomery–Buffington stream classifications differ in several points which include:

Basis for classification

The Rosgen classification is based on morphometric parameters and precisely differentiates between streams of different slope gradients, width-depth ratios, sinuosity, and entrenchment. The Montgomery–Buffington classification is based on stream types commonly found in the Pacific Northwest where streams traverse the relatively short distance between steep headwaters and sea level in a succession of different stream types. From steep terrain to low gradient, these stream types have an increasing potential to show a morphological response to changes in water and sediment yield.

Appearance of the classification system

The Rosgen classification presents a non-intuitive alphanumeric code. The large number of stream types thus classified can be discouraging for the novice user. The Montgomery–Buffington classification presents five stream types using commonly known fluvial terminology.

Applicability

Based on morphometric parameters, the Rosgen classification system is applicable to any streambed, thus exceeding the range of streams addressed in this manual. The Montgomery–Buffington classification is best suited to describe gravel-, cobble-, and boulder-bed streams in mountainous terrain, from steep headwaters to low gradient valleys and plains, and thus describes the stream types addressed in these guidelines.

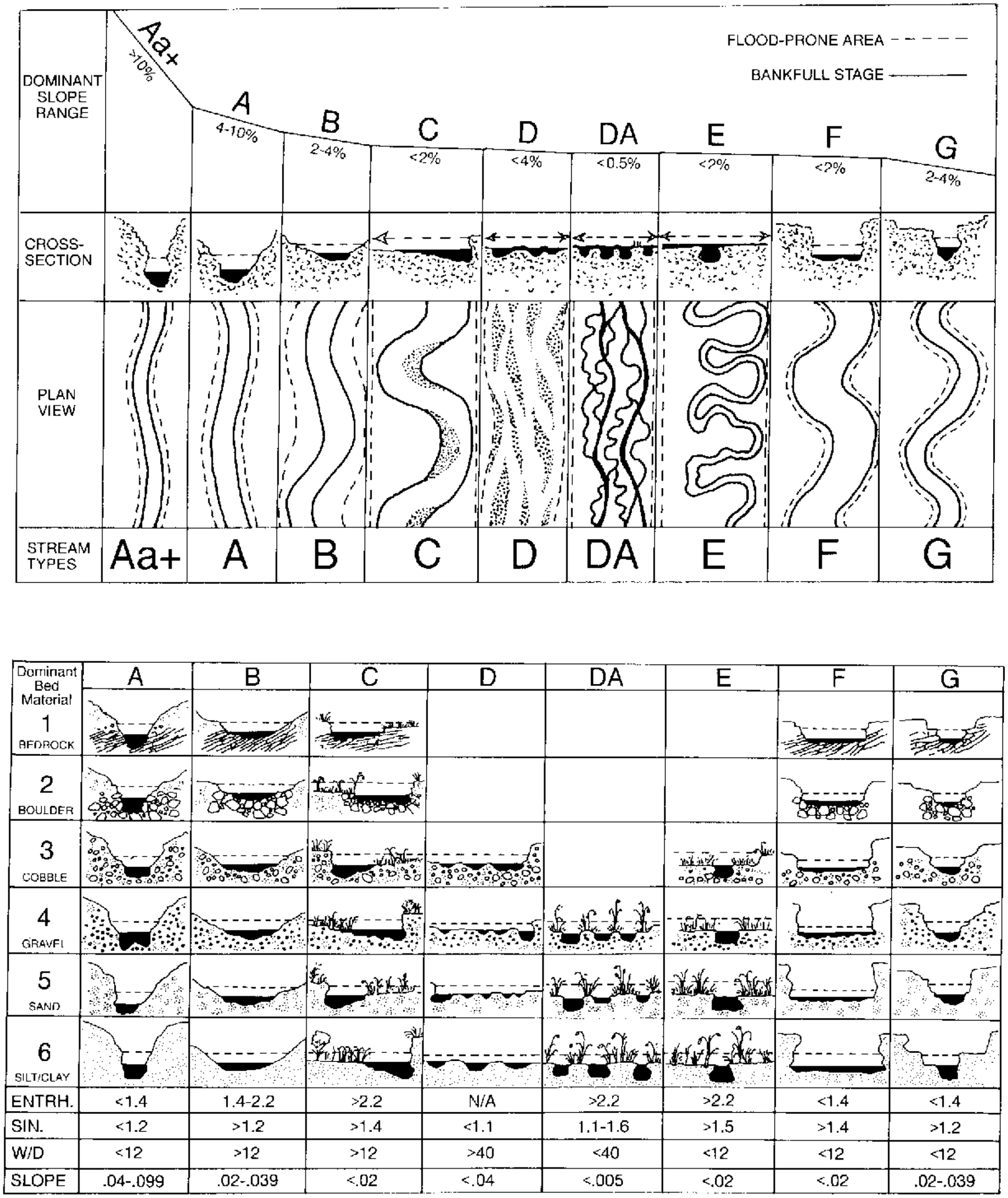

Fig. 1.2: Rosgen's stream classification. Longitudinal, cross-sectional and plan views of mayor stream types (top); Cross-sectional shape, bed-material size, and morphometric delineative criteria of the 41 mayor stream types (bottom). (Redrawn from Rosgen (1994), by permission of Elsevier Science B.V).

Correspondence between the two classification systems

The three stream types step-pool, plane-bed, and pool-riffle, distinguished by the Montgomery-Buffington classification generally correspond to the stream types A, B, and C in the Rosgen classification. The mode of slope gradients observed for these three stream types in the Montgomery-Buffington classification corresponds fairly well to the slope gradients assigned to A, B, and C streams by Rosgen (Fig. 1.3). The Montgomery-Buffington classification provides a wide range of observed slopes, which may overlap between stream types, thus uniting streams with morphometric differences into one stream type if the hydraulic and sedimentary processes are similar. The Rosgen classification creates numerous subgroups, thus differentiating between stream types with slight morphometric differences.

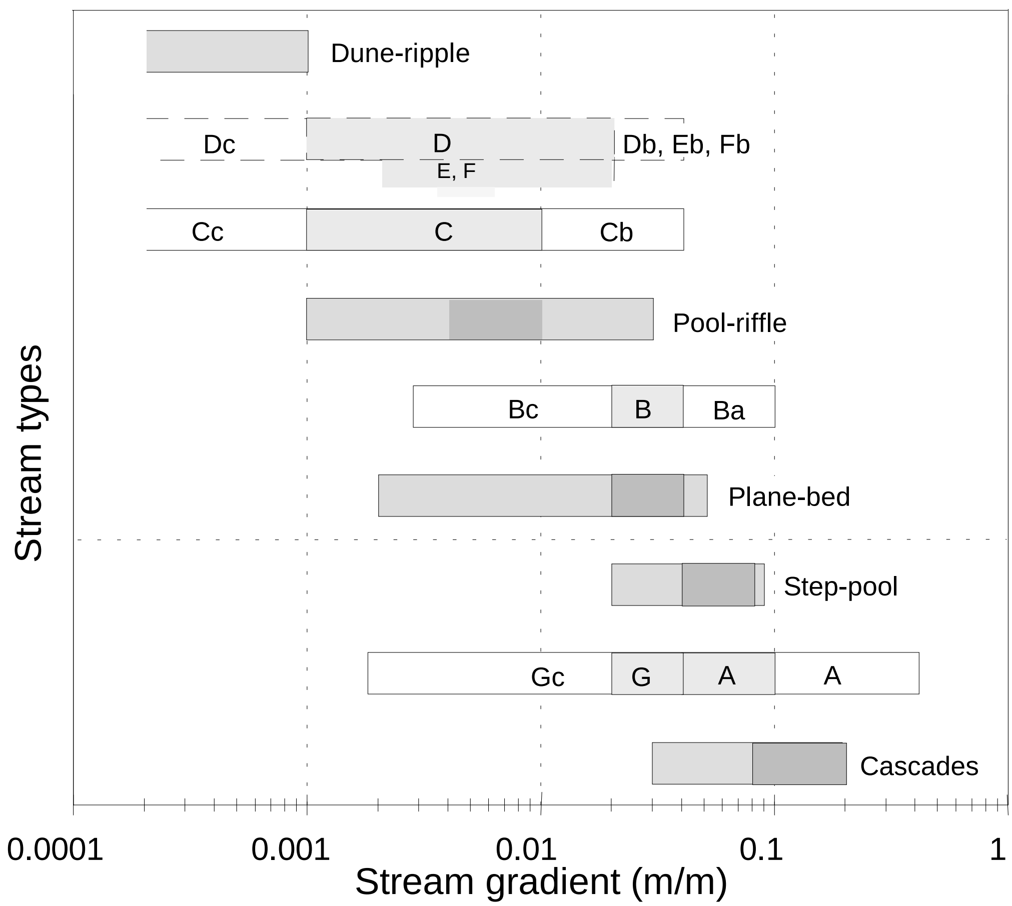

Fig. 1.3: Comparison of stream gradients in the Montgomery-Buffington (1997,1998), and the Rosgen (1994, 1996) classification. The Montgomery-Buffington stream types are pool-riffle, plane-bed, step-pool, and cascades. The light shading indicates the range of observed stream gradients, the dark shading indicates the mode. The letters refer to the Rosgen classification. Light shading indicates the main stream type, whereas subtypes with steeper or gentler stream gradients have no shading. Open-ended boxes indicate stream gradients given in terms of "larger than", or "smaller than".

1.3.4 Sediment source: self-formed versus relict/non-fluvial streams

The distinction between self-formed and relict/non-fluvial gravel-bed rivers is not explicitly part of current classification systems, but this distinction is important because it affects all aspects of bed-material sampling in gravel-bed rivers.

Self-formed streams

Self-formed streams receive their sediment supply almost entirely from upstream (fluvial) sources, the local bed, and erosion of banks composed of sediment transported under the current transport regime. Stream morphology and sediment sizes are exclusively controlled by the interaction between flow and sediment. Consequently, the streambed contains no particles larger than those that can be moved during the highest floods. Because sediment in self-formed streams is not coupled to hillslopes and other non-fluvial sources, such stream systems are also referred to as *uncoupled* streams.

Relict/non-fluvial streams

Relict/non-fluvial streams can receive much of their sediment from non-fluvial sources such as:

- mass movements (debris flows, landslides, avalanches, etc.),
- rock-fall from canyon walls,
- intensive slope wasting, bank undercutting and slumping,
- downcutting into glacial deposits from which the stream unearths large boulders that may be of commonly untransportable size, and
- erosion of bank material deposited under a different regime of flow or sediment supply.

Streams receiving sediment supply from relict-fluvial and non-fluvial sources are often referred to as *coupled*. Coupled streams are common in mountain areas, where nearby hillslopes and glacial deposits contribute to the off-stream sediment supply. The presence of large cobbles and boulders may cause unsystematic spatial variability of bed-material size. Obstacles in the stream flow create local hydraulics that control sedimentation patterns and inhibit the development of a stream morphology expected for a stream with a given gradient, stream flow, and supply of transportable sediment.

Self-formed and relict-non-fluvial streams can be difficult to distinguish in the field, if off-stream sediment supply is low or occurs only sporadically. Whiting and Bradley (1993) defined the likelihood of debris flows reaching the stream for regions prone to debris flows based on the ratio of valley width to stream width. For example, debris flows *seldom* reach a small stream 5 m wide if the valley is more than 250 m wide, but *occasionally* in a valley 50-250 m wide. *Most* debris flows would enter the stream if the valley was 25-50 m wide, and *all* debris flows enter the stream if stream width is equal to valley width. An aspect not considered in this definition is that streams often take a winding course through the valley, being close to the valley wall and even undercutting the hillslopes at some locations. Here, streams can easily receive off-stream sediment, even in wide valleys.

1.3.5 Wadable and non-wadable streams

These guidelines applies to gravel- and cobble-bed streams that are generally wadable. Nevertheless, most of the techniques discussed in this document could also be applied to deeper streams if a team of experienced divers were available. Some sampling techniques and equipment may have to be adjusted to fit underwater conditions.

Wadable streams are easier to sample when less water is in the channel. In some streams, the annual low flow exposes only a small proportion of the bed, so that wading and sampling techniques that work in submerged conditions are required year-round. In other streams, much of the bed is exposed during low flows, which makes those times preferable for many sampling studies.

Within the range of wadable flows, fast flowing water often causes more sampling difficulties than deep water. Not only is there a safety hazard when venturing into fast flow with velocities exceeding 1.5 m/s (Abt et al. 1989), but sampling results are likely to become inaccurate and biased in fast water. Fine particles can easily be washed from an operator’s hand, and fast flow, often combined with turbid water, does not allow the operator to visually distinguish individual particles on the channel bottom. This requires that much of the work be performed by feel. Fast flow adds to the difficulty of extracting large or wedged particles from the bed.

Sampling in locally deep flow has its challenges as well because it makes some stream locations inaccessible to wading or an operator may not be able to touch the stream bottom by hand without getting his face wet. However, problems posed by deep water can often be mitigated, for example by visually estimating the size class of a particle to be included in the sample, or by sampling with long-handled scoops while using a flotation device. Relatively warm water may encourage getting wet in swimming clothes, but submersion or diving in cold water requires dry suit equipment.