A Geomorphic Principles Applied in Stream Simulation

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Appendix A—Geomorphic Principles Applied in Stream Simulation

This appendix very briefly reviews fluvial processes (i.e., processes pertaining to river or stream action) and channel characteristics that project teams consider when evaluating site conditions at road-stream crossings and designing stream-simulation structures. Chapters 4, 5, and 6 describe how teams apply these concepts in stream-simulation site assessment and design.

Training and experience in geomorphology are essential for assessing channel conditions, interpreting channel responses and fluvial processes, and designing a simulated streambed. Most hydrologists, **geomorphologists**, geotechnical engineers, and hydraulic engineers already will be familiar with many of the concepts we are presenting here. If you are a reader for whom the material is new, the information in this appendix is not adequate for developing journey-level geomorphology skills. You may want to review the references cited here and attend training courses to expand your knowledge. Project team members are responsible for recognizing when additional expertise must be brought in—especially when channel conditions are complex and difficult to interpret (see sidebar in section 3.3).

A.1 WHY CONSIDER FLUVIAL PROCESSES IN CROSSING DESIGN?

Streams are dynamic systems that can readily change in response to human or natural disturbances. Streams continually erode sediment and wood from their boundaries and redeposit that material at other locations in the channel. Many streams also shift location laterally across the valley bottom. Streambed elevations change as the stream transports, deposits, and stores **woody debris** and sediment. During floods, streams overflow the flood-plain surface, eroding and depositing sediment and debris, and constructing riparian habitats.

Road-stream crossings are rigid structures that lock the stream in place and elevation, preventing these normal dynamic processes. In the past, crossings have typically been narrower than the stream, causing backwatering and sediment deposition at the inlet [figure A.1(a)]. Narrow culverts also increase water velocity causing channel scour in or downstream of the crossing [figure A.1(b)].

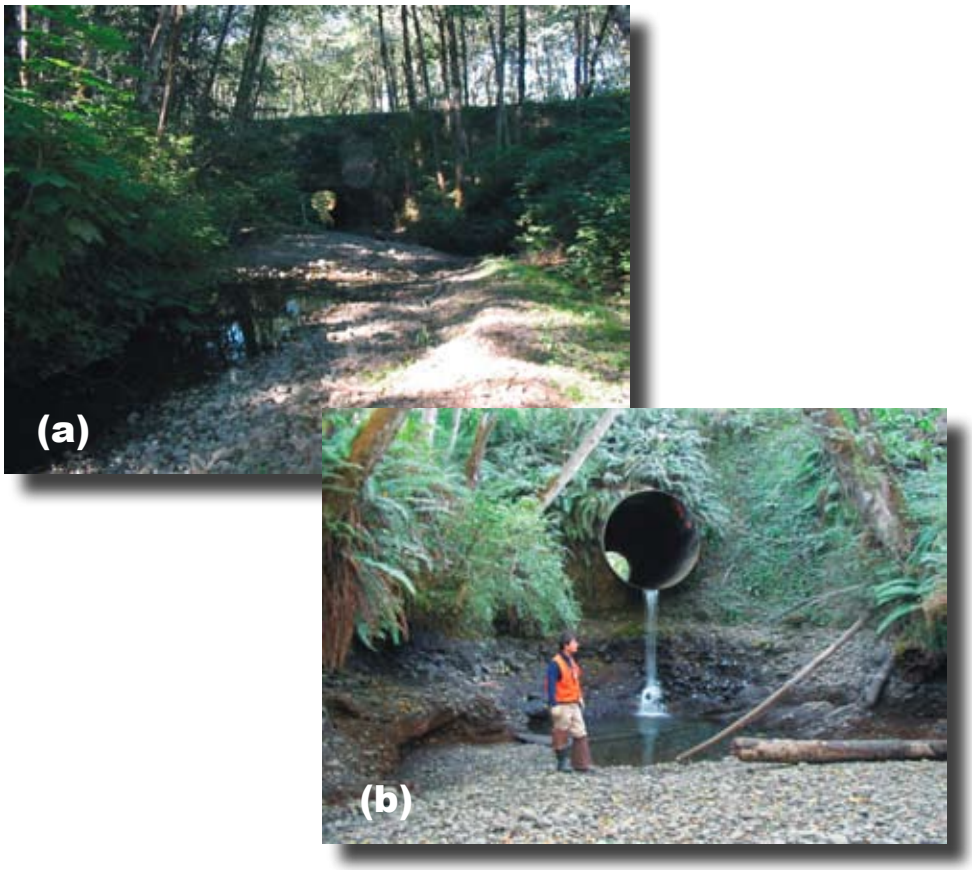

Figure A.1—(a) Aggraded (filled) channel upstream of narrow culvert; (b) incised (scoured) channel downstream of culvert, Save Creek, Olympic National Forest, Washington.

As chapter 1 explains, such channel responses to culverts can ultimately inhibit or prevent aquatic species passage. These responses also can cause massive problems—both for the road and the stream—during large floods. Plugging with **debris** and sediment is common at culverts. Fill failure or stream diversion can follow, as the water overtops the road or runs along the road until it pours off onto a hillslope or into another drainage (figure 1.17). Scouring at narrow bridges or open-bottom arches can also cause these structures to fail.

Stream-simulation design provides for both aquatic species passage and long-term stability of the structure and the constructed streambed. Within the limits of a necessarily rigid structure, stream simulation aims to provide enough space for the stream channel to adjust to changing flows and **sediment loads**, just as the natural channel does. To achieve this objective, the project team must understand how fluvial processes

shape the current channel at a site. The team must be able to predict future channel responses to changes in watershed and climatic conditions, and they must also be able to predict how the channel will respond to the new crossing structure.

A.2 THE WATERSHED CONTEXT

The site's location in the watershed is important. Depending in part on their position in the watershed, channel **reaches** (stream segments with relatively homogenous characteristics) can be divided into three general types (Montgomery and Buffington 1993, 1997):

(1) Source reaches are headwater channels with few if any fluvial characteristics. Hill-slope processes such as surface erosion and soil creep deliver sediment to these channels, which store it until large flow events or debris flows scour it out.

(2) Transport reaches are typically steep streams that tend to resist erosion, because they have persistent bed and bank structures dominated by large particle sizes (boulders, cobbles, gravels, and wood). Although these reaches store some sediment (e.g., behind pieces of woody debris), in general they have high transport capacities. When sediment supply increases, they tend to pass the increase quickly to lower-gradient reaches. Channel morphology does not change very much in response to changes in water or sediment inputs.

(3) Response reaches are lower-gradient reaches where sediment transport is limited by relatively low transport capacity. That is, when sediment supply from upstream increases, it is likely to deposit in a response reach. The reach will often respond to changes in sediment supply or discharge by making large adjustments in channel size, shape, slope, or pattern. As Montgomery and Buffington (1993) point out, the first response reach downstream of a series of transport reach is likely to be an extremely sensitive site when water or **sediment regimes** change in the upstream watershed.

This appendix refers to these reach types throughout. They are helpful as shorthand descriptors of likely channel responsiveness to environmental change. Understanding the differences between streams in their responsiveness to environmental changes is very important in stream-simulation design.

While some watersheds have a more or less regular sequence of source, transport, and response reaches from headwaters to mouth (figure A.2), reach types are often distributed in a more complex way. Local geologic controls can create meandering mountain meadow streams (response reaches) near the headwaters, and very steep transport reaches may be near the downstream end of tributaries on river breaks.

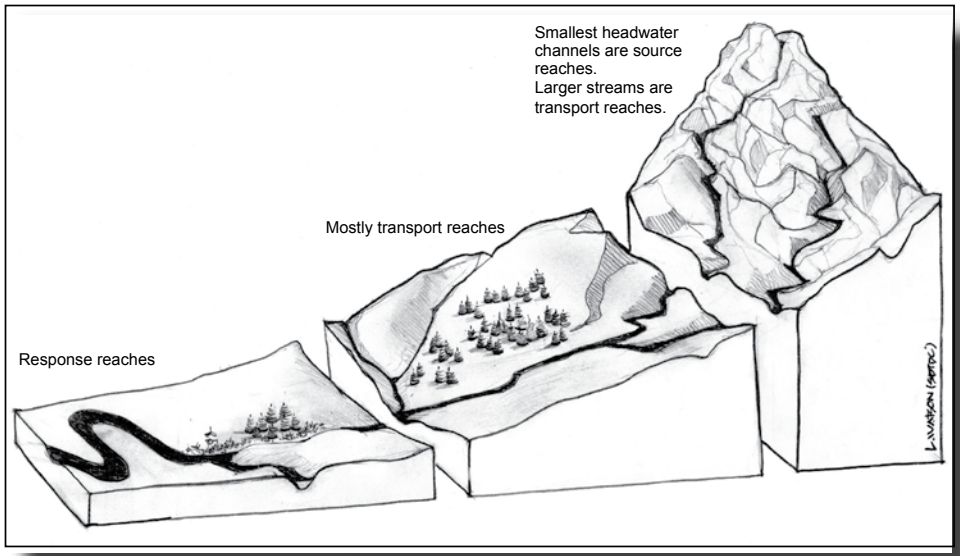

Figure A.2—Idealized distribution of reach types in a watershed. Drawn by L'Tanga Watson.

As integral parts of the watershed ecosystem, streams reflect the effects of climate, geology, soils, vegetation, basin shape, and land use in the watershed. These factors control water and sediment inputs to the stream. In turn, water and sediment, interacting with **riparian vegetation** and channel boundary materials, control fluvial processes and determine channel characteristics.

Much can happen to change these controlling factors over the lifetime of a crossing structure. Land use is changing rapidly in many areas, particularly near national forest boundaries where people can build homes and interface directly with "nature." Road building is continuing in some locations, and roads are being improved for recreation access. Off-road vehicle use can affect the hydrologic system, as can grazing and fire. In many locations, streams are experiencing or recovering from large-scale mining, logging, and removing of woody debris. All these changes can have large individual and cumulative effects on the hydrologic regime. Even a single unusual flood can create large, long-lasting changes in a stream system, requiring decades for recovery.

Obviously, what happens upstream in a watershed affects downstream channel reaches. However, downstream-land use or river changes also can affect upstream areas if they induce **channel incision** (i.e., downcutting). For example, **channelization** for urban or agricultural development speeds up water flow, increases its erosive power and causes channels to incise. Removal of woody debris from a channel, e.g., to reduce the risk of flooding can have the same effect. Gravel-mining operations that dig in-channel pits can lower the **base level** for all upstream reaches. These actions often produce **headcutting**, in which an oversteepened **nickpoint** migrates upstream (figure A.3), causing the bed to incise until it equilibrates at a lower, less erodible slope. Many existing culverts are functioning as **grade controls**, protecting upstream reaches from channel incision caused by migrating headcuts.

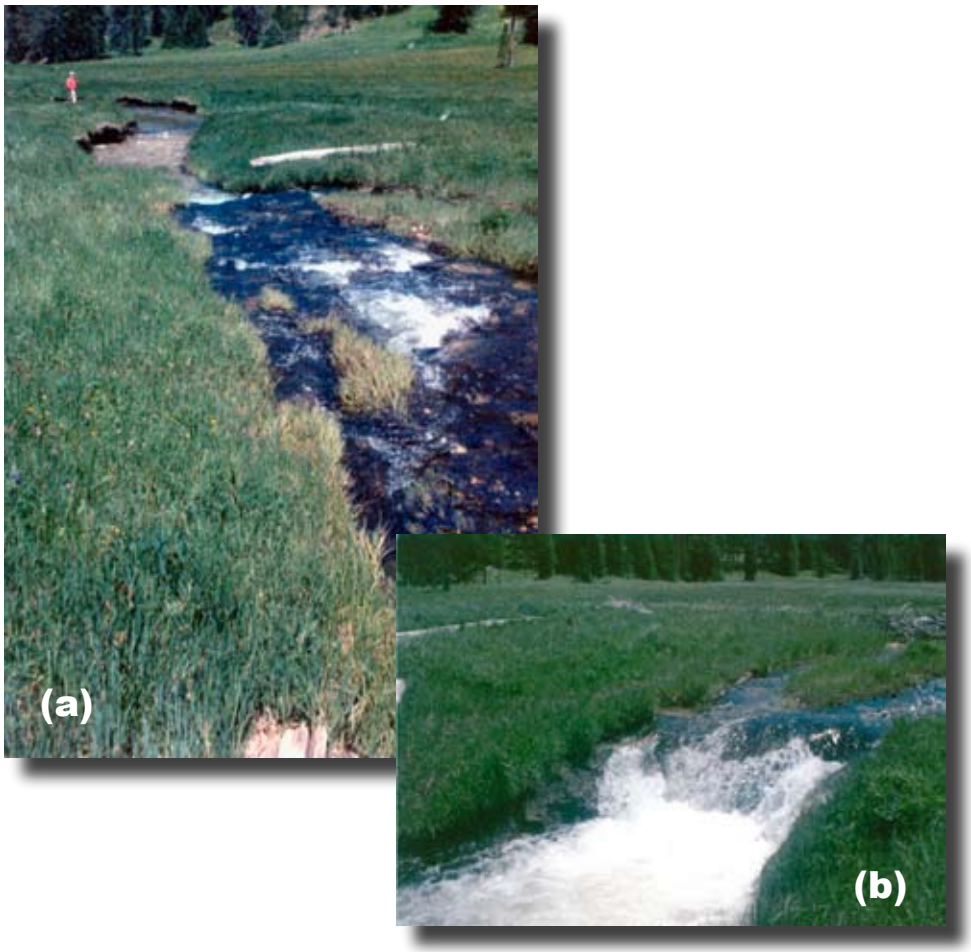

Figure A.3—Active nickpoint migrating upstream, Meadow Creek, Nez Perce National Forest, Idaho. (a) Looking downstream across nickpoint; (b) looking upstream at nickpoint. Bright streambed indicates recently mobilized material.

Cause and effect can be difficult to determine, not only because unseen offsite changes may be affecting a site but also because a significant lag time may exist between cause and effect. For example, headcuts related to channel straightening in the 1960s were still actively migrating upstream in northern Mississippi in the 1980s (Harvey et al. 1983). There can also be cascading effects. If bank vegetation is removed (e.g., by agriculture, logging, grazing, or construction) from a particularly sensitive reach, the channel may respond dramatically. Bank erosion could cause the affected reach to widen significantly, releasing large volumes of sediment. That sediment may be deposited in a downstream reach, potentially destabilizing streambanks there.

Existing channel conditions may depend on factors or events far removed spatially and temporally from the site. To understand the past and predict future channel responses, analyze the temporal sequence and spatial distribution of watershed activities. This information is critical to making informed and accurate interpretations of channel conditions at the road-stream crossing. This analysis is part of phase 1 of a stream-simulation project—the initial watershed review (see chapter 4).

A.3 CHANNEL CHARACTERISTICS

A.3.1 Streambed Material

A channel reach can be described as bedrock, colluvial, or alluvial according to the composition of its bed and banks (Montgomery and Buffington 1997; Knighton 1998). Bedrock channels have considerable segments of resistant bedrock (in excess of 50 percent) exposed along the **flow boundary** or the bedrock may be overlaid by a thin veneer of **alluvium**, i.e., material transported by the stream (Tinkler and Wohl 1998) (figure A.4). Bedrock channels tend to be quite stable. Many are situated in narrow valleys and lack flood plains. The lack of sediment in bedrock channels indicates that sediment is efficiently transported through the reach (Montgomery and Buffington 1997). Even in these transport reaches, however, there are usually localized, transient sediment accumulations behind woody debris or other channel features, and these accumulations may form very important habitats for aquatic species (McBain and Trush 2004).

Channels composed of material deposited by gravity-driven processes such as creep, surface erosion, debris flows, landslides, and rockfalls are referred to as colluvial channels (a type of source reach, figure A.2). Typically, they are located in the steep headwater areas of the watershed,

where **mass wasting** is the dominant geomorphic process (Montgomery and Buffington 1993, 1997). Colluvial channels are composed of angular boulders, cobbles, gravels, and sands. Normal (shallow) streamflow is insufficient for mobilizing most of the material; intermittent debris flows are the primary process for mobilizing and delivering the coarse colluvial material downstream (Montgomery and Buffington 1997).

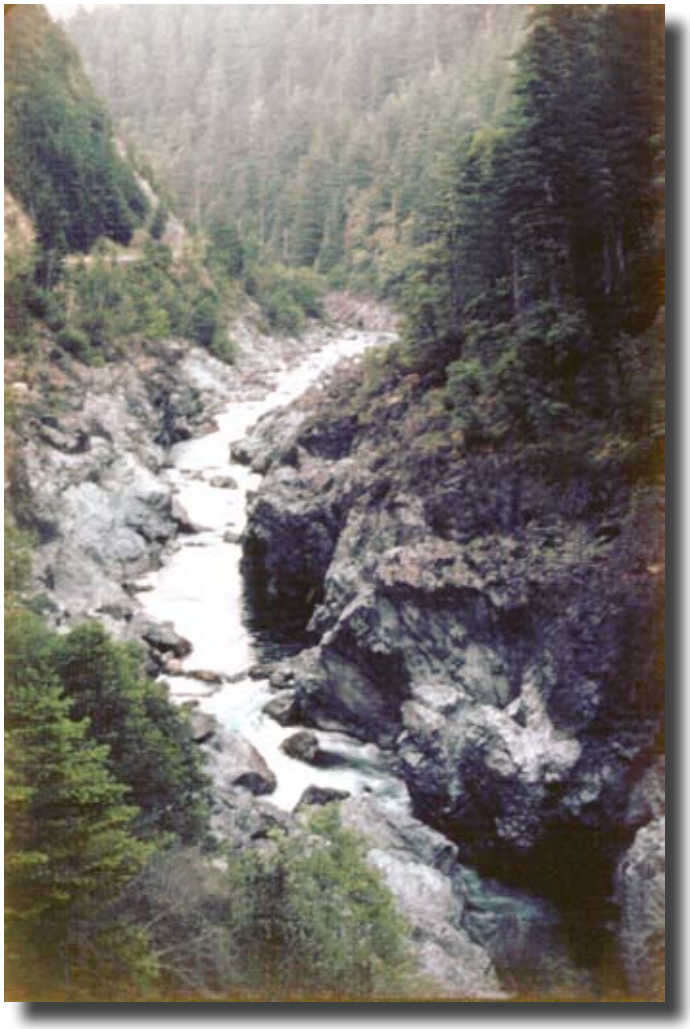

Figure A.4—Bedrock channels are transport reaches.

Alluvial channels are composed of alluvium; that is, their bank and bed materials were transported and deposited by the stream. They are able to adjust their form by eroding and depositing sediment in response to changes in flow and sediment transport conditions. The frequency and degree of **channel adjustment** is strongly related to particle size; channels composed of gravel and small cobbles (figure A.5) are more responsive to flow and sediment supply changes, whereas channels composed of large cobbles and boulders are relatively stable at most flows and may only

change form during infrequent, exceptional floods with large sediment inputs. Sand-bed channels are highly responsive, and their beds are usually continuously in motion at most flows.

Figure A.5—Alluvial response reach.

Channels in **cohesive materials** (with significant clay content) may or may not be alluvial. Many are incised into **residual soils**. Although their characteristics vary greatly depending on slope, in general they do not transport very much bed load. Most sediment is transported in suspension.

In channels composed of gravels, cobbles, and boulders, bed material is often segregated into two layers (figure A.6). The bed surface consists of a one- or two-grain-thick layer of coarser particles overlying smaller gravels or sands beneath the surface. This overlying coarse layer is referred to as the armor layer. The median particle size of the armor layer is usually 1.5- to 3.0-times coarser than the median particle size of the subarmor layer (Reid et al. 1998; Bunte and Abt 2001), although ratios as high as 6 and 7 have been reported (e.g., Andrews and Parker 1987; King et al. 2004; Barry et al. 2004). The presence of an armor layer indicates that the channel can transport more sediment than is available from upstream areas, whereas the lack of an armor layer indicates a balance between sediment supply and transport capacity (Montgomery and Buffington 1997). The armor layer increases the streambed's resistance to erosion. Once the armor breaches, however, the whole streambed can mobilize, and general scour occurs. In general, un**armored streambeds** are more mobile than armored ones; that is, bed sediment moves at lower flows and more frequently in an unarmored streambed than it would in an armored one.

Note: The particle size terminology we use in this document is from the Wentworth classification system, in which particle diameter doubles for each successive category (table A.1).

Table A.1—Definitions of particle size categories used in this guide: Wentworth classification system

Particle Description	mm	inches
Bedrock	>2,048	80
Large – very large boulders	1,024 – 2,048	40 – 80
Medium boulders	512 – 1,024	20 – 40
Small boulders	256 – 512	10 – 20
Large cobbles	128 – 256	5 – 10
Small cobbles	64 – 128	2.5 – 5
Very coarse gravels	32 – 64	1.26 – 2.5
Coarse gravels	16 – 32	0.63 – 1.26
Medium gravels	8 – 16	0.31 – 0.63
Fine gravels	4 – 8	0.16 – 0.31
Very fine gravels	2 – 4	0.08 – 0.16
Very coarse sands	1.0 – 2.0	0.04 – 0.08
Coarse sands	0.50 – 1.0	0.02 – 0.04
Medium sands	0.25 – 0.50	0.01 – 0.02
Fine sands	0.125 – 0.25	0.005 – 0.01
Very fine sands	0.062 – 0.125	0.002 – 0.005
Silts/clays	< 0.062	< 0.002

Figure A.6—The armor layer can be seen on this eroded gravel bar, Flathead River, Montana.

A.3.2 Channel Slope

Slope is an important variable determining the overall energy of the stream for transporting water and sediment. Slope is also one of the channel characteristics most frequently altered by crossing structures that are undersized or installed at slopes different from that of the natural channel.

As a general rule, channel slope decreases going downstream in the watershed from the headwaters to the lower sediment deposition zone (figure A.2). Locally, the channel slope may steepen or flatten because of factors such as bedrock, coarser material, tectonic activity, and base-level changes (Knighton 1998). The general decrease in channel slope across the watershed corresponds to an increase in flood-plain width, channel sinuosity (see A.3.3), and average flow depth; a decrease in bed material size; and a decrease in the interactions between valley slopes and the stream. Steep channels usually have coarser sediments, discontinuous narrow flood plains or no **flood plains**, narrow valley bottoms, and relatively straight **planforms** when compared to low-gradient channels.

A base-level control is any structure that fixes the lowest elevation to which a stream reach can downcut. Common examples of base-level controls are very stable debris jams or concrete weirs. For a tributary, the ultimate base level is the elevation of the master stream at a tributary junction. When a base-level control is removed or altered, upstream channel slope changes concomitantly. Base-level control is an important concept in stream simulation. If the base-level control changes over the life of the structure, the altered slope may destabilize the simulated streambed.

At the reach scale, channel slope can be measured as the slope of the channel bed or as the slope of the water surface. It also can be measured along the thalweg (representing low flow) or along the midpoint of the channel (representing high flow). In stream-simulation design, the channel bed along both the thalweg and the **bankfull** water surface slope can be important (see section 5.2.2.2 bankfull sidebar).

The **thalweg** is a line running along the channel bed (i.e., longitudinally), connecting the lowest points. In figure A.7, the thalweg meanders along the bottom of the otherwise straight channel. The thalweg in figure A.7 is longer than the channel as a whole, because the thalweg bends back and forth along the channel bottom. The thalweg's longer length makes its slope lower than the average channel slope. As the water surface rises in this channel during a high-flow event, flow straightens out and slope increases.

Figure A.7—This straight reach of the San Pedro River, Arizona, has a meandering thalweg.

Local channel slopes vary, reflecting the presence of multiple **bedforms** such as steps, riffles, pools, and obstructions (figure A.8). At higher flows, water surface slope evens out somewhat because bedforms are submerged.

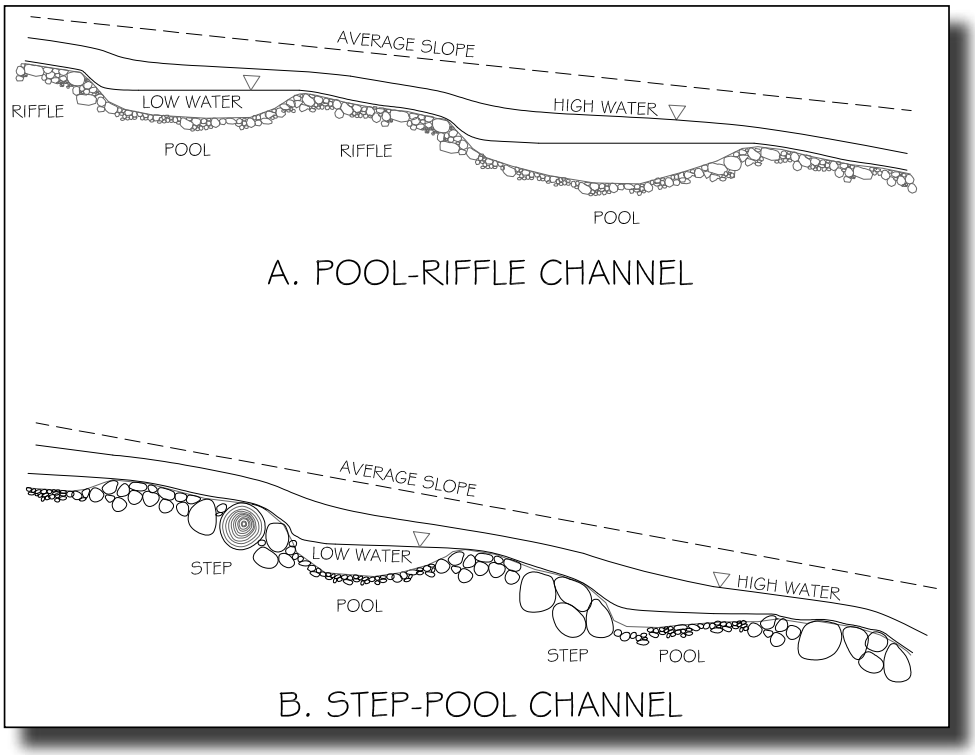

Figure A.8—Pool-riffle and step-pool channel profiles showing variable local slopes. From Knighton (1998). permission to use requested.

A.3.3 Channel Pattern

Channel patterns—also referred to as planform characteristics—are usually classified as straight, meandering, braided, or anastomosing (figure A.9). Pattern is determined by factors like slope, confinement, sediment supply, channel and valley materials, and riparian vegetation (Knighton 1998).

Straight alluvial channels are relatively rare in nature. Most streams tend to meander, unless they are tightly confined in a narrow valley or gully. Channel sinuosity—the ratio of stream length to valley length—describes the degree of meandering (see figure A.10). Meandering streams are inherently more dynamic, and their tendency to shift location across the valley bottom increases with sinuosity, bed load, and slope. The more erodible the banks, the more changeable the stream.

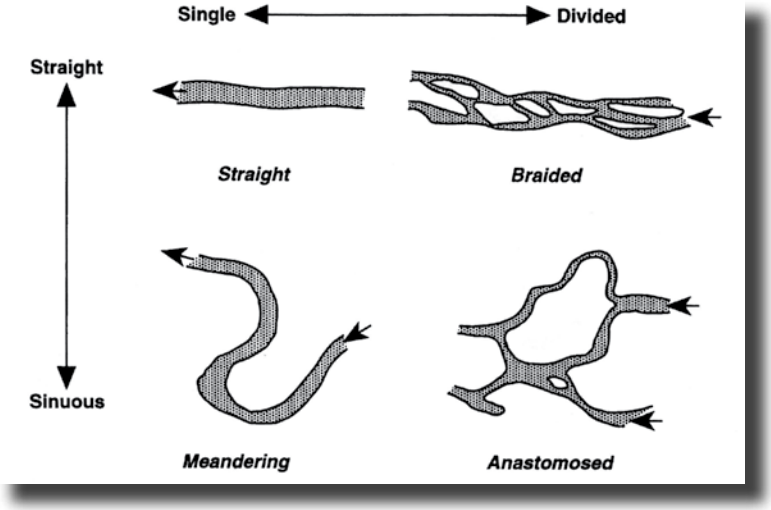

Figure A.9—Channel patterns. From Thorne et al. (1997), reproduced with permission from John Wiley and Sons, Ltd.

Meander wavelength (L), amplitude (A), and **radius of curvature** (R_c) describe the geometry of individual meanders (figure A.11). The radius of curvature is of particular interest in stream-simulation design, because it affects the distribution of water velocities across the channel. At a bend, water velocity is higher near the outside bank than near the inside bank. This cross-sectional difference in velocity causes erosion on the outer bank and deposition on the inside bank, often resulting in meander shift. At road-stream crossings, radius of curvature can affect the risk of alignment changes over the life of the crossing (see section 6.1.1).

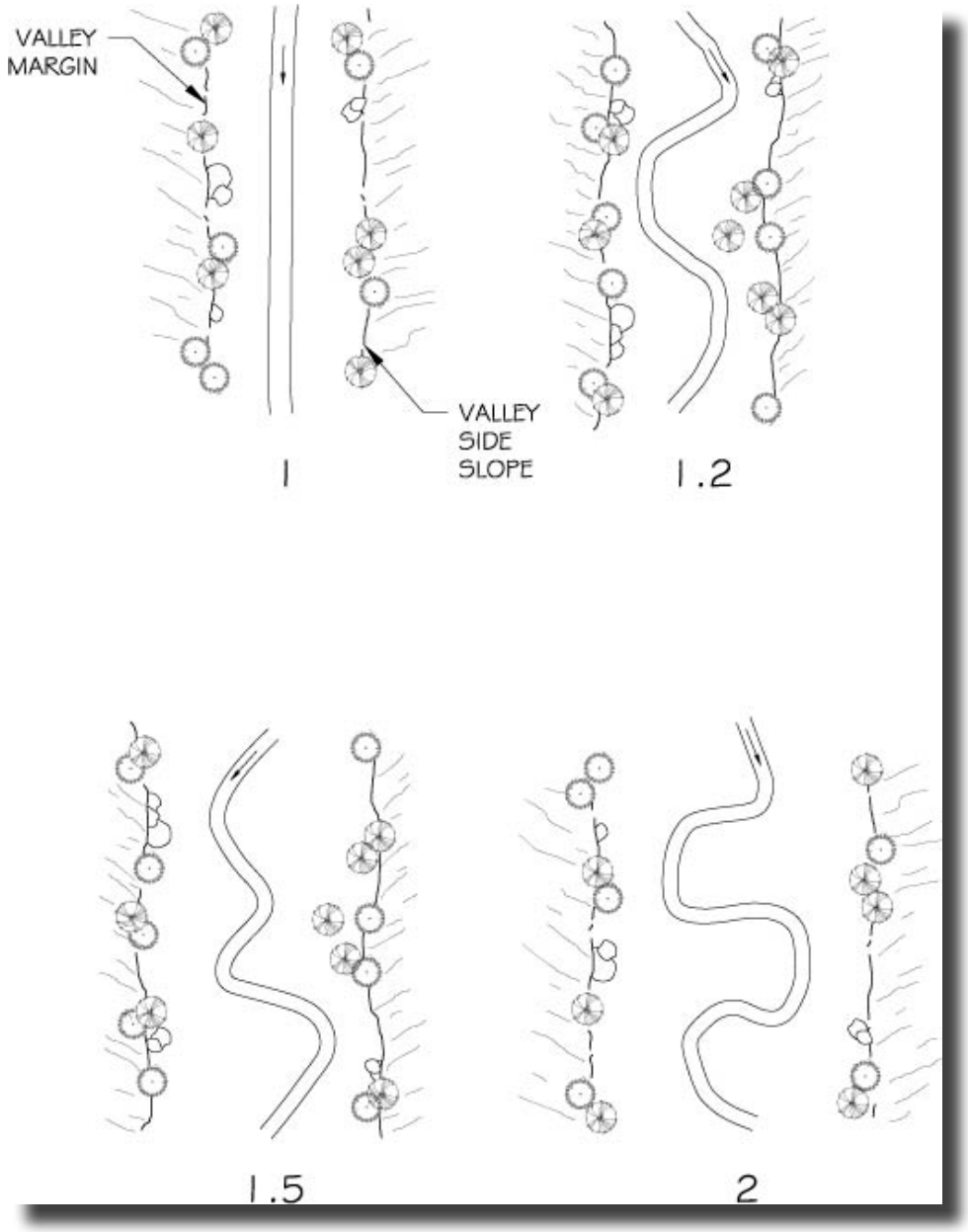

Figure A.10—Channel sinuosity is channel length divided by valley length.

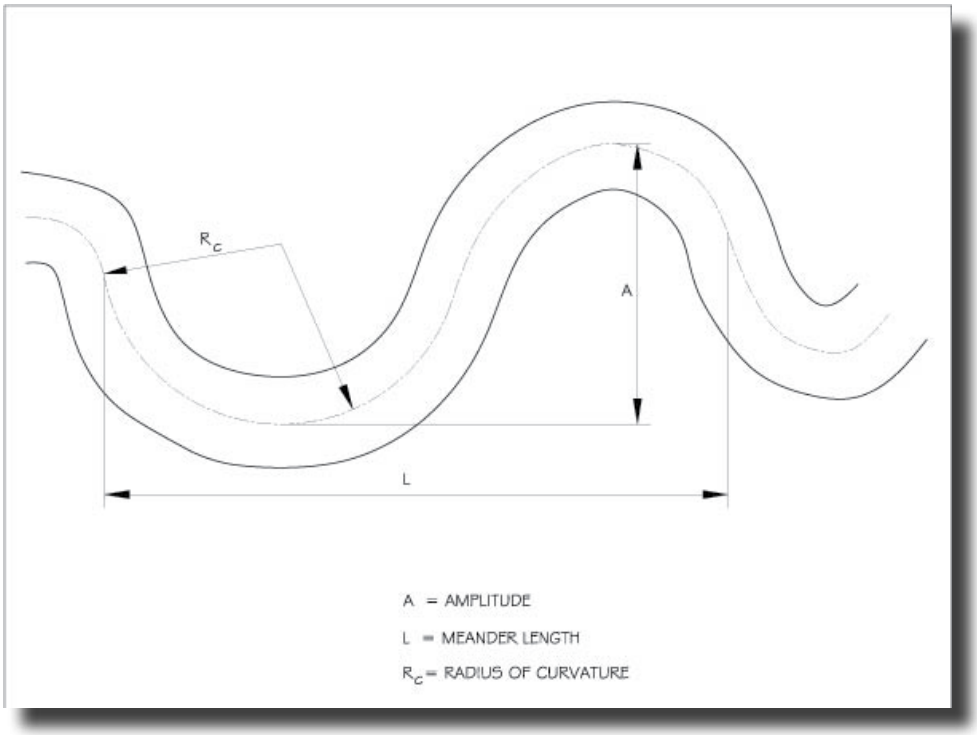

Figure A.11—Common meander geometry measurements.

Braided channels consist of multiple wide and shallow channels separated by poorly vegetated bar deposits. Individual channels and bars frequently shift position [figure A.12(b)]. A braided pattern indicates that sediment supply is high and that the channel bed and banks are readily eroded. Despite the fact that channels and bars continually shift, the size and slope of the channel within the limits of the braided area may remain the same. A braided channel like this is in **dynamic equilibrium** with existing geomorphic conditions (Knighton 1998).

Anastomosing channels are also multithreaded. However, the individual channels are separated by highly stable vegetated bars or islands [figure A.12(c)]. Anastomosing channels typically form in environments where the valley bottom is wide, flooding is highly variable, flood plains are frequently inundated, and banks are relatively resistant to erosion (Knighton 1998).

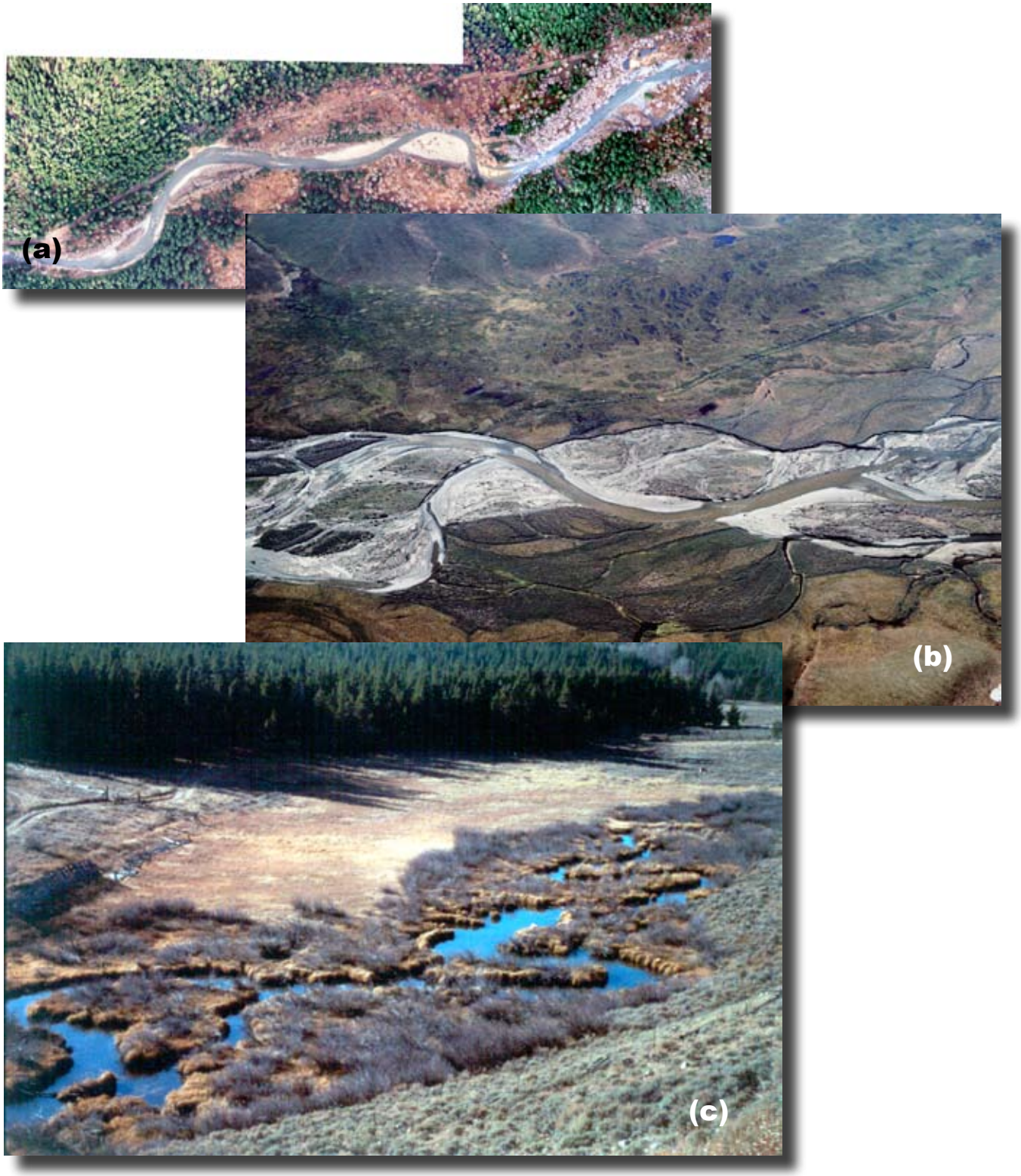

Figure A.12—Stream patterns (a) meandering reach on the Dosewallips River, Olympic National Forest, Washington; (b) braided river in the Arctic National Wildlife Refuge. (USFWS Alaska photo gallery); (c) anastomosing reach on Medicine Bow National Forest, Wyoming.

A.3.4 Channel Dimensions, Confinement, and Entrenchment

Width-to-depth ratios are often used to characterize channel dimensions (usually bankfull channel dimensions—see section A.4.1). Low width-to-depth ratios indicate the channel is narrow and deep, whereas high width-to-depth ratios indicate that the channel is wide and shallow. Width-depth ratios, however, do not describe a cross-section's symmetry. Both symmetry and width-to-depth relations vary longitudinally along a given channel, and, in meandering channels, they are strongly influenced by the cross-section's location relative to bends. Cross sections located at channel bends typically have asymmetric shapes reflecting the pool and point bar (channel type C, figure A.13), whereas cross sections in straight channel segments have symmetrical, more rectangular shapes (channel type B, figure A.13).

Vegetation strongly influences channel shape. Banks densely vegetated with deep-rooted species have narrower and deeper channels than those with thinly vegetated, grassy banks (Hey and Thorne 1986). The cohesiveness of the bank material also influences channel shape. Channels with cohesive banks (silts and clays) have narrower and deeper channels than channels with **noncohesive** (sand, gravel) banks (Knighton 1998).

The term "channel entrenchment" describes the degree to which flow is vertically contained (figure A.13). That is, as discharge increases, flow in an entrenched stream is confined either by the valley walls or by steep, high streambanks. This guide uses Rosgen's (1994) definition of channel entrenchment: the ratio between flood-prone width and channel bankfull width. Flood-prone width is the width of the flood plain or valley bottom at an elevation two times the **maximum bankfull depth**. Generally, the flood-prone width is considered to correspond with floods having **recurrence intervals** of less than 50 years (Rosgen 1994).

Channels with entrenchment ratio values less than 1.4 are "entrenched," indicating either that the valley bottom is narrow or that the adjacent valley surface is not frequently flooded (e.g., it is a terrace). Channels with entrenchment-ratio values greater than 2.2 are "slightly entrenched," indicating that the flood-prone valley bottom surface is wide relative to the channel. Channels with entrenchment ratio values between 1.4 and 2.2 are considered moderately entrenched.

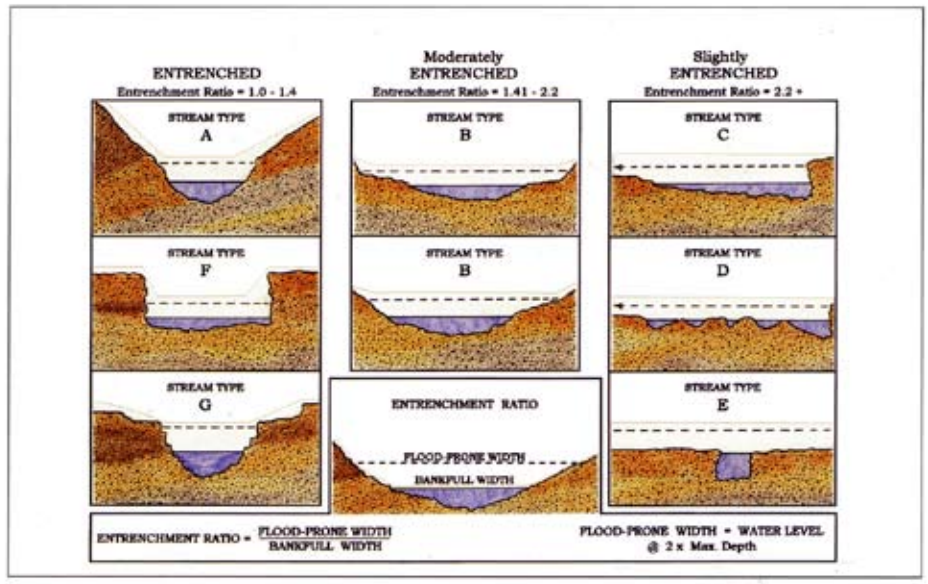

Figure A.13—Channel entrenchment (from Rosgen 1994).

In stream simulation we use the entrenchment ratio as an indicator of potential site risks associated with future alignment changes; that is, slightly entrenched channels tend to undergo alignment changes as they shift across the flood plain. Slightly entrenched channels also are more likely to have roadfills that obstruct flood plains. Flood-plain obstruction can cause problems for a crossing structure by concentrating flood flows through it.

A.3.5 Channel Bedforms

Natural stream channels have a variety of **bed structures** known as bedforms, which reflect local variations in hydraulics, particle size, and sediment transport. In coarse-grained channels, structures such as **pebble clusters**, transverse ribs, and cobble-boulder steps cause complex flow patterns of convergence and divergence. These patterns in turn influence **bedload transport rates** and patterns (Brayshaw et al. 1983; Koster 1978; Whitaker and Jaeggi 1982). In sand-bed channels (figure A.14), the channel bed is easily mobilized into different bedforms (ripples, dunes, antidunes) that correspond to variations in flow intensity (Knighton 1998).

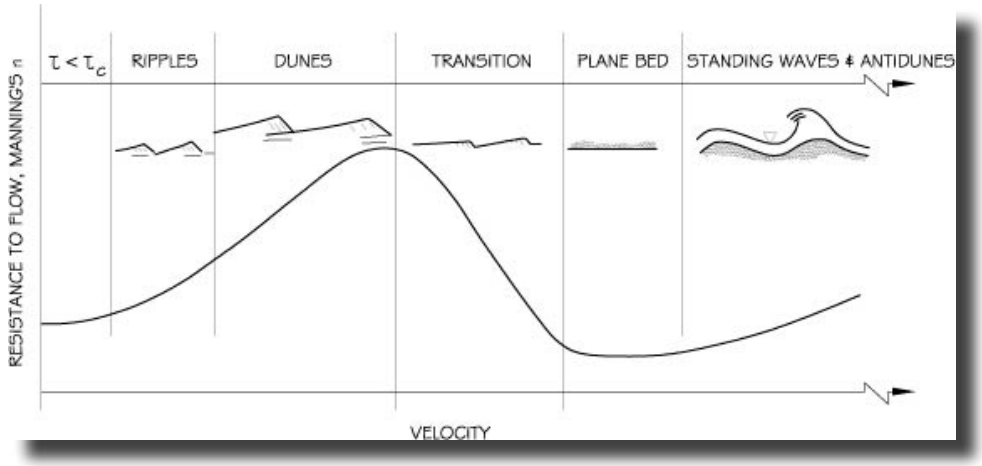

Figure A.14—Depending on flow intensity, bed structures such as ripples, dunes, and antidunes can form in sand bed channels, dramatically changing channel roughness. Redrawn after Simons, Li & Associates 1982.

In gravel-bed channels, the dominant form of bed topography tends to be alternating pools and riffles in low-gradient channels, and pools and steps in high-gradient channels. In pool-riffle channels, pools are scoured along the outer margins of channel bends and downstream from obstructions such as bedrock outcrops or large woody debris structures that locally constrict the channel. Pools and point bars are located at bends, and riffles are located in straight channel segments between successive meanders. At low flows, flow is deep and slow in pools, whereas flow in the adjacent, steeper riffles is shallow and fast (figure A.15). The average spacing between pools in a pool-riffle channel is generally between 5- to 7-channel widths, but spacing is variable along a given channel and can range from 1.5- to 23.3-channel widths (Keller and Melhorn 1978). The spacing of pool-riffle sequences can be influenced by large woody debris, large obstructions, or bedrock outcrops (Lisle 1986; Montgomery et al. 1995).

Figure A.15—A pool-riffle reach on the Flathead River, Montana.

Step-pool sequences are common bedforms in high-gradient, coarse-bed alluvial channels. Steps are composed of cobbles, boulders, bedrock, and/or large woody debris that extend across the entire channel perpendicular or oblique to flow (figure A.16). Plunge pools form at the base of each step and often contain finer material. In step-pool channels, the spacing between steps ranges between 1- and 4-channel widths and is primarily a function of gradient, with less distance between steps as gradient increases (Whitaker 1987; Chin 1989; Montgomery and Buffington 1997). The height and length of steps are also a function of gradient, with step heights increasing and step lengths decreasing as gradient increases (Whitaker 1987; Grant et al. 1990).

Figure A.16—Step-pool channel in northern Idaho.

A.3.6 Flow Resistance or Channel Roughness

Water velocity in a stream depends on channel resistance (**roughness**), as well as water depth and channel slope. A stream simulation mimics natural-channel roughness to keep velocities similar and to recreate the velocity diversity that allows for a wide variety of species to pass the crossing.

Total **flow resistance** is influenced by the combined interactions of channel-bed material, bedforms, water-surface and bed-surface slope variability, channel alignment, bank irregularities, and vegetation. Total flow resistance can be divided into the following three categories (Bathurst 1997; Knighton 1998):

- *Free-surface resistance* represents energy losses associated with surface waves and **hydraulic jumps** (e.g., flow plunging over a step).
- *Channel resistance* represents energy losses caused by water-surface and bed-surface slope variability (e.g., slope variability associated with pool-riffle and step-pool sequences), bank irregularities (e.g., bedrock outcrops, large woody debris complexes), and variability in channel alignment (e.g., channel bends).
- *Boundary resistance* represents energy losses caused by a number of factors, including grain roughness, form roughness, and vegetation roughness.

Channel resistance can be very significant in channels with many pieces of debris, rock outcrops or large boulders, and/or sharp bends. However, boundary resistance is the primary factor influencing total flow resistance of most channels (Limerinos 1970; Hey 1979; Bathurst 1985; Jarrett 1985). Boundary resistance includes the following components:

- Grain roughness represents energy losses caused by the size of the particles and the height to which they project into the flow: Larger particles have greater flow resistance than small particles.
- Form roughness represents energy losses caused by bedforms.
- Vegetation roughness represents energy losses associated with type and density of vegetation along channel banks. Taller, more rigid, and more densely packed stems increase vegetation resistance to flow and reduce shear stresses on bank and flood-plain surfaces (Arcement and Schneider 1989).

Boundary resistance varies with discharge, because the depth of water influences the degree to which the channel-bed sediments, bedforms, and bank vegetation interact with the flowing water. As water depth increases, the influence of grain and form roughness decreases while vegetation roughness increases, because more water is in contact with the bank vegetation. Boundary resistance on the flood plain, caused by microtopography, vegetation, etc., also controls the amount of water flowing over the flood plain (i.e., **flood-plain conveyance**).

In gravel- and cobble-bed channels, grain roughness is the primary component of boundary resistance. In boulder-bed channels with step topography, the combination of individual particles (grain roughness) and steps (form roughness) determines boundary resistance. In sand-bed channels, form roughness is more important than grain roughness, because continual bedform changes (ripples, dunes, antidunes) cause variations in boundary resistance (figure A.14).

A.4 CHANNEL STABILITY AND EQUILIBRIUM

Stable channels are channels that are not experiencing rapid, lasting change in dimensions or slope. While stable channels adjust to a wide range of flows and sediment inputs, their average dimensions remain the same over long periods (decades to centuries).

In the short term, a stable channel reach may adjust width, depth, and/or slope in response to a flow or sediment input event such as a flood or landslide. However, with time, channel dimensions return to the equilibrium state. On average, a stable reach is neither aggrading nor incising, neither widening nor narrowing, and the amount of sediment coming in is the same as the amount leaving it. Recognizing that such channels are stable but not static, we describe them as being in quasi-equilibrium (figure A.17).

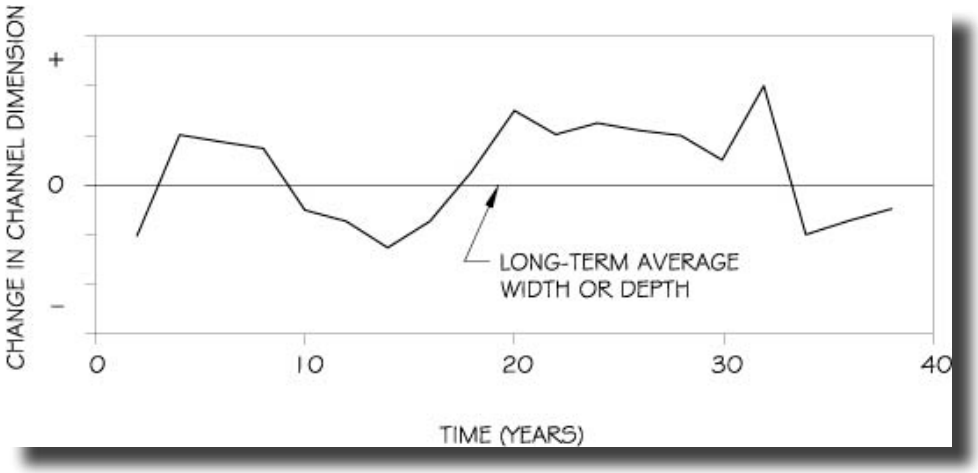

Figure A.17—In quasi-equilibrium channels, width and depth vary around long-term average values. After Schumm (1977).

For a channel to be in quasi-equilibrium, environmental conditions, such as the amount and timing of runoff and sediment input, also must be approximately constant (or changing very slowly) over the decade-to-century time scale. Base level also must remain the same. If these controls change enough to cross a "response threshold," the destabilized channel can change dramatically and rapidly, going through a series of adjustments before reaching a new quasi-equilibrium state (Schumm 1977).

As we gain more understanding of climatic variability, and as human uses of land and rivers intensify, geomorphologists are increasingly skeptical about whether modern streams actually achieve quasi-equilibrium over "engineering time" (Macklin and Lewin 1997). El Niño and the North Atlantic Oscillation cause changes in rainfall regimes large enough to cause river adjustments (Lewin et al. 1988) on decade and longer time scales. In many forested environments, changing land management may be expected to progressively alter runoff and sediment-load regimes. Crossing designers should recognize the possibility that the conditions controlling stream morphology may not be stable over a structure's lifetime. Watershed-scale investigations that deal with past, present, and future conditions, such as those outlined in chapter 4, are critical for providing the context needed for prudent design.

Most channels immediately adjacent to a narrow road-stream crossing structure adjust their form to establish a "new" quasi-equilibrium with the conditions imposed by the undersized structure (culvert). Typical responses include aggradation and channel widening immediately upstream from the culvert inlet, and channel widening and incision immediately downstream from the culvert outlet. These adjustments make the channel more efficient in transporting sediment and dissipating flow energy, and create a more stable channel form. However, these same adjustments may prevent aquatic organisms from migrating freely along the **stream corridor**. A stream-simulation structure will restore stream and ecological connectivity at the road-stream crossing. During and after construction of the stream-simulation structure, the channel will adjust its form to establish a new quasi-equilibrium.

A.4.1 Equilibrium and Bankfull Flow

Observable channel characteristics are the result of both a range of past discharges and the temporal sequence of floods. Nonetheless, a single discharge value is commonly used to represent the "**channel-forming flow**" (Knighton 1998). Bankfull discharge—the maximum discharge the channel can contain before water overtops its banks onto the flood plain—is generally taken to represent the channel-forming discharge in response channels and moderate-gradient transport channels. In many environments, bankfull is a peak that is equaled or exceeded frequently—about every 1½ to 2 years. Because this peak is frequent and because it usually transports a significant amount of sediment, it is generally found to transport more sediment cumulatively than any other flow over a long period of time (Hey 1997).

Since water and sediment inputs continually fluctuate, the channel continually adjusts. However, unless it is truly unstable, its dimensions will vary around equilibrium values that can often be consistently related to bankfull discharge (Emmett and Wolman 2000) (see figure A.18). Based on these relationships, bankfull discharge is often used as the reference discharge for designing channels (Hey 1997). We use bankfull in stream simulation for the same reason.

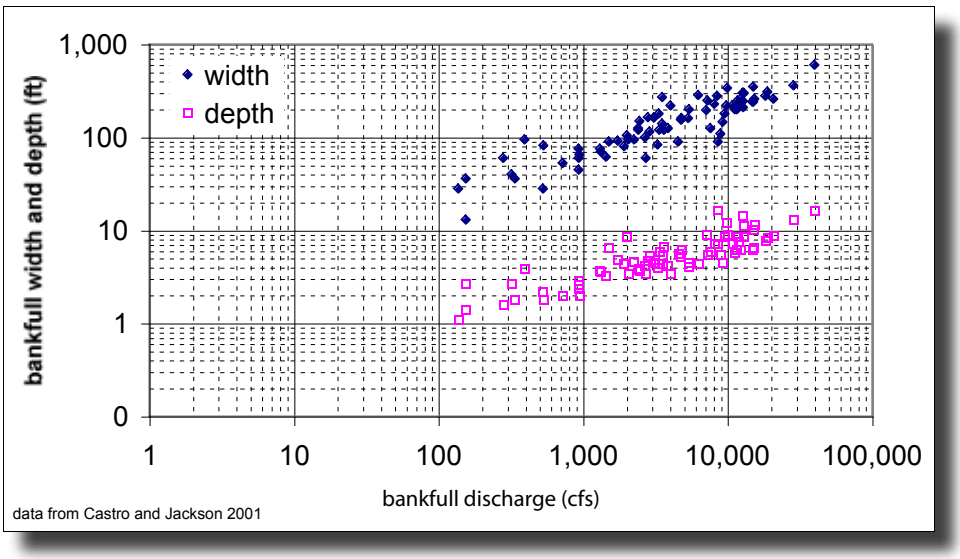

Figure A.18—Relationship of bankfull channel dimensions (determined in the field using geomorphic indicators) to bankfull discharge (determined from gauge records at observed bankfull elevation). Data from Castro and Jackson (2001).

Bankfull is not the channel-forming flow in all streams. In steep transport streams with large bed material, the flow that moves the large, structural bedforms can be much higher (i.e., less frequent) than in low-gradient alluvial channels. The channel-forming flow may be the 25-year flow or higher in a boulder-bed channel, depending on sediment inputs from the watershed (Montgomery and Buffington 1996; Grant et al. 1990).

A.5 FLUVIAL PROCESSES

This section describes key processes that both are created and affected by channel morphologic characteristics such as pattern, channel shape, slope, and bed structure. Understanding these processes is central to designing a stream-simulation structure that can sustain itself in the changing stream environment over the long term.

A.5.1 Sediment Dynamics

The morphology of a channel reflects the interaction between hydrodynamic forces acting on the channel bed and the resisting forces of the materials that make up the channel bed. When the hydrodynamic (lift and drag) forces exceed the resisting forces (particle weight and friction), sediment is entrained (mobilized), transported, and later deposited, causing the channel to change its form or grain-size distribution.

Generally, sediment is entrained and transported as water rises and peaks in a runoff event, and it is deposited again as high flow recedes. Stability of a constructed streambed—like all streambeds—depends on the balance between entrainment and transport of bed material and resupply by deposition of material transported from upstream.

Entrainment of noncohesive sediments by flowing water depends on:

- Sediment properties: size, shape, density, **pivot angle**.
  - Larger, heavier particles require faster deeper flow to move. Angular rocks tend to lock together better than rounded rocks, and they resist rolling. Elongated rocks tend to ‘shingle’ or **imbricate** (overlap) along the direction of flow, and they can form very resistant bed surfaces.

- Channel-bed composition: particle packing and orientation, **sorting**, distribution of bedforms, and degree of particle exposure to flow.
  - In poorly sorted channel beds, the stability of a particle is influenced by the particles adjacent to it (Andrews 1983; Wiberg and Smith 1987; Komar 1987) (figure E.1). Smaller particles are shielded behind larger particles in poorly sorted beds, and stronger flows are necessary for entraining them than in a well-sorted bed. Larger particles, in contrast, are entrained at weaker flows than in a well-sorted bed, because they project into the flow. Particles that project higher are more exposed to the force of the water, and this increased exposure enhances their entrainment despite their greater weight.
- Flow hydraulics: velocity, slope, water depth, and turbulence.

Shear stress is a measure of the hydrodynamic force exerted by flow on the channel bed and banks. Critical shear stress for a particle is the force that entrains it, that is, that initiates its motion by lifting it off or dragging it along the bed.

Water velocity and shear stress vary with local changes in channel slope controlled by such things as woody debris, rock weirs, steps, or gravel bars. These bed structures flatten local slope so that the upstream bed retains smaller particles than a bed of uniform slope. Even small embedded pieces of wood can control slope. In stream simulation, average slope is an important parameter, but the team must also pay attention to the bed structures that control slope and create both ‘sediment storage sites’ and diverse pathways for animal movement.

Understanding the relative mobility of different bed materials and structures is also critical. For example, sand-bed channels are highly mobile, and their beds are continuously in motion at most flows. In some gravel- and cobble-bed channels, the surface of coarse gravels and cobbles is relatively stable during frequent, moderate floods, although large quantities of sands and gravels move over the coarse surface layer (Jackson and Beschta 1982). Many gravel-bed streams are armored, and their tightly packed surface layers have been winnowed of finer materials. These intermediate-mobility streams may transport very little sediment until flow is able to breach the armor layer. Cobble- and boulder-bed channels are quite resistant to erosion, and these large rocks move only

during infrequent, exceptional floods (Montgomery and Buffington 1993; Knighton 1998). During frequent, moderate floods, however, large quantities of sand and gravel can be transported over and around the relatively immobile cobble and boulder structures.

A.5.2 Vertical Channel Adjustment

As high flow entrains sediment, parts of the streambed may lower or rise by inches or even feet. Then, as flow recedes and **sediment transport capacity** drops, the scoured or filled sections may return to their preflood elevation (Andrews 1979). After the event, that scour and fill occurred may not be at all evident, because the streambed often equilibrates at the same elevation as before. Stream-simulation culverts need enough headroom and bed depth to permit these processes to occur. High flow scour and fill is less important in streambeds that are resistant to erosion (e.g., where bed material is large, well-packed, or imbricated).

Longer-lasting vertical changes occur when sediment or water regimes change, or when channels are straightened or cleared of debris. Channels aggrade (fill) when sediment supplied from upstream exceeds the local transport capacity, and they degrade or incise (cut) when the reverse is true. Aggradation is the vertical rise in the bed elevation, a rise resulting from sediment deposition, which can occur upstream of a backwater structure such as a beaver dam or an undersized culvert. Aggradation is a common risk at concave slope transitions (figure 5.12). It also can occur if flow is removed from a channel by diversion or if sediment loads increase as a result of land use changes.

Channel incision (or degradation) is a lowering of channel elevation that occurs when local erosion exceeds deposition of sediment transported from upstream. Following are some familiar locations where channel incision commonly occurs:

- Stream reaches below dams, which cut off the supply of sediment and alter the **flow regime**.
- Forest streams where wood that controlled grade has been removed.
- Watersheds where the frequency or magnitude of peak flows has increased due to land cover or climatic changes.

Channel incision can create a self-reinforcing feedback loop. As the channel deepens, larger and larger floods are contained within its banks. The stream bed experiences increasing shear stress, and continues to incise until it encounters erosion-resistant material.

All these processes can severely affect simulated streambeds. Project teams should understand the direction and magnitude of probable vertical channel change over the lifetime of the planned structure, and they should design the structure to accommodate those changes.

A.5.3 Lateral Channel Adjustment

Many styles of lateral channel adjustment exist, and some of them occur in response to vertical adjustments. Aggrading channels tend to widen because, as the channel fills, flows apply more erosive pressure to the banks (figure 4-3). On the other hand, sediment deposition also can result in channel narrowing if vegetation is able to colonize new bar deposits along the banks. Although incising channels are initially narrow, they tend to widen as their banks become taller and more prone to sloughing (figures 4.6 and A.28).

Another fluvial process important in stream-simulation design is lateral-channel migration. As described in chapter 1, lateral shifting can change the stream's alignment to a crossing, and affect the crossing's ability to pass water, sediment, and debris. A crossing located on a channel bend may need to be positioned asymmetrically over the channel to accommodate future channel shifting. If the bend is sharp or the rate of channel migration is high, alternative solutions such as a bridge spanning the zone of potential lateral migration may be necessary.

In narrow valleys where the valley walls are close to the channel, the potential for lateral-channel migration is limited. However, streams in wide alluvial valleys shift position laterally across the valley bottom, and the process may be either gradual or rapid. Low-gradient sand and gravel channels gradually shift by meander migration; during frequent, moderate floods, the stream erodes the outer banks of bends and builds the point bar on the inside bank. Sudden and pronounced lateral shifting can occur during infrequent, large-magnitude floods or when water scours around obstructions such as sediment or wood accumulations.

The rate of meander migration depends on:

- Bend geometry (tighter bends tend to migrate faster).
- The resistance of the outer bank to erosion (bank height, materials, vegetation, moisture, etc.).
- The magnitude and duration of the hydraulic forces acting on the bank (Knighton 1998).

Certain types of sinuous planform patterns indicate a systematic downstream, down-valley meander migration, while others indicate a process of periodic bend cut-offs (Thorne 1997; Knighton 1998) (figure A.19).

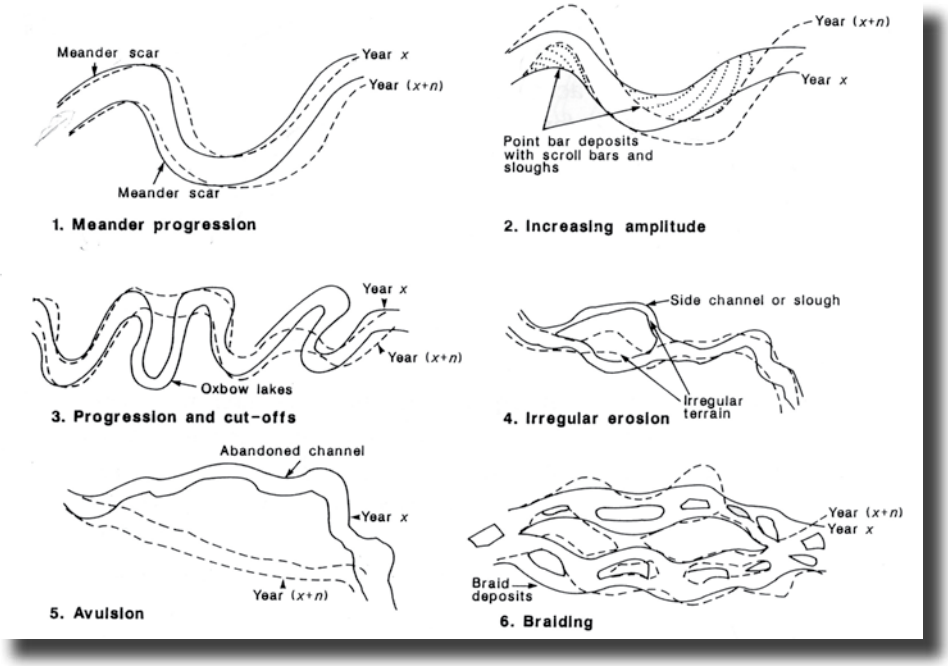

Figure A.19—Types of lateral-channel adjustment. From Thorne (1997). Reproduced with permission from John Wiley & Sons, Ltd.

Regardless of valley width, standing trees and large woody debris in and along the stream can substantially affect channel processes by increasing flow resistance, affecting bank erodibility, and providing obstructions to flow (Hickin 1984; Thorne1990). Large woody debris deposited in and along channel/flood-plain margins can alter **channel patterns** by diverting flow around the obstruction or creating low-velocity zones where sediment and organic matter deposit (Fetherston et al. 1995; Abbe and Montgomery 1996). This deposition in turn provides fresh surfaces for the establishment of new vegetation. Depending on the vegetation type, rooting strength can stabilize those surfaces and influence the degree of later channel migration.

Bank vegetation has a strong influence on lateral adjustability. Deep-rooted native species often provide very strong bank reinforcement. If native species are replaced by shallower-rooted exotic plants, bank erosion can accelerate, causing the channel to widen or increasing the rate of meander migration.

A.5.4 Flood-plain Inundation and Dynamics

A flood plain is a valley surface being constructed as the current stream deposits sediment. It is a temporary sediment storage area along the valley bottom, composed of sediments deposited during overbank floods. In meandering, low-gradient channels with relatively large, well-developed flood plains, **lateral accretion** is the dominant flood-plain formation process. In other words, the flood-plain surface is formed as the stream builds point bars during meander migration (Nanson and Croke 1992). In steep channels with narrow, **discontinuous flood plains**, **vertical accretion** (sediment deposition on top of the flood plain) is the dominant flood-plain forming process, because coarse channel sediments inhibit channel lateral migration (Nanson and Croke 1992).

Flow occurs frequently over a true flood plain (whenever bankfull discharge is exceeded). Other, higher flat valley surfaces (terraces) are flooded at less frequent intervals. Terrace surfaces are not being constructed by the current stream, although it may be eroding them. Both low terraces and flood plains can have erosion and deposition features, and the "**flood-prone zone**" (figure A.13) may encompass both.

Flood plains are key elements affecting channel stability in many response reaches. The stream's ability to overflow the flood plain limits channel erosion during high flows by limiting flow depth inside the main channel. During a flood, flow in the main channel is fast and deep, while flow over the flood-plain surface is slower and shallower. There is growing recognition that riparian forests play a significant role in the development of channel and flood-plain morphology. These forests stabilize flood plains during high flows and contribute large woody debris in and along channels that modifies flow hydraulics and sediment transport (e.g., Thorne 1990; Abbe and Montgomery 1996).

The density and type of vegetation on the flood plain influence the velocity and depth of flow over its surface, thereby influencing flood-plain conveyance, which is the water discharge (volume per unit time) across the flood plain or flood-prone zone. Flood-plain conveyance is a very important variable at a stream-simulation crossing, because during a flood the volume of flow on a high-conveyance flood plain may be so large that it requires special handling to avoid concentrating flow through the crossing.

A.6 CHANNEL CLASSIFICATION SYSTEMS

To provide a framework for assessing channel conditions, interpreting fluvial processes, predicting channel responses, and making design recommendations, this guide uses the channel-type classifications that Montgomery and Buffington (1993, 1997) and Rosgen (1994, 1996) developed. Both classifications are useful in stream simulation for somewhat different purposes.

As the information in this appendix only summarizes these classifications briefly, we strongly encourage you to read the original papers.

A.6.1 Montgomery and Buffington Channel Classification

The Montgomery and Buffington channel-classification system is based primarily on streambed structure (bedforms). The classification, which applies to mountain streams, identifies six distinct alluvial channel types and two nonalluvial channel types (bedrock and colluvial, section A.3.1). The classification of the alluvial types is based on bed structure and the resulting channel roughness and energy dissipation characteristics. Montgomery and Buffington (1993, 1997) also distinguish "forced morphologies," in which flow obstructions (such as wood) "force" a channel morphology that is different from what would exist if the obstructions were not present.

Cascade channels (figure A.20) generally occur on steep slopes (i.e., about 10- to 30-percent slope), and are frequently confined by valley walls. Their beds are 'disorganized,' with cobbles and boulders scattered or clustered throughout. Small pools that do not span the entire channel width—and tumbling, turbulent flow over the individual rocks—characterize this type. The large particles that form the bed mobilize only during very large floods (50- to 100-year flows), and they may include hillslope-derived materials (e.g., colluvium from debris flows, rock falls) as well as fluvially placed sediments.

Step-pool reaches (figure A.21) have large rocks or pieces of wood that form channel-spanning steps, usually spaced at about one to four channel widths. Below each step is a pool containing finer sediment. Because energy is efficiently dissipated as flow falls into the pools, this bed structure is more stable than would be expected for a less organized streambed. The steps mobilize and reform during large floods, but finer sediment moves over the steps during moderate high flows. Typical average channel slopes range from 3- to 10-percent slope.

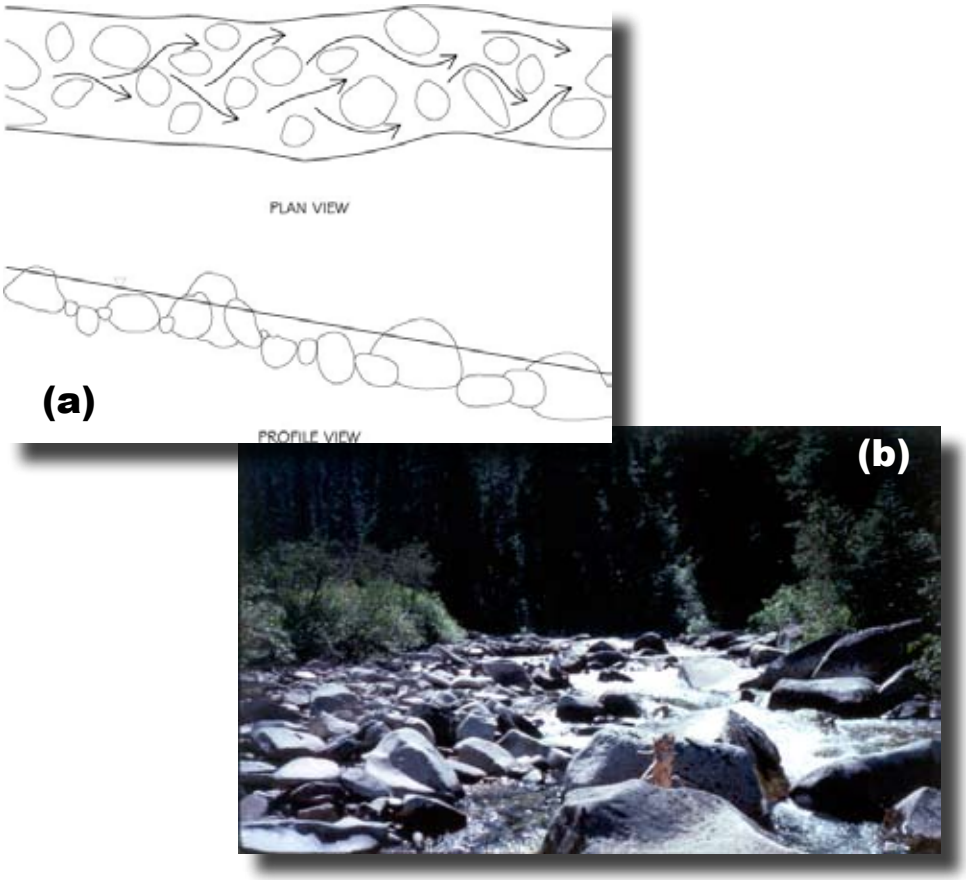

Figure A.20—Cascade reach: (a) schematic planview and profile, and (b) cascade reach on Selway River, Idaho.

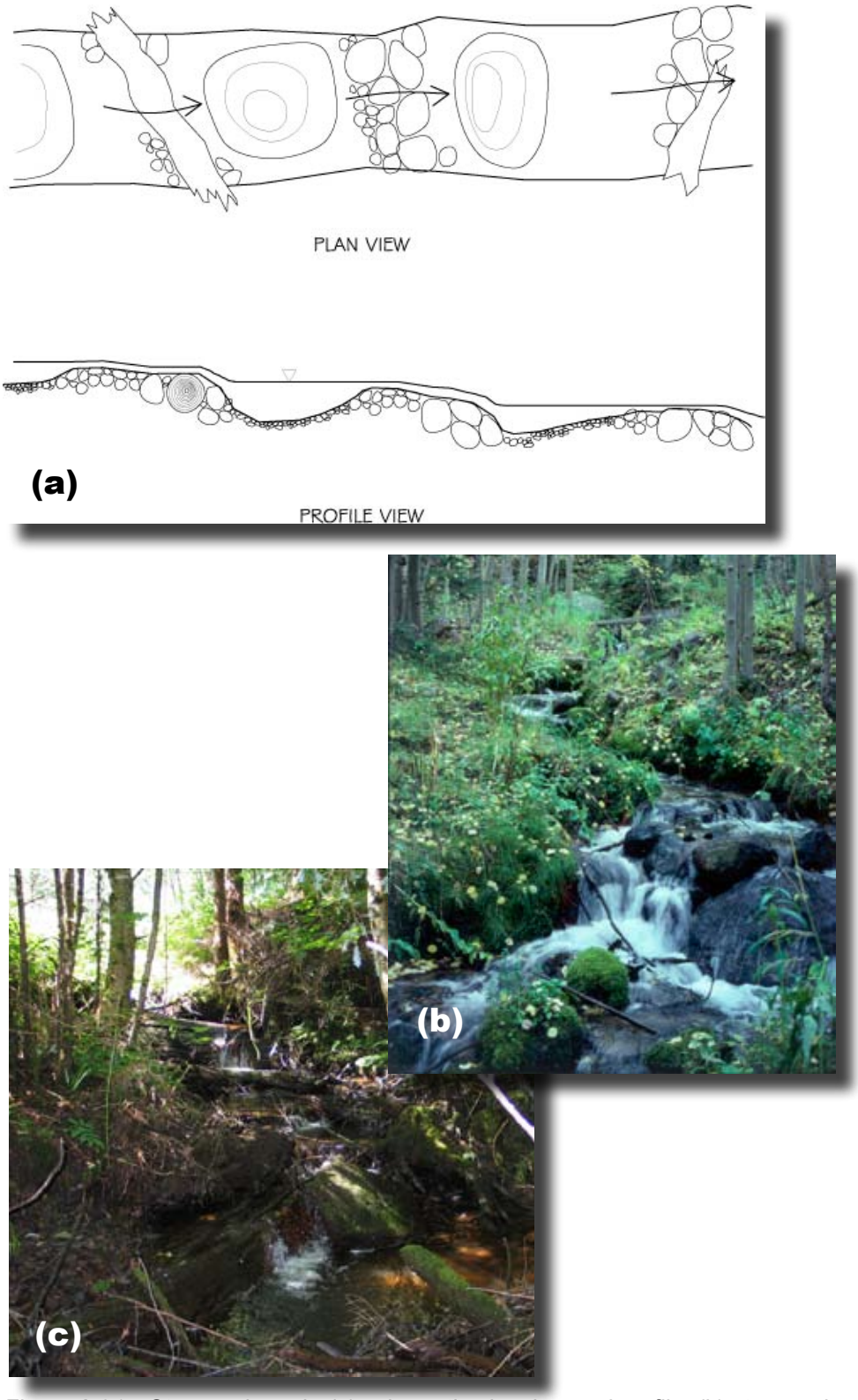

Figure A.21—Step-pool reach: (a) schematic planview and profile, (b) step-pool reach on Boulder Creek, Colorado, and (c) forced step-pool channel, Mitkof Island, Alaska.

Plane-bed reaches (figure A.22) "have long stretches of relatively featureless bed" (Montgomery and Buffington 1993, 1997) without organized bedforms. They are on "moderate to high slopes in relatively straight channels," usually with armored gravel-cobble beds. Bed mobilization occurs at flows near bankfull. In Rosgen's system, a plane-bed reach might be either a B- or G-channel type, and could have bed material as fine as sand.

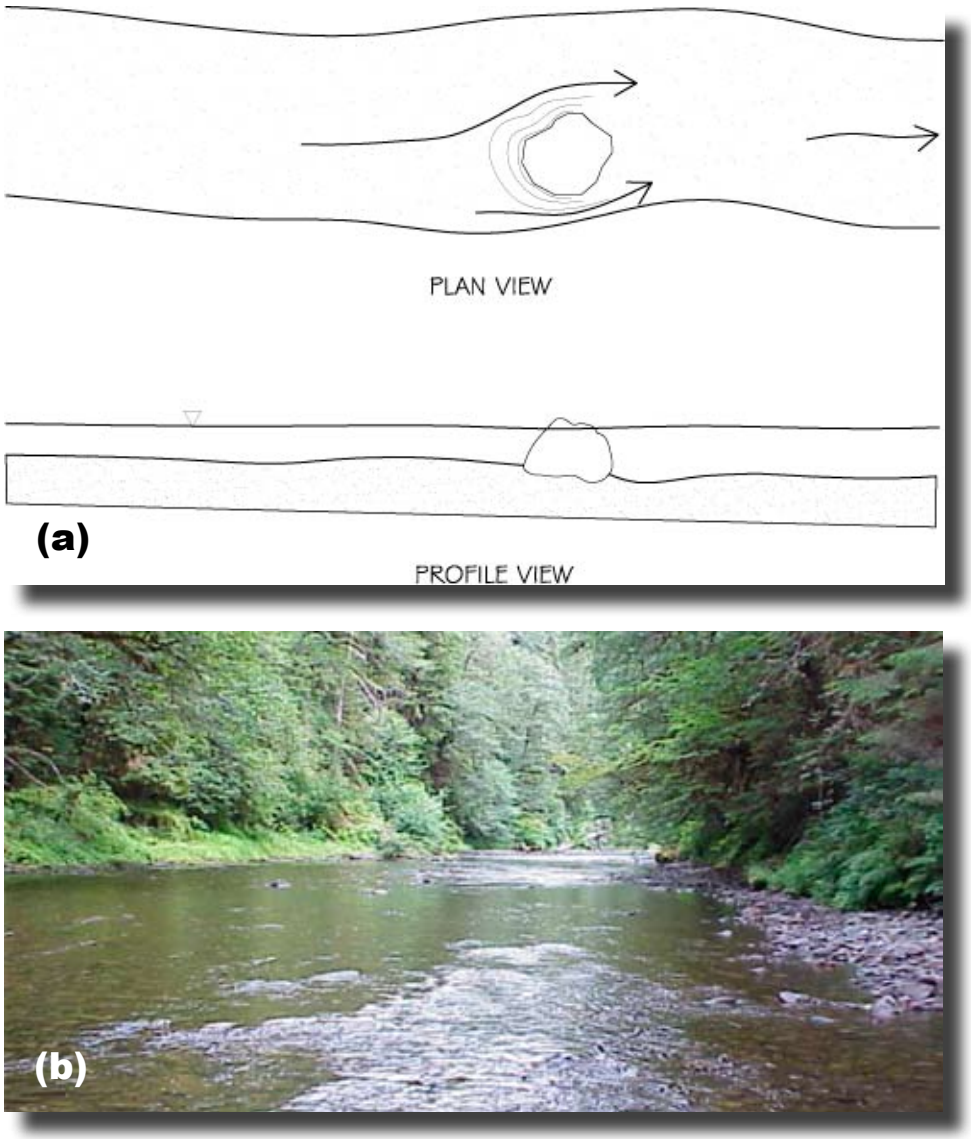

Figure A.22—Plane-bed reach: (a) schematic planview and profile, and (b) plane-bed reach on the Sitkum River, Washington.

Pool-riffle reaches (figure A.23) have longitudinally undulating beds, with a repeating sequence of bars, pools, and riffles regularly spaced at about 5- to 7-channel widths apart. Large woody debris can alter the spacing. These

channels, which usually have flood plains, may be sand- to cobble-bedded streams. Depending on their degree of armoring, bed mobilization may occur at or below bankfull. These may be Rosgen C, E, or F streams (see section A.6.2 for Rosgen classifications).

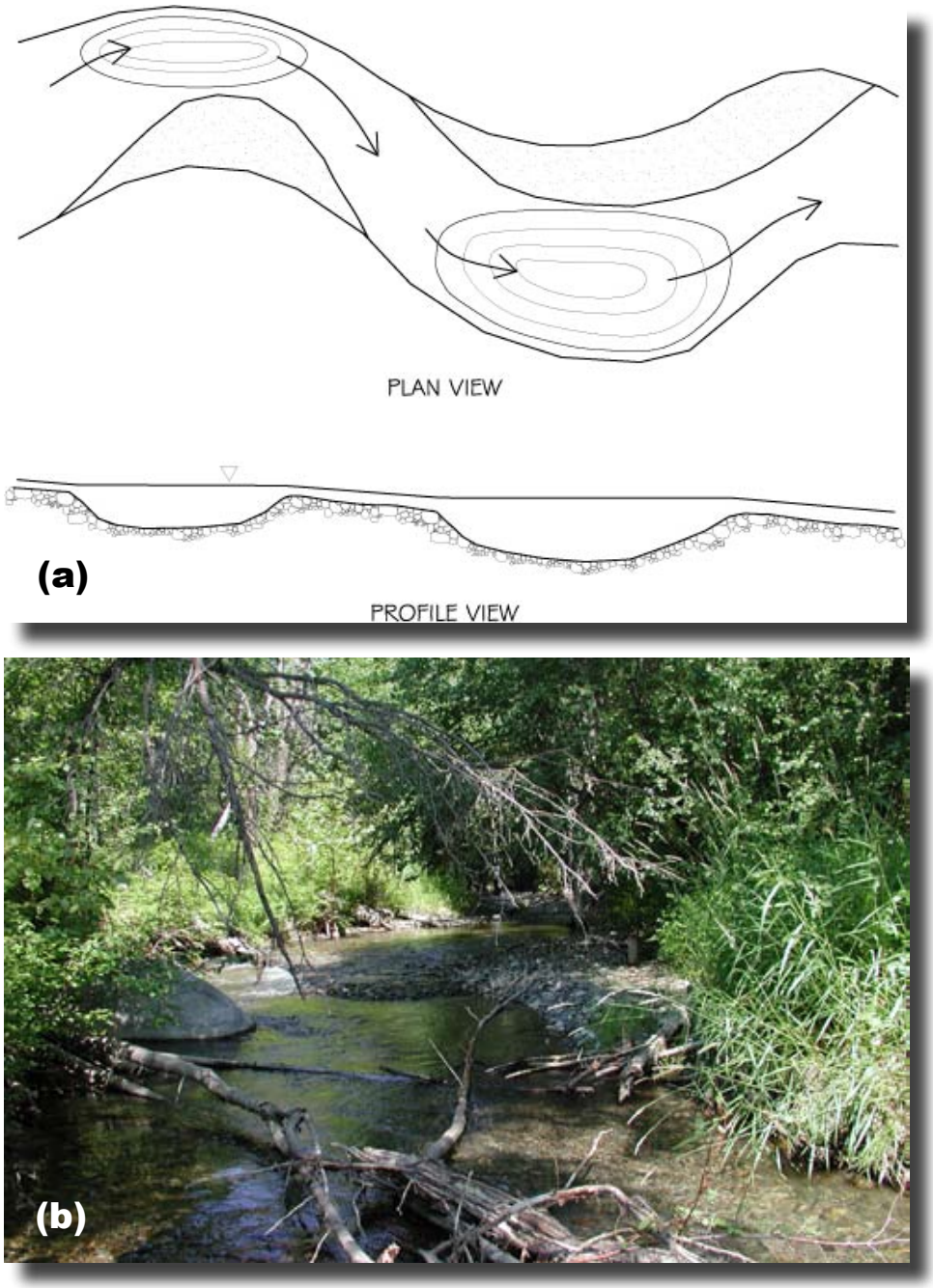

Figure A.23—Pool-riffle reach: (a) schematic planview and profile, (b) pool-riffle reach on Libby Creek, Washington.

Dune-ripple reaches (figure A.24) have low gradients with sand and fine-gravel beds. These streambeds transport sediment at virtually all flows, and the bedforms change depending on water depth and velocity (figure A.14). If the channel is sinuous, these streams also can have point bars.

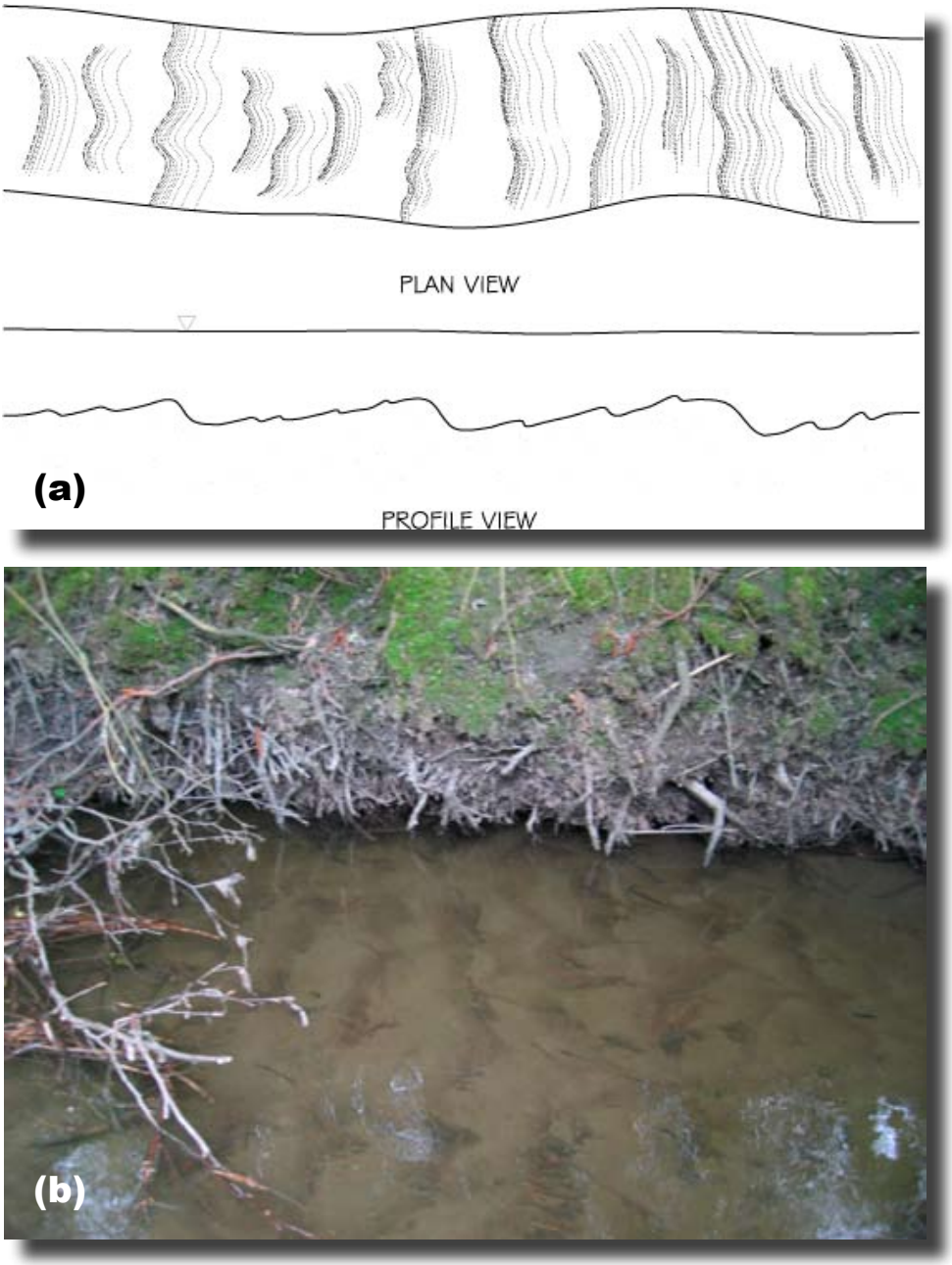

Figure A.24—Dune-ripple reach: (a) schematic planview and profile, and (b) dune-ripple reach on Coal Creek, Washington. Photo: Kozmo Ken Bates.

Because the Montgomery and Buffington channel types are based on streambed morphology, they are highly useful for stream-simulation design, where we mimic bed structure and channel roughness to create a **simulated channel** that will adjust similarly to its surrounding reaches. Each type is uniquely adjusted to the relative magnitudes of sediment supply and transport capacity. This relationship determines how sensitive the channel is to changes in water and sediment inputs.

Montgomery and Buffington (1997) were able to determine for each channel type the typical frequency with which the streambed is mobilized (table A.2). Knowing the typical frequency is important for stream simulation, because the simulated bed should mobilize at the same flows as the surrounding reaches. Transport reaches such as cascade and step-pool channels, for example, are relatively stable. The coarse bed material that controls channel form in these channel types mobilizes only in infrequent floods, although finer sediments and debris are efficiently conveyed over the large rocks during normal high flows. Response reaches such as pool-riffle and dune-ripple channels can experience significant and persistent changes in channel dimension, slope, and planform when hydrologic conditions and sediment supply change. These channels offer more challenge to crossing designers than do the more stable transport reach types. Chapter 6 outlines design options for stream simulations in various channel types. See Montgomery and Buffington (1993, 1997) for a complete explanation of their classification system.

Table A.2—Characteristics of channel types (adapted from Montgomery and Buffington, (1993, 1997)

REACH TYPE			TYPICAL CONDITIONS				
			Bed material	**Dominant roughness and structural elements[1]**	**Slope[2]**	**Entrenchment**	**Streambed mobility**
Alluvial reaches	**Response reaches**	Dune-ripple	Sand to medium gravel	Sinuosity, bedforms, banks. Small debris may provide structure.	<0.1%	Slight	Termed "live bed"; significant sediment transport at most flows.
		Pool-riffle	Gravel, often armored	Bars, pools, grains, sinuosity, banks.	0.1-2%	Slight	Armored beds usually mobilize near bankfull.
		Plane-bed	Gravel to cobble, usually armored	Grains, banks.	1-3%	Slight to entrenched	Near bankfull or at higher flows, depending on grain size.
	Transport reaches	Step-pool	Cobble to boulder	Steps, pools, banks. Debris may add significant structure.	3-6%	Moderately entrenched to entrenched	Fine material moves over larger grains at frequent flows. Bed-forming rocks move at higher flows depending on size; often >Q_{30}.
		Cascade	Boulder	Grains, banks.	6-30%	Entrenched	Smaller bed material moves at moderate frequencies (floods higher than bankfull). Larger rocks are immobile in flows smaller than ~Q_{50}.
Nonalluvial reaches		Bedrock	Rock with sediment of various sizes in transport over rock surface	Bed and banks.	Any	Any	Bedload moves over bedrock at various flows depending on its size. May be thin layer of alluvium over bedrock. Wood can strongly affect sediment mobility.
		Channels in cohesive materials (si/cl)	Silt to clay	Sinuosity, banks, bed irregularities.	Any	Any	Fine sediment moves over immobile bed at moderate flows depending on its size. May be thin layer of alluvium *over immobile bed.*

[1] Any channel type can be 'forced.' In forced channels, woody debris is an important structural element.

[2] Slope is not a diagnostic criterion, and slope ranges overlap more than the 'typical' values in this table reflect. Slope ranges shown here are from figures 16 and 19 in Montgomery and Buffington (1993). See also figure 6 and related text in Montgomery and Buffington (1997).

A.6.2 Rosgen Channel Classification

Rosgen's (1994) major channel types are based on the following channel variables: entrenchment, **width-depth ratio**, pattern, and gradient. Rosgen's major channel type classes are particularly useful in stream simulation because they reflect the degree of channel entrenchment—an important variable for assessing risks associated with stream simulation. Streams with high entrenchment ratios (unentrenched channels, Rosgen types C, DA, and E) have relatively wide flood plains that may be flooded frequently. To avoid concentrating overbank flood-plain flows through the pipe, teams must incorporate special design features in stream-simulation installations on these channel types. Streams with low-entrenchment ratios (**entrenched channels**, Rosgen types A, B, and G) have fewer risks associated with flood-plain inundation and lateral adjustment potential.

Each of Rosgen's nine major channel types (see figure A.25) has typical slope ranges that can be quite broad. Subgroups within each of the major types are divided by bed material type and designated with numbers. Rosgen's system does not specifically consider channels where woody debris is a dominant influence on morphology.

Rosgen (1994) developed interpretations of each channel type's sensitivity to a disturbance, its recovery potential, susceptibility to bank erosion, and reliance on vegetation for form and stability. His interpretations about channel responses to disturbance are very useful for predicting how the channel might change when some change occurs in water or sediment input, when local conditions (such as riparian vegetation) change, or during and after channel incision (see also section A.7). Project teams need to consider these potential changes when assessing site and watershed risks and potential channel responses to the crossing (chapter 4).

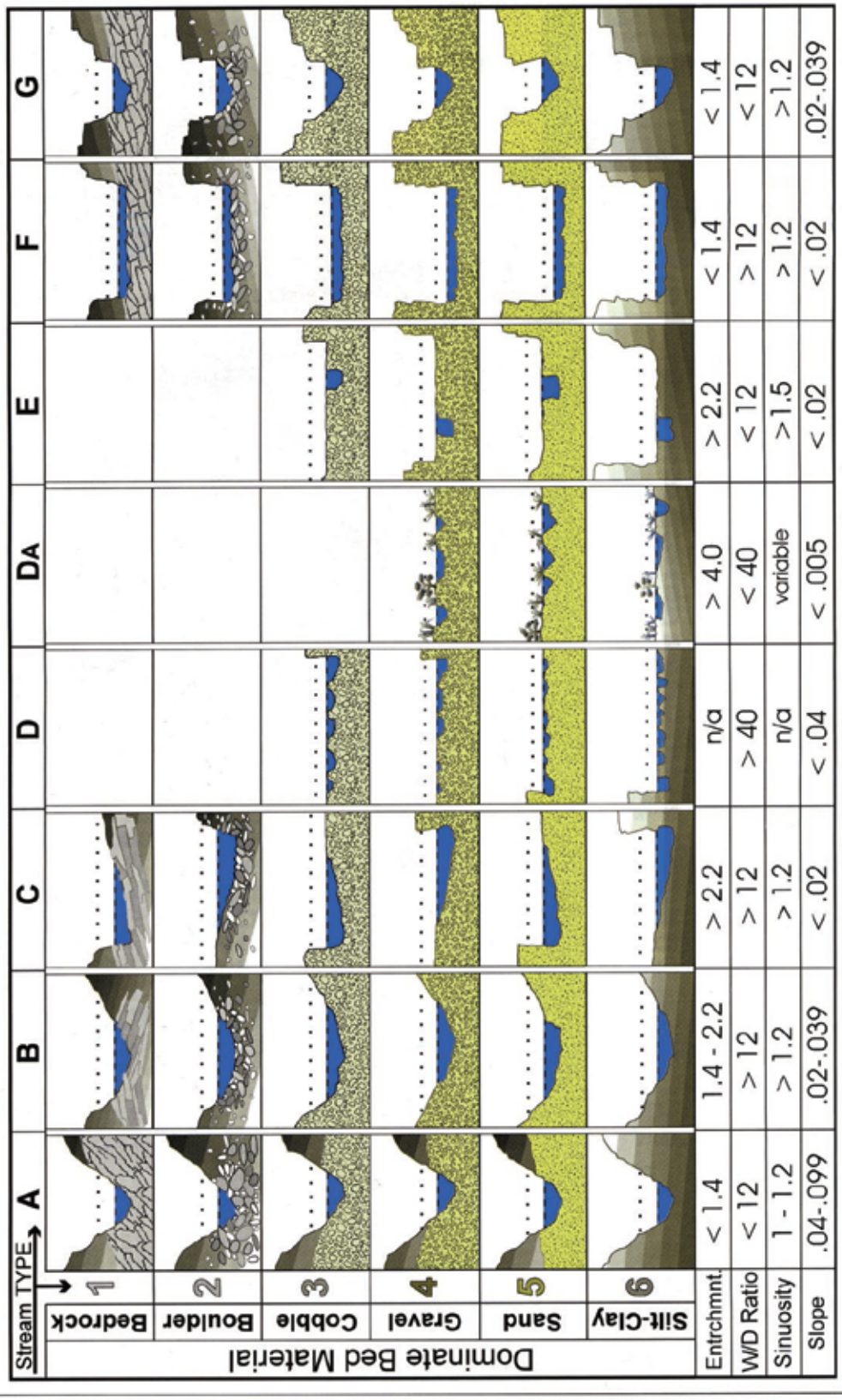

Figure A.25—Channel types defined by Rosgen (1994). Used by permission.

A.7 UNSTABLE CHANNELS

A.7.1 Inherently Unstable Landforms and Channel Types

Some channel types are inherently unstable; that is, they are naturally subject to rapid changes in channel location, dimension, or slope. Certain landforms also are naturally unstable, and the channels that drain them are subject to episodic (and sometimes unpredictable) changes, which may destabilize them for a period of time. Like streams affected by unusually large floods or other events, recovery can take years or decades, depending on channel resilience after disturbance.

Braided streams [figure A.12(b)] are difficult sites for road-crossing structures, because they have high sediment loads that can plug structures and because individual channels can change location during floods. These streams are best avoided as crossing sites. (However, where the braided channel as a whole is confined and unable to shift location, a team might consider an open structure that crosses the entire channel.)

Active alluvial fans are located where a **confined channel** emerges into a wider valley, spreads out, and deposits sediment (figure A.26). During high debris-laden flows, so much sediment may be deposited that it blocks the major channel; consequently, flow jumps to a new location and forms a new channel. Several channels may be active at once. Crossing structures can be isolated when the channel changes location, and structures can also exacerbate the likelihood of channel shift if they plug frequently. Even where a fan does not appear to be active, it still constitutes a risky location for structures of any kind, because a rare flood/debris flow event can result in catastrophic sediment deposition.

Figure A.26—Alluvial fan bordering the Noatak River, Alaska. Photo: USFWS Alaska Image Library.

For all of these reasons, avoid placing new crossings on fans and braided channels.

Arroyos are incised or incising channels, usually with ephemeral flow regimes. They are found in semiarid and arid environments where high flows are often extremely **flashy**. Little or no riparian vegetation may border an arroyo channel, and the banks can be highly erodible. During high flows, the channel may carry large amounts of sediment and debris, and may be prone to shifting location. Some of these channels are braided, and the problems they pose for crossings of any kind are the same as those for braided streams.

On or near *slopes prone to mass wasting*, large erosional events can be expected to cause significant changes in the downstream channel (figure A.27). Even stable transport reaches, if they are immediately downstream of a slope prone to landslides, **earthflow**, gullying, or severe bank erosion, can be expected to undergo flow events where sediment loads are high enough to cause a culvert to plug. In steep terrain, where many crossings exist on a single channel, the domino effect of a single crossing failure can cascade downstream and actually cause a debris flow. Unconsolidated fine-grained glacial deposits are especially subject to rapid surface erosion and slumping, and we can expect channels draining them to experience large bed-elevation changes from both headcutting and episodic sediment inputs from surrounding slopes. Sites located at the transition point between a transport and response reach are particularly vulnerable to sediment deposition during large erosional events.

*Figure A.27—Stream eroding the toe of a **slump** is likely to transport large volumes of sediment that may plug downstream culverts.*

Unconfined meandering streams on wide flood plains are prone to channel shift by meander migration, as described earlier. Such streams are nonetheless considered to be in equilibrium as long as they maintain consistent channel dimensions and slope. In many cases, their rate of meander migration may be slow relative to the life of the structure. However, land development and management frequently accelerate this natural process of channel migration, a consideration to bear in mind before investing in a crossing structure. A shifting channel can move so that it no longer approaches the crossing perpendicularly—and a sharp angle of approach tends to increase sediment deposition above the inlet by forcing the water to turn. Likewise, a sharp angle increases the potential for debris blockage and therefore overtopping failure.

An additional effect of crossings on such channels is that their approaches are often on roadfill raised above seasonally wet or inundated flood plains. Blocking the flood plain obstructs to some degree the erosional and depositional processes that construct and maintain flood plains and the diverse habitats they offer. The roadfill may obstruct **side channels** that are essential habitats and migration corridors for fish. Forcing the **overbank flows** to concentrate in the structure can also cause scour through or downstream of the crossing.

A.7.2 Channels Responding to Disturbances

Streams that have been destabilized by changes in vegetative cover, **base level control**, climatic events, earthquake, etc., can undergo major changes in elevation, channel width and depth, and/or other characteristics before returning to a quasi-equilibrium state. The changes often occur in a predictable sequence, represented conceptually as channel-evolution models.

One classic channel-evolution model is especially important to understand during work on stream crossings. This model (Schumm, Harvey, and Watson 1984) describes channel incision that could be due either to channelization (channel straightening and/or constriction), base-level lowering, or increases in runoff. In this model (figure A.28), an unentrenched stream downcuts, banks become unstable and erode, and the channel widens until a new flood plain and/or unentrenched stream system establishes at the lower elevation.

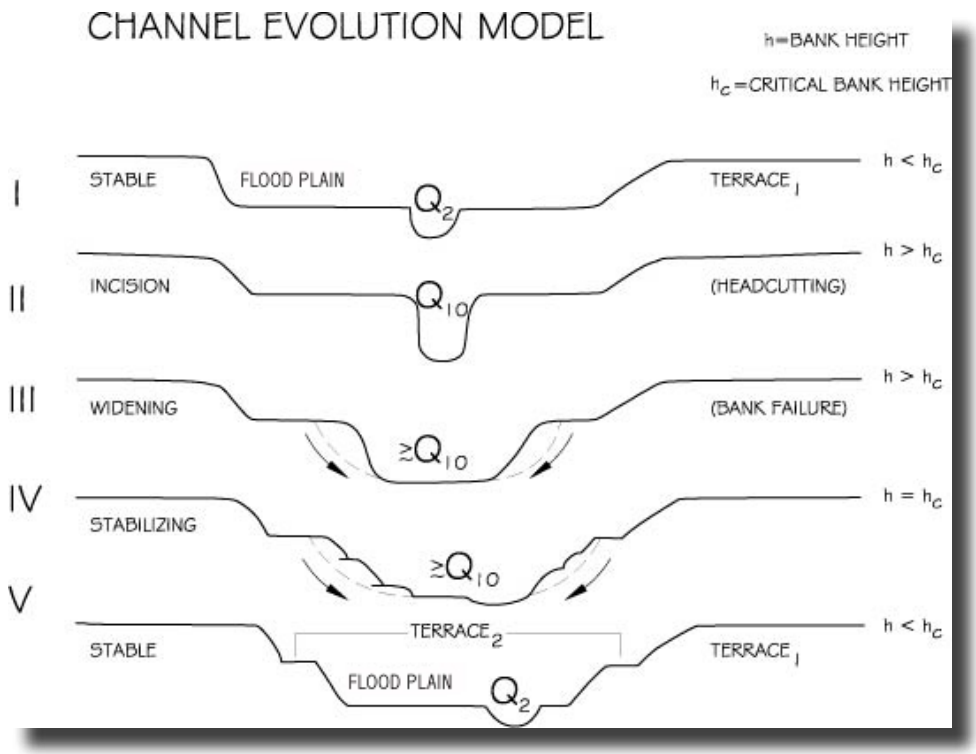

Figure A.28—Channel evolution model shows how a channel evolves from active incision to stabilization (Castro 2003).

Channel incision progresses upstream unless the headcut is checked by a natural- or engineered-grade control, such as a road-stream crossing structure. Downstream reaches are at a later stage in the evolutionary sequence than upstream ones, and can therefore be useful for predicting the magnitude of changes to be expected upstream. This evolution can take years, decades, or centuries, depending on the resistance of the materials being eroded, and can affect entire drainage basins. Tributaries far removed from the original cause of incision can be affected as headcuts move up the main channel and lower the base level for tributaries. The stages are more clearly distinguishable in streams with cohesive bed and banks where actively eroding features (eroding banks, nickpoints) hold steep slopes. In **granular materials** (figure A.3), the features are less easily distinguished because they are less abrupt (Federal Interagency Stream Restoration Working Group 1998). Where channel segments upstream and downstream of a crossing have very different characteristics, understanding whether those differences are due to channel evolution or some other cause is critical to a stream-simulation design.

If it is not possible to avoid an unstable channel by relocating the crossing, predict the direction of future change, and design the structure to accommodate it. Doing all of this well requires a background and experience in fluvial geomorphology and **river dynamics**.