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., 2005; 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.

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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 (Doyle et al., 2000). This has caused some to question the value of morphologic classification of rivers (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

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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 Platts, 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

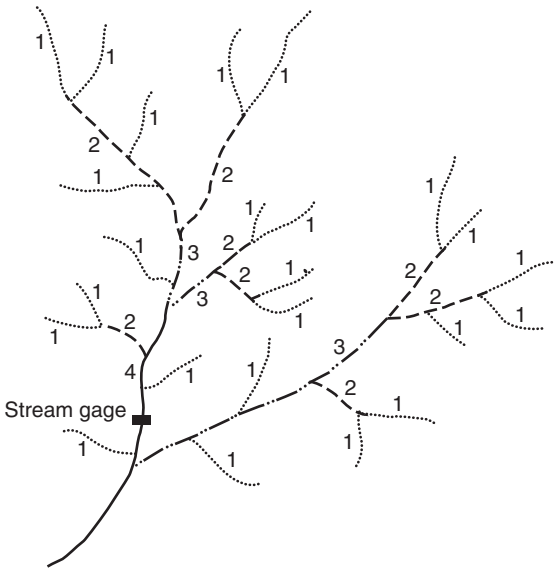


Figure 1 Channel classification using stream order (Horton, 1945; Strahler, 1957). Reproduced with permission from Morisawa, M., 1968. Streams: Their Dynamics and Morphology. McGraw-Hill, New York, 175 pp.

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.

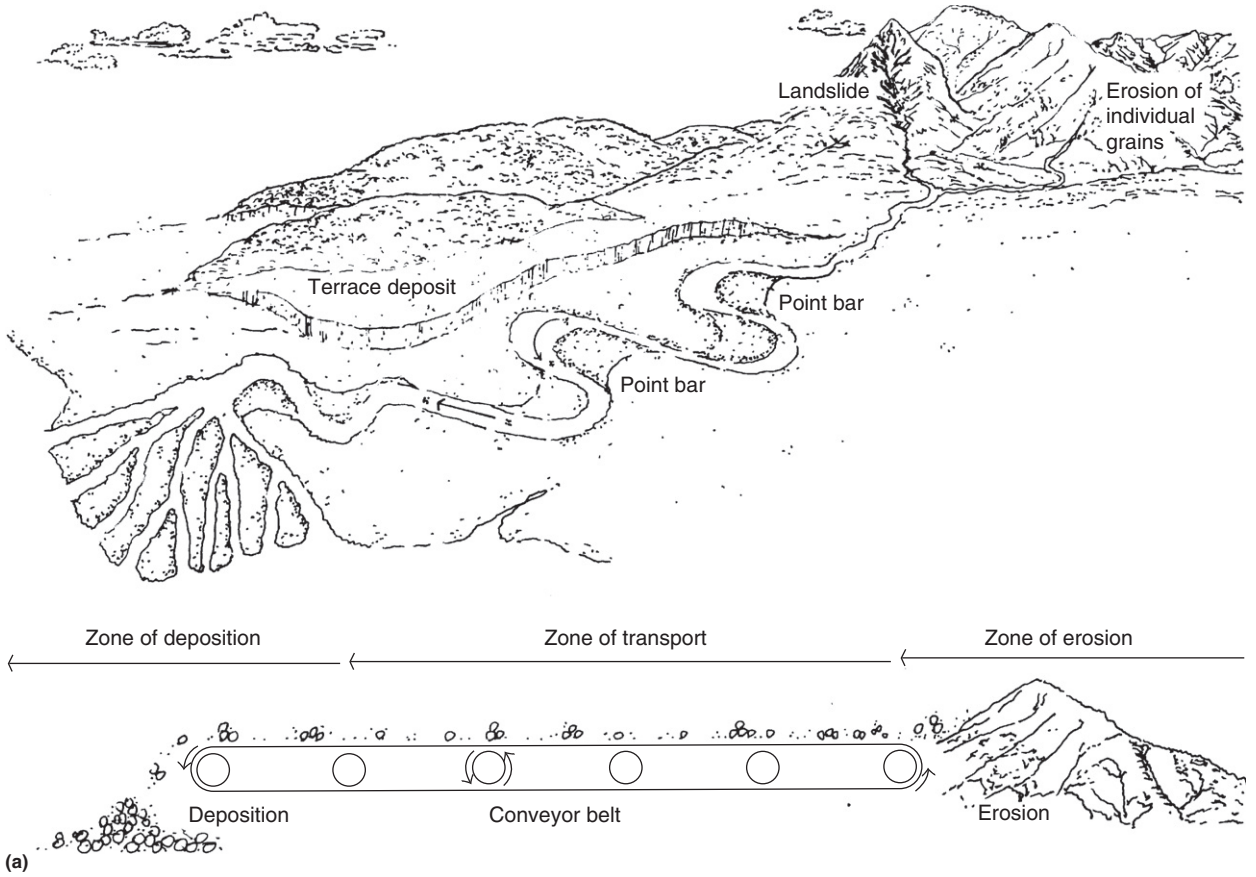
9.36.3.3 Channel Pattern

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 multithread 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; Piégay 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 armoring 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



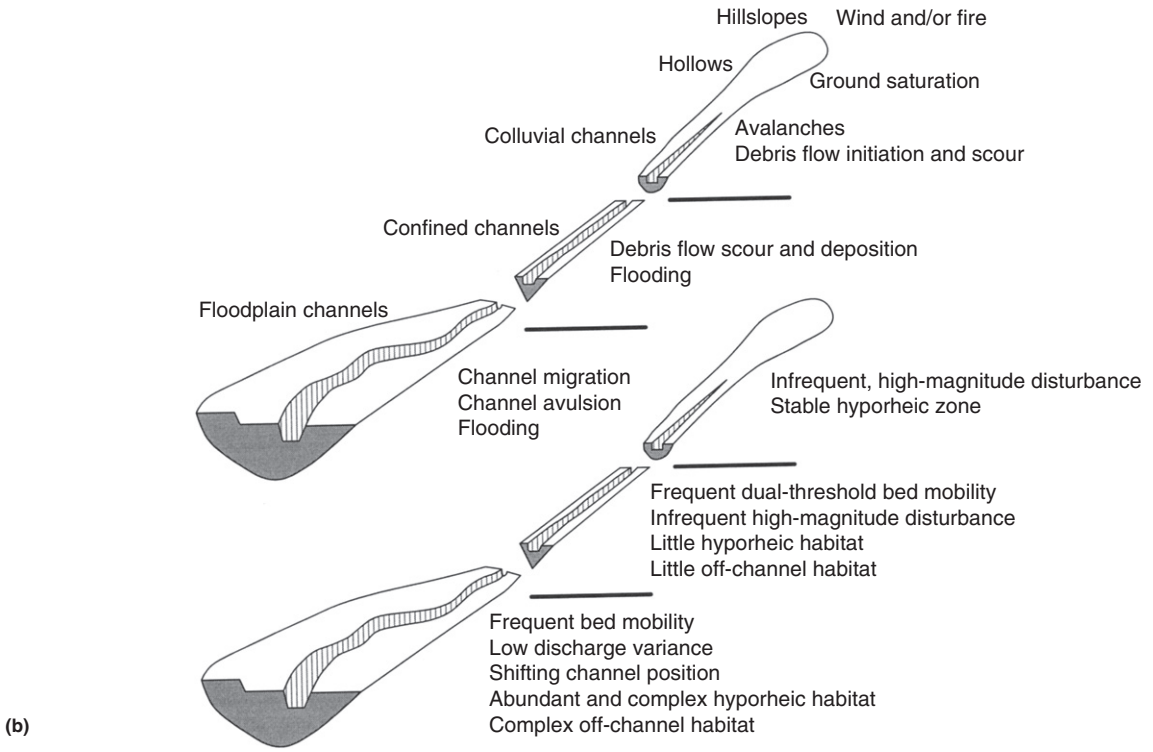


Figure 2 Process domains defined by (a) Schumm (1977) (as depicted by Kondolf, 1994) and (b) Montgomery (1999). (a) Reprinted from Kondolf, G.M., 1994. Geomorphic and environmental effects of instream gravel mining. Landscape and Urban Planning 28, 225–243. (b) Reproduced from Montgomery, D.R., 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35, 397–410.

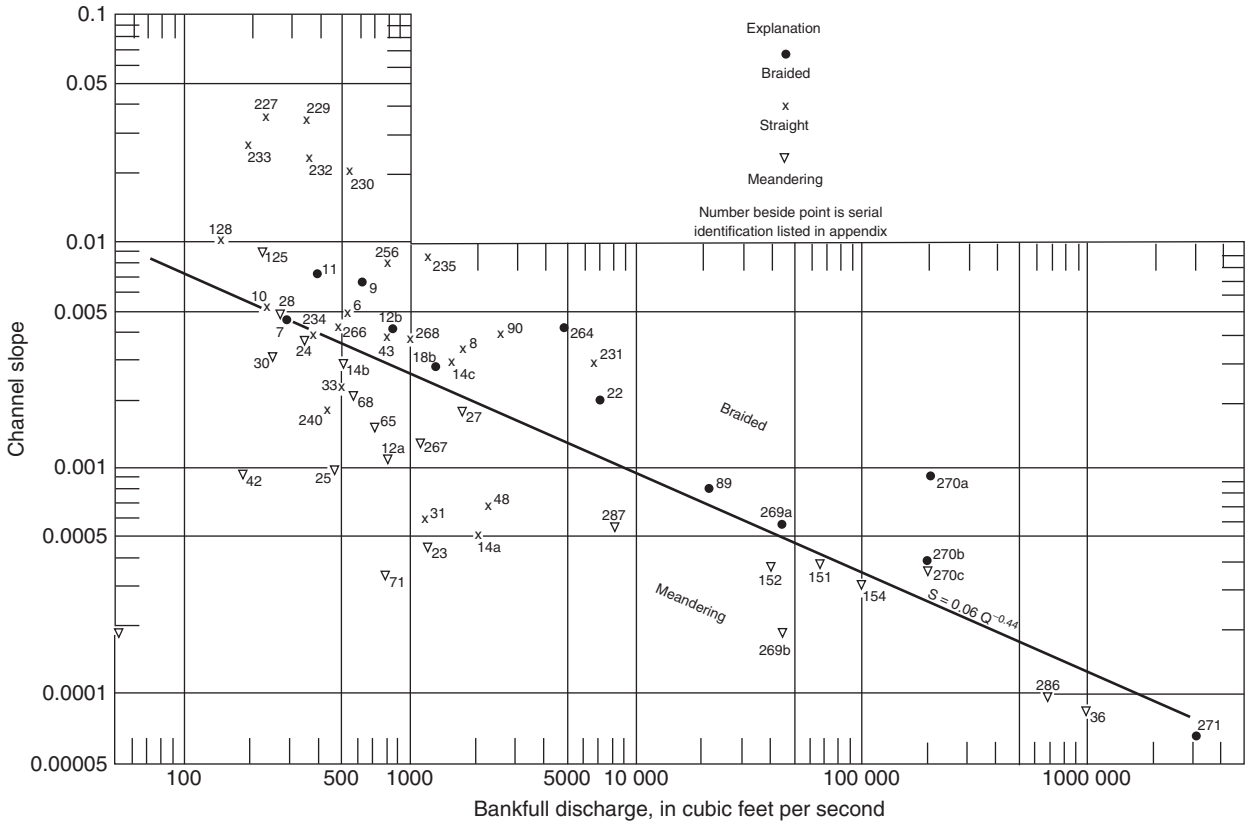


Figure 3 Channel pattern (meandering, straight, braided) as a function of channel slope and bankfull discharge. Reproduced with permission from Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. U.S. Geological Survey Professional Paper 282-B, Washington, DC, pp. 39–84.

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,

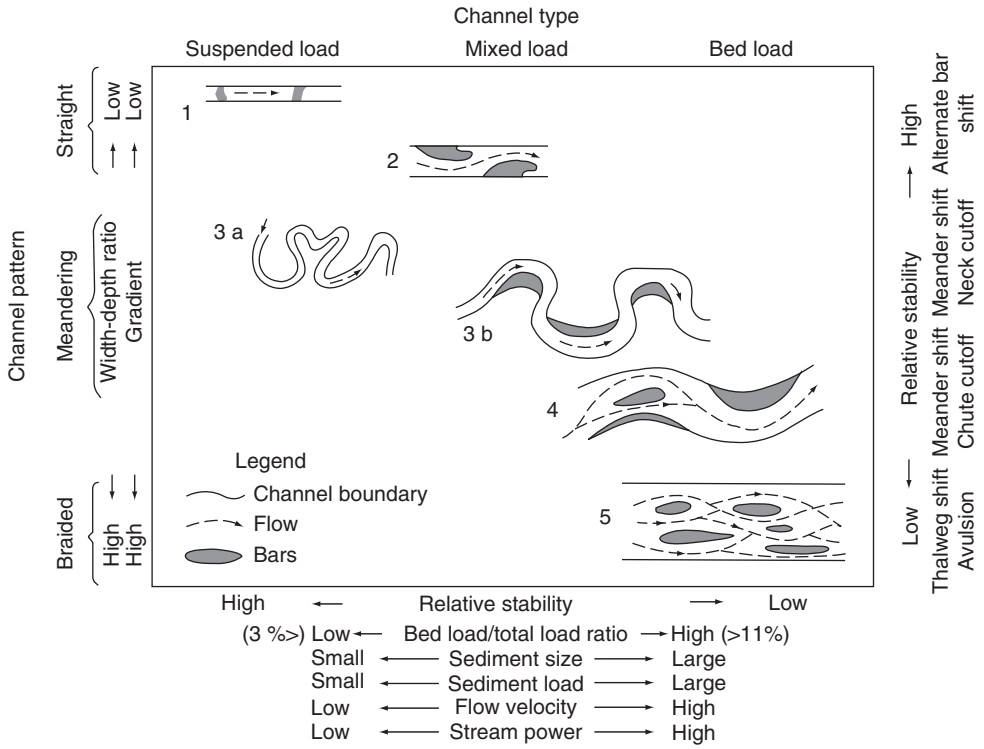


Figure 4 Schumm's (1963a, 1977, 1981, 1985) classification of alluvial rivers. Reproduced from Figure 4 in Schumm, S.A., 1981. Evolution and response of the fluvial system, sedimentological implications. In: Ethridge, F.G., Flores, R.M. (Eds.), Recent and Nonmarine Depositional Environments. SEPM (Society for Sedimentary Geology), Special Publication 31, Tulsa, OK, pp. 19–29, with permission from SEPM; Figure 1 in Schumm, S.A., Meyer, D.F., 1979. Morphology of alluvial rivers of the Great Plains. In: Riparian and Wetland Habitats of the Great Plains. Proceedings of the 31st Annual Meeting, Forestry Committee. Great Plains Agricultural Council Publication 91, Lincoln, NE, pp. 9–14; and Figure 3 in Shen, H.W., Schumm, S.A., Doehring, D.O., 1979. Stability of stream channel patterns. Transportation Research Record 736, National Academy of Sciences, Washington, DC, pp. 22–28, with permission from Transportation Research Board.

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; Fenneman, 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

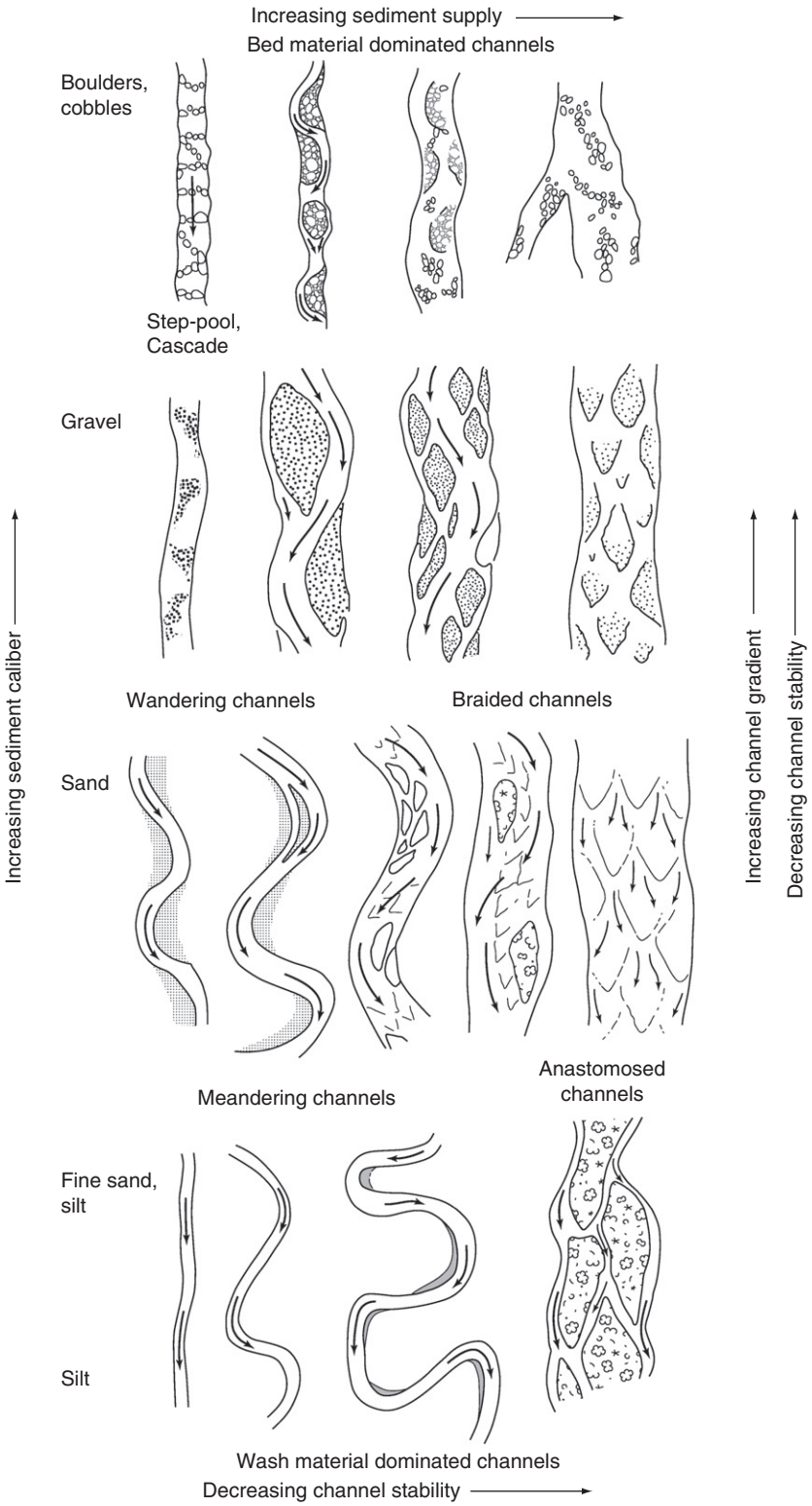


Figure 5 Schumm's (1977, 1981, 1985) classification of channel pattern and response potential as modified by Church (2006). Reproduced from Church, M., 2006. Bed material transport and the morphology of alluvial rivers. Annual Review of Earth and Planetary Sciences 34, 325–354, with permission from Annual Reviews, Inc.

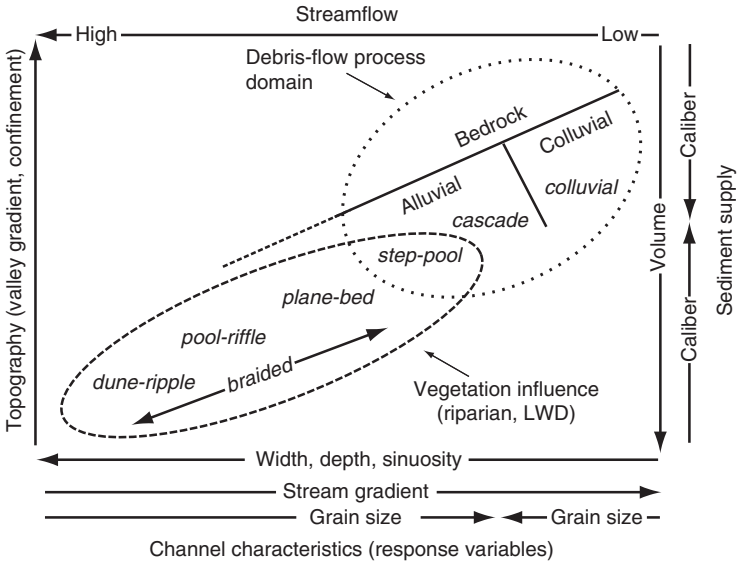


Figure 6 Montgomery and Buffington (1997) channel types (italicized text) and associated channel characteristics (width, depth, sinuosity, stream gradient, grain size) as a function of imposed basin conditions (topography (valley gradient, confinement), streamflow, and sediment supply (caliber, volume)). Process domains are shown for the influence of vegetation and debris flows, and different valley types are indicated (alluvial, bedrock, colluvial). Modified from Buffington, J.M., 2012. Changes in channel morphology over human time scales. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), Gravel-bed Rivers: Processes, Tools, Environments. Wiley, Chichester, UK, pp. 435–463. Based on concepts from Mollard (1973), Kellerhals and Church (1989), and Schumm (1963a, 1977, 1981, 1985).

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; García, 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

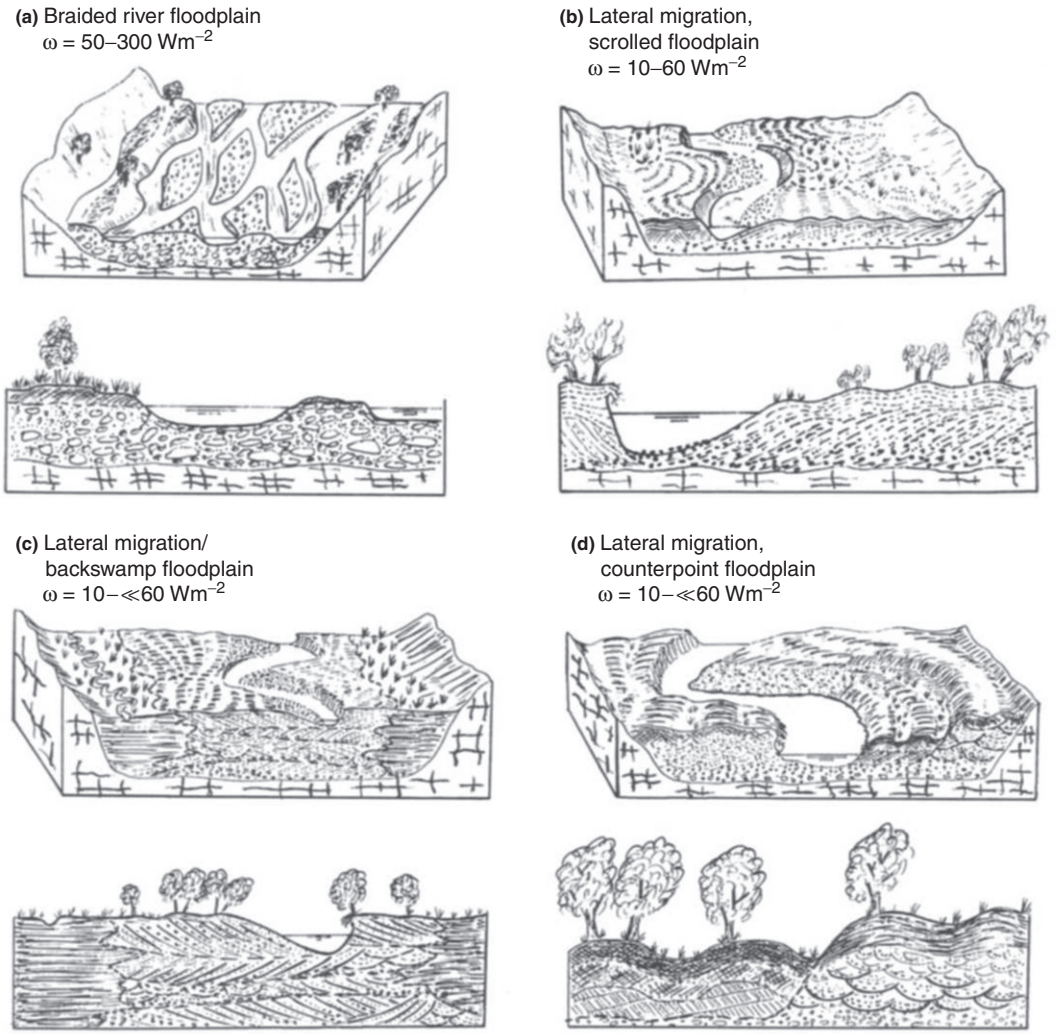


Figure 7 Example river–floodplain types from the Nanson and Croke (1992) classification, showing medium-energy, noncohesive environments. ω is the specific stream power. Reproduced from Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology 4(6), 459–486.

(Buffington, 2012), 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

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 classification 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 regime, channel morphology, and channel stability, elaborating on Schumm's (1963a, 1977, 1981, 1985) classification and work by Dade and Friend (1998). Church's (2002, 2006) method identifies six channel types (**Table 1**) that are comparable to the primary reach-scale morphologies used in other classifications (e.g., Rosgen, 1994, 1996b; Montgomery and Buffington, 1997, 1998).

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 likelihood 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 competence 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, riffles) that form the building blocks of larger reach-scale morphologies, such as step-pool or pool-riffle channels. Bisson et al. (1982) developed 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 characteristics 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 qualitative 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 hydraulically turbulent, *sensu stricto*. Most channel-unit classifications focus on the wetted channel, generally excluding bars, but a detailed classification of bar types and associated physical 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 geomorphic 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 holistic 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 associated channel types (estuarine, floodplain, palustrine, alluvial fan, glacial outwash, large contained (i.e., confined), moderate-gradient contained, moderate-gradient mixed control, and high-gradient contained channels), with channels visually classified and subdivided into 38 subgroups. Coarse-level classification is initially carried out from aerial photographs, with subsequent field validation and refinement. Overall, the approach is a mixture of descriptive measurements 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., 2006, 2008).

Similar to Paustian et al. (1992), a hierarchical channel classification was developed to manage mountain rivers in

Table 1 Classification of river channels and riverine landscapes modified from Church (2006)

Channel type/Bankfull Shields stress ($\tau*_{bf}$)[a]	*Sediment type*	*Sediment transport regime*[b]	*Channel morphology*[c]	*Channel stability*
Jammed channel; $\tau*_{bf} = 0.04^{+}$	Cobble- or boulder-gravel	Low total transport, but subject to debris flows; bed load transport is a high percentage of the total load (q_b/q_t typically >10%)	Step-pool or boulder cascades; width typically a low multiple of largest boulder size; Slope (S) >3°	Stable for long periods of time with throughput of bed load finer than structure-forming clasts; subject to catastrophic destabilization in debris flows
Threshold channel; $\tau*_{bf} = 0.04^{+}$	Cobble-gravel	Schumm's "bed load" channels; low to moderate total transport, with a high percentage of bed load (q_b/q_t typically >10%), but usually limited to partial mobility (*sensu* Wilcock and McArdell, 1993)	Cobble-gravel channel bed; single thread or wandering; highly structured bed; relatively steep; low sinuosity; width-to-depth (w/h) >20, except in headwater boulder channels	Relatively stable for extended periods, but subject to major floods causing lateral channel instability and avulsion; may exhibit serially reoccupied secondary channels
Threshold channel; $\tau*_{bf}$ up to 0.15	Sandy-gravel to cobble-gravel	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)	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 (>40)	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
Transitional channel; $\tau*_{bf} = 0.15$–1.0	Sand to fine gravel	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	Mainly single-thread, irregularly sinuous to meandered; lateral/point bar development by lateral and vertical accretion; levees present; moderate gradient; sinuosity < 2; w/h >40	Single-thread channels, irregular lateral instability or progressive meanders; braided channels laterally unstable; degrading channels exhibit both scour & channel widening
Labile channel; $\tau*_{bf}$ >1.0	Sandy channel bed, fine sand to silt banks	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	Single thread, meandered with point bar development; significant levees; low gradient; sinuosity >1.5; w/h <20; serpentine meanders with cutoffs	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
Labile channel; $\tau*_{bf}$ up to 10	Silt to sandy channel bed, silty to clay-silt banks	High total transport, almost exclusively suspended and wash load (q_b/q_t typically < 1%); minor bed form development	Single-thread or anastomosed channels; prominent levees; very low gradient; sinuosity >1.5; w/h <15 in individual channels	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

[a]The bankfull Shields stress describes the relative mobility of the median grain size (D_{50}) at bankfull flow. $\tau*_{bf} = \tau_{bf}/[(\rho_s - \rho)g\,D_{50}]$, where τ_{bf} is the bankfull shear stress, ρ_s and ρ 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).

[b]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).

[c]Channel morphologies shown in Figure 5.

Source: Modified from Church, M., 2006. Bed material transport and the morphology of alluvial rivers. Annual Review of Earth and Planetary Sciences 34, 325–354, with permission from Annual Reviews, Inc.; based on concepts from Schumm (1963a, 1971, 1977, 1985) and Dade and Friend (1998).

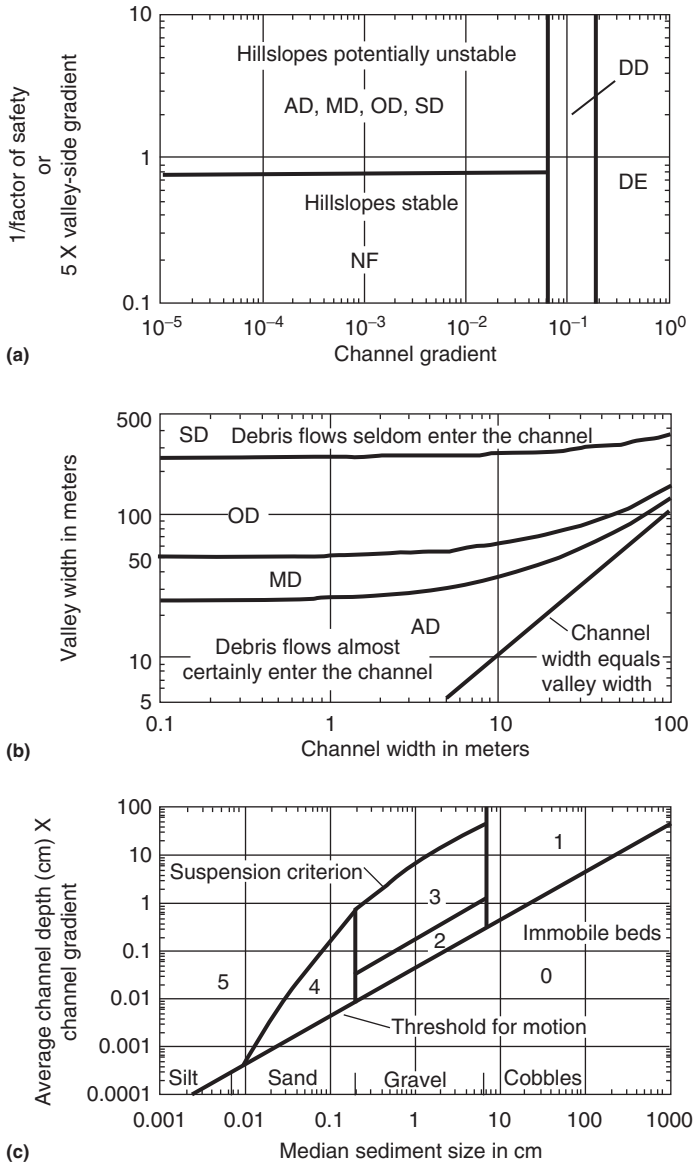


Figure 8 Whiting and Bradley (1993) classification for headwater channels. (a) Assesses the probability of mass wasting adjacent to the channel (side-slope failures AD-SD as defined in (b)) and whether the sediment input deposits within the channel (DD) or scours it as a debris flow (DE). (b) Determines 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.

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

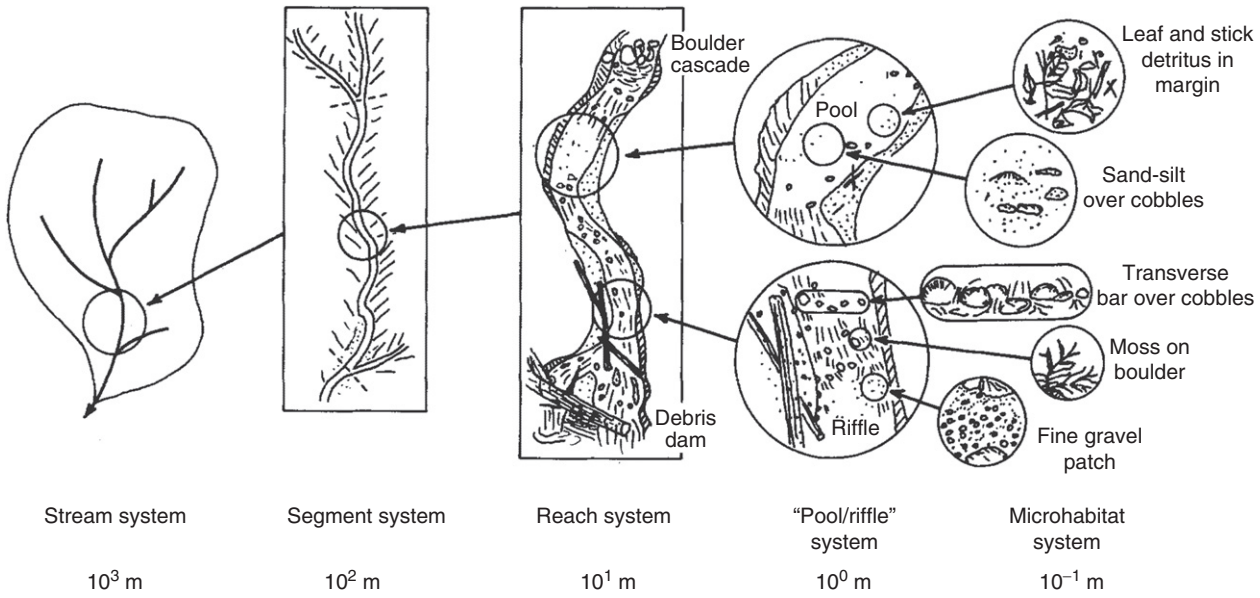


Figure 9 Hierarchical channel classification of Frissell et al. (1986). Reproduced from Frissell, C.A., Liss, W.J., Warren, C.E., Hurley, M.D., 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10, 199–214, with permission from Springer Science + Business Media.

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 streambed 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.

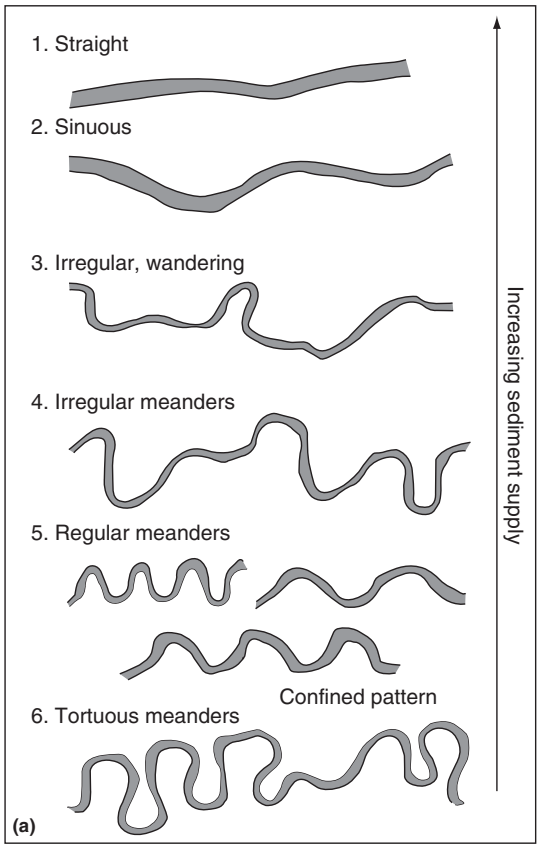
One of the most widely used hierarchical channel classification systems was developed by Rosgen (1985, 1994, 1996b) for mountain basins. His approach involves four scales of analysis, ranging from broad-scale delineation of landform and valley type to small-scale measurements of physical processes (e.g., 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).

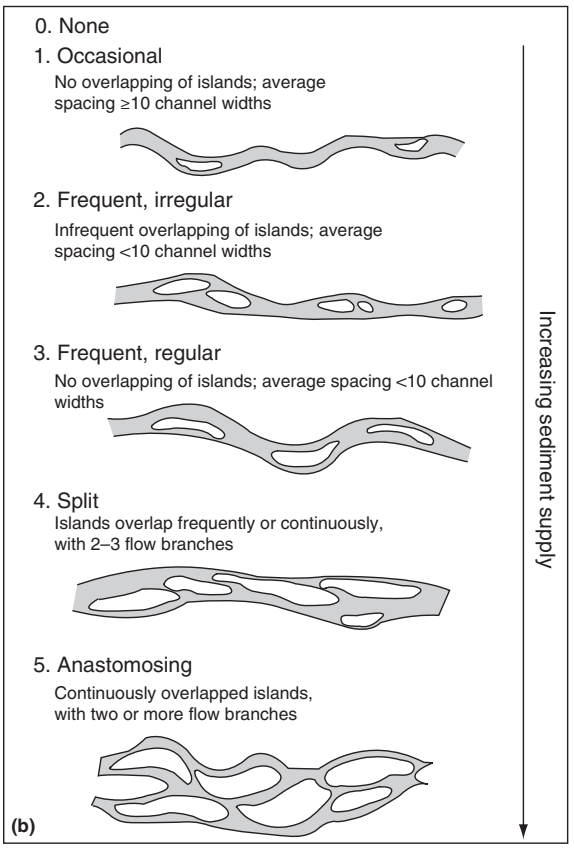
Another widely used hierarchical channel classification for mountain basins was developed by Montgomery and Buffington (1997, 1998) based on synthesis of field observations and prior studies in the geomorphic literature, emphasizing process-based interpretations. Their approach recognizes nested physical scales ranging from geomorphic provinces to channel units, and identifies eight reach-scale morphologies based on visual identification (**Table 2**), with transitional morphologies

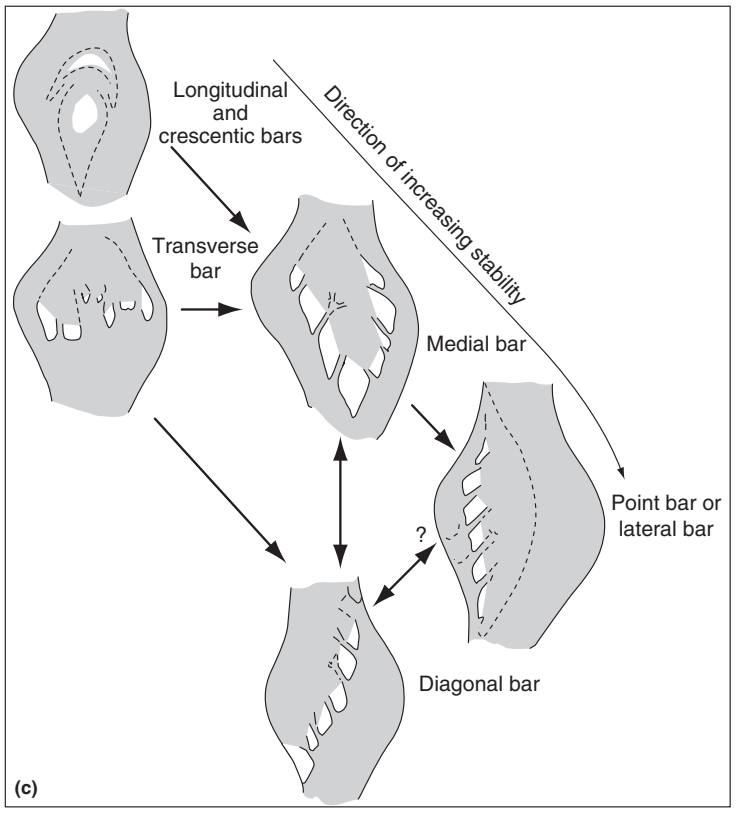
also possible (Montgomery and Buffington, 1997; Gomi et al., 2003). Observed channel morphologies are hypothesized to represent stable conditions for imposed values of valley slope, discharge, and sediment supply (Montgomery and Buffington, 1997; Buffington et al., 2003). A critical aspect of their approach is identification of morphogenic 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 Buffington, 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 Buffington (1997) channel types show basin-specific variability (McDavitt, 2004; Wohl and Merritt, 2005; Flores et al., 2006; Thompson et al., 2006; Addy, 2009).

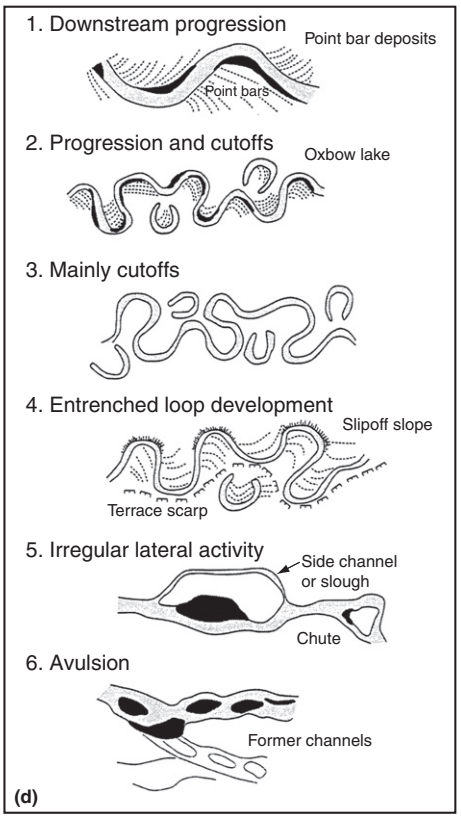
Another more recent hierarchical classification is the river styles framework (Brierley and Fryirs, 2000; 2005; Brierley et al., 2002; Fryirs, 2003; Fryirs and Brierley, 2000), which uses successional (evolutionary) models to assess channel condition and to inform restoration actions. It builds from 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
Confined pattern
6. Tortuous meanders
Increasing sediment supply
(a)


0. None
1. Occasional
No overlapping of islands; average spacing ≥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
(b)


Longitudinal and crescentic bars
Direction of increasing stability
Transverse bar
Medial bar
Point bar or lateral bar
?
Diagonal bar
(c)


1. Downstream progression
Point bar deposits
Point bars
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
(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 entrenchment) are not explicitly accounted for in such comparisons, limiting the cross walk. 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

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.

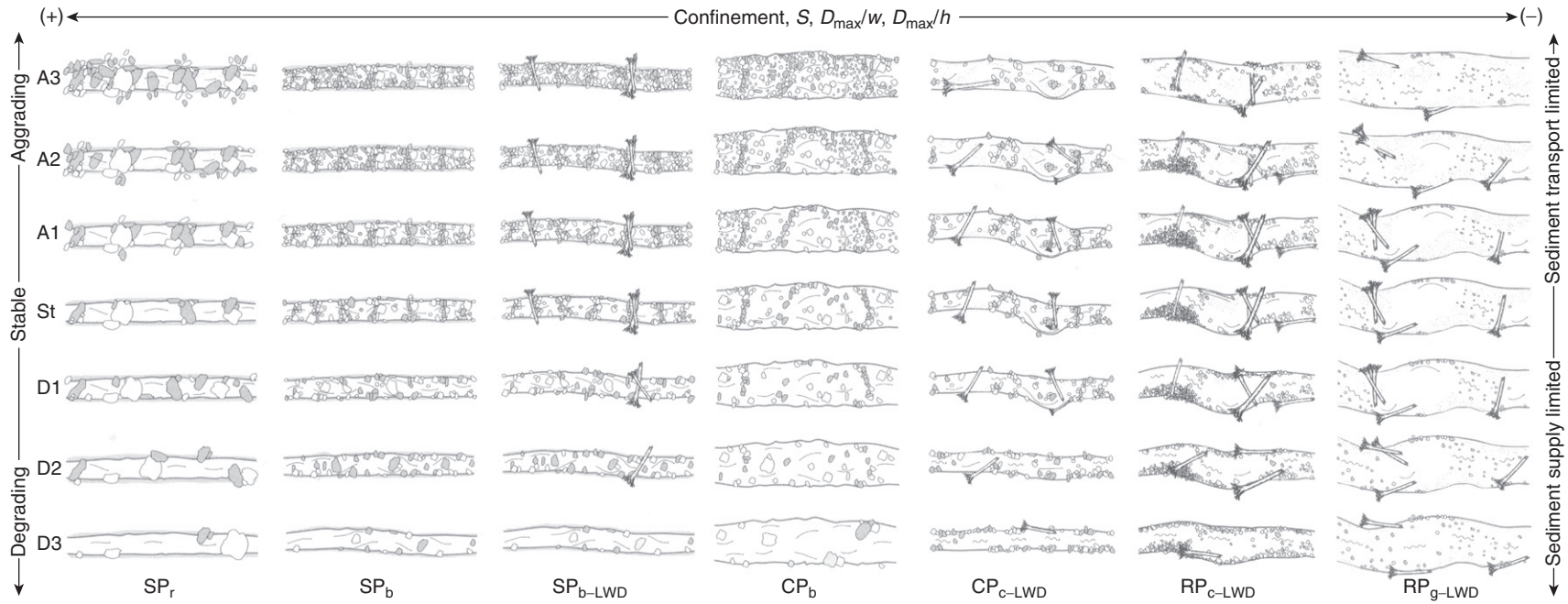


Figure 11 FPC (1996b) classification of small and intermediate channels (bankfull width <20–30 m), showing potential wood loading and surface grain-size characteristics as a function of disturbance (degradation/aggradation, left side of figure) and the corresponding supply- vs. transport-limited conditions (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

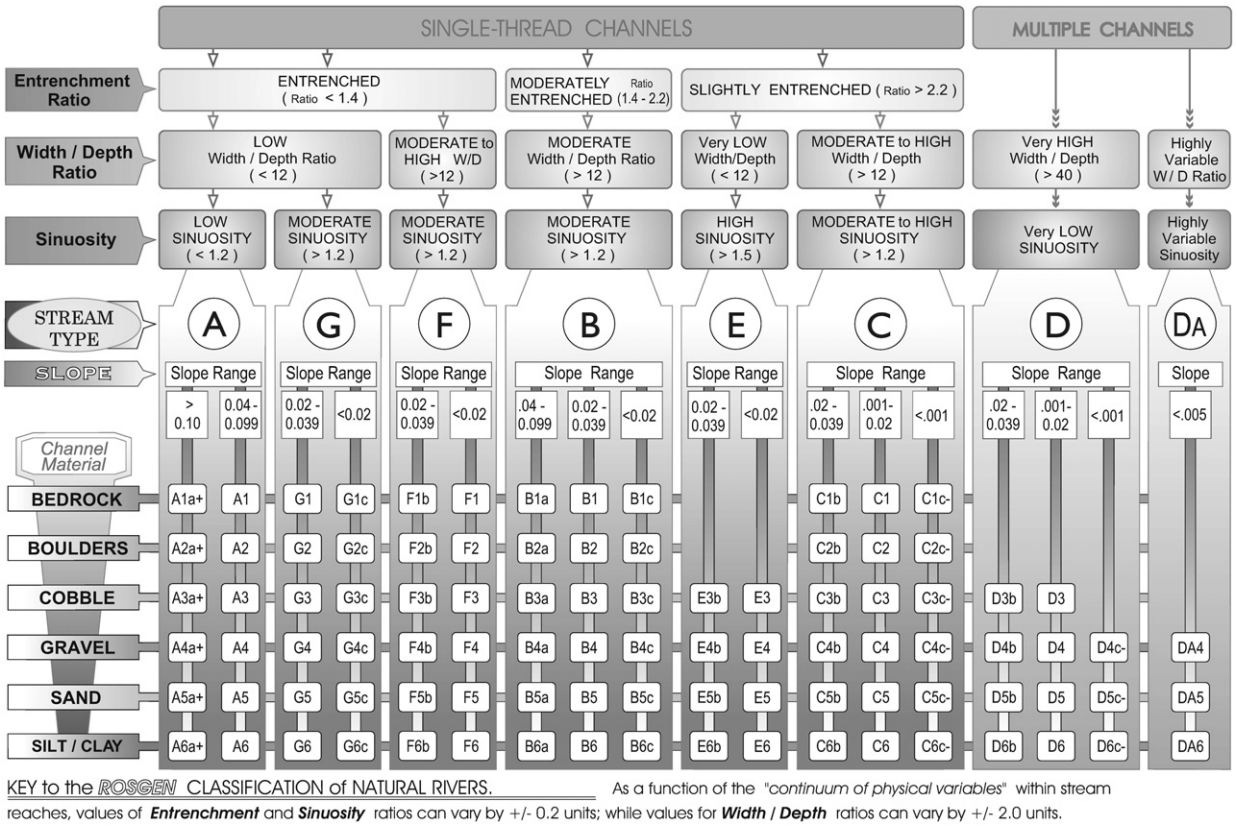


Figure 12 Rosgen (1994, 1996b) stream type classification. Reprinted with permission from Figure 5.3 in Rosgen, D.L., 1996b. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO.

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 C and F stream types (pool-riffle morphology), whereas 40% of the pool-riffle channels are classified as Rosgen B and G 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

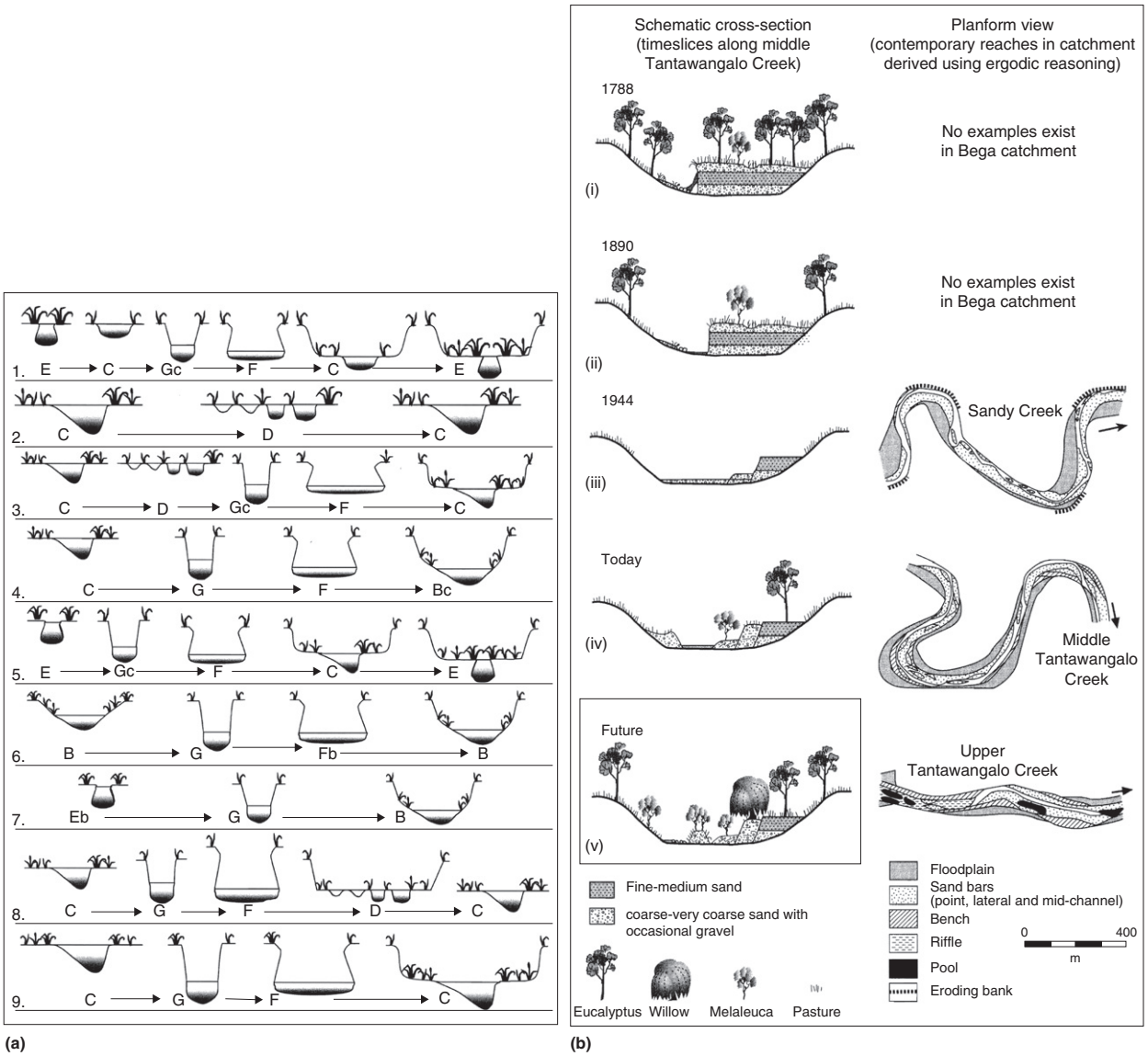


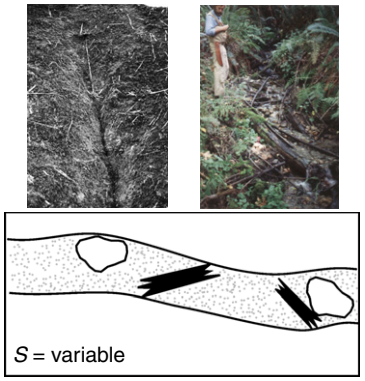
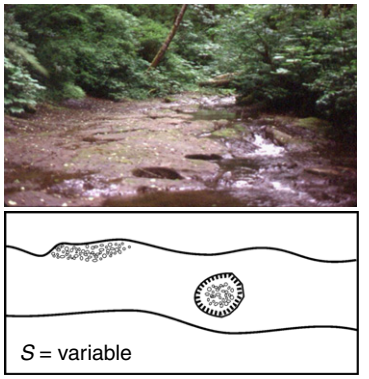
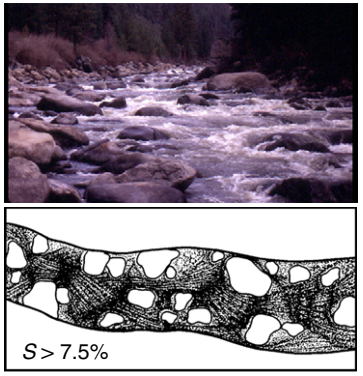
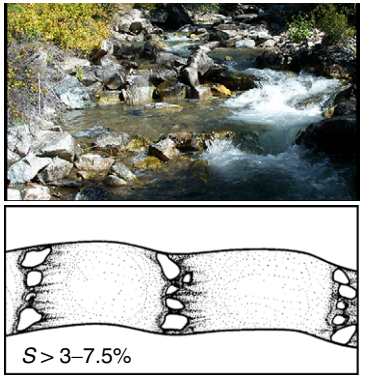
Figure 13 Examples of descriptive stream succession (evolutionary) models developed by (a) Rosgen (2006b) and (b) Brierley and Fryirs (2005). Letters in (a) correspond with Rosgen stream types given in **Figure 12**. Panel (a) reprinted with permission from Figure 2.38 in Rosgen, D.L., 2006b. Watershed Assessment of River Stability and Sediment Supply (WARSSS). Wildland Hydrology, Fort Collins, CO. Panel (b) reproduced from Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell, Oxford, UK, 398 pp., with permission from Blackwell (Wiley).

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.

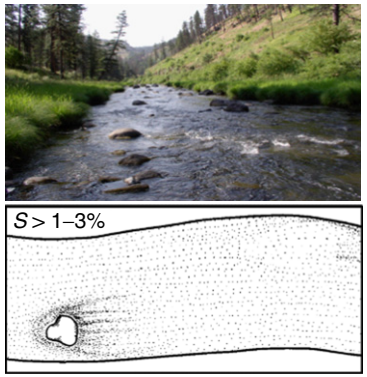
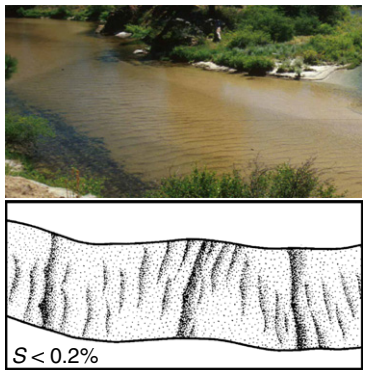
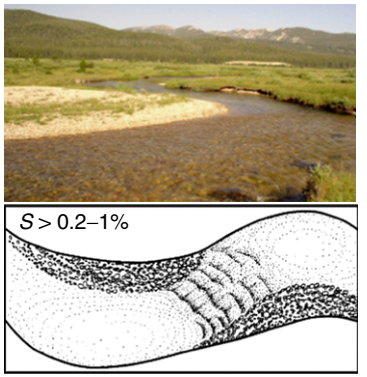
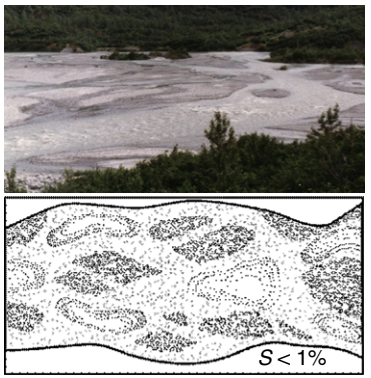
One of the strongest factors governing the use of different classifications may be the value of the classification for one's particular goals. A closely related factor is ease of use. For example, Rosgen's (1994, 1996b) cookbook approach makes it easy to use and, thus, appeals to practitioners and land 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

Table 2 Montgomery and Buffington (1997) stream types

Channel type[a,b]			
	*Colluvial* – 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.		*Bedrock* – 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.
	*Cascade* – 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 ($2.3 < \tau^*_{bf}/\tau^*_{c50} < 4$).[c] 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 ($6 < w/h < 14$) and low values of relative submergence (ratio of bankfull flow depth to median particle size; $3 < h/D_{50} < 7$). May be prone to debris-flow passage.		*Step-pool* – 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 ($1.1 < \tau^*_{bf}/\tau^*_{c50} < 3$). 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 ($9 < w/h < 19$) and low relative submergence ($3 < h/D_{50} < 7$). May be prone to debris-flow passage.

(*Continued*)

Table 2 Continued

Channel type[a,b]	
	*Plane-bed* – 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 ($12 < w/h < 24$) and low relative submergence ($5 < h/D_{50} < 11$) 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 ($1 < \tau^*_{bf}/\tau^*_{c50} < 2$). 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 armoring and shift the effective discharge to smaller, more frequent floods. Susceptible to obstruction-forced pool formation.
	*Dune-ripple* – 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 floodplain 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 ($26 < \tau^*_{bf}/\tau^*_{c50} < 90$). Low roughness due to large width-to-depth ratios ($12 < w/h < 47$) and large relative submergence ($3000 < h/D_{50} < 32000$), but bed form roughness may be significant. Extensive sediment storage in bed forms and floodplain. Photo used with permission, courtesy of Carter Borden.
	*Pool-riffle* – 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 ($15 < w/h < 33$) and large relative submergence ($13 < h/D_{50} < 40$). 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} ($0.9 < \tau^*_{bf}/\tau^*_{c50} < 2.2$), and the bankfull flow is the effective discharge, unless shifted to smaller, more frequent floods by high sediment supplies and reduced armoring. Susceptible to obstruction-forced pool formation.
	*Braided* – Multithread rivers with large width-to-depth ratios ($33 < w/h < 130$) and a wide range of slopes. Bed material may be sand or gravel/cobble, with correspondingly different values of both relative submergence ($14 < h/D_{50} < 64$, gravel; $5000 < h/D_{50} < 11000$, sand) and bed mobility at bankfull flow ($1.2 < \tau^*_{bf}/\tau^*_{c50} < 2.7$, gravel; $23 < \tau^*_{bf}/\tau^*_{c50} < 68$, 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.

[a]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, 2003).

[b]Channel slope (S), bankfull width-to-depth ratio (w/h), relative submergence (h/D_{50}) and excess Shields stress (τ^*_{bf}/τ^*_{c50}) are from data compiled by Buffington (2012). Reported values for w/h, h/D_{50}, and τ^*_{bf}/τ^*_{c50} 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).

[c]The bankfull Shields stress (τ^*_{bf}) is defined as $\tau_{bf}/[(\rho_s - \rho)g\,D_{50}]$, where τ_{bf} is the bankfull shear stress, ρ_s and ρ are the sediment and fluid densities, respectively, and g is the gravitational acceleration. Critical Shields stress (τ^*_{c50}) is determined from Lamb et al. (2008; $\tau^*_{c50} = 0.15S^{0.25}$), 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

River style	*Confinement/land type*	*River character*			*River behavior*
		Channel planform	*Bed material*	*Geomorphic units*	
Steep headwater	Confined/uplands	Single, highly stable channel	Boulder-bed-rock-gravel-sand	Discontinuous floodplain, pools, riffles, glides, runs, vegetated islands	Bedrock channel with a heterogeneous assemblage of geomorphic units. Sediment flushed through the confined valley. Limited ability for lateral adjustment
Gorge	Confined/ escarpment	Single, straight, highly stable channel	Boulder-bedrock	No floodplain, bedrock steps, pools & riffles, cascades	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
Confined valley with occasional flood-plain pockets	Confined/rounded foothills	Single, straight, highly stable channel	Bedrock-sand	Discontinuous pockets of floodplain, extensive bedrock outcrops, sand sheets, pools	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
Partly confined valley, with bedrock-controlled discontinuous floodplain	Partly confined/ rounded foothills and base of escarpment	Single, moderately stable, sinuous channel	Bedrock-sand	Discontinuous floodplain, point bars, point benches and sand sheets, mid-channel bars, pools and riffles, bedrock outcrops	Sinuous valleys. River progressively transfers sediment from point bar to point bar. Sediment accumulation and floodplain formation is restricted primarily to the insides 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
Low-sinuosity boul-der bed	Laterally unconfined/ base of escarpment	Single channel trench consisting of multiple low-flow threads around boulder islands; highly stable	Boulder-bedrock	Fans extend to valley margins. Channel consists of boulder islands, cascades, runs, pools, bedrock steps	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
Intact valley fill	Laterally unconfined/ base of escarpment	No channel	Mud-sand	Continuous, intact swamp	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
Channelized fill	Laterally unconfined/ base of escarpment	Single, straight, unstable channel	Sand	Continuous valley fill, terraces, inset features, sand sheets, sand bars	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
Low-sinuosity sand bed	Laterally unconfined/ lowland floodplain	Single channel, with an anabranching network of low-flow channels; potentially avulsive and unstable	Sand	Continuous floodplain, with backswamps, levees, benches, mid-channel islands and sand bars	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

Source: Reproduced from Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell, Oxford, UK, 398 pp., with permission from Blackwell (Wiley).

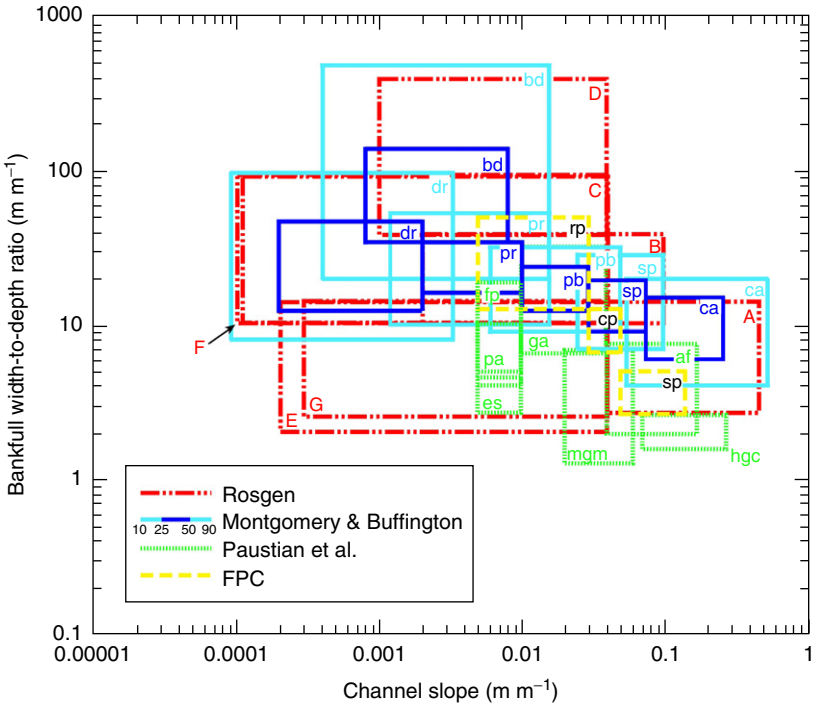


Figure 14 Comparison of typical channel slopes (S) and bankfull width-to-depth ratios (w/h) for several channel classifications developed for mountain rivers in western North America. Values for Rosgen A-G stream types were determined from his Figure 5-3 (Rosgen, 1996b), including allowable variation 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), glacial outwash (ga), 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).

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

Table 4 Expected correspondence between Montgomery and Buffington (1997) and Rosgen (1994, 1996b) channel types

Montgomery and Buffington (1997)	*Rosgen (1994, 1996b)*
Bedrock	A1, possibly G/F/B/C1
Colluvial	A6 with occasional boulders; possibly A3-5
Cascade	A2-3, possibly B2-3
Step-pool	A/G2-3, possibly B2-3
Plane-bed	B3-4
Pool-riffle	C/E/F3-5
Dune-ripple	possibly C/E/F5
Braided	D3-5

Source: Reproduced from Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109, 596–611; Rosgen, D.L., 1994. A classification of natural rivers. Catena 22, 169–199, and Rosgen, D.L., 1996b. Applied River Morphology. Wildland Hydrology, Pagosa, Springs, CO.

Table 5 Observed correspondence between Montgomery and Buffington (1997) and Rosgen (1994, 1996b) channel types

Rosgen	*Montgomery and Buffington*						
	Bedrock	*Cascade*	*Step-pool*	*Plane-bed*	*Pool-riffle*	*Dune-ripple*	*Braided*
Northern California (Butt, 1999)							
A	12[a]	82	51	13	4	3	
B		1	35	46	23	3	
C			1	5	52	16	
D						7	10
E			4	9	27	12	
F		1	5	17	25	15	
G	1		5	6	4	2	
Southeastern Oregon (Roper et al., 2008; Buffington et al., 2009)[b,c]							
A			3				
B			18	11	6		
C				6	8		
E					3		
F				4	1		
G					2		
Northern Idaho (Whiting et al., 1999)[c]							
A			1	1			
B			2	11			
C			1	5	2		
Northern Utah (McDavitt, 2004)[c]							
A			1	1			
B			2	2	1		
Northwestern Montana (Madsen, 1995)[c]							
A		3	32				
B			27		5	1	
C					32		
E					2	4	
G						1	
Western Washington (Southerland, 2003)[c]							
B					3		
C				1	55		

[a]Shading: dark shading indicates the expected primary correspondence, whereas light shading indicates the expected possible correspondence (**Table 4**).

[b]Data are from individual observations made by the AREMP (Aquatic and Riparian Effectiveness Monitoring Program) and PIBO (PACFISH/INFISH Biological Opinion Monitoring Program) field crews, both of which followed the Rosgen (1996b) method (Buffington et al., 2009). Roper et al.'s (2008) consistency rule was only applied if stream type was not classifiable without Rosgen's (1996b) allowable variation of classification parameters (see **Figure 12** footnote), and if the latter resulted in multiple stream types (see Roper et al. (2008) and Buffington et al. (2009) for further detail).

[c]Rosgen channel types are limited to those observed in each study.

Source: Modified from Butt, A.Z., 1999. Stream channel morphology in the Lake Tahoe basin with a hierarchical framework: a geomorphic perspective. Ph.D. dissertation, University of Nevada, Reno, NV, 355 pp.

by the National Center for Earth-Surface Dynamics (NCED, http://www.nced.umn.edu/).

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;

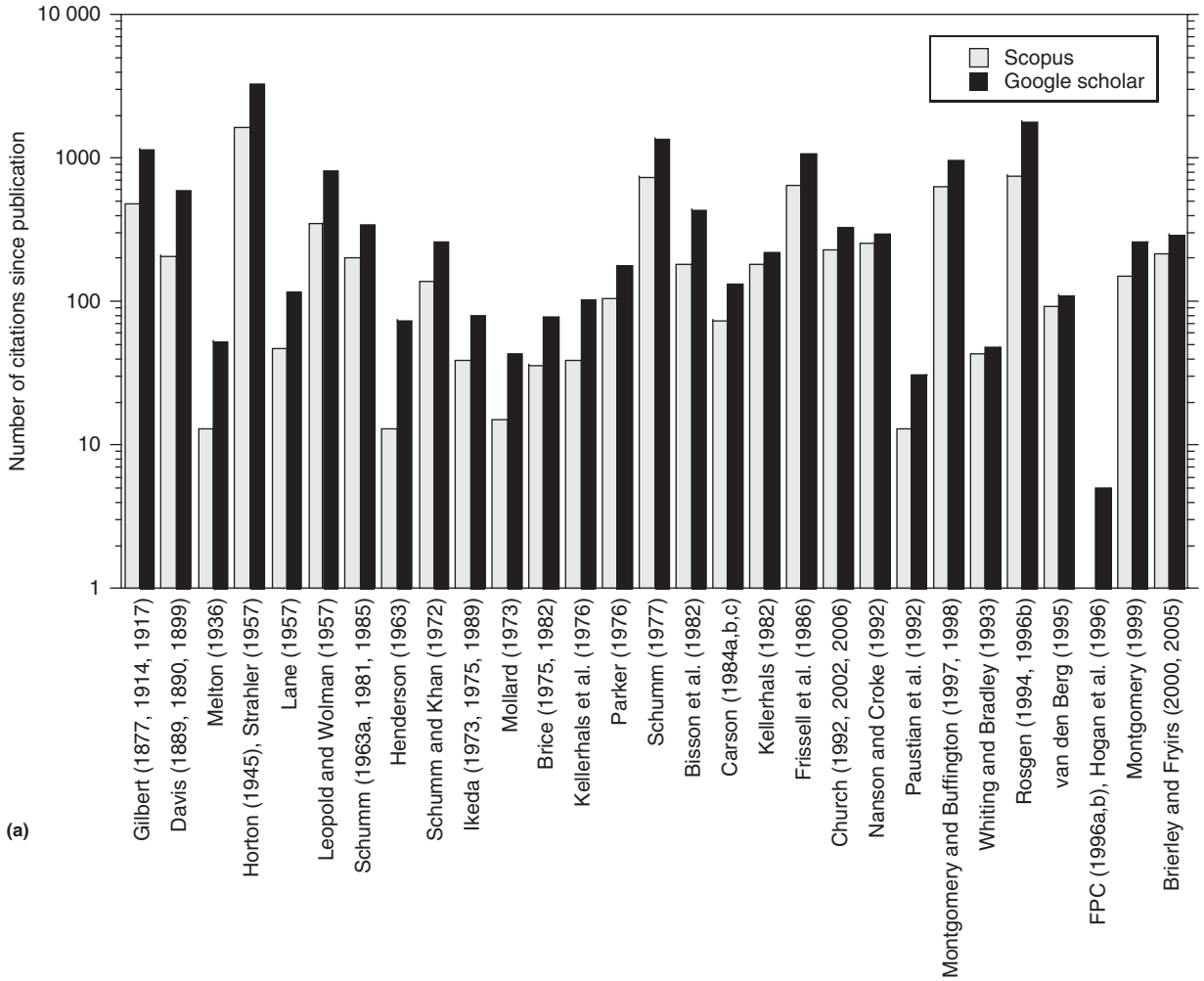
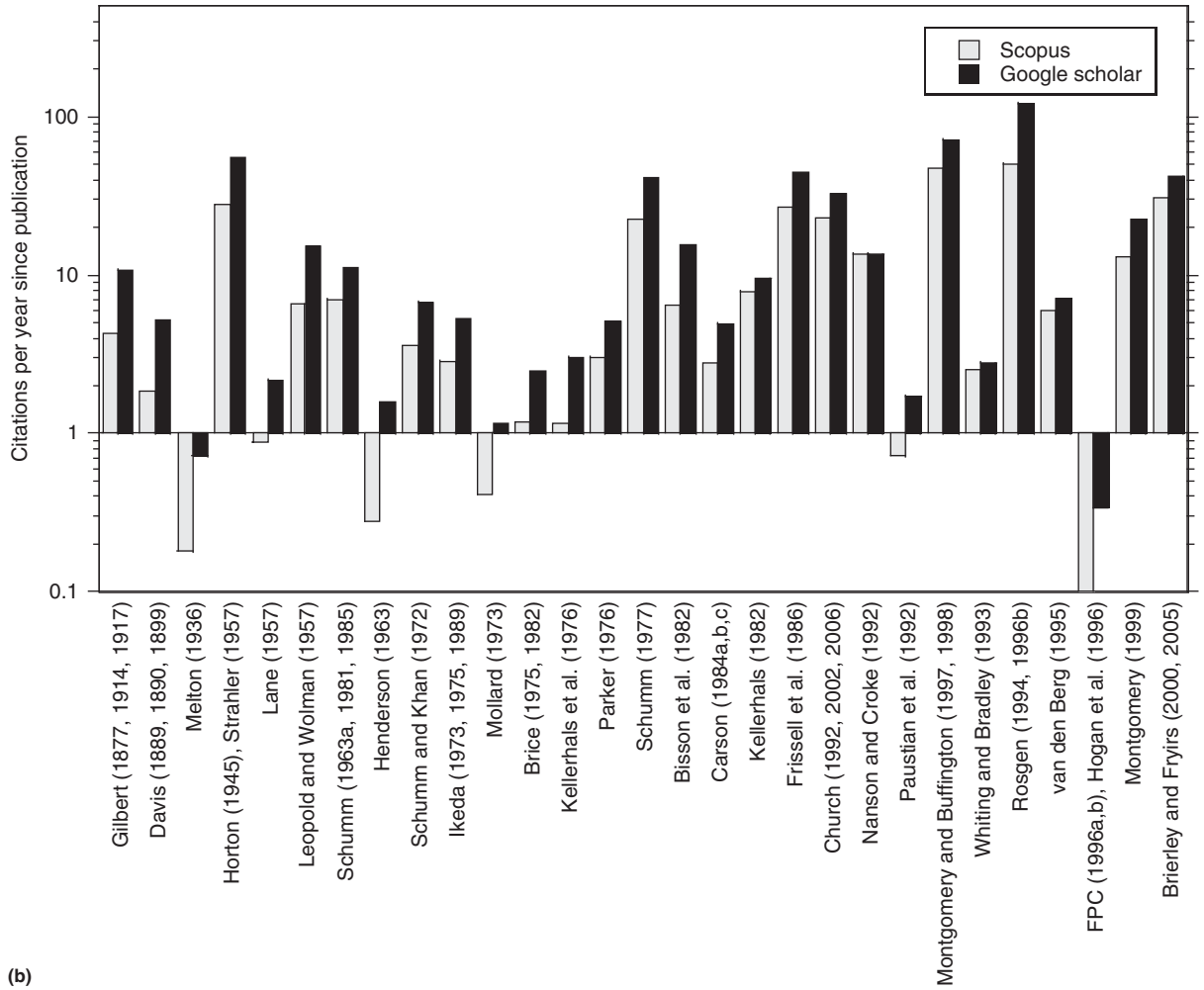


Figure 15 Number of (a) total citations and (b) citations per year since publication for select channel classifications as of 2010. The number of citations is assumed to be correlated with the use of a given classification, but is not an exact measure of use, since citations may also include criticism or discussion of the publication, without actual use of the related classification. Furthermore, these statistics may not include citation within gray literature and contract reports, which may be a more relevant index for use by practioners. Values reported for Schumm (1963a, 1981, 1985) also include Schumm and Meyer (1979); values for Schumm and Khan (1972) include Schumm et al. (1972); values for Ikeda (1973, 1975, 1989) include Florsheim (1985) and Buffington et al. (2003); values for Brice (1975, 1982) include Brice and Blodgett (1978a,b); values for Kellerhals (1982) include Ferguson (1984, 1987), Desloges and Church (1989), and Kellerhals and Church (1989); values for Montgomery and Buffington (1997, 1998) include Montgomery and Buffington (1993), Bisson and Montgomery (1996), and Bisson et al. (2006); and values for Brierley and Fryirs (2000, 2005) include Brierley et al. (2002), Fryirs (2003), and Fryirs and Brierley (2000).

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)



(b)

Figure 15 Continued.

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 (USFS 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.

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References

Addy, S., 2009. Hierarchical controls on river channel morphology in montane catchments in the Cairngorms, Scotland. Ph.D. dissertation, University of Aberdeen, Aberdeen, Scotland, 192 pp.

Allen, J.R.L., 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5, 89–191.

Allmendinger, N.E., Pizzuto, J.E., Potter, N., Johnson, T.E., Hession, W.C., 2005. The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. Geological Society of America Bulletin 117, 229–243.

Altunkaynak, A., Strom, K.B., 2009. A predictive model for reach morphology classification in mountain streams using multilayer perceptron methods. Water Resources Research 45, W12501.

Andrews, E.D., 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geological Society of America Bulletin 95, 371–378.

ASCE, 1998a. River width adjustment. I: Processes and mechanisms. Journal of Hydraulic Engineering 124, 881–902.

ASCE, 1998b. River width adjustment. II. Modeling. Journal of Hydraulic Engineering 124, 903–917.

Ashmore, P., 1999. What would we do without Rosgen? Rational regime relations and natural channels. Second International Conference on Natural Systems Design, Niagara Falls, Canada, CD-ROM.

Barry, J.J., 2007. Bed load transport in gravel-bed rivers. Ph.D. dissertation, University of Idaho, Boise, ID, 164 pp.

Barry, J.J., Buffington, J.M., King, J.G., 2004. A general power equation for predicting bedload transport rates in gravel bed rivers. Water Resources Research 40, W10401.

Barry, J.J., Buffington, J.M., King, J.G., 2007. Correction to "A general power equation for predicting bed load transport rates in gravel bed rivers". Water Resources Research 43, W08702.

Baxter, C.V., Hauer, F.R., 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences 57, 1470–1481.

Beechie, T.J., Liermann, M., Beamer, E.M., Henderson, R., 2005. A classification of habitat types in a large river and their use by juvenile salmonids. Transactions of the American Fisheries Society 134, 717–729.

Beechie, T.J., Liermann, M., Pollock, M.M., Baker, S., Davies, J., 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. Geomorphology 78, 124–141.

Beechie, T.J., Moir, H.J., Pess, G., 2008. Hierarchical physical controls on salmonid spawning location and timing. In: Sear, D.A., DeVries, P. (Eds.), Salmonid Spawning Habitat in Rivers. American Fisheries Society Symposium 65, Bethesda, MD, pp. 83–101.

Beechie, T.J., Sear, D.A., Olden, J.D., et al., 2010. Process-based principles for restoring river ecosystems. BioScience 60, 209–222.

Benda, L., 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surface Processes and Landforms 15, 457–466.

Benda, L., Poff, N.L., Miller, D., Dunne, T., Reeves, G., Pess, G., Pollock, M., 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54, 413–427.

Benda, L., Veldhuisen, C., Black, J., 2003. Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington. Geological Society of America Bulletin 115, 1110–1121.

Bisson, P.A., Montgomery, D.R., 1996. Valley segments, stream reaches, and channel units. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology, First ed. Academic Press, San Diego, CA, pp. 23–52.

Bisson, P.A., Montgomery, D.R., Buffington, J.M., 2006. Valley segments, stream reaches, and channel units. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology, Second ed. Academic Press/Elsevier, San Diego, CA, pp. 23–49.

Bisson, P.A., Nielsen, J.L., Palmason, R.A., Grove, L.E., 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. In: Armantrout, N.B. (Ed.), Proceedings of a Symposium on Acquisition and Utilization of Aquatic Habitat Inventory Information. Western Division of the American Fisheries Society, Bethesda, MD, pp. 62–73.

Bisson, P.A., Sullivan, K., Nielsen, J.L., 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. Transactions of the American Fisheries Society 117, 262–273.

Bledsoe, B.P., Watson, C.C., 2001. Logistic analysis of channel pattern thresholds: meandering, braiding, and incising. Geomorphology 38, 281–300.

Brardinoni, F., Hassan, M.A., 2006. Glacial erosion, evolution of river long profiles, and the organization of process domains in mountain drainage basins of coastal British Columbia. Journal of Geophysical Research-Earth Surface 111, F01013.

Brardinoni, F., Hassan, M.A., 2007. Glacially induced organization of channel-reach morphology in mountain streams. Journal of Geophysical Research-Earth Surface 112, F03013.

Bray, D.I., 1982. Regime equations for gravel-bed rivers. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed Rivers. Wiley, Chichester, UK, pp. 517–552.

Brice, J.C., 1975. Airphoto interpretation of the form and behavior of alluvial rivers. Final report to the U.S. Army Research Office, Durham, NC, Washington University, St. Louis, MO, 10 pp.

Brice, J.C., 1982. Stream channel stability assessment. US Department of Transportation, Federal Highway Administration Report FHWA/RD-82/021, Washington, DC, 42 pp.
Brice, J.C., Blodgett, J.C., 1978a. Countermeasures for Hydraulic Problems at Bridges, Vol. 1, Analysis and Assessment. Federal Highway Administration FHWA/RD-78-162, Washington, DC, 184 pp.
Brice, J.C., Blodgett, J.C., 1978b. Countermeasures for Hydraulic Problems at Bridges, Vol. 2, Case Histories for Sites 1-283. Federal Highway Administration FHWA/RD-78-163, Washington, DC, 554 pp.
Bridge, J.S., 1993. The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geological Society, London, Special Publication 75, pp. 13–71.
Brierley, G.J., Fryirs, K., 2000. River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. Environmental Management 25, 661–679.
Brierley, G.J., Fryirs, K., Outhet, D., Massey, C., 2002. Application of the river styles framework as a basis for river management in New South Wales, Australia. Applied Geography 22, 91–122.
Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell, Oxford, UK, 398 pp.
Brownlie, W.R., 1981. Prediction of flow depth and sediment discharge in open channels. W.M. Keck Laboratory of Hydraulics and Water Resources Report KH-R-43A. California Institute of Technology, Pasadena, CA, 232 pp.
Bryant, M.D., Wright, B.E., Davies, B.J., 1992. Application of a hierarchical habitat unit classification system: stream habitat and salmonid distribution in Ward Creek, southeast Alaska, USDA Forest Service, PNW Research Station, Research Note PNW-RN-508, 18 pp.
Buffington, J.M., 2012. Changes in channel morphology over human time scales. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), Gravel-bed Rivers: Processes, Tools, Environments. Wiley, Chichester, UK, pp. 435–463.
Buffington, J.M., Lisle, T.E., Woodsmith, R.D., Hilton, S., 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18, 507–531.
Buffington, J.M., Montgomery, D.R., 1999a. A procedure for classifying textural facies in gravel-bed rivers. Water Resources Research 35, 1903–1914.
Buffington, J.M., Montgomery, D.R., 1999b. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35, 3507–3522.
Buffington, J.M., Montgomery, D.R., 1999c. Effects of sediment supply on surface textures of gravel-bed rivers. Water Resources Research 35, 3523–3530.
Buffington, J.M., Montgomery, D.R., 2001. Reply to comments on "Effects of hydraulic roughness on surface textures of gravel-bed rivers" and "Effects of sediment supply on surface textures of gravel-bed rivers" by John M. Buffington and David R. Montgomery. Water Resources Research 37, 1529–1533.
Buffington, J.M., Montgomery, D.R., Greenberg, H.M., 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Canadian Journal of Fisheries and Aquatic Sciences 61, 2085–2096.
Buffington, J.M., Roper, B.E., Archer, E., Moyer, C., 2009. Reply to discussion by David L. Rosgen on "The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams". Journal of the American Water Resources Association 45, 1298–1312.
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.
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.
Bunte, K., Abt, S.R., Swingle, K.W., Potyondy, J.P., 2010. Bankfull mobile particle size and its prediction from a Shields-type approach. Proceedings of the 2nd Joint Federal Interagency Conference (9th Federal Interagency Sedimentation Conference, 4th Federal Interagency Hydrologic Modeling Conference), CD-ROM, 27 June–1 July. Las Vegas, NV, http://acwi.gov/sos/pubs/2ndJFIC/.
Butt, A.Z., 1999. Stream channel morphology in the Lake Tahoe basin with a hierarchical framework: a geomorphic perspective. Ph.D. dissertation, University of Nevada, Reno, NV, 355 pp.
Carling, P.A., 1988a. Channel change and sediment transport in regulated U.K. rivers. Regulated Rivers: Research and Management 2, 369–387.
Carling, P., 1988b. The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds. Earth Surface Processes and Landforms 13, 355–367.
Carson, M.A., 1984a. The meandering–braided river threshold: a reappraisal. Journal of Hydrology 73, 315–334.
Carson, M.A., 1984b. Observations on the meandering-braided river transition, The Canterbury Plains, New Zealand: part one. New Zealand Geographer 40, 12–17.
Carson, M.A., 1984c. Observations on the meandering-braided river transition, The Canterbury Plains, New Zealand: part two. New Zealand Geographer 40, 89–99.
Charlton, F.G., Brown, P.M., Benson, R.W., 1978. The hydraulic geometry of some gravel rivers in Britain. Report IT 180, Hydraulics Research Station, Wallingford, UK, 48 pp.
Chin, A., 2006. Urban transformation of river landscapes in a global context. Geomorphology 79, 460–487.
Church, M., 1992. Channel morphology and typology. In: Carlow, P., Petts, G.E. (Eds.), The Rivers Handbook. Blackwell, Oxford, UK, pp. 126–143.
Church, M., 2002. Geomorphic thresholds in riverine landscapes. Freshwater Biology 47, 541–557.
Church, M., 2006. Bed material transport and the morphology of alluvial rivers. Annual Review of Earth and Planetary Sciences 34, 325–354.
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.
Church, M.A., McLean, D.G., Wolcott, J.F., 1987. River bed gravels: sampling and analysis. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel-Bed Rivers. Wiley, Chichester, UK, pp. 43–88.
Collins, B.D., Montgomery, D.R., Sheikh, A.J., 2003. Reconstructing the historical riverine landscape of the Puget Lowland. In: Montgomery, D.R., Bolton, S., Booth, D.B., Wall, L. (Eds.), Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA, pp. 79–128.
Connell, J.H., 1978. Diversity in tropical rain forests and coral reefs. Science 199, 1302–1310.
Cupp, C.E., 1989. Valley segment type classification for forested lands of Washington. Washington State Department of Natural Resources. Timber, Fish, and Wildlife Agreement Report TFW-AM-89-001, Olympia, WA, 44 pp.
Dade, W.B., 2000. Grain size, sediment transport and alluvial channel pattern. Geomorphology 35, 119–126.
Dade, W.B., Friend, P.F., 1998. Grain-size, sediment-transport regime, and channel slope in alluvial rivers. The Journal of Geology 106, 661–675.
Davis, W.M., 1889. The rivers and valleys of Pennsylvania. National Geographic Magazine 1, 183–253.
Davis, W.M., 1890. The rivers of northern New Jersey with notes on the classification of rivers in general. National Geographic Magazine 2, 81–110.
Davis, W.M., 1899. The geographical cycle. Geographical Journal 14, 481–504.
Davis, W.M., 1913. Meandering valleys and underfit rivers. Annals of the Association of American Geographers 3, 3–28.
Desloges, J.R., Church, M.A., 1989. Wandering gravel-bed rivers. The Canadian Geographer 33, 360–364.
Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature 340, 215–217.
Dietrich, W.E., Nelson, P.A., Yager, E., Venditti, J.G., Lamb, M.P., Collins, L., 2006. Sediment patches, sediment supply and channel morphology. In: Parker, G., Garcia, M.H. (Eds.), River, Coastal and Estuarine: Morphodynamics. Taylor and Francis/Balkema, The Netherlands, pp. 79–90.
Dietrich, W.E., Power, M.E., Sullivan, K.O., Montgomery, D.R., 1996. The use of an analytical reference state in watershed analysis. Geological Society of America Abstracts with Programs 28, Cordilleran Section, Abstract 27906A.
Downs, P.W., Gregory, K.J., 2004. River Channel Management. Oxford University Press, New York, 395 pp.
Doyle, M.W., Harbor, J.M., 2000. Discussion of "Evaluation of Rosgen's streambank erosion potential assessment in northeast Oklahoma". Journal of the American Water Resources Association 36, 1191–1192.
Doyle, M.W., Miller, D.E., Harbor, J.M., 2000. Should river restoration be based on classification schemes or process models? Insights from the history of geomorphology. In: Walton, R., Nece, R.E. (Eds.), Proceedings of the 1999 International Water Resources Engineering Conference. Water Resources Publications, Highlands Ranch, CO, CD-ROM.
Dunne, T., Leopold, L.B., 1978. Water in Environmental Planning. Freeman, San Francisco, CA, 818 pp.
Eaton, B., 2006. Bank stability analysis for regime models of vegetated gravel bed rivers. Earth Surface Processes and Landforms 31, 1438–1444.
Eaton, B.C., Church, M., 2007. Predicting downstream hydraulic geometry: a test of rational regime theory. Journal of Geophysical Research-Earth Surface 112, F03025.

Eaton, B.C., Moore, R.D., Giles, T.R., 2010. Forest fire, bank strength and channel instability: the 'unusual' response of Fishtrap Creek, British Columbia. Earth Surface Processes and Landforms 35, 1167–1183.

Epstein, C.M., 2002. Application of Rosgen analysis to the New Jersey Pine Barrens. Journal of the American Water Resources Association 38, 69–78.

Faux, R., Buffington, J.M., Whitley, G., Lanigan, S., Roper, B., 2009. Use of airborne near-infrared LiDAR for determining channel cross-section characteristics and monitoring aquatic habitat in Pacific Northwest rivers: a preliminary analysis. In: Bayer, J.M., Schei, J.L. (Eds.), Remote Sensing Applications for Aquatic Resource Monitoring, Proceedings of the 2008 Annual Conference of the American Society of Photogrammetry and Remote Sensing. Pacific Northwest Aquatic Monitoring Partnership, Cook, WA, pp. 43–60.

Fenneman, N.M., 1906. Floodplains produced without floods. Bulletin of the American Geographical Society 38, 89–91.

Ferguson, R.I., 1984. The threshold between meandering and braided. In: Smith, K.V.H. (Ed.), Proceedings of the First International Conference on Hydraulic Design. Springer-Verlag, New York, pp. 6-15–6-29.

Ferguson, R.I., 1987. Hydraulic and sedimentary controls of channel pattern. In: Richards, K.S. (Ed.), River Channels: Environment and Process. Blackwell, Oxford, UK, pp. 129–158.

Flores, A.N., Bledsoe, B.P., Cuhaciyan, C.O., Wohl, E., 2006. Channel-reach morphology dependence on energy, scale, and hydroclimatic processes with implications for prediction using geospatial data. Water Resources Research 42, W06412.

Florsheim, J.L., 1985. Fluvial requirements for gravel bar formation in northwestern California. M.S. thesis, Humboldt State University, Arcata, CA, 105 pp.

FPC, 1996a. Channel Assessment Procedure Guidebook. Forest Practices Code. British Columbia Ministry of Forests, Vancouver, BC, 37 pp.

FPC, 1996b. Channel Assessment Procedure Field Guidebook. Forest Practices Code. British Columbia Ministry of Forests, Vancouver, BC, 95 pp.

Frissell, C.A., Liss, W.J., Warren, C.E., Hurley, M.D., 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10, 199–214.

Fryirs, K., 2003. Guiding principles for assessing geomorphic river condition: application of a framework in the Bega catchment, South Coast, New South Wales, Australia. Catena 53, 17–52.

Fryirs, K., Brierley, G.J., 2000. A geomorphic approach to the identification of river recovery potential. Physical Geography 21, 244–277.

Fryirs, K., Brierley, G.J., 2010. Antecedent controls on river character and behaviour in partly confined valley settings: upper Hunter catchment, NSW, Australia. Geomorphology 117, 106–120.

García, M.H., 2000. Discussion of "The legend of A.F. Shields" by J.M. Buffington. Journal of Hydraulic Engineering 126, 718–719.

Gilbert, G.K., 1877. Report on the geology of the Henry Mountains. U.S. Geographical and Geological Survey of the Rocky Mountain Region, First ed. Government Printing Office, Washington, DC, 160 pp.

Gilbert, G.K., 1914. The transportation of débris by running water, U.S. Geological Survey Professional Paper 86, Washington, DC, 263 pp.

Gilbert, G.K., 1917. Hydraulic-mining débris in the Sierra Nevada. U.S. Geological Survey Professional Paper 105, Washington, DC, 154 pp.

Gillian, S., 1996. Use and misuse of channel classification. Stream Notes October 1996, 4–5.

Gomez, B., Church, M., 1989. An assessment of bed load sediment transport formulae for gravel bed rivers. Water Resources Research 25, 1161–1186.

Gomi, T., Sidle, R.C., Woodsmith, R.D., Bryant, M.D., 2003. Characteristics of channel steps and reach morphology in headwater streams, southeast Alaska. Geomorphology 51, 225–242.

Goode, J.R., Luce, C.H., Buffington, J.M., 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology 139–140, 1–15.

Goodwin, C.N., 1999. Fluvial classification: neanderthal necessity or needless normalcy. In: Olsen, D.S., Potyondy, J.P. (Eds.), Wildland Hydrology, TPS-99-3. American Water Resources Association, Herndon, VA, pp. 229–236.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geological Society of America Bulletin 102, 340–352.

Gresswell, R.E., Torgersen, C.E., Bateman, D.S., Guy, T.J., Hendricks, S.R., Wofford, J.E.B., 2006. A spatially explicit approach for evaluating relationships among coastal cutthroat trout, habitat, and disturbance in small Oregon streams. In: Hughes, R.M., Wang, L., Seelbach, P.W. (Eds.), Landscape Influences on Stream Habitats and Biological Assemblages. American Fisheries Society Symposium 48, Bethesda, MD, pp. 457–471.

Habersack, H.M., 2000. The river-scaling concept (RSC): a basis for ecological assessments. Hydrobiologia 422/423, 49–60.

Halwas, K.L., Church, M., 2002. Channel units in small high gradient streams on Vancouver Island, British Columbia. Geomorphology 43, 243–256.

Halwas, K.L., Church, M., Richardson, J.S., 2005. Benthic assemblage variation among channel units in high-gradient streams on Vancouver Island, British Columbia. Journal of the North American Benthological Society 24, 478–494.

Hawkes, H.A., 1975. River zonation and classification. In: Whitton, B.A. (Ed.), River Ecology. Blackwell, London, pp. 312–374.

Hawkins, C.P., Hogue, J.N., Decker, L.M., Feminella, J.W., 1997. Channel morphology, water temperature, and assemblage structure of stream insects. Journal of the North American Benthological Society 16, 728–749.

Hawkins, C.P., Kershner, J.L., Bisson, P.A., et al., 1993. A hierarchical approach to classifying stream habitat features. Fisheries 18, 3–12.

Henderson, F.M., 1963. Stability of alluvial channels. American Society of Civil Engineers Transactions 128, 657–720.

Hession, W.C., Pizzuto, J.E., Johnson, T.E., Horwitz, R.J., 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology 31, 147–150.

Hey, R.D., Thorne, C.R., 1986. Stable channels with mobile gravel beds. Journal of Hydraulic Engineering 112, 671–687.

Hoey, T., 1992. Temporal variations in bedload transport rates and sediment storage in gravel-bed rivers. Progress in Physical Geography 6, 319–338.

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.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56, 275–370.

Ikeda, H., 1973. A study on the formation of sand bars in an experimental flume. Geographical Review of Japan 46, 435–451(in Japanese, with English abstract).

Ikeda, H., 1975. On the bed configuration in alluvial channels: Their types and condition of formation with reference to bars. Geographical Review of Japan 48, 712–730(in Japanese, with English abstract).

Ikeda, H., 1989. Sedimentary controls on channel migration and origin of point bars in sand-bedded meandering channels. In: Ikeda, S., Parker, G. (Eds.), River Meandering. American Geophysical Union, Washington, DC, pp. 51–68.

Inoue, M., Nakano, S., 1999. Habitat structure along channel-unit sequences for juvenile salmon: a subunit-based analysis of in-stream landscapes. Freshwater Biology 42, 597–608.

Inoue, M., Nakano, S., Nakamura, F., 1997. Juvenile masu salmon (*Oncorhynchus masou*) abundance and stream habitat relationships in northern Japan. Canadian Journal of Fisheries and Aquatic Science 54, 1331–1341.

IPCC, 2007. Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri, R.K, Reisinger, A. (Eds.), Climate Change 2007. IPCC, Geneva, Switzerland, 104 pp.

Jackson, R.G., 1975. Hierarchical attributes and a unifying model of bed forms composed of cohesionless material and produced by shearing flow. Geological Society of America Bulletin 86, 1523–1533.

Jackson, W.L., Beschta, R.L., 1982. A model of two-phase bedload transport in an Oregon Coast Range stream. Earth Surface Processes and Landforms 7, 517–527.

Jain, V., Fryirs, K., Brierley, G.J., 2008. Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. Geological Society of America Bulletin 120, 127–141.

Johnson, P.A., Fecko, B.J., 2008. Regional channel geometry equations: a statistical comparison for physiographic provinces in the Eastern US. River Research and Applications 24, 823–834.

Juracek, K.E., Fitzpatrick, F.A., 2003. Limitations and implications of stream classification. Journal of the American Water Resources Association 39, 659–670.

Kappesser, G.B., 2002. A riffle stability index to evaluate sediment loading to streams. Journal of the American Water Resources Association 38, 1069–1081.

Kaufmann, P.R., Faustini, J.M., Larsen, D.P., Shirazi, M.A., 2008. A roughness-corrected index of relative bed stability for regional stream surveys. Geomorphology 99, 150–170.

Kaufmann, P.R., Larsen, D.P., Faustini, J.M., 2009. Bed stability and sedimentation associated with human disturbances in Pacific Northwest streams. Journal of the American Water Resources Association 45, 434–459.

Kellerhals, R., 1982. Effect of river regulation on channel stability. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed Rivers. Wiley, Chichester, UK, pp. 685–715.

Kellerhals, R., Bray, D.I., 1971. Sampling procedures for coarse fluvial sediments. Journal of the Hydraulics Division, American Society of Civil Engineers 97, 1165–1180.
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.
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.
Knighton, A.D., Nanson, G.C., 1993. Anastomosis and the continuum of channel pattern. Earth Surface Processes and Landforms 18, 613–625.
Kondolf, G.M., 1994. Geomorphic and environmental effects of instream gravel mining. Landscape and Urban Planning 28, 225–243.
Kondolf, G.M., 1995. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. Aquatic Conservation: Marine and Freshwater Ecosystems 5, 127–141.
Kondolf, G.M., 1998. Lessons learned from river restoration projects in California. Aquatic Conservation: Marine and Freshwater Ecosystems 8, 39–52.
Kondolf, G.M., Montgomery, D.R., Piégay, H., Schmitt, L., 2003. Geomorphic classification of rivers and streams. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. Wiley, Chichester, UK, pp. 171–204.
Kondolf, G.M., Smeltzer, M., Railsback, S.F., 2001. Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. Environmental Management 28, 761–776.
Lamb, M.P., Dietrich, W.E., Venditti, J.G., 2008. Is the critical Shields stress for incipient sediment motion dependent on channel-bed slope? Journal of Geophysical Research-Earth Surface 113, F02008.
Lane, E.W., 1957. A study of the shape of channels formed by natural streams flowing in erodible material. U.S. Army Engineer Division, Missouri River, Corps of Engineers, MRD Sediment Series no. 9, Omaha, NE, 106 pp.
Lave, R., 2008. The Rosgen wars and the shifting political economy of expertise. Ph.D. dissertation, University of California, Berkeley, 251 pp.
Lave, R., 2009. The controversy over natural channel design: substantive explanations and potential avenues for resolution. Journal of the American Water Resources Association 45, 1519–1532.
Lave, R., Doyle, M., Robertson, M., 2010. Privatizing stream restoration in the US. Social Studies of Science 40, 677–703.
Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. U.S. Geological Survey Professional Paper 282-B, Washington, DC, pp. 39–84.
Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco, CA, 522 pp.
Lewin, J., 1978. Floodplain geomorphology. Progress in Physical Geography 2, 408–437.
Li, R., Simons, D.B., Stevens, M.A., 1976. Morphology of cobble streams in small watersheds. Journal of the Hydraulics Division, American Society of Civil Engineers 102, 1101–1117.
Lisle, T.E., 2005. Bed mobility: a key linkage between channel condition and lotic ecosystems. Eos, Transactions, American Geophysical Union 86, Joint Assembly Supplement, Abstract B44B-01.
Lotspeich, F.B., Platts, W.S., 1982. An integrated land-aquatic classification system. North American Journal of Fisheries Management 2, 138–149.
Madsen, S.W., 1995. Channel response associated with predicted water and sediment yield increases in northwest Montana. Ph.D. dissertation, Colorado State University, Fort Collins, CO, 230 pp.
Malakoff, D., 2004. The river doctor. Science 305, 937–939.
Malard, F., Tockner, K., Dole-Olivier, M.-J., Ward, J.V., 2002. A landscape perspective of surface-subsurface hydrological exchanges in river corridors. Freshwater Biology 47, 621–640.
Marcus, W.A., 2012. Remote sensing of the hydraulic environment in gravel-bed rivers. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), Gravel-bed Rivers: Processes, Tools, Environments. Wiley, Chichester, UK, pp. 261–285.
Massong, T.M., Montgomery, D.R., 2000. Influence of lithology, sediment supply, and wood debris on the distribution of bedrock and alluvial channels. Geological Society of America Bulletin 112, 591–599.
Matthes, G.H., 1934. Floods and their economic importance. Transactions, American Geophysical Union 15(2), 427–432.
Maxwell, J.R., Edwards, C.J., Jensen, M.E., Paustian, S.J., Parrott, H., Hill, D.M., 1995. A hierarchical framework of aquatic ecological units in North America (Nearctic Zone), USDA Forest Service, North Central Forest Experiment Station, General Technical Report NC-176, St. Paul, MN, 72 pp.
McDavitt, W.N., 2004. Application of a stream channel classification in a mountainous setting. M.S. thesis, Utah State University, Logan, UT, 109 pp.
McKean, J., Isaak, D., 2009. Improving stream studies with a small-footprint green LiDAR. Eos, Transactions, American Geophysical Union 90, 341–342.
McKean, J.A., Isaak, D.J., Wright, C.W., 2008. Geomorphic controls on salmon nesting patterns described by a new, narrow-beam terrestrial–aquatic lidar. Frontiers in Ecology 6, 125–130.
McKean, J., Nagel, D., Tonina, D., Bailey, P., Wright, C.W., Bohn, C., Nayegandhi, A., 2009. Remote sensing of channels and riparian zones with a narrow-beam aquatic-terrestrial LiDAR. Remote Sensing 1, 1065–1096.
Melton, F.A., 1936. An empirical classification of flood-plain streams. Geographical Review 26, 593–609.
Micheli, E.R., Kirchner, J.W., 2002a. Effects of wet meadow riparian vegetation on streambank erosion. 1. Remote sensing measurements of streambank migration and erodibility. Earth Surface Processes and Landforms 27, 627–639.
Micheli, E.R., Kirchner, J.W., 2002b. Effects of wet meadow riparian vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics. Earth Surface Processes and Landforms 27, 687–697.
Micheli, E.R., Kirchner, J.W., Larsen, E.W., 2004. Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, central Sacramento River, California, USA. River Research and Applications 20, 537–548.
Millar, R.G., 2000. Influence of bank vegetation on alluvial channel patterns. Water Resources Research 36, 1109–1118.
Millar, R.G., Quick, M.C., 1993. Effect of bank stability on geometry of gravel rivers. Journal of Hydraulic Engineering 119, 1343–1363.
Miller, D.J., Burnett, K.M., Benda, L., 2008. Factors controlling availability of spawning habitat for salmonids at the basin scale. In: Sear, D.A., DeVries, P. (Eds.), Salmonid Spawning Habitat in Rivers. American Fisheries Society Symposium 65, Bethesda, MD, pp. 103–120.
Miller, J.R., Ritter, J.B., 1996. An examination of the Rosgen classification of natural rivers. Catena 27, 295–299.
Milner, V.S., 2010. Assessing the performance of morphologically based river typing in Scotland using a geomorphological and ecological approach. Ph.D. dissertation, University of Sterling, Sterling, Scotland, 318 pp.
Moir, H.J., Gibbins, C.N., Buffington, J.M., Webb, J.H., Soulsby, C., Brewer, M.J., 2009. A new method to identify the fluvial regimes used by spawning salmonids. Canadian Journal of Fisheries and Aquatic Sciences 66, 1404–1408.
Moir, H.J., Gibbins, C.N., Soulsby, C., Webb, J., 2004. Linking channel geomorphic characteristics to spatial patterns of spawning activity and discharge use by Atlantic salmon (*Salmo salar* L.). Geomorphology 60, 21–35.
Moir, H.J., Gibbins, C.N., Soulsby, C., Webb, J.H., 2006. Discharge and hydraulic interactions in contrasting channel morphologies and their influence on site utilization by spawning Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 63, 2567–2585.
Moir, H.J., Soulsby, C., Youngson, A.F., 2002. Hydraulic and sedimentary controls on the availability and use of Atlantic salmon (*Salmo salar*) spawning habitat in the River Dee system, north-east Scotland. Geomorphology 45, 291–308.
Mollard, J.D., 1973. Air photo interpretation of fluvial features. Fluvial Processes and Sedimentation. National Research Council of Canada, Ottawa, ON, pp. 341–380.
Montgomery, D.R., 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35, 397–410.
Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M., Stock, J.D., 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381, 587–589.
Montgomery, D.R., Beamer, E.M., Pess, G.R., Quinn, T.P., 1999. Channel type and salmonid spawning distribution and abundance. Canadian Journal of Fisheries and Aquatic Sciences 56, 377–387.
Montgomery, D.R., Bolton, S.M., 2003. Hydrogeomorphic variability and river restoration. In: Wissmar, R.C., Bisson, P.A. (Eds.), Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural Systems. American Fisheries Society, Bethesda, MD, pp. 39–80.
Montgomery, D.R., Buffington, J.M., 1993. Channel classification, prediction of channel response, and assessment of channel condition. Washington State Department of Natural Resources. Timber, Fish, and Wildlife Agreement Report TFW-SH10-93-002, Olympia, WA, 84 pp.
Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109, 596–611.
Montgomery, D.R., Buffington, J.M., 1998. Channel processes, classification, and response. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management. Springer-Verlag, New York, pp. 13–42.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., Pess, G., 1995. Pool spacing in forest channels. Water Resources Research 31, 1097–1105.
Montgomery, D.R., Collins, B.D., Buffington, J.M., Abbe, T.B., 2003. Geomorphic effects of wood in rivers. In: Gregory, S., Boyer, K., Gurnell, A.M. (Eds.), The Ecology and Management of Wood in World Rivers. American Fisheries Society, Bethesda, MD, pp. 21–47.
Montgomery, D.R., Dietrich, W.E., Sullivan, K., 1998. The role of GIS in watershed analysis. In: Lane, S.N., Richards, K.S., Chandler, J.H. (Eds.), Landform Monitoring, Modelling, and Analysis. Wiley, Chichester, UK, pp. 241–261.
Montgomery, D.R., Foufoula-Georgiou, E., 1993. Channel network source representation using digital elevation models. Water Resources Research 29, 3925–3934.
Morisawa, M., 1968. Streams: Their Dynamics and Morphology. McGraw-Hill, New York, 175 pp.
Morisawa, M.E., 1957. Accuracy of determination of stream lengths from topographic maps. Transactions, American Geophysical Union 38, 86–88.
Mosley, M.P., 1987. The classification and characterization of rivers. In: Richards, K.S. (Ed.), River Channels, Environment and Process. Blackwell, Oxford, pp. 295–320.
Mosselman, E., 1998. Morphological modelling of rivers with erodible banks. Hydrological Processes 12, 1357–1370.
Naiman, R.J., 1998. Biotic stream classification. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management. Springer-Verlag, New York, pp. 97–119.
Naiman, R.J., Lonzarich, D.G., Beechie, T.J., Ralph, S.C., 1992. General principles of classification and the assessment of conservation potential in rivers. In: Boon, P.J., Calow, P., Petts, G.E. (Eds.), River Conservation and Management. Wiley, Chichester, UK, pp. 93–123.
Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology 4, 459–486.
Newson, M.D., Clark, M.J., Sear, D.A., Brookes, A., 1998. The geomorphological basis for classifying rivers. Aquatic Conservation: Marine and Freshwater Ecosystems 8, 415–430.
Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408.
Omernik, J.M., 2003. The misuse of hydrologic unit maps for extrapolation, reporting, and ecosystem management. Journal of the American Water Resources Association 39, 563–573.
Osterkamp, W.R., 1978. Gradient, discharge, and particle-size relations of alluvial channels in Kansas, with observations on braiding. American Journal of Science 278, 1253–1268.
Parfit, M., 1993. Restoration: new ideas, new understanding, new hope. National Geographic Magazine 184 (5), Special Edition, Water: the power, promise, and turmoil of North America's fresh water, pp. 108–119.
Parker, G., 1976. On the cause and characteristic scales of meandering and braiding in rivers. Journal of Fluid Mechanics 76, 457–480.
Parker, G., 1978. Self-formed straight rivers with equilibrium banks and mobile bed. Part 2. The gravel river. Journal of Fluid Mechanics 89, 127–146.
Parker, G., Toro-Escobar, C.M., Ramey, M., Beck, S., 2003. Effect of floodwater extraction on mountain stream morphology. Journal of Hydraulic Engineering 129, 885–895.
Paustian, S.J., Anderson, K., Blanchet, D., et al., 1992. A channel type user guide for the Tongass National Forest, southeast Alaska. USDA Forest Service, Alaska Region, Technical Paper R10-TP-26, 179 pp.
Piégay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Research and Applications 21, 773–789.
Piégay, H., Schumm, S.A., 2003. System approaches in fluvial geomorphology. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. Wiley, Chichester, UK, pp. 105–134.
Poole, G.C., 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. Freshwater Biology 47, 641–660.
Poole, G.C., Stanford, J.A., Running, S.W., Frissell, C.A., Woessner, W.W., Ellis, B.K., 2004. A patch hierarchy approach to modeling surface and subsurface hydrology in complex flood-plain environments. Earth Surface Processes and Landforms 29, 1259–1274.
Powell, J.W., 1875. Exploration of the Colorado River of the west and its tributaries. Government Printing Office, Washington, DC, 291 pp.
Powell, J.W., 1896. Physiographic features. In: Powell, J.W. (Ed.), Physiography of the United States, National Geographic Society Monographs. American Book Co., New York, pp. 33–64.
Revenga, C., Brunner, J., Henninger, N., Payne, R., Kassem, K., 2000. Pilot analysis of global ecosystems: freshwater systems. World Resources Institute, Washington, DC, 65 pp.
Rice, S., Church, M., 1996. Bed material texture in low order streams on the Queen Charlotte Islands, British Columbia. Earth Surface Processes and Landforms 21, 1–18.
Rice, S.P., Greenwood, M.T., Joyce, C.B., 2001a. Macroinvertebrate community changes at coarse sediment recruitment points along two gravel bed rivers. Water Resources Research 37, 2793–2803.
Rice, S.P., Greenwood, M.T., Joyce, C.B., 2001b. Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrate fauna along river systems. Canadian Journal of Fisheries and Aquatic Sciences 58, 824–840.
Rice, S.P., Kiffney, P., Greene, C., Pess, G.R., 2008. The ecological importance of tributaries and confluences. In: Rice, S.P., Roy, A.G., Rhoads, B.L. (Eds.), River Confluences, Tributaries and the Fluvial Network. Wiley, Chichester, UK, pp. 209–242.
Rieman, B.E., Dunham, J.B., 2000. Metapopulations and salmonids: a synthesis of life history patterns and empirical observations. Ecology of Freshwater Fish 9, 51–64.
Rinaldi, M., Darby, S.E., 2008. Modelling river-bank-erosion processes and mass failure mechanisms: progress towards fully coupled simulations. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Gravel-bed Rivers VI: From Process Understanding to River Restoration. Elsevier, Amsterdam, pp. 213–239.
Roper, B.B., Buffington, J.M., Archer, E., Moyer, C., Ward, M., 2008. The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams. Journal of the American Water Resources Association 44, 417–427.
Roper, B.B., Buffington, J.M., Bennett, S., et al., 2010. A comparison of the performance and compatibility of protocols used by seven monitoring groups to measure stream habitat in the Pacific Northwest. North American Journal of Fisheries Management 30, 565–587.
Rosgen, D.L., 1985. A stream classification system, Riparian Ecosystems and Their Management: Reconciling Conflicting Uses. Rocky Mountain Forest and Range Experiment Station RM-120, Fort Collins, CO, pp. 91–95.
Rosgen, D.L., 1994. A classification of natural rivers. Catena 22, 169–199.
Rosgen, D.L., 1996a. A classification of natural rivers: reply to the comments by J. R. Miller and J. B. Ritter. Catena 27, 301–307.
Rosgen, D.L., 1996b. Applied River Morphology. Wildland Hydrology, Pagosa, Springs, CO.
Rosgen, D.L., 2003. Applied river morphology. Ph.D. dissertation, University of East Anglia, Norwich, Norfolk, UK, 27 pp., plus appendices.
Rosgen, D.L., 2006a. The application of stream classification using the fluvial geomorphology approach for natural channel design: the rest of the story. In: Graham, R. (Ed.), World Environmental and Water Resource Congress 2006: Examining the Confluence of Environmental and Water Resource Concerns. American Society of Civil Engineers, New York, CD-ROM.,
Rosgen, D.L., 2006b. Watershed Assessment of River Stability and Sediment Supply (WARSSS). Wildland Hydrology, Fort Collins, CO.
Rosgen, D.L., 2008. Discussion of "Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel responses". Journal of the American Water Resources Association 44, 782–792.
Rosgen, D.L., 2009. Discussion of "The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams". Journal of the American Water Resources Association 45, 1290–1297.
Schmitt, L., Maire, G., Nobelis, P., Humbert, J., 2007. Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. Earth Surface Processes and Landforms 32, 1726–1747.
Schumm, S.A., 1960. The shape of alluvial channels in relation to sediment type. U.S. Geological Survey Professional Paper 352-B, Washington, DC, pp. 17–30.
Schumm, S.A., 1963a. A Tentative Classification of Alluvial River Channels. U.S. Geological Survey Circular 477, Washington, DC, 10 pp.
Schumm, S.A., 1963b. Sinuosity of alluvial rivers on the Great Plains. Geological Society of America Bulletin 74, 1089–1100.
Schumm, S.A., 1968. Speculations concerning paleohydrologic controls of terrestrial sedimentation. Geological Society of America Bulletin 79, 1573–1588.
Schumm, S.A., 1971a. Fluvial geomorphology: channel adjustment and river metamorphosis. In: Shen, H.W. (Ed.), River Mechanics. H.W. Shen, Fort Collins, CO, pp. 5-1–5-22.
Schumm, S.A., 1971b. Fluvial geomorphology: the historical perspective. In: Shen, H.W. (Ed.), River Mechanics. H.W. Shen, Fort Collins, CO, pp. 4-1–4-29.
Schumm, S.A., 1977. The Fluvial System. Blackburn Press, Caldwell, NJ, 338 pp.
Schumm, S.A., 1981. Evolution and response of the fluvial system, sedimentological implications. In: Ethridge, F.G., Flores, R.M. (Eds.), Recent and

Nonmarine Depositional Environments. SEPM (Society for Sedimentary Geology), Special Publication 31, Tulsa, OK, pp. 19–29.
Schumm, S.A., 1985. Patterns of alluvial rivers. Annual Review of Earth and Planetary Sciences 13, 5–27.
Schumm, S.A., Khan, H.R., 1972. Experimental study of channel patterns. Geological Society of America Bulletin 83, 1755–1770.
Schumm, S.A., Khan, H.R., Winkley, B.R., Robbins, L.B., 1972. Variability of river patterns. Nature 237, 75–76.
Schumm, S.A., Meyer, D.F., 1979. Morphology of alluvial rivers of the Great Plains. In: Riparian and Wetland Habitats of the Great Plains. Proceedings of the 31st Annual Meeting, Forestry Committee. Great Plains Agricultural Council Publication 91, Lincoln, NE, pp. 9–14.
Seaber, P.R., Kapinos, F.P., Knapp, G.L., 1987. Hydrologic unit maps. U.S. Geological Survey Water-Supply Paper 2294, Denver, CO, 63 pp.
Shen, H.W., Schumm, S.A., Doehring, D.O., 1979. Stability of stream channel patterns. Transportation Research Record 736, 22–28.
Shields, A., 1936. Anwendung der Ähnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. Mitteilungen der Preußischen Versuchsanstalt für Wasserbau und Schiffbau 26, 1–26 (in German).
Simon, A., Bennett, S.J., Castro, J.M. (Eds.), 2011. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. American Geophysical Union, Washington, DC, 544 pp.
Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27, 527–546.
Simon, A., Doyle, M., Kondolf, M., Shields, F.D., Rhoads, B., McPhillips, M., 2007. Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response. Journal of the American Water Resources Association 43, 1117–1131.
Simon, A., Doyle, M., Kondolf, M., Shields, F.D., Rhoads, B., McPhillips, M., 2008. Reply to discussion by Dave Rosgen, "Critical evaluation of how the Rosgen classification and associated 'natural channel design' methods fail to integrate and quantify fluvial processes and channel responses". Journal of the American Water Resources Association 44, 793–802.
Simons, D.B., 1963. Discussion of "Stability of alluvial channels" by F.M. Henderson. American Society of Civil Engineers Transactions 128, 698–705.
Smartt, P.F.M., Grainger, J.E.A., 1974. Sampling for vegetation survey: some aspects of the behaviour of unrestricted, restricted, and stratified techniques. Journal of Biogeography 1, 193–206.
Smith, D.G., 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geological Society of America Bulletin 87, 857–860.
Smith, S.M., Prestegaard, K.L., 2005. Hydraulic performance of a morphology-based stream channel design. Water Resources Research 41, W11413.
Snelder, T.H., Biggs, B.J.F., 2002. Multiscale river environment classification for water resources management. Journal of the American Water Resources Association 38, 1225–1239.
Snyder, N.P., 2009. Studying stream morphology with airborne laser elevation data. Eos, Transactions, American Geophysical Union 90, 45–46.
Southerland, W. B., 2003. Stream geomorphology and classification in glacial-fluvial valleys of the north Cascade Mountain Range in Washington State. Ph.D. dissertation, Washington State University, Pullman, WA, 129 pp.
Stanford, J.A., 2006. Landscapes and riverscapes. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology. Academic Press, San Diego, CA, pp. 3–21.
Stevens, D.L., Olsen, A.R., 2004. Spatially balanced sampling of natural resources. Journal of the American Statistical Association 99, 262–278.
Stevens, M.A., Simons, D.B., Richardson, E.V., 1975. Nonequilibrium river form. Journal of the Hydraulics Division American Society of Civil Engineers 101, 557–566.
Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions, American Geophysical Union 38, 913–920.
Sullivan, K., 1986. Hydraulics and fish habitat in relation to channel morphology. Ph.D. dissertation, Johns Hopkins University, Baltimore, MD, 407 pp.
Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326.
Thompson, C.J., Croke, J., Ogden, R., Wallbrink, P., 2006. A morpho-statistical classification of mountain stream reach types in southeastern Australia. Geomorphology 81, 43–65.
Thompson, C.J., Croke, J., Takken, I., 2008. A catchment-scale model of mountain stream channel morphologies. Geomorphology 95, 119–144.
Thorne, C.R., 1997. Channel types and morphological classification. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), Applied Fluvial Geomorphology for River Engineering and Management. Wiley, Chichester, UK, pp. 175–222.
Thorp, J.H., Thoms, M.C., Delong, M.D., 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Research and Applications 22, 123–147.
Trimble, S.W., 1997. Stream channel erosion and change resulting from riparian forests. Geology 25, 467–469.
USFS and ESSA, 2010. River bathymetry toolkit (RBT), http://www.fs.fed.us/rm/boise/AWAE/projects/river_bathymetry_toolkit.shtml.
van den Berg, J.H., 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology 12, 259–279.
Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37, 130–137.
Varnes, D.J., 1958. Landslide types and processes. Highway Research Board Special Report 29, Washington, DC, pp. 20–47.
Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319, 299–304.
Whiting, P.J., Bradley, J.B., 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18, 603–612.
Whiting, P.J., Stamm, J.F., Moog, D.B., Orndorff, R.L., 1999. Sediment transporting flows in headwater streams. Geological Society of America Bulletin 111, 450–466.
Wilcock, P.R., McArdell, B.W., 1993. Surface-based fractional transport rates: mobilization thresholds and partial transport of a sand–gravel sediment. Water Resources Research 29, 1297–1312.
Wilkerson, G.V., 2008. Improved bankfull discharge prediction using 2-year recurrence-period discharge. Journal of the American Water Resources Association 44, 243–258.
Wilkins, B.C., Snyder, N.P., 2011. Geomorphic comparison of two Atlantic coastal rivers: toward an understanding of physical controls on Atlantic salmon habitat. River Research and Applications 27, 135–156.
Wohl, E., 2000. Mountain Rivers. American Geophysical Union, Water Resources Monograph 14, Washington, DC, 320 pp.
Wohl, E., Madsen, S., MacDonald, L., 1997. Characteristics of log and clast bed-steps in step-pool streams of northwestern Montana. Geomorphology 20, 1–10.
Wohl, E., Merritt, D., 2005. Prediction of mountain stream morphology. Water Resources Research 41, W08419.
Wolman, M.G., 1954. A method of sampling coarse bed material. Transactions, American Geophysical Union 35, 951–956.
Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68, 54–74.
Wood-Smith, R.D., Buffington, J.M., 1996. Multivariate geomorphic analysis of forest streams: implications for assessment of land use impact on channel condition. Earth Surface Processes and Landforms 21, 377–393.
Zimmermann, A., Church, M., 2001. Channel morphology, gradient profiles and bed stress during flood in a step-pool channel. Geomorphology 40, 311–327.
Zimmermann, A., Church, M., Hassan, M.A., 2008. Identification of steps and pools from stream longitudinal profile data. Geomorphology 102, 395–406.

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

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

Kellerhals (1982), Ferguson (1984; 1987), Desloges and Church (1989), Kellerhals and Church (1989), Church (1992; 2002): *S–Q* domains for braided vs. wandering vs. meandering channels, stratified by sand vs. gravel/cobble beds	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	"		✓
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)	Small to large rivers, with cobble to silt beds of various slope; literature synthesis & worldwide compilation	"	✓	✓
Millar (2000): *S–QD* domains for braided vs. meandering channels stratified by vegetative bank strength; derived, in part, from Parker (1976)	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	"	✓	
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	Moderate-slope (10^{-2} to 10^{-3}), laboratory sand-bed channels	"		✓
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	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)	"	✓	
Excess shear velocity (u_*/u_{*c}) & 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	Laboratory sand-bed channels & small to large, floodplain rivers, with cobble to sand beds, moderate to low slopes (10^{-2} to 10^{-5}) & variable confinement; Japan	"		✓
Florsheim (1985): Extension of Ikeda framework to bar formation & reach type in mountain rivers (plane-bed, alternate bars without pools, pool-riffle, step-pool)	Small- to medium-sized, gravel/cobble-bed rivers, with variable confinement & steep to moderate slopes (10^{-1} to 10^{-3}); northern California	Reach		✓
Buffington et al. (2003): Domains for Montgomery and Buffington (1997) alluvial channel types, including braided rivers	Small to large rivers, with boulder to gravel beds, steep to low slopes (10^{-1} to 10^{-4}) & variable confinement; data compilation from conterminous western U.S., Alaska, Scotland & Norway	Reach to valley		✓
van den Berg (1995): Stream power–grain size threshold for braided vs. meandering channels	Small to large, floodplain rivers, with cobble to sand beds, moderate to low slopes (10^{-2} to 10^{-4}) & variable confinement; worldwide compilation	"		✓
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	Small to large rivers, with boulder to sand beds, steep to low slopes (10° to 10^{-4}) & variable confinement; worldwide data compilation	"		✓
Channel pattern: conceptual frameworks	Alluvial floodplain rivers (unconfined to partly confined):			
Schumm (1963a; 1977; 1981; 1985), Allen (1965): 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 gravel to sand beds, & moderate to low slopes (10^{-2} to 10^{-4}); 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)	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	Reach to valley	✓	✓
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	Small to large rivers, with cobble/gravel beds, & moderate slopes (10^{-2} to 10^{-3}); New Zealand; concepts generally applicable	"	✓	
Church (1992; 2006): Synthesis and generalization of the above conceptual frameworks by Schumm and Mollard (**Figure 5**)	Applicable to most types of alluvial rivers (boulder to silt beds, confined headwaters to unconfined lowlands)	"	✓	✓
Channel–floodplain interactions				
Melton (1936): Floodplain formation by lateral accretion, vertical accretion, or braiding processes	Large, alluvial, floodplain rivers of various slope; unconfined to partly confined; synthesis of rivers throughout U.S. & Canada	"	✓	✓
Nanson and Croke (1992), Brierley and Fryirs (2005): Genetic sequences (**Figures 7** and **13(b)**)	Synthesis of alluvial floodplain rivers from around the world; silt- to boulder-bed rivers of various size, confinement, & slope	"	✓	✓
Aerial photographs:				
Mollard (1973): Same as Mollard (1973) above	Same as Mollard (1973) above	"	✓	✓
Brice (1975): Recognizes 67 channel types as a function of the degree & character of sinuosity, braiding, & anabranching	Medium to large alluvial rivers of various slope, grain size & floodplain extent; conterminous U.S., central Alaska & select international rivers (unspecified locations)	"		✓
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	Same as above	"	✓	✓
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**)	Medium to large alluvial rivers, with cobble to sand beds, moderate to low slopes (10^{-2} to 10^{-5}) & variable floodplain extent; Canadian Rocky Mountains & Interior Plains (Alberta)	"	✓	✓
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	Small- to medium-sized, alluvial & bedrock rivers, with very steep to moderate slopes (10^{0} to 10^{-3}) & variable confinement; western U.S. (southern Utah, northern California, western Washington); concepts generalizable to any environment	"	✓	
Bed mobility:				
Henderson (1963), Simons (1963): Recognizes the dichotomy between live-bed (sand/silt) rivers and threshold (gravel/cobble) channels	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- and gravel/cobble-bed rivers	"	✓	

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)	"	✓	
Channel units				
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 & subdivision of "shallows" into various steep vs. low-gradient types; e.g., cascade, riffle, glide) & 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)	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	Channel unit	✓	✓
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	Small, very steep to moderate gradient (10^{0} to 10^{-2}), cobble- & boulder-bed channels of the Pacific Northwest, with moderate to high confinement; concepts generalizable to other environments	"	✓	✓
Church and Jones (1982): Visual classification of bar types & processes	Large, gravel/cobble, floodplain rivers of various slope, with unconfined to partially confined valleys; synthesis of Canadian rivers & select U.K. and New Zealand rivers; concepts generally applicable to any coarse-grained, bar-form river	"	✓	✓
Buffington et al. (2002): Visual classification of obstruction-forced pools and their associated hydraulics and scour mechanisms	Small- to medium-sized, gravel/cobble-bed rivers, with moderate slopes (10^{-2} to 10^{-3}) & unconfined to partially confined valleys; northern California, southern Oregon & southeastern Alaska; concepts generalizable to other pool-forming rivers	"	✓	✓
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	Micro to reach, viewed within a basin context	✓	✓
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^{-3}), boulder to sand beds, & variable confinement; mountain basins of southeastern Alaska; some concepts generalizable, but process domains are region specific	Reach, viewed within a valley & basin context	✓	✓

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^{-4}), 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^{0}-$< 10^{-3}$), 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 (headwaters to lowlands); mountain basins of Australia and New Zealand, but concepts are generalizable to other environments	"	✓	✓

[a]Channel slopes (S) are described as very steep ($S \geq 10^{-1}$), steep ($3 \bullet 10^{-2} < S < 10^{-1}$), moderate ($10^{-3} < S < 3 \bullet 10^{-2}$), and low ($S \leq 10^{-3}$). Similarly, channel sizes are described in terms of bankfull width (w) as small ($w \leq 20$ m), medium ($20\ \text{m} < w < 100$ m), and large ($w \geq 100$ m).

[b]Spatial scale is expressed in terms of bankfull width, w, using approximate orders of magnitude from micro to valley scales: micro ($\leq 10^{-1}\ w$), channel unit (10^{-1} to $10^{0}\ w$), reach (10^{1} to $10^{2}\ w$), valley ($> 10^{2}\ w$). Larger spatial scales are expressed in terms of the network and basin structure: network link, subbasin, and basin.

[c]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.