9.36 Geomorphic Classification of Rivers

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9.36.1 Introduction

Over the last several decades, environmental legislation and a growing awareness of historical human disturbance to rivers worldwide (Schumm, 1977; Collins et al., 2003; Surian and Rinaldi, 2003; Nilsson et al., 2003; Chin, 2006; Walter and Merritts, 2008) have fostered unprecedented collaboration among scientists, land managers, and stakeholders to better understand, monitor, and restore riverine ecosystems. The additional concern over climate change (IPCC, 2007) and the need for securing supplies of clean water for the burgeoning world population (Revenga et al., 2000) have further spurred collaborative watershed analyses. In geomorphology, much of this effort focuses on assessing the effects of natural and anthropogenic disturbances of the landscape in order to understand past response, determine current conditions, and predict likely responses to future disturbance, including land management and restoration activities (e.g., Kondolf et al., 2001; Brierley and Fryirs, 2005; Simon et al., 2011). Channel classification is one tool that is used to address these needs. This chapter reviews the purposes of geomorphic channel classification, the different types of classifications that have been developed, and their use, compatibility, and popularity, and concludes with a look at future needs and directions for channel classification.

9.36.2 Purpose of Classification

A basic tenet in geomorphology is that ‘form implies process’. As such, numerous geomorphic classifications have been developed for landscapes (Davis, 1899), hillslopes (Varnes, 1958), and rivers (Section 9.36.3). The form–process paradigm is a potentially powerful tool for conducting quantitative geomorphic investigations. However, many river classifications are largely descriptive, lacking a clear articulation of the associated processes (e.g., Goodwin, 1999), particularly if form is not uniquely related to a single process or if it can arise through multiple pathways (i.e., equifinality). To address this concern, it is important to distinguish whether a river classification is descriptive or process based. The issue is not whether a given classification is quantitative; descriptive classifications are commonly quantitative, involving the measurement of various physical parameters, whereas process-based classifications may be conceptual (i.e., qualitative). Rather, the issue is whether the classification is founded on mechanistic arguments and explanation of the physical processes associated with a given channel morphology.

Although descriptive classifications lack a process-based foundation, they can nevertheless be valuable. For example, descriptive river classifications are useful inventory and pattern-recognition tools that can be developed into a GIS layer that may subsequently stimulate research or management questions. However, without a process-based underpinning, descriptive river classifications are not defensible means for assessing landscape condition or for making management decisions.
decisions in and of themselves. Consequently, the value that can be gained from a channel classification depends, in part, on a thorough understanding of the classification and recognition of whether it is descriptive or process based.

Process-based channel classifications have several potential purposes. They can be used to simplify the complex continuum of processes and conditions within a landscape by identifying places that function in a similar manner. This reduces the amount of time and effort needed to characterize a basin because such classification allows stratified sampling; a small number of samples can be applied to similar-functioning landscape units throughout a basin without having to resort to more intensive, grid, or random sampling of the entire river network (e.g., Smartt and Grainger, 1974; Stevens and Olsen, 2004).

More importantly, a process-based understanding allows one to develop conceptual models for interpreting and assessing current conditions and to develop hypotheses regarding past/future responses to landscape disturbance. Combined with digital elevation models (DEMs), process-based classification can also be used to interpret spatial and temporal patterns within the landscape; one can assess how different parts of the landscape are linked to one another and influenced by each other, allowing the development of a holistic understanding of the landscape and its processes. As such, process-based classification can provide a framework for hypothesis testing and offers much more than just an inventory tool or a GIS layer.

Beyond the goal of classifying form and process, numerous purposes have been stated for channel classifications, such as standardizing communication, relating physical and biological processes, assessing and monitoring ecosystem condition, predicting response to natural/anthropogenic disturbance, and designing stream restoration (e.g., Hawkes, 1975; Lotspeich and Platt, 1982; Frissell et al., 1986; Mosley, 1987; Kellerhals and Church, 1989; Naiman et al., 1992; Paustian et al., 1992; Rosgen, 1994; Kondolf, 1995; FPC, 1996a,b; Montgomery and Buffington, 1997; Naiman, 1998; Kondolf et al., 2003; Brierley and Fryirs, 2005). These different purposes have resulted in a multitude of proposed classifications.

### 9.36.3 Types of Channel Classification

Numerous geomorphic classifications have been developed for rivers over the past century, with early approaches focusing on the genetic structure and evolution of rivers as influenced by tectonics and geologic structure of the landscape (e.g., Powell, 1875; Gilbert, 1877; Davis, 1889, 1890, 1899). Furthermore, many of the classifications that have been developed are inherently regional, imposing order on different suites of river types and associated land forms to address regional questions. The various approaches for channel classification are reviewed here, expanding on a previous review by Montgomery and Buffington (1998). This review summarizes benchmark and recent channel classification efforts in geomorphology, but is by no means exhaustive, with additional reviews presented elsewhere (e.g., Mosley, 1987; Kellerhals and Church, 1989; Naiman et al., 1992; Rosgen, 1994; Kondolf, 1995; Thorne, 1997; Naiman, 1998; Newson et al., 1998; Goodwin, 1999; Wohl, 2000; Juracek and Fitzpatrick, 2003; Kondolf et al., 2003; Downs and Gregory, 2004; Simon et al., 2007; Milner, 2010).

#### 9.36.3.1 Stream Order

Stream order (Horton, 1945; Strahler, 1957) is perhaps the most widely used descriptive classification for rivers (Figure 1). In this approach, the river network is divided into links between network nodes (channel heads and tributary junctions), and links are numbered according to their position in the network: First-order channels are those at the tips of the river network (channel head to first tributary junction), second-order channels occur below the confluence of two first-order channels, and so on down through the river network. Stream order correlates with link length, drainage area, slope, and channel size, providing a relative sense of physical conditions, but is sensitive to how the river network is defined. For example, the extent of the river network and consequent stream ordering may differ for (1) blue lines shown on topographic maps, (2) synthetic stream networks based on area–slope criteria, and (3) field observations of the channel network (Morisawa, 1957; Montgomery and Foufoula-Georgiou, 1993). Moreover, not all channels of a given order behave similarly. For example, reach-scale morphology and the associated processes that occur in first-order channels will depend on basin topography (i.e., channel slope and confinement) and physiography (the supply of water and sediment to the channel), such that first-order channels in mountain basins may be very different from those of plateaus, coastal plains, or glacial lowlands (e.g., Paustian et al., 1992).

Hence, stream order provides little information about stream morphology and processes; rather, it classifies the river network structure. Nevertheless, it is a useful communication tool for describing relative stream size and location within a basin, as well as the overall basin size in terms of maximum stream.
order. Structural classifications have also been developed for nested scales of subbasins (hydrologic units) within watersheds (Seaber et al., 1987; Omernik, 2003), but as with stream order, they offer little inherent insight regarding geomorphic processes.

9.36.3.2 Process Domains

Schumm (1977) divided rivers into sediment production, transfer, and deposition zones, providing a process-based view of sediment movement through river networks over geologic time (Figure 2(a)). Building from this approach and from work by Paustian et al. (1992), Montgomery and Buffington (1997) classified mountain rivers into source, transport, and response reaches. Montgomery (1999) subsequently developed the notion of process domains as an alternative to the river continuum concept (Vannote et al., 1980). Process domains are portions of the river network characterized by specific suites of interrelated disturbance processes, channel morphologies, and aquatic habitats, and at a general level roughly correspond with source, transport, and response reaches in mountain basins (Figure 2(b); Montgomery, 1999). Process domains are implicit in other channel classifications (e.g., Cupp, 1989; Nanson and Croke, 1992; Paustian et al., 1992; Rosgen, 1994, 1996b; Brierley and Fryirs, 2005), but are recognized mainly from a descriptive point of view in terms of identifying land types (e.g., headwaters, glaciated terrain, estuaries), with little specification of the associated processes and their control on channel morphology. Classification of rivers using process domains is a coarse filter (typically lumping several channel types), but it identifies fundamental geomorphic units within the landscape that structure general river behavior and associated aquatic habitats. Hence, it is a valuable tool for land management and conservation efforts.

9.36.3.3 Channel Pattern

Most river classifications that have been developed involve classification of channel pattern (i.e., planform geometry, such as straight, meandering, or braided), which can be broadly divided into two approaches: (1) quantitative relationships (which may be either empirical or theoretical) and (2) conceptual frameworks.

Quantitative relationships – Lane (1957) and Leopold and Wolman (1957) observed that for a given discharge, braided channels occur on steeper slopes than meandering rivers (Figure 3). Both studies recognized a continuum of channel pattern, but Leopold and Wolman (1957) proposed a threshold between meandering and braided rivers (Figure 3), providing a means for predicting changes in channel pattern as a function of altered discharge or channel slope. Both studies also recognized that additional factors affect channel pattern, such as grain size, sediment load, riparian vegetation, channel roughness, width, and depth. Subsequent investigators modified the Figure 3 framework to include grain size (which alters the location of the boundary between different channel patterns) and to distinguish anastomosing and wandering channels (Henderson, 1963; Osterkamp, 1978; Bray, 1982; Kellerhals, 1982; Ferguson, 1987; Desloges and Church, 1989; Kellerhals and Church, 1989; Knighton and Nanson, 1993; Church, 1992, 2002); wandering rivers are transitional between meandering and braided morphologies (Desloges and Church, 1989), whereas anastomosed rivers are multi-thread channels separated by islands cut from the floodplain (Knighton and Nanson, 1993) and are distinguished from braided channels that are formed by bar deposition and subsequent in-channel flow splitting (e.g., Leopold and Wolman, 1957; Bridge, 1993). A variety of other factors have also been proposed for discriminating channel pattern, such as valley slope rather than stream slope, stream power, width-to-depth ratio, excess shear velocity or excess Shields stress (ratio of applied shear velocity or Shields stress to the critical value for incipient motion of the streambed), Froude number, bed load supply relative to transport capacity, and bank strength (e.g., Schumm and Khan, 1972; Schumm et al., 1972; Ikeda, 1973, 1975, 1989; Parker, 1976; Carson, 1984a,b,c; van den Berg, 1995; Millar, 2000; Buffington et al., 2003; Dade, 2000; also see reviews by Bridge, 1993 and Thorne, 1997).

More recently, Beechie et al. (2006) developed a GIS model for predicting channel pattern as a function of slope and discharge, demonstrating that unstable and laterally migrating channels (i.e., braided and meandering patterns) have correspondingly younger and more dynamic floodplain surfaces than stable, straight channels. This finding has relevance for ecosystem management because channel and floodplain dynamics affect the diversity and quality of riverine habitats for aquatic, riparian, and hyporheic organisms (e.g., Malard et al., 2002; Poole et al., 2004; Stanford, 2006; Buffington and Tonina, 2009). For example, Beechie et al. (2006) found that the age diversity of floodplain vegetation is maximized at intermediate disturbance frequencies, following the classic intermediate disturbance hypothesis recognized by ecologists (Connell, 1978). Beechie et al. (2006) also showed that a threshold channel size is required for lateral migration (bankfull widths of 15–20 m), below which meandering and braided morphologies do not occur. The observed threshold was attributed to bank reinforcement by riparian vegetation and the depth of the local rooting zone, with lateral migration requiring channels that are deep enough to erode below the root mat (Beechie et al., 2006). These findings highlight the control of bank erosion/narrowing on channel pattern and the modulating effect of vegetation. Processes responsible for bank erosion include fluvial entrainment of bank material, mass wasting (frequently triggered by fluvial undercutting), and biogenic activity (e.g., tree throw and animal trampling), whereas channel narrowing may occur through abandonment of channel branches, vegetation encroachment during periods of reduced flow, and bank accretion due to lateral siltation and bar growth (see reviews by ASCE, 1998a, b; Mosselman, 1998; Piegay et al., 2005; Rinaldi and Darby, 2008). Bank erodibility is controlled by factors such as the stability of cohesionless bank material (a function of grain size, friction angle, and bank slope), the silt and clay content of the bank (physical cohesion), the presence of bank vegetation (root strength/biotic cohesion and roughness), the bank height (risk of mass wasting), and bank armor by extrinsic factors (e.g., bedrock outcrops, boulders, tree roots, wood debris).

The above approaches, patterned after Lane (1957) and Leopold and Wolman (1957), allow quantitative prediction of channel pattern and assessment of potential changes that might result from a given disturbance, but they are largely...
empirical and apply to a subset of channels within a given basin (i.e., floodplain alluvial rivers). Process-based explanations for hydraulic and sedimentary controls on channel pattern have been presented (Leopold and Wolman, 1957; Parker, 1976; Osterkamp, 1978; Carson, 1984a, b, c; Ferguson, 1987; Bridge, 1993; Knighton and Nanson, 1993; Beechie et al., 2006), but the slope–discharge framework for classifying channel pattern remains empirical and descriptive.

**Conceptual frameworks** – Schumm’s (1960, 1963b, 1968, 1971a, b, 1977) work on sand- and gravel-bed rivers in the Great Plains of the western U.S. emphasized that channel pattern and stability are strongly influenced by the imposed load of the river (size of sediment and mode of transport) and the silt-clay content of the floodplain (providing cohesion necessary for the development of river meandering). Based on these observations, Schumm (1963a, 1977, 1981, 1985) proposed a conceptual framework for classifying alluvial rivers that related channel pattern and stability to (1) the silt-clay content of the banks, (2) the mode of sediment transport (suspended load, mixed load, bed load), (3) the ratio of bed load to total load (a function of stream power, sediment size, and supply), and (4) the slope and width-to-depth ratio of the channel (Figure 4). Subsequent studies noted the role of riparian vegetation and root strength in affecting bank cohesion, channel width, and channel pattern (Schumm, 1968; Smith, 1976; Charlton et al., 1978; Hey and Thorne, 1986; Andrews, 1984; Millar and Quick, 1993; Trimble, 1997; Buffington and Montgomery, 1999b; Millar, 2000; Micheli and Kirchner, 2002a,b; Simon and Collison, 2002; Hession et al., 2003; Montgomery et al., 2003; Micheli et al., 2004; Allmendinger et al., 2005; Beechie et al., 2006; Eaton, 2006; Eaton and Church, 2007; Eaton et al., 2010). Because the total transport in most floodplain rivers is dominated by suspended load and wash load, Schumm’s three types of sediment transport (suspended load, mixed load, bed load) should not be considered as dominant modes of transport. Rather, they are descriptive terms indicating changes in the relative proportion of bed load transport and its importance in shaping channel and floodplain morphology. For example, bed load transport is highest in “bed load channels,” but nevertheless represents a small percentage of the total load (11% or more, Figure 4).

Schumm’s (1963a, 1977, 1981, 1985) classification has since been refined to include a broader range of channel types (Mollard, 1973; Brice, 1982), including steeper morphologies present in mountain rivers (Church, 1992, 2006; Figure 5). A similar framework has been used to array Montgomery and Buffington (1997) channel types, additionally identifying process domains for the effects of vegetation and debris flows, and identifying different valley and substrate types (alluvial, bedrock, colluvial) (Buffington et al., 2003; Buffington, 2012) (Figure 6). Channel pattern is also a primary discriminator in the classification schemes developed by Paustian et al. (1992), Rosgen (1994,
1996b), and Brierley and Fryirs (2005). The above approaches derived from Schumm (1963a, 1977, 1981, 1985) provide powerful conceptual models for understanding basin controls on channel morphology, as well as likely response to perturbations in discharge and sediment supply, but are mainly qualitative and, in most cases, have been developed for large floodplain rivers. Furthermore, these approaches are typically descriptive (associating physical conditions with channel morphology, but not explaining the underlying processes) or involve a mixture of descriptive and process-based interpretations.

### 9.36.3.4 Channel–Floodplain Interactions

Interactions between the river and its surrounding floodplain can exert strong controls on physical processes, morphology, response potential, and the quality and diversity of habitat for both the river and its floodplain. Several classifications explicitly incorporate channel–floodplain interaction. In one of the earliest approaches, Melton (1936) synthesized work from prior studies (Gilbert, 1877; Powell, 1896; Emmons, 1906; Davis, 1913; Matthes, 1934) to classify channels based on whether their floodplains were formed by meandering (lateral accretion), overbank (vertical accretion), or braiding processes. Nanson and Croke’s (1992) classification of floodplain rivers similarly recognizes that characteristic floodplain morphologies reflect specific styles of fluvial processes (Figure 7) and highlights genetic (i.e., evolutionary) sequences of channel and floodplain morphology in response to environmental perturbations (changes in stream flow and sediment supply). A similar genetic coupling of river and floodplain processes is also used in the river styles classification (Brierley and Fryirs, 2005), which further recognizes that channel–floodplain interactions may be modulated by extrinsic factors (e.g., bedrock outcrops, glacial moraines, relict terraces) in partly confined rivers (a transitional morphology between confined and unconfined river valleys (Brierley and Fryirs, 2005; Jain et al., 2008; Fryirs and Brierley, 2010), sometimes referred to as semialluvial (e.g., Brice, 1982)). Channel–floodplain interactions are also implicit in classifications of channel pattern (Section 9.36.3.3), but may not be articulated.

Because channel–floodplain approaches focus on overbank flows that are capable of eroding banks and doing work on the floodplain, they tend to describe longer term processes and recognize that channel and floodplain conditions represent a distribution of flood events, with smaller floods modifying and sculpting the morphologic legacy of larger floods (Melton, 1936; Stevens et al., 1975). Furthermore, different scales of bedform and floodplain features may occur, representing a
hierarchy of flow and sediment transport events (Jackson, 1975; Lewin, 1978; Church and Jones, 1982). Alternatively, channel processes and floodplain features may be out of phase, with floodplain features representing climatic or geomorphic legacies, rather than current channel processes. This broader spatial and temporal view contrasts with other in-channel classifications that focus on single flows, such as bankfull, and concepts of dominant discharge (e.g., Wolman and Miller, 1960; Carling, 1988b).

Several descriptive classifications of channel and floodplain features have also been developed using interpretation of aerial photographs (e.g., Mollard, 1973; Brice, 1975, 1982; Kellerhals et al., 1976). These approaches were designed to determine the stability of large alluvial rivers for use in documenting and predicting response to engineering projects (e.g., bridges, floodplain development, dams, and flow diversion). More recent approaches using GIS have also been developed, as discussed above (Beechie et al., 2006).

Many channel–floodplain classifications are inherently process based, but they are limited to unconfined, or partly confined, alluvial rivers. Nevertheless, their explicit inclusion of channel–floodplain interactions allows the development of stronger linkages between fluvial processes, riparian ecosystems, and human uses of floodplain corridors.

9.36.3.5 Bed Material and Mobility

Substrate – Gilbert (1877, 1914, 1917) presented a process-based division of rivers based on substrate, distinguishing alluvial versus bedrock channels. He proposed that bedrock rivers occur where transport capacity exceeds sediment supply, and conversely, alluvial rivers occur where supply matches or exceeds capacity. This hypothesis was supported in subsequent studies of mountain rivers (Montgomery et al., 1996; Massong and Montgomery, 2000). However, bedrock channels can also occur in streams that have been recently scoured by debris flows (e.g., Benda, 1990) and, therefore, are not always fluvial features. Although process based, Gilbert’s (1877, 1914, 1917) division of rivers is too broad for most land management applications because it does not account for the diversity of alluvial channel types found in most river basins.

Bed mobility – A variety of process-based classifications have been developed based on bed mobility. For example, synthesizing results from prior studies, Henderson (1963) distinguished two types of alluvial rivers based on substrate mobility: Live-bed channels that transport sediment at most discharges (i.e., sand- and silt-bed rivers) and threshold channels that exhibit a near-bankfull threshold for bed mobility (i.e., gravel- and cobble-bed rivers) (also see discussion by Simons, 1963). Later work by Church (2002, 2006) proposed a similar framework, referring to live-bed channels as “labile,” but further recognizing a transitional bed mobility class between threshold and live-bed channels. The dichotomy between live-bed and threshold channels is supported by numerous studies. For example, data compiled from a variety of sources clearly demonstrate relative differences in bankfull mobility between fine-grained (silt, sand) and coarse-grained (gravel, cobble) rivers when plotted on Shields (1936) diagrams (Dade and Friend, 1998; Garcia, 2000; Parker et al., 2003; Church, 2006; Bunte et al., 2010); gravel-bed rivers have a near-bankfull threshold for mobilizing the median grain size ($D_{50}$), while the bankfull shear stress in sand-bed rivers can be more than 100 times greater than the critical shear stress
indicating a high degree of transport at bankfull stage in sand-bed rivers. Field studies also show that gravel-bed rivers have grain sizes similar to what is predicted for a bankfull-threshold channel, whereas sand-bed rivers have sizes much smaller than the bankfull competence (Buffington and Montgomery, 1999b), further supporting the above differences in mobility. The notion that the streambed has a near-bankfull threshold for mobility is a useful first-order approximation for some gravel- and cobble-bed rivers (Leopold et al., 1964; Li et al., 1976; Parker, 1978; Andrews, 1984; Buffington and Montgomery, 1999b; Bunte et al., 2010; Buffington, 2012), but should be recognized as a simplifying construct, even in those environments. For example, it applies mainly to Phase Two transport of the coarser fraction of the bed material, not Phase One transport of the finer fraction (sensu Jackson and Beschta, 1982; Barry, 2007). Moreover, at the bankfull stage, the mobility of the median grain size systematically increases with channel slope in coarse-grained rivers (Buffington, 2012), suggesting mobility at stages less than bankfull in steeper channels or the need to correct boundary shear stress for systematic increases in roughness with greater slope (i.e., smaller values of both the width-to-depth ratio and relative submergence; Buffington and Montgomery, 2001; Buffington, 2012). Mobility in gravel-bed rivers also increases with sediment supply (Dietrich et al., 1989; Lisle, 2005), producing a systematic departure from bankfull-threshold conditions (Buffington and Montgomery, 1999c). The above observations indicate that care should be exercised in applying the bankfull-threshold concept, as its application is limited to a certain class of channels (gravel- and cobble-bed rivers). For example, Kaufmann et al. (2008, 2009) recently proposed a technique for regional assessments of sediment loading based on comparing observed grain sizes with those predicted for bankfull-threshold conditions, expanding on prior work developed for gravel-bed channels (Dietrich et al., 1996; Buffington and Montgomery, 1999c; Kappesser, 2002). While Kaufmann et al.’s (2008, 2009) technique is viable in bankfull-threshold conditions, it becomes less effective as the channel mobility increases beyond bankfull thresholds due to the systematic increases in channel roughness with greater slope.

Figure 7  Example river–floodplain types from the Nanson and Croke (1992) classification, showing medium-energy, noncohesive environments. ω is the specific stream power. Reproduced from Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology 4(6), 459–486.
channels (gravel- and cobble-bed rivers; pool-riffle and plane-
bed morphologies), it yields incorrect predictions of grain size
and sediment loading in both sand- and boulder-bed rivers
(dune-ripple, step-pool, and cascade morphologies) because
bed mobility in those channels does not have a bankfull
threshold (Bunte et al., 2010; Buffington, 2012).

Although Henderson’s (1963) division of rivers into
live-bed and threshold channels is too broad for most classi-
fication applications, Church (2002; 2006) offers a finer scale
classification of bed mobility (defined in terms of the bankfull
Shields stress) that he relates to sediment size, transport re-
gime, channel morphology, and channel stability, elaborating
on Schumm’s (1963a, 1977, 1981, 1985) classification and
method identifies six channel types (Table 1) that are com-
parable to the primary reach-scale morphologies used in other
classifications (e.g., Rosgen, 1994, 1996b; Montgomery

Bed mobility of headwater channels – Whiting and Bradley
(1993) proposed a bed mobility classification for headwater
rivers that is perhaps the most process-based classification
developed to date (Figure 8). Using a series of mechanistic
equations, their approach considers (1) the potential for
hillslope mass wasting adjacent to the channel, (2) the like-
lihood that such an event will enter the channel (a function of
channel width relative to valley width; i.e., confinement), (3)
whether the sediment pulse deposits in the channel or scours
it as a debris flow, (4) whether the channel has the com-
petence to move deposited material, and (5) the mode of
fluvial transport of this material (bed load vs. suspended
load). Channels are classified alpha-numerically according
to the risk of disturbance and response potential using the
above matrix of factors (Figure 8). The Whiting and Bradley
(1993) classification is appealing because it is strongly
process based and, therefore, more defensible than descriptive
approaches, but its application is limited to headwater
channels.

9.36.3.6 Channel Units

Channel units are subreach-scale morphologic units (e.g.,
different types of pools, bars, steps, ripples) that form
the building blocks of larger reach-scale morphologies, such as
step-pool or pool-riffle channels. Bisson et al. (1982) de-
volved a detailed, descriptive classification of channel units
in Pacific Northwest streams to quantify different types of
physical habitat for salmonids. Subsequent work by others
examined the hydraulics of channel units (Sullivan, 1986;
Buffington et al., 2002), their response to timber harvest and
removal of large woody debris (LWD) (Wood-Smith and
Buffington, 1996), and the physical and biological charac-
teristics of channel units in steep streams (e.g., Grant et al., 1990;
Wohl et al., 1997; Zimmermann and Church, 2001; Halwas
and Church, 2002; Gomi et al., 2003; Halwas et al., 2005). In
addition, hierarchical classifications of channel units and their
hydraulics have been developed (Sullivan, 1986; Bryant et al.,
1992; Church, 1992; Hawkins et al., 1993; Wood-Smith and
Buffington, 1996), but these approaches mainly use qualita-
tive descriptions of flow (fast vs. slow water) and water-surface
roughness (“turbulent” vs. “nonturbulent”). Bisson et al.
(2006) recommend that the latter terms be replaced by
“rough” vs. “smooth” flow, since most river flows are hy-
draulically turbulent, sensu stricto. Most channel-unit classifi-
cations focus on the wetted channel, generally excluding bars,
but a detailed classification of bar types and associated phys-
ical processes has been developed by Church and Jones
(1982).

Channel unit classification continues to be one of the most
popular approaches for describing physical habitat in fisheries
studies (e.g., Bisson et al., 1988; Bryant et al., 1992; Hawkins
et al., 1997; Inoue et al., 1997; Inoue and Nakano, 1999;
Beechie et al., 2005), and it has been argued that channel units
are the most relevant scale for relating fluvial processes to
salmonid spawning habitat (Moir et al., 2009). However,
channel unit classification is too detailed for most basin-scale
applications and channel units are not uniquely correlated
with reach-scale morphologies, which arguably have more
gemorphic relevance for mechanistic investigation of
fluvial processes and basin function (Montgomery and
Buffington, 1997).

9.36.3.7 Hierarchical Classifications

Recent approaches for river classification focus on watershed
analysis related to land management and stream restoration,
using a hierarchical approach that nests successive scales of
physical and biological conditions and allows a more hol-
istic understanding of basin processes. One of the first
hierarchical approaches was presented by Frissell et al.
(1986), who identified multiple scales of river morphology
and associated aquatic habitat (Figure 9), and described the
physical processes controlling each spatial scale. Paustian
et al. (1992) subsequently presented a hierarchical channel
classification system for mountain basins in southeastern
Alaska that emphasized land type, sediment movement (i.e.,
Schumm’s (1977) erosion, transport, and deposition zones),
aquatic habitat, and sensitivity to landscape disturbance.
Their classification identifies nine process domains and as-
associated channel types (estuarine, floodplain, palustrine, al-
luvial fan, glacial outwash, large contained (i.e., confined),
moderate-gradient contained, moderate-gradient mixed con-
trol, and high-gradient contained channels), with channels
visually classified and subdivided into 38 subgroups. Coarse-
level classification is initially carried out from aerial photo-
graphs, with subsequent field validation and refinement.
Overall, the approach is a mixture of descriptive measure-
ments and process-based interpretations. Paustian et al’s
(1992) classification is tailored to the specific landscape and
management issues of southeastern Alaska, which makes it
less likely to be used elsewhere, but highlights the fact that
successful application of a given channel classification
scheme will likely entail user modification to suit local
landscapes and management/research goals. For example, the
Montgomery and Buffington (1997, 1998) classification has
recently been tested and tailored for use in both Scotland
(Addy, 2009; Milner, 2010) and Australia (Thompson et al.,

Similar to Paustian et al. (1992), a hierarchical channel
classification was developed to manage mountain rivers in
Classification of River Channels and Riverine Landscapes

<table>
<thead>
<tr>
<th>Channel Type/Bankfull Shields Stress ($\tau_{bf}$)</th>
<th>Sediment Type</th>
<th>Sediment Transport Regime</th>
<th>Channel Morphology</th>
<th>Channel Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jammed channel; $\tau_{bf} = 0.04$</td>
<td>Cobble- or boulder-sand</td>
<td>Low total transport, but subject to debris flows</td>
<td>Step-pool or boulder cascades; width typically a low multiple of largest boulder size; slope ($S$) &gt; 3</td>
<td>Stable for long periods of time with throughput of bed load finer than structure-forming clasts; subject to catastrophic destabilization in debris flows</td>
</tr>
<tr>
<td>Threshold channel; $\tau_{bf} = 0.04$</td>
<td>Cobble-gravel</td>
<td>Schumm’s “bed load” channels: low to moderate total transport, with a high percentage of bed load ($q_b/q_t$ typically &gt; 10%), but usually limited to partial mobility (sensu Wilcock and McArdell, 1993)</td>
<td>Cobble-gravel channel bed; single thread or wandering; highly structured bed; relatively steep; low sinuosity; width-to-depth ($w/h$) &gt; 20, except in headwater boulder channels</td>
<td>Relatively stable for extended periods, but subject to major floods causing lateral channel instability and avulsion; may exhibit serially reoccupied secondary channels</td>
</tr>
<tr>
<td>Threshold channel; $\tau_{bf}$ up to 0.15</td>
<td>Sandy-gravel to cobble-gravel</td>
<td>Moderate total transport, with a moderate to high percentage of bed load ($q_b/q_t$ typically 5–10%); partial transport to full mobility (sensu Wilcock and McArdell, 1993)</td>
<td>Gravel to sandy-gravel single thread to braided; limited, local bed structure; complex bar development by lateral accretion; moderately steep; low sinuosity; $w/h$ very high (&gt;40)</td>
<td>Subject to avulsion and frequent channel shifting; braid-form channels may be highly unstable, both laterally and vertically; single-thread channels subject to chute cutoffs at bends; deep scour possible at sharp bends</td>
</tr>
<tr>
<td>Transitional channel; $\tau_{bf} = 0.15–1.0$</td>
<td>Sand to fine gravel</td>
<td>Schumm’s “mixed load” channels: moderate to high total transport, with a moderate percentage of bed load ($q_b/q_t$ typically 3–5%); full mobility, with sandy bed forms</td>
<td>Mainly single-thread, irregularly sinuous to meandered; lateral/point bar development by lateral and vertical accretion; levees present; moderate gradient; sinuosity &lt; 2; $w/h$ &gt; 40</td>
<td>Single-thread channels, irregular lateral instability or progressive meanders; braided channels laterally unstable; degrading channels exhibit both scour &amp; channel widening</td>
</tr>
<tr>
<td>Labile channel; $\tau_{bf}$ &gt; 1.0</td>
<td>Sandy channel bed, fine sand to silt banks</td>
<td>Schumm’s “suspended load” channels: high total transport, with a low to moderate percentage of bed load ($q_b/q_t$ typically 1–3%); fully mobile, sand bed forms; sediment transport at most stages</td>
<td>Single thread, meandered with point bar development; significant levees; low gradient; sinuosity &gt; 1.5; $w/h$ &lt; 20; serpentine meanders with cutoffs</td>
<td>Single-thread, highly sinuous channel; loop progression and extension with cutoffs; anastomosis possible, islands are defined by vegetation; vertical accretion in the floodplain; vertical degradation in channel</td>
</tr>
<tr>
<td>Labile channel; $\tau_{bf}$ up to 10</td>
<td>Silt to sandy channel bed, silty to clay-silt banks</td>
<td>High total transport, almost exclusively suspended and wash load ($q_b/q_t$ typically &lt; 1%); minor bed form development</td>
<td>Single-thread or anastomosed channels; prominent levees; very low gradient; sinuosity &gt; 1.5; $w/h$ &lt; 15 in individual channels</td>
<td>Single-thread or anastomosed channels; common in deltas and inland basins; extensive wetlands and floodplain lakes; vertical accretion in floodplain; slow or no lateral movement of individual channels</td>
</tr>
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</table>

The bankfull Shields stress describes the relative mobility of the median grain size ($D_{50}$) at bankfull flow. $\tau_{bf} = \tau_{bf}/(\rho_b - \rho)D_{50}$, where $\tau_{bf}$ is the bankfull shear stress, $\rho_b$ and $\rho$ are the sediment and fluid densities, respectively, and $g$ is the gravitational acceleration. Where bankfull information was unavailable, other channel-forming flows were used by Church (2006) (e.g., the 2-year or the mean annual flood).

Descriptions modified from those given by Church (2006). Bed load percentages are estimated and can vary considerably with basin geology (e.g., lithologies that naturally produce high sand/silt loads), geomorphic history (e.g., occurrence of loess deposits, fine-grained glacial outwash, or volcanic ash) and land use (e.g., roads, mining, and agriculture). Channel morphologies shown in Figure 5.

coastal British Columbia (BC) in the 1990s (FPC, 1996a, b; Hogan et al., 1996). Although the BC and Alaskan approaches were contemporaneous and developed for similar landscapes and similar land management concerns (timber harvest, salmonid habitat), the two methods differ considerably. The BC classification focuses on channel condition and stability as a function of sediment supply across multiple spatial and temporal scales. Similar to the Alaskan approach, aerial photographs are used for coarse-level classification, but process domains are not explicitly identified. Instead, the river network is divided into roughly homogeneous reaches based on factors such as channel pattern, stream gradient, sediment supply, riparian vegetation, bed and bank material, channel confinement, tributary confluences, and coupling between the channel, hillslopes, and floodplain. Channel condition and response to management activities are assessed through more detailed classification and reach subdivision. For larger rivers (bankfull width > 20–30 m), the approach of Kellerhals et al. (1976) is used to further classify planform morphology in terms of channel pattern/sinuosity, frequency of channel islands, bar type, and lateral activity of the channel and floodplain as observed from aerial photographs (Figure 10). Changes in these features over space and time are used to assess the corresponding changes in sediment supply and channel stability using Schumm’s (1981, 1985) conceptual framework as modified by Church (1992, 2006; Figures 5 and 10). Small

Figure 8  Whiting and Bradley (1993) classification for headwater channels. (a) Assess the probability of mass wasting adjacent to the channel (side-slope failures AD-SD as defined in (b)) and whether the sediment input deposits within the channel (DD) or scours it as debris flow (DE). (b) Determines the risk of a side-slope mass wasting event entering the channel as a function of channel width relative to valley width. (c) Determines the mode of fluvial transport for material deposited in the channel by a mass wasting event. Redrafted from Whiting, P.J., Bradley, J.B., 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18, 603–612, with permission from Wiley.
and intermediate channels (bankfull width <20–30 m), which are difficult to observe on aerial photographs, are subdivided into three channel types (riffle-pool, cascade-pool, step-pool) based on Church’s (1992) classification and field measurements of channel slope, relative width (ratio of maximum grain size to bankfull width), and relative roughness (ratio of maximum grain size to bankfull flow depth) (Figure 11). The three channel types are further divided based on grain size (gravel, cobble, boulder) and the presence of LWD. Channel condition (stable, degrading, aggrading) is related to observed reach-scale morphology and lists of diagnostic indicators related to bank condition, LWD characteristics (size, function), and sedimentation (depositional topography and streamed bed texture (percentage of fine material and composition of textural patches; e.g., Buffington and Montgomery, 1999a, b, c; Dietrich et al., 2006). The BC methodology is more objective and more generalizable than Paustian et al.’s (1992) classification, but both were developed for a narrow range of mountain environments and similar sorts of disturbances, process domains, and management issues. A variety of such approaches have been developed throughout the western U.S., including Cupp’s (1989) valley segment classification for Washington State, and Lotspeich and Platt’s (1982) land type classification for western basins in North America.

One of the most widely used hierarchical channel classification systems was developed by Rosgen (1985, 1994, 1996b) for mountain basins. His approach involves four scales of analysis, ranging from broad-scale delineation of landform and valley type to small-scale measurements of physical processes (e.g., bed load transport, bank erosion) and biological inventories (vegetation, aquatic organisms). In practice, the classification is focused on delineating reach-scale morphologies and recognizes eight major stream types based on entrenchment (ratio of floodplain width to channel width), width-to-depth ratio, and sinuosity (Figure 12). Reach morphologies are further subdivided into 94 minor channel types as a function of slope and grain size. Additional stream types for different landscapes have also been proposed by subsequent investigators (e.g., Epstein, 2002). Channel characteristics in the Rosgen (1994, 1996b) approach are measured using classic field techniques adapted from Dunne and Leopold (1978). A primary goal of the Rosgen (1994, 1996b) method is “natural channel design” for use in stream restoration. More recently, the classification has been modified into a method for assessing sediment loading and channel condition as a function of hierarchical measurements and descriptive stream succession models (i.e., genetic/evolutionary response to environmental perturbations, Figure 13(a); Rosgen, 2006b). Similar genetic models are used by Nanson and Croke (1992) and Brierley and Fryirs (2005). The Rosgen (1996b, 2006b) methods are widely used by consultants and state and federal land managers (see the recent reviews by Johnson and Fecko, 2008; Wilkerson, 2008; Lave, 2008, 2009; Lave et al., 2010), but are largely descriptive and controversial (e.g., Gillian, 1996; Miller and Ritter, 1996; Rosgen, 1996a, 2003, 2006a, 2008, 2009; Kondolf, 1998; Ashmore, 1999; Doyle and Harbor, 2000; Kondolf et al., 2001, 2003; Juracek and Fitzpatrick, 2003; Malakoff, 2004; Smith and Prestegaard, 2005; Simon et al., 2007, 2008; Roper et al., 2008; Buffington et al., 2009; Lave, 2008, 2009; Lave et al., 2010).

Another widely used hierarchical channel classification for mountain basins was developed by Montgomery and Buffington (1997, 1998) based on synthesis of field observations and prior studies in the geomorphic literature, emphasizing process-based interpretations. Their approach recognizes nested physical scales ranging from geomorphic provinces to channel units, and identifies eight reach-scale morphologies based on visual identification (Table 2), with transitional morphologies...
also possible (Montgomery and Buffington, 1997; Gomi et al., 2003). Observed channel morphologies are hypothesized to represent stable conditions for imposed values of valley slope, discharge, and sediment supply (Montgomery and Buffington, 1997; Buffington et al., 2003). A critical aspect of their approach is identification of morphogenetic processes and response potential associated with each channel type. At larger spatial scales, channels are grouped into source, transport, and response reaches, as well as process domains for the dominance of fluvial versus debris-flow processes in controlling valley form and channel morphology (Figures 2(b) and 6; Montgomery and Brierley and Fryirs, 1997, 1998; Buffington et al., 2003; Buffington, 2012). Their approach also emphasizes that channel morphology and response potential are influenced by the degree of hillslope confinement, transport capacity relative to sediment supply, external forcing by LWD (Montgomery et al., 1995, 2003; Buffington et al., 2002), and geomorphic history (i.e., inherited landscape features) (Buffington et al., 2003; Montgomery and Bolton, 2003). Montgomery and Buffington (1997) channel types have also been related to salmonid habitat at local (Moir et al., 2002, 2004, 2006) and basin scales (Montgomery et al., 1999; Buffington et al., 2004; Addy, 2009), highlighting how geomorphic processes can structure the spatial distribution of available habitats and metapopulation dynamics (e.g., Frissell et al., 1986; Rieman and Dunham, 2000; Gresswell et al., 2006; Miller et al., 2008). The potential influence of reach-scale morphology on hyporheic flow and the quality and spatial distribution of hyporheic habitats have also been examined using this classification (Buffington and Tonina, 2009). Further work by other investigators has identified transitional morphologies associated with other process domains (e.g., glaciated headwaters [Brardinoni and Hassan, 2006, 2007] and glaciated lowlands [Moir et al., 2006; Addy, 2009; Milner, 2010], emphasizing the control of geomorphic history and lithology on channel morphology (Thompson et al., 2006, 2008). Regional comparisons also note that channel characteristics (e.g., slope, width-to-depth ratio) of the Montgomery and Brierley (1997) channel types show basin-specific variability (McDavitt, 2004; Wohl and Merritt, 2005; Flores et al., 2006; Thompson et al., 2006; Addy, 2009).

Another more recent hierarchical classification is the river styles framework (Brierley and Fryirs, 2000; 2005; Brierley et al., 2002; Fryirs, 2003; Fryirs and Brierley, 2000), which uses successional (evolutionary) models to assess channel condition and to inform restoration actions. It builds from the above hierarchical and channel pattern classifications, describing physical processes over catchment to channel-unit scales. In this approach, a “river style” is a process-based description of (1) land type and degree of confinement, (2) river character (channel pattern, bed material, and geomorphic units (type of valley fill, floodplain characteristics, channel-unit assemblages)), and (3) river behavior (description of associated fluvial processes) (Table 3). Application of the Brierley and Fryirs (2005) method involves dividing the channel network into a series of river styles, each of which is linked to descriptive models for cross-section and floodplain succession based on a mixture of process-based arguments and historical case studies of response (Figure 13(b)); the current state and response potential of each section of the river is evaluated within the context of these evolutionary models. Inherited landscapes, climatic legacies, historic human disturbance (altered discharge, sediment supply, riparian vegetation), and range of channel variability (both under natural conditions and human-induced ones) are also emphasized in the river styles successional models. The Brierley and Fryirs (2005) approach describes the behavior of each river style (Table 3), but lacks process-based descriptions for the morphogenesis of a given style (e.g., the flow and sediment transport processes that give rise to a given channel morphology). Instead, morphogenesis is described in terms of observed historical changes in basin characteristics (discharge, sediment supply, riparian vegetation) and the consequent morphologic response within a given channel succession sequence. Descriptive successional models such as these have a long history of use in geomorphology for documenting channel and floodplain changes over a variety of time scales (e.g., Davis, 1899; Schumm, 1977). The Brierley and Fryirs (2005) classification exemplifies a recent resurgence in using successional models, in this case for application to current land management problems (also see Piégay and Schumm, 2003; Rosgen, 2006b).

Hierarchical classifications have also been developed for managing riverine ecosystems (e.g., Maxwell et al., 1995; Habersack, 2000; Poole, 2002; Snelder and Biggs, 2002; Thorp et al., 2006). These approaches build from earlier work by Frissell et al. (1986), linking physical processes and ecological habitat across multiple, nested scales. Some organisms, such as salmonids, show a strong hierarchical structure, making such approaches particularly useful for those species. For example, Beechie et al. (2008) demonstrated hierarchical physical controls on salmonid habitat ranging from continental to microhabitat scales. In addition to morphologic controls, they emphasized the effects of stream temperature, timing of annual runoff, and hydrologic regime (rainfall, snowmelt, and transitional runoff). Salmonid habitat is also affected by nested scales of hyporheic flow forced by large-scale changes in channel confinement and smaller scale changes in bed topography (Baxter and Hauer, 2000; Buffington and Tonina, 2009). Although riverine habitat is structured by hierarchical processes and process domains, it is also affected by discrete physical disturbances, such as LWD jams, debris flows, or tributary junctions, that can interrupt and reset downstream trends in (1) fluvial features (channel slope, valley width, grain size, channel geometry, channel type), (2) water quality (stream temperature, water chemistry), (3) nutrients, and (4) food (organic matter, invertebrate drift). These discontinuities in the river network can have significant influences on faunal distributions and are frequently biological hotspots (Vannote et al., 1980; Rice et al., 2001a,b, 2008; Thorp et al., 2006) that may be either ephemeral (e.g., stochastic LWD jams) or chronic (fixed in time and space; e.g., tributary junctions). Chronic disturbances over geologic time (e.g., repeated debris-flow deposition at tributary junctions) can have long-term effects on river profiles (Benda et al., 2003), channel morphology, and associated riverine habitats. The ecological effects of such disturbances are generally site specific, influenced by both the structure of the river network (Benda et al., 2004) and hierarchical patch dynamics (local interaction of neighboring habitat patches and ecotones over space and time; Poole, 2002).
1. Straight
2. Sinuous
3. Irregular, wandering
4. Irregular meanders
5. Regular meanders
6. Tortuous meanders - Confined pattern

Increasing sediment supply

0. None
1. Occasional
   No overlapping of islands; average spacing \( \geq 10 \) channel widths

2. Frequent, irregular
   Infrequent overlapping of islands; average spacing <10 channel widths

3. Frequent, regular
   No overlapping of islands; average spacing <10 channel widths

4. Split
   Islands overlap frequently or continuously, with 2–3 flow branches

5. Anastomosing
   Continuously overlapped islands, with two or more flow branches

Increasing sediment supply

(a)

(b)

1. Downstream progression
   Point bar deposits

2. Progression and cutoffs
   Oxbow lake

3. Mainly cutoffs

4. Entrenched loop development
   Slipoff slope
   Terrace scarp

5. Irregular lateral activity
   Side channel or slough
   Chute

6. Avulsion
   Former channels

(c)

(d)
9.36.3.8 Statistical Classifications

Statistical techniques offer a means for objective classification and prediction of channel morphology. For example, spatial statistics have been used to objectively classify reach morphology based on significant differences in bed topography and channel unit architecture (e.g., Thompson et al., 2006). Similarly, dimensionless parameters and rules have been proposed for objective classification of channel unit morphology (e.g., steps and pools; Wood-Smith and Buffington, 1996; Zimmermann et al., 2008). Statistical techniques have also been used to identify channel pattern thresholds (e.g., Bledsoe and Watson, 2001) and to identify physical controls on observed reach types in order to develop predictive models for the spatial distribution of channel morphologies (e.g., Wohl and Merritt, 2005; Flores et al., 2006; Brardinoni and Hassan, 2007; Schmitt et al., 2007; Altunkayak and Strom, 2009; Milner, 2010). These statistical approaches are frequently empirical, requiring interpretation of the underlying physical processes, but they offer means to identify new channel types (particularly transitional morphologies) and to make basin-scale predictions of channel morphology and associated habitat under different disturbance/management scenarios.

9.36.4 Use and Compatibility of Channel Classifications

The appendix summarizes the above classification approaches, the physical environment for which each classification was developed, spatial scale of application, and whether a given classification is process based or descriptive (many are a mixture of both).

Because of different purposes and methods of the above classifications, it is difficult to catalog them in terms of use and compatibility. Unlike other studies of performance, such as comparisons of different bed load transport equations (e.g., Gomez and Church, 1989; Barry et al., 2004, 2007), there are few absolute, objective criteria for comparison of channel classifications. Furthermore, no one classification can be assumed to be the standard for comparison in terms of accuracy, particularly where measurements are made using different methods and over different spatial scales. Consequently, the value of any given classification depends on how it is used and the objectives of the user.

Correlations and cross-walks can be developed to translate one classification into another, similar to what has been done for bed material sampling (Kellerhals and Bray, 1971), but with limitations due to differences in the classification criteria, methods, scale of analysis, and purpose of each classification, as discussed above. Such comparisons can be carried out theoretically using parameters common to each method or empirically by conducting multiple classifications at a given set of field sites.

Theoretical comparisons are necessarily limited to factors common to each classification. For example, the major reach-scale channel types among different classifications for mountain rivers in western North America can be compared as a function of channel slope and width-to-depth ratio (Figure 14). Results show overlap of channel types among the different classifications and a certain degree of correspondence, but it is clear that each approach yields fundamentally different classifications, despite seemingly similar descriptions of channel morphology. The lack of correspondence between the various classifications partially stems from the fact that such comparisons are incomplete; factors that are not common to each approach (e.g., Rosgen's (1994, 1996b) sinuosity and entrenchedment) are not explicitly accounted for in such comparisons, limiting the crosswalk. Furthermore, fundamental differences in the classification approach can nullify theoretical comparisons. For example, slope is a classification parameter in the Rosgen (1994, 1996b) scheme, but not in the Montgomery and Buffington (1997) approach. Instead, in their approach, channels are classified visually based on morphology; each channel type may have an associated range of characteristic slopes (Montgomery and Buffington, 1997; Buffington et al., 2003; 2004), but those values are not diagnostic in the classification nor are they universal between basins or regions (e.g., McDavitt, 2004; Wohl and Merritt, 2005; Flores et al., 2006; Thompson et al., 2006; Addy, 2009). Consequently, slope provides only an approximate and context-dependent translation between these two classifications. Similarly, Rosgen (1994, 1996b) stream types mix some of the morphologies identified in the Montgomery and Buffington (1997) approach, making for an imperfect correspondence between the two in terms of expected relationships (Table 4).

Few empirical comparisons of channel classifications have been made, but there are some examples. Butt (1999) conducted an extensive comparison of the Rosgen (1994, 1996b) and Montgomery and Buffington (1997) classifications in northern California, showing a fuzzy correspondence of some stream types, but with considerable uncertainty (Table 5). The

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Figure 10  Classification of the planform characteristics of large alluvial rivers from aerial photographs (Kellerhals et al., 1976): (a) channel pattern/sinuosity, (b) frequency of islands, (c) bar types (Church and Jones, 1982), and (d) lateral activity of channel and floodplain. Channel response to increasing sediment supply is shown for panels (a) and (b). In panel (c), increasing bar stability is associated with decreasing sediment supply. Redrafted from Kellerhals, R., Church, M., Bray, D.I., 1976. Classification and analysis of river processes. Journal of the Hydraulics Division, American Society of Civil Engineers 102, 813–829, with permission from ASCE; Kellerhals, R., Church, M., 1989. The morphology of large rivers: characterization and management. In: Dodge, D.P. (Ed.), Proceedings of the International Large River Symposium. Department of Fisheries and Oceans Canada, Canadian Special Publication of Fisheries and Aquatic Sciences 106, Ottawa, ON, pp. 31–48, with permission from Fisheries and Oceans Canada; Church, M., Jones, D., 1982. Channel bars in gravel-bed rivers. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed Rivers: Fluvial Processes, Engineering and Management. Wiley, Chichester, UK, pp. 291–338, with permission from Wiley, and Hogan, D.L., Bird, S.A., Wilford, D.J., 1996. Channel Conditions and Prescriptions Assessment (interim methods). British Columbia Ministry of Environment, Lands and Parks and Ministry of Forests, Watershed Restoration Technical Circular no. 7, Victoria, BC, 42 pp., with permission from the Province of British Columbia.
Figure 11  FPC (1996b) classification of small and intermediate channels (bankfull width <20–30 m), showing potential wood loading and surface grain-size characteristics as a function of disturbance (degradation/aggradation, left side of figure) and the corresponding supply- vs. transport-limited conditions (right side). Channel types are step-pool (SP), cascade-pool (CP), and riffle-pool (RP). Subscripts indicate grain size (r = boulder block, b = boulder, c = cobble, g = gravel) and presence of large woody debris (LWD). Channel types occur across a gradient of confinement, slope ($S$), relative width (maximum grain size divided by bankfull width, $D_{max}/w$), and relative roughness (maximum grain size divided by bankfull depth, $D_{max}/h$) (top of figure). Based on concepts from Schumm (1963a, 1977, 1981, 1985), Mollard (1973), and Church (1992, 2006). Modified from FPC, 1996b. Channel Assessment Procedure Field Guidebook. Forest Practices Code. British Columbia Ministry of Forests, Vancouver, BC, 95 pp., with permission of the Province of British Columbia, and USDA. [www.ipp.gov.bc.ca](http://www.ipp.gov.bc.ca)
two classifications generally match the Table 4 expectations of correspondence, but some of the discrepancies between the classifications are particularly discouraging. For example, 32% of the plane-bed channels are classified as Rosgen C, E, or F stream types (pool-riffle morphology; Rosgen, 1994, 1996b). Similarly, 23% of the pool-riffle channels are classified as either B streams (riffle-dominated (i.e., plane-bed) morphology Rosgen, 1994, 1996b) or A and G streams (step-pool/cascade morphology; Rosgen, 1994, 1996b). Data from streams in southeastern Oregon (Roper et al., 2008; Buffington et al., 2009) show similar results, but for a smaller sample size (Table 5). Correspondence between the two classifications roughly matches expectations (Table 4), but 48% of the plane-bed channels are classified as Rosgen B and C stream types (pool-riffle morphology), whereas 40% of the pool-riffle channels are classified as Rosgen B and C stream types (plane-bed and step-pool/cascade morphologies, respectively). Similar results are observed in northern Idaho and northern Utah (Whiting et al., 1999; McDavitt, 2004) for small sample sizes, but good correspondence between the two classifications is observed in western Washington (Southerland, 2003) and northwestern Montana (Madsen, 1995) (Table 5). Hence, correspondence between the two classifications is approximate at best and varies between regions and observers (e.g., Roper et al., 2008; Buffington et al., 2009). The lack of better correspondence between the classifications is not surprising, given their fundamental differences in methodology as discussed above. Despite the fact that both approaches are intended to describe reach-scale morphology of mountain basins, they cannot be compared sensu stricto because of differences in methodology and classification philosophy. This is true, in general, among the available channel classification schemes. Furthermore, the fact that one classification is more detailed than another (i.e., having more classification factors and categories) does not necessarily make it any more valuable if those categories do not offer meaningful insights for the user (a matter of user-specific goals and objectives).

9.36.5 The Rise and Fall of Classifications: Why Are Some Channel Classifications More Used Than Others?

Although there are many channel classifications to choose from, some are used more than others (Figure 15). This may be linked to changing scientific and societal needs, such that the purpose or the underlying philosophy of a given classification has a limited time of being in vogue (Kondolf, 1995; Kondolf et al., 2003). For example, hierarchical channel classifications are currently in vogue because they address a need for holistic, basin-wide studies of physical and biological processes in response to recent environmental laws and calls for interdisciplinary collaboration among scientists, managers, and stakeholders. In contrast, genetic classifications were...
popular in the late 1800s and early 1900s following Darwin’s work on evolution (Kondolf, 1995).

The popularity of a given channel classification is also related to the generality of the approach in terms of its application both within and between basins/regions. For example, the Whiting and Bradley (1993) classification is limited to headwater channels, which may explain its infrequent use (Figure 15), despite the fact that the approach has a strong process basis.

One of the strongest factors governing the use of different classifications may be the value of the classification for one’s particular goals. A closely related factor is ease of use. For example, Rosgen’s (1994, 1996b) cookbook approach makes it easy to use and, thus, appeals to practitioners and land managers, many of whom are not formally trained in geomorphology (Kondolf, 1995, 1998; Doyle et al., 2000), but the approach is frequently criticized by academically trained geomorphologists (see reviews by Malakoff, 2004; Lave, 2008, 2009; Lave et al., 2010). This divide is partly an issue of scientific rigor and partly a cultural difference between academics and practitioners in terms of the desired goals (i.e., detailed research vs. reconnaissance-level measurements for rapid, practical application). Conflict arises when reconnaissance-level measurements are extended beyond their...
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<th>Channel type</th>
<th>Description</th>
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<tbody>
<tr>
<td>Colluvial</td>
<td>First-order channels incised into colluvial valleys by overland flow and seepage erosion. Streamflow may be perennial or ephemeral, with streambeds characterized by poorly sorted sand- to boulder-sized sediment, and bed morphology that is strongly controlled by stochastically occurring obstructions (boulders, wood, in-channel vegetation). Steep channel gradients, but little scouring energy because of shallow stream flows and in-channel obstructions that are large relative to channel size. Directly coupled to confining hillslopes. Prone to mass wasting and bulking debris flows.</td>
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<tr>
<td>Bedrock</td>
<td>Typically confined, steep reaches lacking a persistent or continuous alluvial bed due to bed load transport rate greater than sediment supply, or due to the recent occurrence of debris-flow scour. Pools and flow obstructions may occasionally retain alluvial pockets of irregular extent and depth. Log jams may force temporary alluviation.</td>
</tr>
<tr>
<td>Cascade</td>
<td>Chaotic arrangement of boulder-sized bed material and continuous macroscale turbulence. Channel is typically confined by valley walls and directly coupled to hillslopes. Boulders are lag deposits supplied from adjacent hillslopes, upstream debris flows, or paleofloods. Steep gradients and concentrated flow allow efficient transport of cobble- to sand-sized sediment during annual floods, but movement of the channel-forming boulders requires infrequent large floods. High mobility of the median grain size ($D_{50}$) at bankfull flow, as indexed by the excess Shields stress ($2.3 &lt; \tau_{c,bf}/\tau_{c,bf} &lt; 4$). Little sediment storage due to the shallow depth to bedrock and lack of floodplain development. Infrequent, turbulent pools of small volume. Significant channel roughness due to low bankfull width-to-depth ratios ($6 &lt; w/h &lt; 14$) and low values of relative submergence (ratio of bankfull flow depth to median particle size; $3 &lt; h/D_{50} &lt; 7$). May be prone to debris-flow passage.</td>
</tr>
<tr>
<td>Step-pool</td>
<td>Repeating sequences of steps and plunge pools formed by wood debris, resistant bedrock, or by boulders that accumulate either as kinematic waves, macroscale antidunes, or jammed structures. Steep-gradient, confined channels, with little floodplain development, and directly coupled to hillslopes. High transport capacities that efficiently transport cobble- to sand-sized material (pool substrate) on an annual basis. Moderate to high mobility of $D_{50}$ at bankfull flow ($1.1 &lt; \tau_{c,bf}/\tau_{c,bf} &lt; 3$). Supply and mobility of boulders same as cascade channels. The amplitude and wavelength of steps and pools may be adjusted to maximize hydraulic resistance, stabilize channel form, and equilibrate rates of sediment supply and bed load transport. Significant roughness due to low width-to-depth ratios ($9 &lt; w/h &lt; 19$) and low relative submergence ($3 &lt; h/D_{50} &lt; 7$). May be prone to debris-flow passage.</td>
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Table 2
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Channel type

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<th>Channel type</th>
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<tr>
<td>Plane-bed</td>
<td>Long reaches of glide, run, or riffle morphology lacking significant pool or bar topography. Moderate-gradient channels dominated by gravel/cobble bed material, with some sand and occasional boulders. Variable confinement and correspondingly variable floodplain extent and hillslope coupling. Low width-to-depth ratios (12 &lt; w/h &lt; 24) and low relative submergence (5 &lt; h/D_{50} &lt; 11) damp lateral flow oscillations that would otherwise create an alternate bar morphology. Bed surface is typically armored, with a near-bankfull threshold for significant bed load transport (1 &lt; τ_{bf}/τ_{c,50} &lt; 2). Two-phase bed load transport is common, characterized by supply-limited transport of fine grains over an immobile armor during low flows (Phase 1), and transport-limited motion (i.e., partial transport) of the armor during high flows (Phase 2). Bankfull discharge is typically the effective discharge (that which transports the most sediment over time), with a recurrence interval of about 1–2 years (although regionally variable). High sediment supplies reduce the degree of armorizing and shift the effective discharge to smaller, more frequent floods. Susceptible to obstruction-forced pool formation.</td>
</tr>
<tr>
<td>Dune-ripple</td>
<td>Low-gradient, unconfined, sand-bed rivers occupying large alluviated valleys and typically decoupled from hillslopes. Variety of mobile bed forms (ripples, dunes, sand waves, plane-bed, and antidunes) that depend on stage, Froude number, and transport intensity. Well-defined dune-ripple morphology, with a bankfull recurrence interval of roughly 1–2 years; also the effective discharge. Transport-limited, with a low threshold for bed load transport and very high bankfull mobility (26 &lt; τ_{bf}/τ_{c,50} &lt; 90). Low roughness due to large width-to-depth ratios (12 &lt; w/h &lt; 47) and large relative submergence (3000 &lt; h/D_{50} &lt; 32000), but bed form roughness may be significant. Extensive sediment storage in bed forms and floodplain. Photo used with permission, courtesy of Carter Borden.</td>
</tr>
<tr>
<td>Pool-riffle</td>
<td>Alternating pool and bar topography caused by laterally oscillating flow that forces complementary zones of flow convergence (pool scour) and divergence (bar deposition). Spatial variation of flow and bed form deposition promoted by moderate width-to-depth ratios (15 &lt; w/h &lt; 33) and large relative submergence (13 &lt; h/D_{50} &lt; 40). Typically moderate- to low-gradient, unconfined channels, with gravel/cobble/sand bed material and extensive floodplains. Decoupled from hillslopes and lateral sediment inputs, except in locations where the channel has migrated against a valley wall/terrace. Extensive sediment storage in floodplains and bar forms. As with plane-bed channels, the bed is typically armored, exhibits two-phase bed load transport, has a near-bankfull mobility for D_{50} (0.9 &lt; τ_{bf}/τ_{c,50} &lt; 2.2), and the bankfull flow is the effective discharge, unless shifted to smaller, more frequent floods by high sediment supply and reduced armorling. Susceptible to obstruction-forced pool formation.</td>
</tr>
<tr>
<td>Braided</td>
<td>Multithread rivers with large width-to-depth ratios (33 &lt; w/h &lt; 130) and a wide range of slopes. Bed material may be sand or gravel/cobble, with correspondingly different values of both relative submergence (14 &lt; h/D_{50} &lt; 64, gravel; 5000 &lt; h/D_{50} &lt; 11000, sand) and bed mobility at bankfull flow (1.2 &lt; τ_{bf}/τ_{c,50} &lt; 2.7, gravel; 23 &lt; τ_{bf}/τ_{c,50} &lt; 68, sand). Individual braid threads may have a pool-riffle morphology or a bar-riffle morphology lacking pools. Pool scour commonly occurs where braid threads converge. Braiding frequently results from high sediment loads or channel widening caused by bank destabilization. Braided channels commonly occur (1) as glacial outwash channels, (2) in locations overwhelmed by a locally high sediment supply, (3) in alluvial valleys where banks have been destabilized by riparian cutting or livestock trampling, or (4) in semiarid regions with insufficient riparian vegetation to stabilize banks composed of cohesionless sediments. Extensive sediment storage in bed forms.</td>
</tr>
</tbody>
</table>

*Transitional morphologies may also occur (Gomi et al., 2003; Montgomery and Buffington, 1997). Note that the Montgomery and Buffington (1997) approach is a visual classification of channel morphology; each channel type has characteristic ranges of channel slope, grain size, relative roughness, etc. that covary with basin discharge and sediment supply (Buffington et al., 2002, 2003), but those features are not used to classify channel type. Further discussion of the geomorphic processes and factors controlling these different channel types can be found elsewhere (Montgomery and Buffington, 1997, 1998; Buffington et al., 2002, 2003; Montgomery and Bolton, 2005). The channel slope (S), bankfull width-to-depth ratio (w/h), relative submergence (h/D_{50}) and Shields stress (τ_{bf}/τ_{c,50}) are from data compiled by Buffington (2012). Reported values for w/h, τ_{bf}/τ_{c,50} and τ_{bf}/τ_{c,50} represent inner quartile ranges of compiled data distributions for each channel type. S-values represent continuous ranges across channel types, following the procedure described by Buffington et al. (2004). Values may vary regionally (e.g., McDavitt, 2004; Wohl and Merritt, 2005). The bankfull Shields stress (τ_{bf}) is determined from Lamb et al. (2008; τ_{c,50} = 0.15S^{0.25}), except for dune-ripple channels and sand-bed braided streams, where the original Shields (1936) curve was used, as fit by Brownlie (1981). Source: Modified from Buffington, J.M., Woodsmith, R.D., Booth, D.B., Montgomery, D.R., 2003. Fluvial processes in Puget Sound rivers and the Pacific Northwest. In: Montgomery, D.R., Bolton, S., Booth, D.B., Wall, L. (Eds.), Restoration of Puget Sound rivers. University of Washington Press, Seattle, WA, pp. 46–78, and Buffington, J.M., Tonina, D., 2009. Hyporheic exchange in mountain rivers II: effects of channel morphology on mechanics, scales and rates of exchange. Geography Compass 3, 1038–1062.
Table 3  Example of river styles identified in the Bega catchment, New South Wales, Australia

<table>
<thead>
<tr>
<th>River style</th>
<th>Confinement/land type</th>
<th>River character</th>
<th>Bed material</th>
<th>Geomorphic units</th>
<th>River behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steep headwater</td>
<td>Confined/uplands</td>
<td>Single, highly stable channel</td>
<td>Boulder-bedrock</td>
<td>Discontinuous floodplain, pools, riffles, glides, runs, vegetated islands</td>
<td>Bedrock channel with a heterogeneous assemblage of geomorphic units. Sediment flushed through the confined valley. Limited ability for lateral adjustment.</td>
</tr>
<tr>
<td>Gorge</td>
<td>Confined/escarpment</td>
<td>Single, straight, highly stable channel</td>
<td>Boulder-bedrock</td>
<td>No floodplain, bedrock steps, pools &amp; riffles, cascades</td>
<td>Steep, bedrock-controlled river, with an alternating sequence of bedrock steps and pool-riffle-cascade sequences. Efficiently flushes all available sediments. Channel cannot adjust within the confined valley setting.</td>
</tr>
<tr>
<td>Confined valley with occasional floodplain pockets</td>
<td>Confined/rounded foothills</td>
<td>Single, straight, highly stable channel</td>
<td>Bedrock-sand</td>
<td>Discontinuous pockets of floodplain, extensive bedrock outcrops, sand sheets, pools</td>
<td>Occurring in narrow valleys, these rivers move sediment along the channel via downstream propagation of sand sheets. Bedrock-induced pools and riffles. Occasional island development where sediment availability is limited and the bedrock channel is exposed.</td>
</tr>
<tr>
<td>Partly confined valley, with bedrock-controlled discontinuous floodplain</td>
<td>Partly confined/rounded foothills and base of escarpment</td>
<td>Single, moderately stable, sinuous channel</td>
<td>Bedrock-sand</td>
<td>Discontinuous floodplain, point bars, point benches and sand sheets, mid-channel bars, pools and riffles, bedrock outcrops</td>
<td>Sinuous valleys. River progressively transfers sediment from point bar to point bar. Sediment accumulation and floodplain formation is restricted primarily to the inside of bends. Sediment removal along concave banks. Over time, sediment inputs and outputs are balanced. Floodplains are formed from suspended load deposition behind bedrock spurs.</td>
</tr>
<tr>
<td>Low-sinuosity boulder bed</td>
<td>Laterally unconfined/base of escarpment</td>
<td>Single channel trench consisting of multiple low-flow threads around boulder islands; highly stable</td>
<td>Boulder-bedrock</td>
<td>Fans extend to valley margins. Channel consists of boulder islands, cascades, runs, pools, bedrock steps</td>
<td>Lobes of boulder and gravel material have been deposited over the valley floor. The primary incised channel has a heterogeneous assemblage of bedrock- and boulder-induced geomorphic units that are only reworked in large flood events.</td>
</tr>
<tr>
<td>Intact valley fill</td>
<td>Laterally unconfined/base of escarpment</td>
<td>No channel</td>
<td>Mud-sand</td>
<td>Continuous, intact swamp</td>
<td>Intact swamps are formed from dissipation of flow and sediment over a wide valley floor as the channel exits from the escarpment zone. Suspended and bed load materials are deposited as sheets or floodout lobes.</td>
</tr>
<tr>
<td>Channelized fill</td>
<td>Laterally unconfined/base of escarpment</td>
<td>Single, straight, unstable channel</td>
<td>Sand</td>
<td>Continuous valley fill, terraces, inset features, sand sheets, sand bars</td>
<td>Incised channel has cut into swamp deposits of an intact valley fill (above). Large volumes of sediment are released and reworked on the channel bed. The channel has a stepped cross section, with a series of inset features and bar forms. These are a function of cut and fill processes within the incised channel. Channel infilling, lateral low-flow channel movement and subsequent re-incision produce the stepped profile.</td>
</tr>
<tr>
<td>Low-sinuosity sand bed</td>
<td>Laterally unconfined/lowland floodplain</td>
<td>Single channel, with an anabranching network of low-flow channels; potentially avulsive and unstable</td>
<td>Sand</td>
<td>Continuous floodplain, with backswamps, levees, benches, mid-channel islands and sand bars</td>
<td>Occurring in a broad, low-slope valley, the river accumulates sediment in wide, continuous floodplains. Floodplains contain levees and backswamps formed by flow and sediment dispersion over the floodplain. Flood channels may short circuit floodplain segments at the high-flow stage. The channel zone is characterized by extensive sand sheets and sand bars, forming islands where colonized by vegetation. Sediments obliquely accreted against the channel margin form benches.</td>
</tr>
</tbody>
</table>

Figure 14  Comparison of typical channel slopes ($S$) and bankfull width-to-depth ratios ($w/h$) for several channel classifications developed for mountain rivers in western North America. Values for Rosgen A-G stream types were determined from his Figure 5-3 (Rosgen, 1996b), including allowable variation of classification parameters (see Figure 12 footnote); values not reported in his Figure 5-3 were determined from data reported for each channel type (pp. 5-35 to 5-189 of Rosgen (1996b)). Montgomery and Buffington (1997) stream types are cascade (ca), step-pool (sp), plane-bed (pb), pool-riffle (pr), braided (bd), and dune-ripple (dr) channels. Dark blue lines represent the inner quartile ranges of $S$ and $w/h$ distributions of data compiled by Buffington (2012). Paustian et al. (1992) stream types are high-gradient contained (hgc), moderate-gradient mixed (mgm), alluvial fan (af), floodplain (fp), palustrine (pa), and estuarine (es) channels. Data plotted here are ranges of the mean values reported by Paustian et al. (1992) for subsets of each channel type. Some of their confined channel types (large contained and moderate-gradient contained streams) could not be plotted due to insufficient data. Forest Practice Code (FPC, 1996b) stream types (small- to intermediate-sized channels) are step-pool (sp), cascade-pool (cp), and riffle-pool (rp), with $S$ and $w/h$ values obtained from the FPC (1996b) guide. It is unclear whether the values reported by Rosgen (1996b) and FPC (1996b) are full ranges of observed $S$ and $w/h$ distributions or “typical” values (e.g., standard deviation or inner quartiles of the $S$ and $w/h$ distributions).

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Expected correspondence between Montgomery and Buffington (1997) and Rosgen (1994, 1996b) channel types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock</td>
<td>A1, possibly G/F/B/C1</td>
</tr>
<tr>
<td>Colluvial</td>
<td>A6 with occasional boulders; possibly A3-5</td>
</tr>
<tr>
<td>Cascade</td>
<td>A2-3, possibly B2-3</td>
</tr>
<tr>
<td>Step-pool</td>
<td>A/G2-3, possibly B2-3</td>
</tr>
<tr>
<td>Plane-bed</td>
<td>B3-4</td>
</tr>
<tr>
<td>Pool-riffle</td>
<td>C/E/F3-5</td>
</tr>
<tr>
<td>Dune-ripple</td>
<td>possibly C/E/F5</td>
</tr>
<tr>
<td>Braided</td>
<td>D3-5</td>
</tr>
</tbody>
</table>


limitations and are used to perform indefensible assessments of channel condition or to plan unjustified restoration activities (for examples see Gillian, 1996; Kondolf, 1998; Kondolf et al., 2001; Simon et al., 2007). The cookbook approach also appeals to many users because it seems less subjective than visual classifications (e.g., Montgomery and Buffington, 1997), which are more readily used by academically trained geomorphologists because of their familiarity with the underlying concepts and literature (e.g., Milner, 2010), but in reality, visual classifications can be quickly learned by nonexperts.

Marketing is also a factor, with some classifications having established industries for training and application, increasing their use (e.g., the Rosgen (1994, 1996b) and river styles (Brierley and Fryirs, 2005) approaches). These training courses have been extremely valuable for increasing awareness of fluvial geomorphology and for incorporating it into land management and stream restoration activities (e.g., Parfit, 1993; Malakoff, 2004; Lave, 2008; 2009; Lave et al., 2010), but the courses provide a limited view of fluvial geomorphology and a false sense of expertise (Kondolf, 1998), with subsequent management assessments and restoration projects frequently lacking input from fully trained geomorphologists. Consequently, further involvement from the geomorphic community in such efforts is needed, such as the Partnership for River Restoration and Science, and the Stream Restoration Toolbox, both hosted.
9.36.6 Future Needs and Directions

9.36.6.1 Standardization and Sample Size

The proliferation and incompatibility of channel classifications begs the question of whether the geomorphic community should standardize the classification approaches, particularly where there are multiple, competing methods being applied to similar scales and types of analyses. Typical arguments against standardization include the fact that no single method will be suitable for all applications and study goals, and that it may reduce flexibility and creativity. However, standardizing and vetting competing classification methods would benefit monitoring efforts and would facilitate data sharing and comparison of findings between studies (e.g., Roper et al., 2010).

Similarly, there is a need for assessing requisite sample sizes for field measurements that are used to classify or characterize channels. For example, one can statistically assess how many particles should be sampled when conducting grain-size analyses (Wolman, 1954; Church et al., 1987;...
Rice and Church, 1996), but similar rules have not been developed for determining requisite sample sizes for accurately representing the mean and variance of other channel characteristics (e.g., width, depth) in any one channel type, let alone across different channel morphologies. Researchers tend to implicitly recognize and characterize the variability of physical conditions present within streams during field work, but many practitioners opt for rapid field measurements made at characteristic sites within a stream (e.g., sometimes sampling only one cross section to characterize an entire stream reach) in order to maximize the number of reaches sampled. As discussed above, this cultural difference explains, in part, user preference for some classifications over others.

9.36.6.2 Remote Sensing

Using DEMs, one can make first-order predictions of channel type, stream characteristics (width, depth, grain size, channel pattern), and associated aquatic habitat as functions of slope and drainage area (e.g., Montgomery et al., 1998, 1999; Buffington et al., 2004; Beechie et al., 2006; Wilkins and Snyder, 2011; Buffington, 2012; Goode et al., 2012). These approaches require field verification and process-based interpretation of differences between observed and predicted values (e.g., Dietrich et al., 1996; Buffington and Montgomery, 1999b), but nonetheless offer a rapid means for remote sensing of basin features. However, recent advances in LiDAR (Light Detection and Ranging)
have the potential to radically change remote-sensing capabilities.

Airborne LiDAR offers an unprecedented scale of topographic sampling, allowing us to develop continuous samples of entire river networks and to quantify the variability of channel features at scales that were previously unattainable through conventional field surveys. This technology has the potential to significantly expand channel classification, analysis, and monitoring, but currently has several limitations. Terrestrial airborne LiDAR (near-infrared laser) cannot penetrate water, limiting topographic measurements to exposed surfaces and the water surface (e.g., Snyder, 2009; Faux et al., 2009; Wilkins and Snyder, 2011; Marcus, 2012). Hence, it mainly offers remote sensing of channel width, sinuosity, water-surface profile, and floodplain topography. Furthermore, measurement uncertainty and poorly defined floodplain surfaces require data training for correct identification of typically measured channel features, such as bankfull geometry (Faux et al., 2009).

In contrast, airborne bathymetric LiDAR (blue-green laser) penetrates water and can create seamless coverage of both terrestrial and subaqueous topography (e.g., McKean et al., 2008, 2009). Furthermore, tool kits have been developed for geomorphic analysis of LiDAR data (USGS and ESSA, 2010), increasing the number of users and applications. However, shallow flow depths (<10–20 cm), turbidity, and water-surface waves limit the use of bathymetric LiDAR (McKean and Isaak, 2009). Moreover, neither of these airborne LiDAR devices can resolve grain size, and both have difficulty identifying rapid changes in topography (e.g., near-vertical banks) when sample density is low. Consequently, remote sensing of channel characteristics by airborne LiDAR currently provides an incomplete census of physical factors used in channel classification, but significantly enhances the ability to measure channel characteristics over large spatial scales and holds promise for future application to channel classification, monitoring, and topographically driven models of fluvial geomorphology.

**9.36.7 Conclusion**

Defensible land management and stream restoration activities require a quantitative, process-based understanding of fluvial...
geomorphology and biophysical interactions. Process-based classifications are one tool for addressing such problems. Although this is widely acknowledged, most of the currently available channel classification procedures are largely descriptive, offering little process-based insight. Consequently, care should be exercised when selecting a channel classification that is suitable for one’s goals; a thorough understanding of the classification and recognition of whether it is descriptive or process based is needed for defensible application of the results in terms of land management and stream restoration activities. In addition, process-based classifications inherently will have a strong link between form and process, but classification cannot substitute for field measurements and documentation of the physical processes occurring within a river. A common mistake made by classification users is to assert channel processes as described by the original author(s) of a classification, without making any site-specific field measurements or calculations of their own to defend such assertions. Measurements are particularly important if the asserted processes and condition of the river are the basis for management and restoration actions.

An understanding of the river within the context of the basin is also crucial. Management and restoration activities tend to focus on specific, isolated stream reaches and the perceived problems occurring at those locations, without considering the context of the surrounding channel reaches and upstream basin processes that may be contributing to an identified problem. In particular, the downstream sequence of channel types, lateral connectivity to hillslopes and floodplains, and vertical connectivity to hyporheic and groundwater domains affect disturbance propagation, response trajectories, and current conditions. Similarly, it is important to understand the history of the basin over both geologic and human time scales since the current state of the river and its response potential will be governed, in part, by its prior disturbance history (Carling, 1988a; Hoey, 1992; Montgomery and Bolton, 2003; Kondolf et al., 2001; Brierley and Fryirs, 2005; Rosgen, 2006b). Successful management and restoration of riverine ecosystems requires recognition of this broader basin and historical context. Although these principles are well known, they are generally difficult to apply in practice (Beechie et al., 2010), or are not fully addressed, potentially undercutting the success of management actions, even if a process-based understanding of the landscape is attempted.

Acknowledgements

The authors thank Gary Brierley and Jaime Goode for constructive comments on an earlier draft of this manuscript.

References


## Appendix

Classifications summarized by approach, physical environment for which they were developed, spatial scale of application, and assessment of whether the classification is process based or descriptive.

<table>
<thead>
<tr>
<th>Classification approach</th>
<th>Environment</th>
<th>Scale of application</th>
<th>Process based</th>
<th>Descriptive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stream order</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horton (1945), Strahler (1957): Network structure (<a href="#">Figure 1</a>)</td>
<td>Any river network</td>
<td>River network</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td><strong>Process domain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schumm (1977): Sediment production, transfer &amp; deposition zones (<a href="#">Figure 2(a)</a>)</td>
<td>Source to sink (headwaters to lowland depositional zone); generally applicable to any river environment</td>
<td>Basin</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Montgomery (1999): Interaction between disturbance processes, channel morphology, &amp; aquatic habitat (<a href="#">Figure 2(b)</a>)</td>
<td>Mountain rivers of the Pacific Northwest (headwaters to alluvial plains), but concepts applicable to any environment</td>
<td>Valley</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td><strong>Channel pattern: quantitative relationships</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope–discharge (S–Q):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lane (1957): Separate S–Q relationships for braided vs. meandering channels</td>
<td>Alluvial floodplain rivers (unconfined to partly confined): Sand-bed rivers, &amp; limited analysis of gravel/cobble-bed rivers, of various size, with moderate to low slopes (10^{-2} to 10^{-6}); select data from moderate-slope, sand-bed laboratory channels; data compilation from conterminous U.S. &amp; select rivers in central Canada (Manitoba), Mexico, China, Turkey &amp; Egypt</td>
<td>Reach to valley</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Leopold and Wolman (1957): S–Q threshold for braided vs. meandering channels (<a href="#">Figure 3</a>)</td>
<td>Small to large rivers, with cobble to sand beds, &amp; moderate to low slopes (10^{-2} to 10^{-5}); data compilation from U.S. Rocky Mountains, Interior/Great Plains, Appalachians, central Alaska &amp; India</td>
<td>&quot;</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Bray (1982): S–Q threshold for braided vs. meandering channels, with degree of sinuosity &amp; frequency of islands indicated</td>
<td>Small to large, gravel/cobble-bed rivers, with moderate to low slopes (10^{-2} to 10^{-4}); Canadian Rocky Mountains &amp; Interior Plains (Alberta)</td>
<td>&quot;</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Knighton and Nanson (1993): S–Q domain for anastomosed channels added to data reported by Leopold and Wolman (1957) and Ferguson (1987)</td>
<td>Silt- to gravel-bed anastomosed rivers of various size, with moderate to low slopes (10^{-2} to 10^{-4}); data compilation from western North America (Canada &amp; U.S.), Columbia &amp; Australia</td>
<td>&quot;</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Beechie et al. (2006): S–Q thresholds for meandering vs. island-braided vs. braided channels, with critical width for channel migration</td>
<td>Small- to medium-sized rivers, with boulder to gravel beds, &amp; steep to low slopes (10^{-1} to 10^{-4}); Pacific Northwest (Cascade &amp; Olympic Mountains, western Washington)</td>
<td>&quot;</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td><strong>Slope–discharge–grain size (S–Q–D):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Henderson (1963): S–QD threshold for braided vs. meandering &amp; straight channels (latter two share a common space)</td>
<td>Alluvial floodplain rivers (unconfined to partly confined): Re-analysis of Leopold and Wolman (1957)</td>
<td>&quot;</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Osterkamp (1978): S–Q domains for braided vs. meandering channels, stratified by grain size &amp; sinuosity</td>
<td>Sand- to gravel-bed rivers of various size, with moderate to low slopes (10^{-3} to 10^{-5}) (Kansas); supplemental data compilation of laboratory channels &amp; sand to cobble rivers of various size, with moderate slopes (10^{-2} to 10^{-3}), western U.S.</td>
<td>&quot;</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Dade (2000): S-QD domains for channel sinuosity (and thus meandering vs. “braided” channels) stratified by mode of transport (bed load, mixed load, suspended load); derived, in part, from Parker (1976)

Millar (2000): S-QD domains for braided vs. meandering channels stratified by vegetative bank strength; derived, in part, from Parker (1976)

Other discriminators:

Schumm and Khan (1972), Schumm et al. (1972): Straight, meandering & braided channels as a continuous function of S vs. bed load transport rate, or shear stress

Parker (1976): Domains for straight vs. meandering vs. braided channels as a function of bankfull Froude number & channel form index (product of channel slope & width-depth ratio, Sw/h); includes transitional types and braiding intensity

Excess shear velocity (u*/u**) & channel form index (Sw/h) at bankfull stage:

Ikeda (1973; 1975; 1989): Domains for different bar patterns (none, alternate bars without pools, alternate bars with pools, braided) in straight channels

Florsheim (1985): Extension of Ikeda framework to bar formation & reach type in mountain rivers (plane-bed, alternate bars without pools, pool-riffle, step-pool)

Buffington et al. (2003): Domains for Montgomery and Buffington (1997) alluvial channel types, including braided rivers

van den Berg (1995): Stream power–grain size threshold for braided vs. meandering channels

Buffington et al. (2003), Buffington (2012): Domains for Montgomery and Buffington (1997) alluvial channel types, including braided rivers, as a function of dimensionless bankfull discharge and dimensionless bankfull bed load transport rate

Channel pattern: conceptual frameworks


Recognizes 3 primary channel patterns (straight, meandering, braided); channel pattern & stability arrayed as functions of mode of sediment transport, ratio of bed load to suspended load (a function of sediment supply, caliber & stream power), channel gradient & width-to-depth ratio (Figure 4)

Small to large rivers, with cobble to sand beds, & steep to low slopes (10^-1 to 10^-4); unpublished data compilation by M. Church for western North America (U.S. & Canada), Interior & Great Plains (U.S.), southwestern U.S., Canadian Arctic Archipelago, Iceland, Norway, Russia, India & New Zealand

Small to large rivers, with cobble to silt beds of various slope; literature synthesis & worldwide compilation

Small to large, gravel/cobble-bed rivers, with steep to moderate slopes (10^-1 to 10^-3); data compilation for western North America (conterminous U.S. & Canada), U.K. & New Zealand

Moderate-slope (10^-2 to 10^-3), laboratory sand-bed channels

Data compilation, using laboratory sand-bed channels, sand & gravel irrigation canals (U.S. Rocky Mountains & Great Plains) & sand to cobble, floodplain rivers of various size & slope (conterminous U.S., central Alaska & select rivers in China, Norway & India)

Laboratory sand-bed channels & small to large, floodplain rivers, with cobble to sand beds, moderate to low slopes (10^-2 to 10^-3) & variable confinement; Japan

Small- to medium-sized, gravel/cobble-bed rivers, with variable confinement & steep to moderate slopes (10^-1 to 10^-3); northern California

Small to large rivers, with boulder to gravel beds, steep to low slopes (10^-1 to 10^-3) & variable confinement; data compilation from conterminous western U.S., Alaska, Scotland & Norway

Small to large, floodplain rivers, with cobble to sand beds, moderate to low slopes (10^-2 to 10^-3) & variable confinement; worldwide compilation

Small to large rivers, with boulder to sand beds, steep to low slopes (10^-1 to 10^-3) & variable confinement; worldwide data compilation

Alluvial floodplain rivers (unconfined to partly confined): Small to large rivers, with gravel to sand beds, & moderate to low slopes (10^-2 to 10^-3); data synthesis from Great Plains; concepts generally applicable to floodplain rivers
Mollard (1973), Kellerhals and Church (1989): Modification of Schumm’s framework; recognizes 6 major channel types (braided, anastomosed, wandering, confined/truncated meandering, serpentine/unconfined meandering & tortuous meandering) & 17 minor types; channel type & stability arrayed as functions of sediment supply, caliber, ratio of bed load to suspended load, channel gradient & discharge (as modified by river regulation).

Carson (1984a, b, c): Domains for braided vs. wandering vs. meandering channel types as a function of bank strength & bed load supply relative to transport capacity.

Church (1992; 2006): Synthesis and generalization of the above conceptual frameworks by Schumm and Mollard (Figure 5).

Reach to valley

Medium to large rivers, with cobble to silt beds & various slopes; some confined, nonalluvial rivers; western & central Canada (Yukon, British Columbia, Alberta, Saskatchewan, Manitoba, Ontario); concepts generally applicable to floodplain rivers

Small to large rivers, with cobble/gravel beds, & moderate slopes (10⁻² to 10⁻³); New Zealand; concepts generally applicable

Applicable to most types of alluvial rivers (boulder to silt beds, confined headwaters to unconfined lowlands)

Church (1992; 2006): Synthesis and generalization of the above conceptual frameworks by Schumm and Mollard (Figure 5).

Channel–floodplain interactions

Molton (1936): Floodplain formation by lateral accretion, vertical accretion, or braiding processes.

Nanson and Croke (1992), Brierley and Fryirs (2005): Genetic sequences (Figures 7 and 13(b)).

Aerial photographs:

Mollard (1973): Same as Mollard (1973) above

Brice (1975): Recognizes 67 channel types as a function of the degree & character of sinuosity, braiding, & anabranching.

Brice and Blodgett (1978a,b), Brice (1982): Describes alluvial rivers in terms 14 factors, & recognizes 4 major channel types as a function of variability in channel width, nature of point bars, & degree of braiding; channel type correlated with long-term lateral & vertical stability, & short-term bed scour/fill.

Kellerhals et al. (1976), Kellerhals, and Church (1989): Classification of planform features (sinuosity, frequency of channel islands, bar type & lateral activity of the channel & floodplain; Figure 10).

Bed material and mobility

Substrate:

Gilbert (1877, 1914, 1917), Montgomery et al. (1996), Massong and Montgomery (2000): Occurrence of alluvial vs. bedrock rivers as a function of bed load supply relative to transport capacity as modulated by wood jams.

Bed mobility:

Henderson (1963), Simons (1963): Recognizes the dichotomy between live-bed (sand/silt) rivers and threshold (gravel/cobble) channels.

Henderson (1963), Simons (1963): Recognizes the dichotomy between live-bed (sand/silt) rivers and threshold (gravel/cobble) channels.

Small- to medium-sized, alluvial & bedrock rivers, with very steep to moderate slopes (10² to 10⁻³) & variable confinement; western U.S. (southern Utah, northern California, western Washington); concepts generalizable to any environment.

Sand-bed irrigation canals (India), gravel/cobble-bed canals (Colorado) & small to large, floodplain rivers (same as Leopold and Wolman, 1957); concepts generally applicable to most sand- & gravel/cobble-bed rivers.
<table>
<thead>
<tr>
<th><strong>Channel units</strong></th>
<th><strong>Habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisson et al. (1982), Sullivan (1986), Bryant et al. (1992), Church (1992), Hawkins et al. (1993), Wood-Smith and Buffington (1996): Hierarchical classification, recognizing two major channel unit types (pools vs. “shallows”), four or more secondary types (subdivision of pools into scour vs. backwater types &amp; subdivision of “shallows” into various steep vs. low-gradient types; e.g., cascade, riffle, glide) &amp; a variety of tertiary types (e.g., different types of scour pools) using visual assessment of channel topography, hydraulics, grain size and water-surface slope; excludes bars; generally descriptive, but some studies more process-based than others (e.g., Church, 1992)</td>
<td>Moderate-gradient (10(^{-2}) to 10(^{-3})), small- to medium-sized, gravel/cobble-bed rivers of the Pacific Northwest, typically hosting salmonids; concepts generalizable to other environments</td>
</tr>
<tr>
<td>Grant et al. (1990), Halwas and Church (2002), Gomi et al. (2003): Visual classification of steep channel units and associated processes based on topography, hydraulics, grain size and water-surface slope</td>
<td>Small, very steep to moderate gradient (10(^{0}) to 10(^{-2})), cobble- &amp; boulder-bed channels of the Pacific Northwest, with moderate to high confinement; concepts generalizable to other environments</td>
</tr>
<tr>
<td>Church and Jones (1982): Visual classification of bar types &amp; processes</td>
<td>Large, gravel/cobble, floodplain rivers of various slope, with unconfined to partially confined valleys; synthesis of Canadian rivers &amp; select U.K. and New Zealand rivers; concepts generally applicable to any coarse-grained, bar-form river</td>
</tr>
<tr>
<td>Buffington et al. (2002): Visual classification of obstruction-forced pools and their associated hydraulics and scour mechanisms</td>
<td>Small- to medium-sized, gravel/cobble-bed rivers, with moderate slopes (10(^{-2}) to 10(^{-3})) &amp; unconfined to partially confined valleys; northern California, southern Oregon &amp; southeastern Alaska; concepts generalizable to other pool-forming rivers</td>
</tr>
</tbody>
</table>

| **Hierarchical** |
| Frissell et al. (1986): Describes physical conditions & processes across multiple spatial & temporal scales to assess aquatic habitat (Figure 9) | Small- to medium-sized streams in mountain basins of the Pacific Northwest; headwater streams to low-order floodplain channels; steep to moderate slopes (10\(^{-1}\) to 10\(^{-2}\)), boulder to gravel beds & variable confinement; concepts generalizable to other environments & basin sizes |
| Paustian et al. (1992): Recognizes process domains, associated reach types, aquatic habitats & sensitivity to landscape disturbance; see text for further explanation | Alluvial & bedrock rivers spanning a broad range of headwater to lowland process domains; small to large rivers, with steep to moderate slopes (10\(^{-1}\) to 10\(^{-2}\)), boulder to sand beds, & variable confinement; mountain basins of southeastern Alaska; some concepts generalizable, but process domains are region specific |

| **Reach** |
| Paustian et al. (1992): Recognizes process domains, associated reach types, aquatic habitats & sensitivity to landscape disturbance; see text for further explanation | Alluvial & bedrock rivers spanning a broad range of headwater to lowland process domains; small to large rivers, with steep to moderate slopes (10\(^{-1}\) to 10\(^{-2}\)), boulder to sand beds, & variable confinement; mountain basins of southeastern Alaska; some concepts generalizable, but process domains are region specific |
| Church (2002, 2006): Recognizes 6 channel types as a function of bankfull Shields stress, grain size, mode of transport, reach morphology & channel stability (Table 1) | Applicable to most types of alluvial rivers (boulder- to silt-bed, confined headwaters to unconfined lowlands); concepts based on literature synthesis & worldwide compilation of Shields values |
| Whiting and Bradley (1993): Classifies channel type in terms of risk of debris-flow disturbance, mobility of input material & mode of transport (Figure 8) | Small- to medium-sized headwater channels, with boulder to gravel beds & variable confinement; mountain basins of the Pacific Northwest; applicable to mountain basins prone to mass wasting, but concepts generalizable to other types, frequencies & magnitudes of sediment input (pulse vs. press) |
### FPC (1996a, b), Hogan et al. (1996): Uses channel morphology to assess channel condition and stability as a function of sediment supply (Figures 10–11); see text for further explanation

Small, headwater streams to large, lowland rivers; alluvial rivers with boulder to sand beds, steep to low slopes (10⁻¹ to 10⁻⁵) & variable confinement; mountain basins of British Columbia; concepts and classification parameters generally applicable to other environments

Reach, viewed within a valley & basin context

### Rosgen (1994, 1996b, 2006b): Four hierarchical scales of analysis to assess channel condition and develop data for “natural channel design”; recognizes 8 major stream types and 94 minor types determined from field measurements (Figure 12); employs empirical genetic models to predict channel response to disturbance (Figure 13(a)); see text for further discussion

Alluvial & bedrock rivers from headwaters to lowlands; small to large rivers, with steep to low slopes (10⁻¹ to 10⁻⁵), boulder to silt beds & variable confinement; mountain basins of the western U.S.; calibrated to a large number of sites, but published data are limited to summaries; in practice, not typically applied to large rivers or small, headwater channels

Micro to valley, but reach-scale in practice, viewed within a basin context

### Montgomery and Buffington (1997, 1998), Buffington et al. (2003): Recognizes 8 channel types and their response potential within the context of fluvial processes associated with each channel type, process domains, bed load supply relative to transport capacity, external factors (e.g., LWD) & geomorphic history (Table 2, Figures 2(b) and 6); designed for academic and management purposes; see text for further discussion

Alluvial, bedrock & colluvial channels from headwaters to lowlands; small to large rivers, with steep to low slopes (10⁻² to 10⁻³), boulder to sand beds & variable confinement; mountain basins of the western U.S., but concepts and classification parameters are generalizable to other environments

Reach to valley, viewed within a basin context

### Brierley and Fryirs (2000; 2005): Divides a basin into different “river styles” (Table 3), which are used together with genetic models (Figure 13(b)) to assess channel condition and to inform restoration actions; see text for further explanation

Broad range of process domains for alluvial & bedrock rivers of various size, slope, substrate & confinement to lowlands; mountain basins of Australia and New Zealand, but concepts are generalizable to other environments

- Channel slopes (S) are described as very steep (S ≥ 10⁻¹), steep (3•10⁻² < S < 10⁻¹), moderate (10⁻³ < S < 3•10⁻²), and low (S ≤ 10⁻³). Similarly, channel sizes are described in terms of bankfull width (w) as small (w ≤ 20 m), medium (20 m < w < 100 m), and large (w ≥ 100 m).
- Spatial scale is expressed in terms of bankfull width, w, using approximate orders of magnitude from micro to valley scales: micro (≤ 10⁻¹ w), channel unit (10⁻¹ to 10⁻² w), reach (10⁻¹ to 10² w), valley (≥ 10² w). Larger spatial scales are expressed in terms of the network and basin structure: network link, subbasin, and basin.
- Multiple check marks indicate a mixture of both process-based and descriptive approaches, with small check marks indicating a subordinate category.
Biographical Sketch

John M. Buffington is a Research Geomorphologist with the U.S. Forest Service, Rocky Mountain Research Station in Boise, Idaho. He graduated from the University of California Berkeley in 1988 with a BA in geology and from the University of Washington in 1995 and 1998 with MS and PhD degrees in geomorphology. He was a National Research Council Fellow from 1998 to 2000 and a professor in the Center for Ecohydraulics Research at the University of Idaho from 2000 to 2004. His research focuses on fluvial geomorphology of mountain basins, biophysical interactions, and the effects of natural and anthropogenic disturbances on salmonid habitat.

David R. Montgomery is a professor in the Department of Earth and Space Sciences at the University of Washington. He graduated from Stanford University in 1984 with a BS in geology and from U.C. Berkeley in 1991 with a PhD in geomorphology. His research interests range from the coevolution of the Pacific salmon and the topography of the Pacific Northwest to the environmental history of Puget Sound rivers, interactions among climate, tectonics, and erosion in shaping mountain ranges, giant glacial floods in Alaska and Tibet, and the evolution of martian topography.