6.51 Geomorphic Classification of Rivers: An Updated Review

John M. Buffington[a] **and David R. Montgomery**[b], [a] US Forest Service, Rocky Mountain Research Station, Boise, ID, United States; and [b] Department of Earth and Space Sciences, University of Washington, Seattle, WA, United States

6.51.1	**Introduction**	**1143**
6.51.2	**Purpose of classification**	**1143**
6.51.3	**Types of channel classification**	**1144**
6.51.3.1	Stream order	1144
6.51.3.2	Process domains	1145
6.51.3.3	Channel pattern	1145
6.51.3.4	Channel–floodplain interactions	1150
6.51.3.5	Bed material and mobility	1152
6.51.3.6	Channel units	1154
6.51.3.7	Hierarchical classifications	1155
6.51.3.8	Spatial analysis and statistical classifications	1165
6.51.4	**Use and compatibility of channel classifications**	**1166**
6.51.5	**The rise and fall of classifications: Why are some channel classifications more used than others?**	**1170**
6.51.6	**Future needs and directions**	**1172**
6.51.6.1	Standardization and sample size	1172
6.51.6.2	Remote sensing	1172
6.51.7	**Conclusion**	**1173**
6.51.8	**Appendix**	**1174**
Acknowledgments		**1180**
References		**1180**

6.51.1 Introduction

Environmental legislation beginning in the 1960s, coupled with a growing awareness of human disturbance to rivers worldwide (Schumm, 1969, 1977; Williams, 1978; Sedell and Froggatt, 1984; Petts et al., 1989; Graf, 1999; Collins et al., 2003; Surian and Rinaldi, 2003; Nilsson et al., 2005; Chin, 2006; Wohl and Merritts, 2007; Walter and Merritts, 2008; Comiti, 2012; Rubin et al., 2015; Wohl, 2019), have fostered increased collaboration among scientists, land managers, and stakeholders to better understand, monitor, and restore riverine ecosystems. The additional concern over climate change (IPCC, 2021) and the need for securing supplies of clean water for our 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., Thorne et al., 1997; Kondolf et al., 2001; Downs and Gregory, 2004; Brierley and Fryirs, 2005; Simon et al., 2011b). Channel classification is one tool that is used to address these needs. This article reviews the purposes of geomorphic channel classification, the different types of classifications that have been developed, their use, compatibility, and popularity, and concludes with a look at future needs and directions for channel classification.

6.51.2 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 6.51.3**). The form–process paradigm is a potentially powerful tool for conducting quantitative geomorphic investigations. However, many river classifications are largely descriptive, lacking 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 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 nevertheless can be valuable. For example, descriptive river classifications are useful inventory and pattern-recognition tools that can be developed into a GIS layer that may subsequently stimulate research or management questions. However, without a process-based underpinning, descriptive river classifications are not defensible means for assessing landscape condition or for making management decisions in and of themselves. Consequently, the value that one obtains 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, 2016; Brierley and Fryirs, 2005; Gurnell et al., 2016). These different purposes have resulted in a multitude of proposed classifications.

6.51.3 Types of channel classification

Numerous geomorphic classifications have been developed for rivers over the past two centuries, 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 and social agendas (Tadaki et al., 2014). The various approaches for channel classification are reviewed here, expanding on a prior review by Montgomery and Buffington (1998) and updating an earlier version of the current work (Buffington and Montgomery, 2013). 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; Bradley and Whiting, 1992; 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, 2016; Downs and Gregory, 2004; Simon et al., 2007; Milner, 2010; Melles et al., 2012; Tadaki et al., 2014; Gurnell et al., 2016; Praskievicz, 2018).

6.51.3.1 Stream order

Stream order (Horton, 1945; Strahler, 1957) is perhaps the most widely used descriptive classification for rivers (**Fig. 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 one defines the river network. 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. Nevertheless, it is a useful communication tool for describing relative stream size and location within a basin, as well as overall basin size in terms of maximum stream order. Structural classifications have also been developed for nested scales of sub-basins (termed hydrologic units) within watersheds (Seaber et al., 1987; Omernik, 2003), but as with stream order, they offer little inherent insight regarding geomorphic processes.

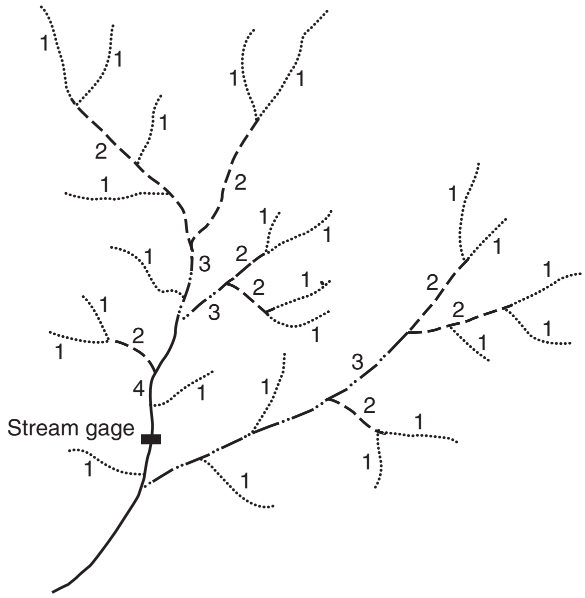


Fig. 1 Channel classification using stream order (Horton, 1945; Strahler, 1957). Reproduced, with permission, from Morisawa M (1968) *Streams: Their Dynamics and Morphology*, 175 pp. New York: McGraw-Hill.

Subsequent work by Orr et al. (2008) developed a nested channel classification that successively subdivides the network by stream order, specific stream power, slope, and floodplain width (a measure of channel confinement). Thresholds for each subordinate parameter determine different channel types and are empirically based on observed frequency distributions of those characteristics, which tailors the classification to a specific study basin/dataset, but the framework is nonetheless generalizable to other study areas. The approach quantifies physical characteristics beyond stream order, but remains descriptive and requires interpretation of the morphogenic processes and response potential of each channel type.

6.51.3.2 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 (**Fig. 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 inter-related disturbance processes, channel morphologies, and aquatic habitats, and at a general level roughly correspond with source, transport, and response reaches in mountain basins (**Fig. 2**B; Montgomery, 1999). Process domains are implicit in other channel classifications (e.g., Platts, 1974; Rosgen, 1985, 1994, 1996b; Frissell et al., 1986; Cupp, 1989; Nanson and Croke, 1992; Paustian et al., 1992; Brierley and Fryirs, 2005; Seelbach et al., 2006; Thorp et al., 2006, 2010; Alexander et al., 2009), 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 and riparian habitats. Hence, it is a valuable tool for land management and conservation efforts.

6.51.3.3 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 (**Fig. 3**). Both studies recognized a continuum of channel pattern, but Leopold and Wolman (1957) proposed a threshold between meandering and braided rivers (**Fig. 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 **Fig. 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,

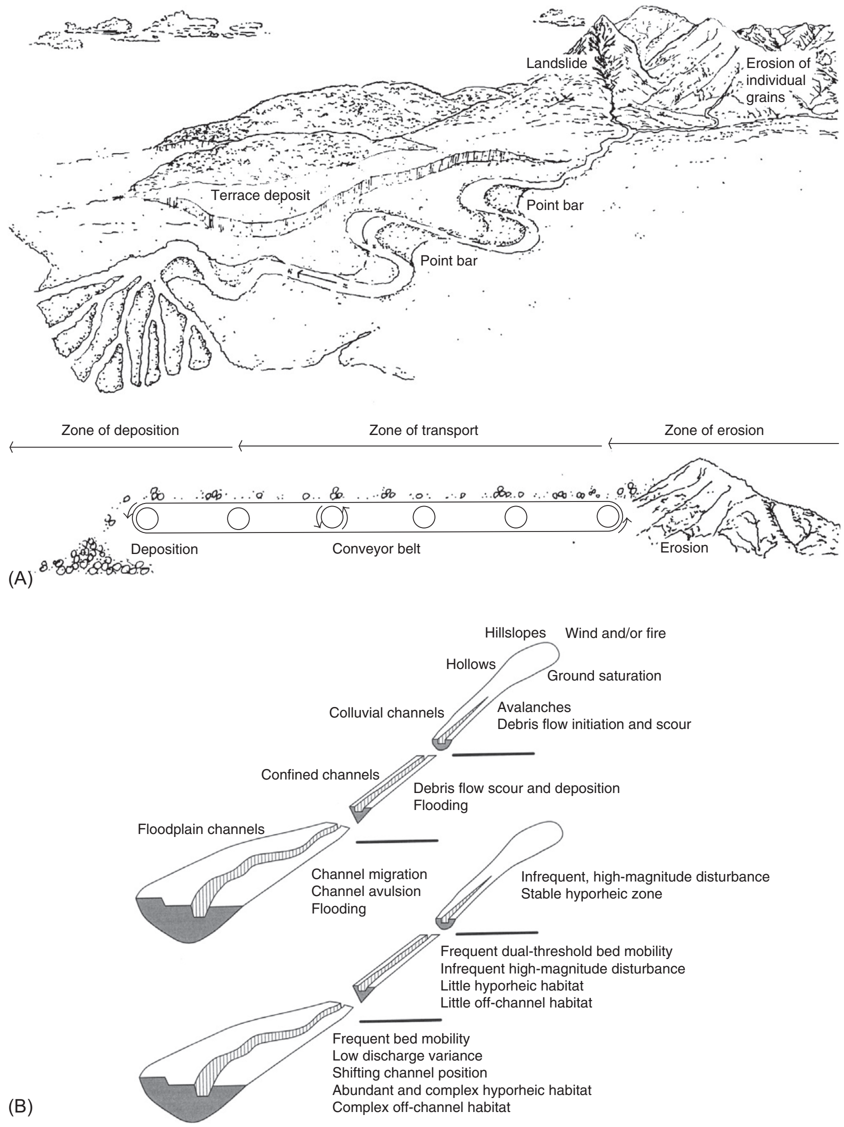


Fig. 2 Process domains defined by (A) Schumm (1977) (as depicted by Kondolf, 1994) and (B) Montgomery (1999). (A) Reprinted with permission from Kondolf GM (1994) Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* 28: 225–243. (B) Reproduced from Montgomery DR (1999) Process domains and the river continuum. *Journal of the American Water Resources Association* 35: 397–410.

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 (Church, 1983; Desloges and Church, 1989), while anastomosed rivers are multithread channels separated by islands cut from the floodplain (Knighton and Nanson, 1993) and are distinguished from braided channels that are initially formed by bar deposition and subsequent in-channel flow splitting (e.g., Leopold and Wolman, 1957; Bridge, 1993; Carling et al., 2014). 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, Shields stress, 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; Anderson et al., 1975; Parker, 1976; Fredsøe, 1978; Carson, 1984a,b,c; van den Berg, 1995; Alabyan and Chalov, 1998; Millar, 2000; Buffington et al., 2003; Dade, 2000; Kleinhans and van den Berg, 2011; Candel et al., 2021; also see reviews by Bridge, 1993, Thorne, 1997, and Kleinhans, 2011).

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,

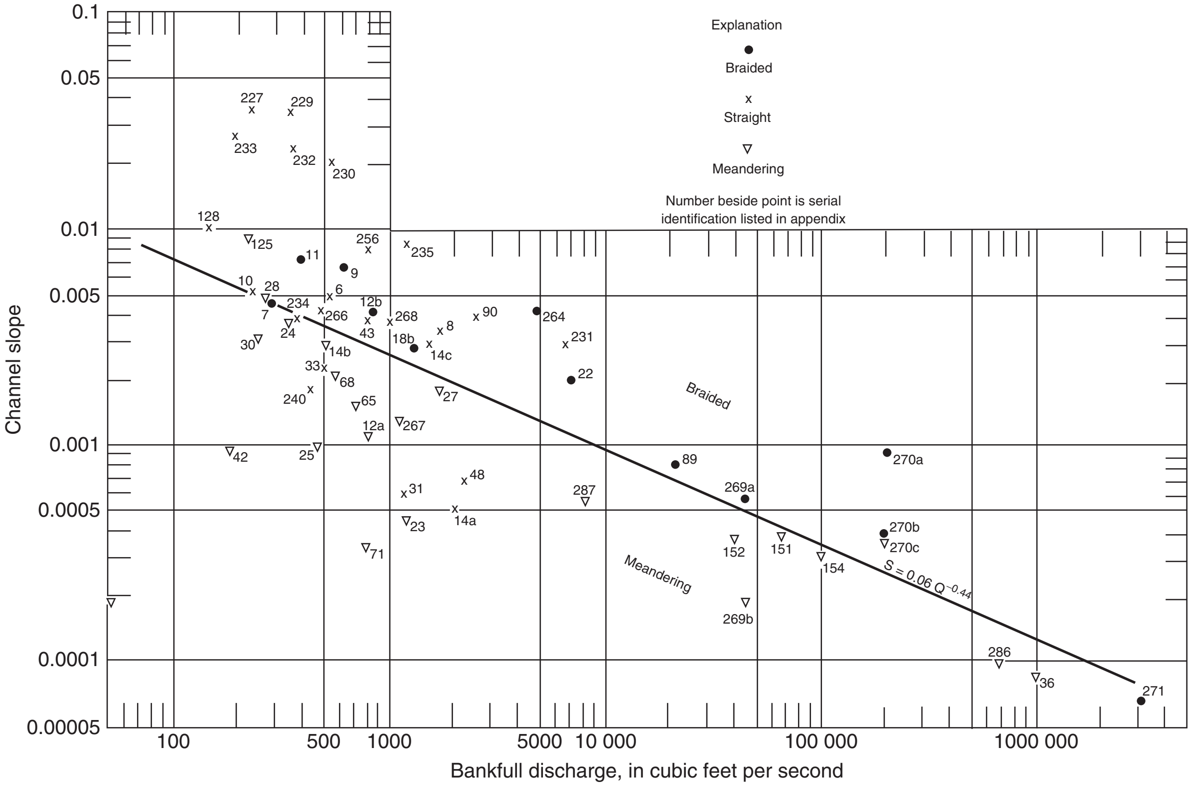


Fig. 3 Channel pattern (meandering, straight, braided) as a function of channel slope and bankfull discharge. Reproduced from Leopold LB and Wolman MG (1957) River channel patterns: Braided, meandering, and straight. Washington, DC: US Geological Survey Professional Paper 282-B, pp. 39–84 (US public domain).

riparian, and hyporheic organisms (e.g., Malard et al., 2002; Poole et al., 2002; Stanford et al., 2005; Buffington and Tonina, 2009; Brennan et al., 2019). 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; Eaton and Giles, 2009). 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) (e.g., Pollen-Bankhead and Simon, 2010; Simon et al., 2011a).

The above approaches patterned after Lane (1957) and Leopold and Wolman (1957) allow quantitative prediction of channel pattern and assessment of potential changes that might result from a given disturbance, but they are largely empirical and apply to a subset of channels within a given basin (i.e., floodplain alluvial rivers). Process-based explanations for hydraulic and sedimentary controls on channel pattern have been presented (Leopold and Wolman, 1957; Parker, 1976; Osterkamp, 1978; Carson, 1984a,b,c; Ferguson, 1987; Bridge, 1993; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Beechie et al., 2006; Eaton and Giles, 2009), but the slope–discharge framework for classifying channel pattern remains empirical and descriptive. Carling et al. (2014) argue that meaningful classification of channel pattern should include the underlying morphogenic processes, particularly for distinguishing different types of multithread channels; i.e., braided (bar deposition and flow splitting) vs. anastomosed (avulsion and floodplain excision) channels. Nanson and Knighton (1996) also note that multithread channels can exhibit a variety of channel patterns (e.g., individual threads may be straight or meandering) and that channel pattern may not indicate a unique process (e.g., sinuous channels may be actively migrating across their floodplains (meandering) or they may be laterally stable, with floodplains mainly formed by vertical accretion).

Conceptual frameworks—Schumm's (1960, 1963b, 1968, 1969, 1971a,b, 1977) work on sand- and gravel-bed rivers in the Great Plains of the western United States 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 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 (**Fig. 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 and Giles, 2009; 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 taken 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; **Fig. 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 different types of anabranching/multithread rivers (Nanson and Knighton, 1996) and steeper morphologies present in mountain rivers (Church, 1992, 2006; **Fig. 5**). A similar framework has been used to array Montgomery and Buffington (1997) channel types, additionally identifying (1) different valley and substrate types (alluvial, bedrock, colluvial), (2) domains for the dominance of fluvial vs. debris-flow processes, and (3) effects of vegetation (**Fig. 6**). Channel pattern is also a primary discriminator in the classification schemes developed by Paustian et al. (1992), Rosgen (1994, 1996b) and Brierley

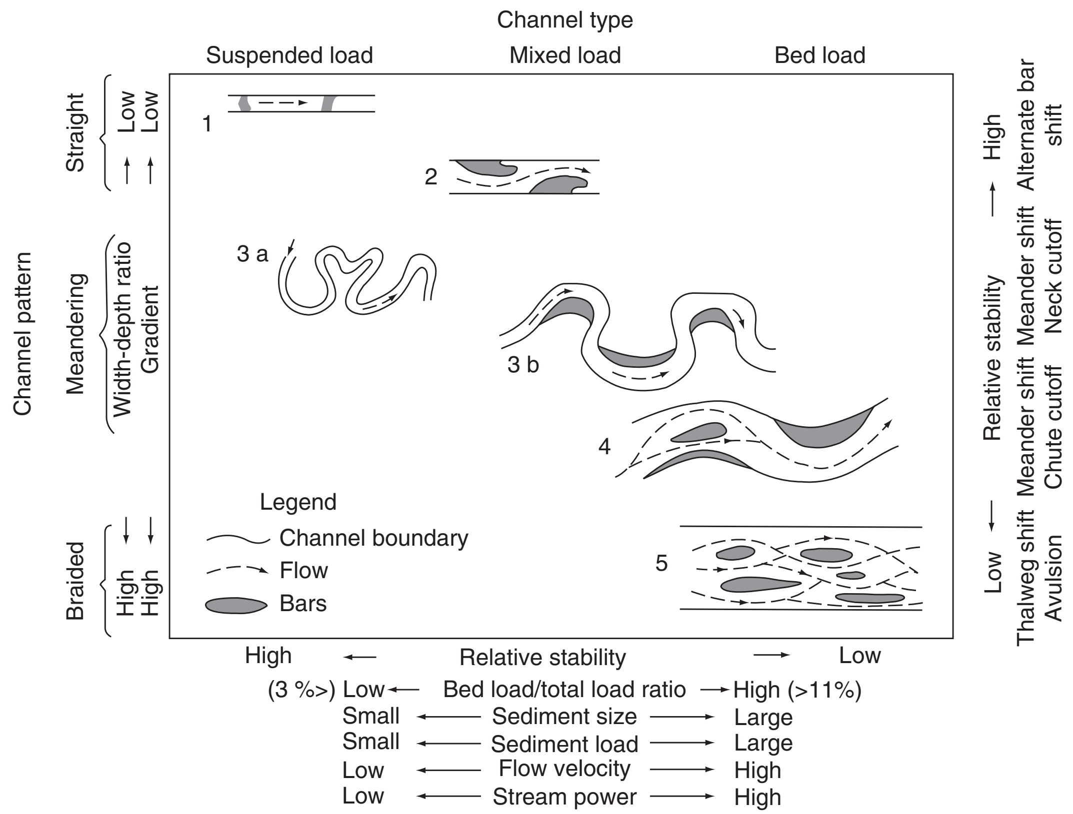


Fig. 4 Schumm's (1963a, 1977, 1981, 1985) classification of alluvial rivers. Reproduced from Fig. 4 in Schumm SA (1981) Evolution and response of the fluvial system, sedimentological implications. In: Ethridge FG and Flores RM (eds.), *Recent and Ancient Nonmarine Depositional Environments*. Tulsa, OK: Society of Economic Paleontologists and Mineralogists Special Publication 31, pp. 19–29, with permission from SEPM; which was modified from Fig. 1 in Schumm SA and Meyer DF (1979) Morphology of alluvial rivers of the Great Plains. In: *Riparian and Wetland Habitats of the Great Plains. Proceedings of the 31st Annual Meeting*. Lincoln, NE: Forestry Committee, Great Plains Agricultural Council Publication 91, pp. 9–14; and from Fig. 3 in Shen HW, Schumm SA, Doehring DO (1979). Stability of stream channel patterns. Washington, DC: National Academy of Sciences. Transportation Research Record 736, pp. 22–28, with permission from the Transportation Research Board.

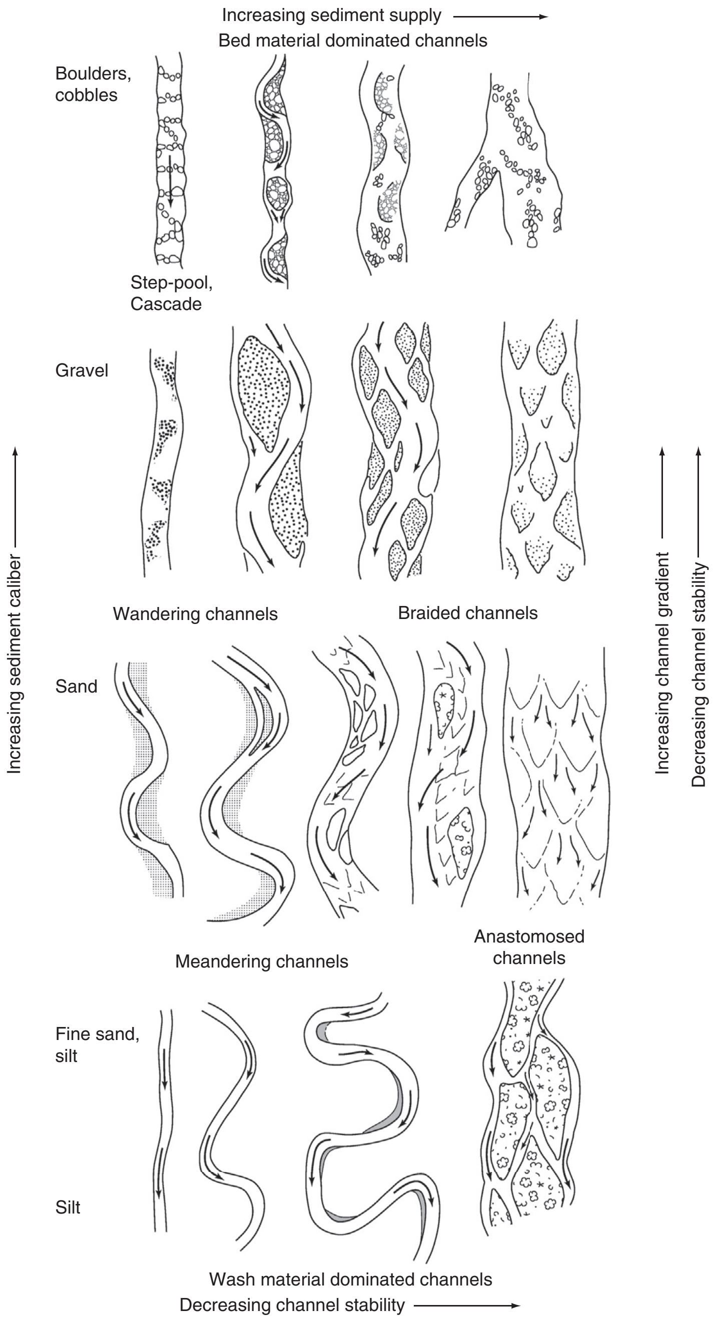


Fig. 5 Schumm's (1977, 1981, 1985) classification of channel pattern and response potential as modified by Church (1992, 2006). Reproduced from Church M (2006) Bed material transport and the morphology of alluvial rivers. *Annual Review of Earth and Planetary Sciences* 34: 325–354, with permission from Annual Reviews, Inc. Also see similar modifications by Ferguson (1987) and Knighton (1998).

and Fryirs (2005). To better recognize biotic controls on channel morphology and habitat, Castro and Thorne (2019) modified Schumm's framework using a ternary diagram with apices of geology, hydrology, and biology, within which channel pattern, reach-scale channel types, and phases of channel evolution can be arrayed. 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, sediment supply, and biotic conditions, but are mainly qualitative and, in most cases, have been developed for large floodplain rivers. Furthermore, these approaches are typically descriptive (associating physical and biological conditions with channel morphology, but not explaining the underlying processes) or involve a mixture of descriptive and process-based interpretations.

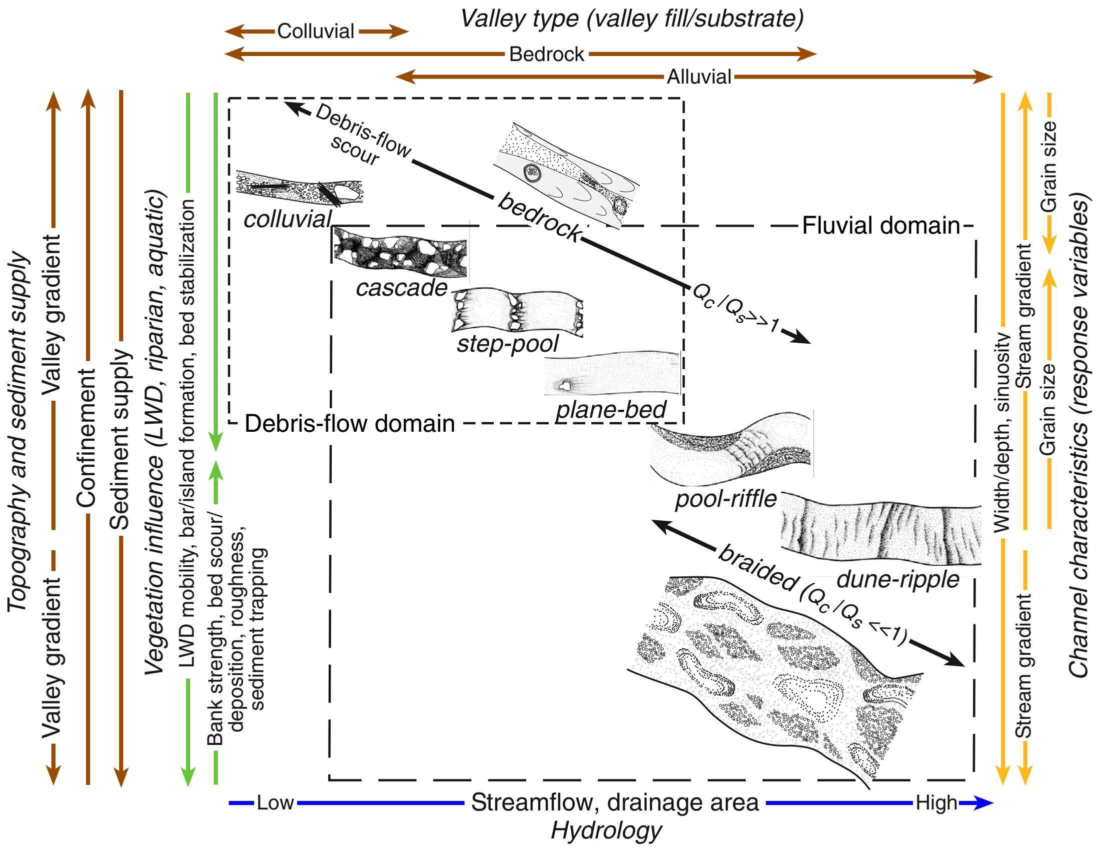


Fig. 6 Imposed basin conditions (left: topography (valley gradient, confinement), sediment supply, vegetation; bottom: streamflow) govern channel characteristics (right: width/depth ratio, sinuosity, stream gradient, grain size) and reach-scale morphology, as illustrated with Montgomery and Buffington (1997) channel types (center). Debris-flow and fluvial process domains are shown (boxes), with competition between the two indicated by domain overlap. Larger-scale valley types (colluvial, bedrock, alluvial) are indicated (top), as well as conditions of transport capacity relative to sediment supply *(Q_c /Q_s)* for bedrock and braided channels. **Table 2** summarizes processes and conditions associated with each channel type. Modified from Fig. 4 in Buffington JM, Woodsmith RD, Booth DB, and Montgomery DR (2003) Fluvial processes in Puget Sound rivers and the Pacific Northwest. In: Montgomery, DR, Bolton S, Booth DB, and Wall L (eds.) *Restoration of Puget Sound Rivers*, pp. 46–78. Seattle, WA: University of Washington Press; and Fig. 32.6b in Buffington JM (2012) Changes in channel morphology over human time scales. In: Church M, Biron PM, and Roy AG (eds.) *Gravel-bed Rivers: Processes, Tools, Environments*, pp. 435–463. Chichester: Wiley. Based on concepts from Lane (1955), Schumm (1963a, 1977, 1981, 1985), Mollard (1973), and Kellerhals and Church (1989).

6.51.3.4 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 (Fig. 7), and highlights genetic (i.e., evolutionary or successional) 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 semi-alluvial (e.g., Brice, 1982). The effect of geomorphic legacies (e.g., glaciation) can also have important controls on sediment supply (caliber and volume) and stream power, influencing fluvial processes and resultant floodplain types (Phillips and Desloges, 2015). Channel–floodplain interactions are also implicit in classifications of channel pattern (**Section 6.51.3.3**), 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

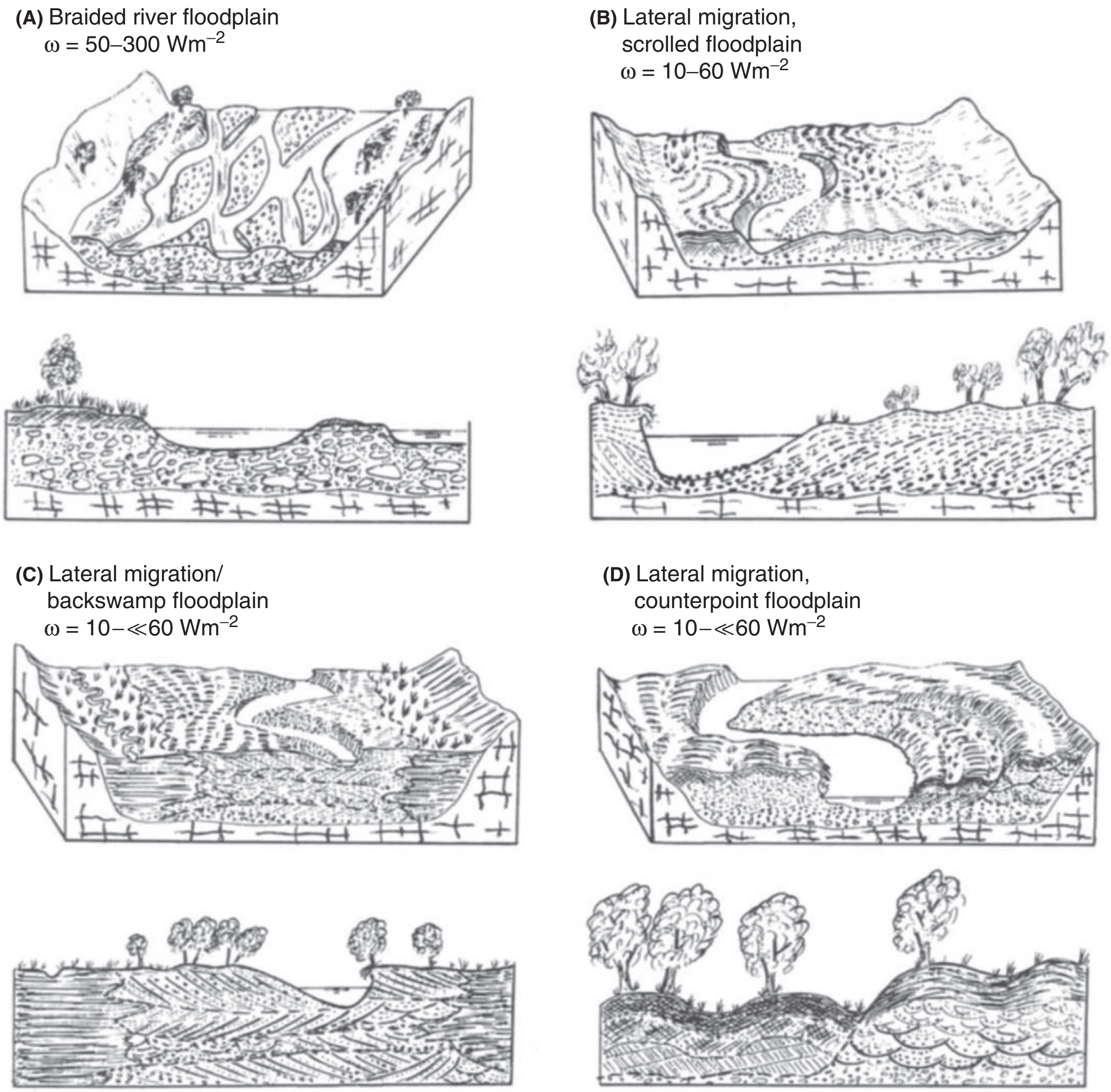


Fig. 7 Example river–floodplain types from the Nanson and Croke (1992) classification, showing medium-energy, non-cohesive environments. ω is the specific stream power. Reproduced with permission from Nanson GC and Croke JC (1992) A genetic classification of floodplains. *Geomorphology* 4(6): 459–486 and sources cited therein.

et al., 1975). Furthermore, different scales of bedform and floodplain features may occur, representing a hierarchy of flow and sediment transport events (Jackson, 1975; Lewin, 1978; Church and Jones, 1982). Alternatively, channel processes and floodplain features may be out of phase, with floodplain features representing climatic or geomorphic legacies, rather than current channel processes. In other cases, floodplain legacies may structure current channel hydraulics and sediment routing, controlling observed channel morphology and processes (Sidorchuk, 2003). This broader spatial and temporal view of channel–floodplain interactions 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 and GIS (e.g., Mollard, 1973; Brice, 1975, 1982; Kellerhals et al., 1976). Many of these approaches were designed to determine the stability of large alluvial rivers for use in documenting and predicting response to engineering projects and land use (e.g., bridges, floodplain development, dams, and flow diversion).

Most 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.

6.51.3.5 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; Talling, 2000; Parker et al., 2003; Church, 2006; Bunte et al., 2010; Wilkerson and Parker, 2011; Trampush et al., 2014; Li et al., 2015); in particular, 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 (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, while 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; Phillips and Jerolmack, 2019), 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). Mobility in gravel-bed rivers also increases with sediment supply (Dietrich et al., 1989; Lisle, 2005; Pfeiffer et al., 2017), producing a systematic departure from bankfull-threshold conditions (Buffington and Montgomery, 1999c). The above observations indicate that care should be taken 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) proposed a technique for regional assessments of sediment loading based on comparing observed grain sizes to 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 typically does not have a bankfull threshold (Buffington and Montgomery, 1999b; Bunte et al., 2010, 2013; 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). The above studies indicate that the bankfull morphology of alluvial rivers may be adjusted to the mode of sediment transport and to the size and volume of the material being transported. For example, although many gravel-bed rivers have a near-bankfull threshold for bedload transport of D_{50}, sand-bed rivers, instead, exhibit a near-bankfull threshold for *mixed- to suspended-load transport* of D_{50} (Trampush et al., 2014), suggesting that the bankfull morphology of these two types of rivers is adjusted to the mode of sediment transport (i.e., bedload vs. mixed/suspended load; Schumm, 1963a, 1977, 1981, 1985; Dade and Friend, 1998; García, 2000; Church, 2006; Wilkerson and Parker, 2011; Trampush et al., 2014; Li et al., 2015). Similarly, sand-bed rivers require a higher Shields stress than gravel-bed rivers to transport the same mass of sediment per unit width, suggesting that bankfull Shields stress is adjusted to both the volume and caliber of the long-term sediment supply, which may explain why bankfull Shields stresses are larger in sand-bed channels than gravel-bed ones (Talling, 2000).

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 (**Fig. 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 risk of disturbance and response potential using the above matrix of factors (**Fig. 8**). The Whiting and Bradley (1993) classification

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

Channel type; bankfull Shields stress (τ^*_{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; τ^*_{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 and 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 bedload (q_b/q_t typically 1–3%); sediment transport at most stages; fully mobile, sandy bed forms	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; τ^*_{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 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, agriculture).

[c]Channel morphologies shown in Fig. 5.

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).

is appealing because it is strongly process based and, therefore, more defensible than descriptive approaches, but its application is limited to headwater channels. In a subsequent study, Hassan et al. (2018) used the classification to explore the relative roles of hillslope–channel coupling, wood jams, and landscape history in modulating channel geometry (width, depth), slope, and grain size in previously glaciated basins of British Columbia. Their analysis demonstrates the need to account for each of those factors to understand downstream trends in channel morphology and processes of headwater basins.

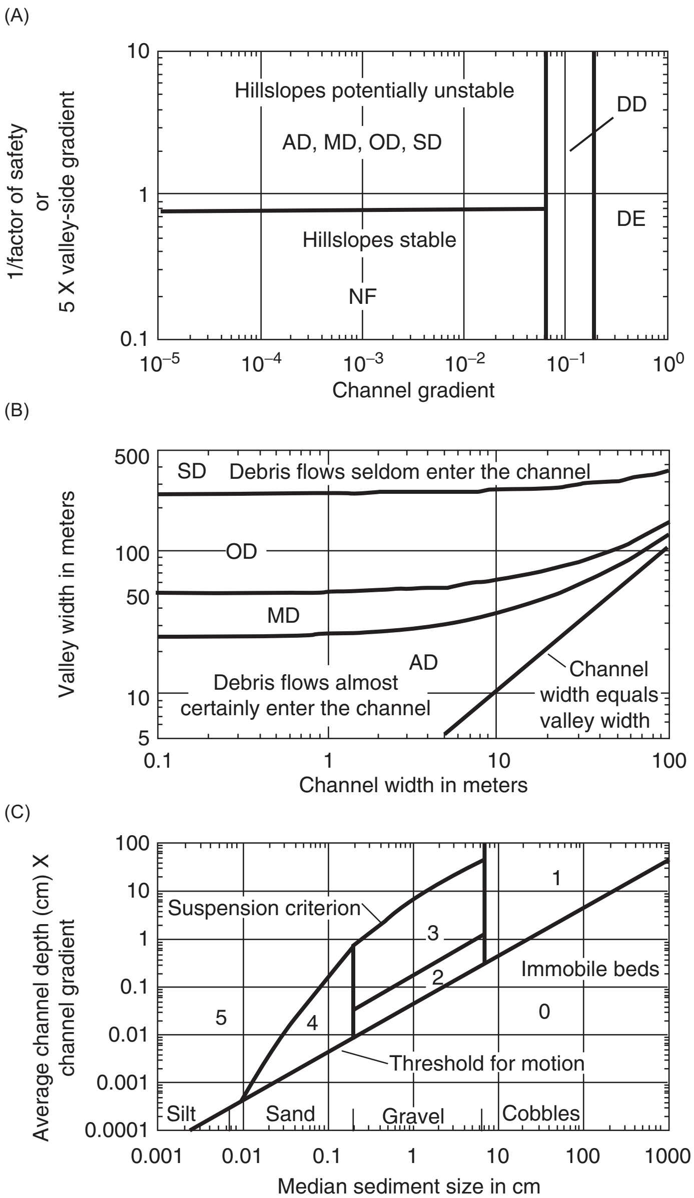


Fig. 8 Whiting and Bradley (1993) classification for headwater channels. (A) assesses the probability of mass wasting adjacent to the channel (side-slope failures AD-SD as defined in (B)) and whether the sediment input deposits within the channel (DD) or scours it as a debris flow (DE). (B) determines 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 PJ and Bradley JB (1993) A process-based classification system for headwater streams. *Earth Surface Processes and Landforms* 18: 603–612, with permission from Wiley.

6.51.3.6 Channel units

Channel units are sub-reach 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 (1) the hydraulics of channel units (Sullivan, 1986; Padmore et al., 1998; Buffington et al., 2002; Moir and Pasternack, 2008), (2) their spatial structure and relation to one another within stream reaches (Wyrick and Pasternack, 2014) and across flow stages (Pasternack et al., 2018), (3) their response to timber harvest and removal of large woody debris (LWD) (Wood-Smith and Buffington, 1996), and (4) 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). Similarly, Wyrick and Klingeman (2011) present a classification of riverine islands that considers morphogenesis, age, and stability, building from earlier work by Osterkamp (1998).

Another more inclusive approach involves classification of "geomorphic units", accounting for a broader variety of in-channel and floodplain elements, such as different types of pools and bars, islands, banks, levees, modern and relict floodplains (i.e., terraces), alluvial fans, oxbow lakes, wetlands/beaver complexes, and active and relict floodplain channels; here, the entire river corridor is mapped into geomorphic facies that link physical conditions to a variety of habitats for flora and fauna (Brierley et al., 2013; Wheaton et al., 2015; Belletti et al., 2017). The approach was originally developed for depositional landforms (Brierley, 1996), but has since been expanded to include erosional elements (Brierley et al., 2013; Wheaton et al., 2015). Remote sensing routines have also been developed for mapping geomorphic units at broad spatial scales (Demarchi et al., 2016; Bangen et al., 2017 as discussed by Williams et al., 2020). Although such classifications are inherently descriptive, they can offer mechanistic insight if the unit types are accompanied by morphogenic interpretation (e.g., **Fig. 7** of Wheaton et al., 2015).

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; Moir and Pasternack, 2008; Schwartz and Herricks, 2008; Schwartz, 2016), 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). Similarly, channel units broadly correspond with functional habitats for benthic macroinvertebrates, influencing their abundance and assemblage (e.g., Newson and Newson, 2000; Halwas et al., 2005). However, channel/geomorphic unit classification is too detailed for most basin-scale applications and the 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). Nevertheless, channel/geomorphic-unit mapping is valuable for documenting local processes, conditions, and response to natural and anthropogenic disturbance within and between sites (e.g., Bryant, 1980, 1985; Hogan, 1986, 1987; Keller et al., 1995; Wood-Smith and Buffington, 1996; Hogan et al., 1998; Wheaton et al., 2015; Belletti et al., 2017).

6.51.3.7 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 (**Fig. 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

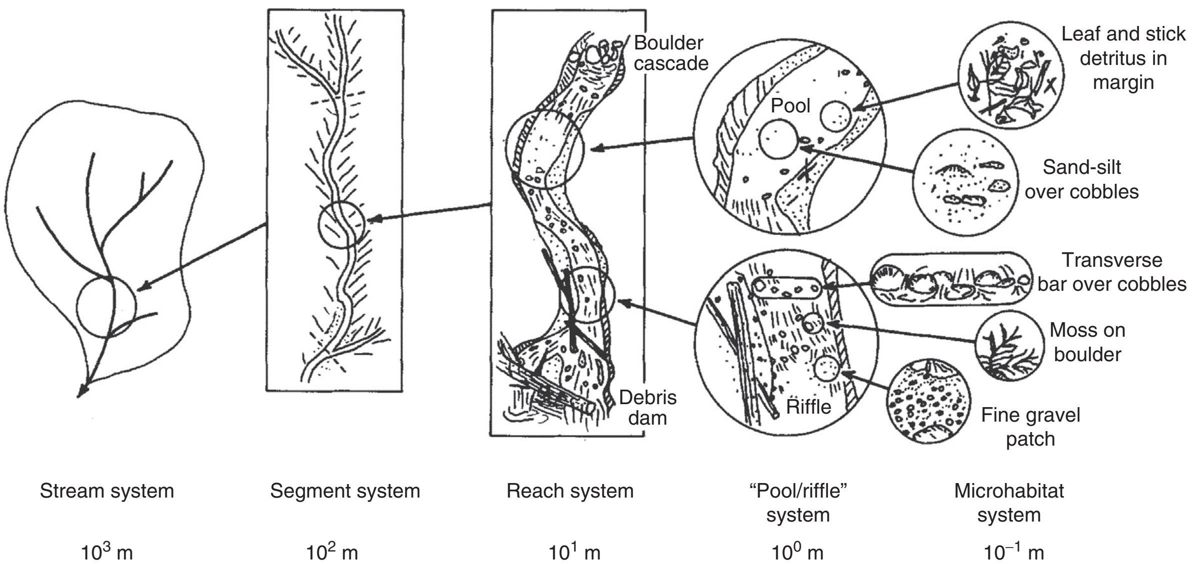


Fig. 9 Hierarchical channel classification of Frissell et al. (1986). Reproduced from Frissell CA, Liss WJ, Warren CE, and Hurley MD (1986) A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management* 10: 199–214, with permission from Springer Nature.

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 sub-groups. Coarse-level classification is initially done 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 Scotland (Addy, 2009; Milner, 2010), Australia (Thompson et al., 2006, 2008), and Italy (Rinaldi et al., 2013).

Similar to Paustian et al. (1992), a hierarchical channel classification was developed to manage mountain rivers in 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 inferred 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 (**Fig. 10**). Changes in these features over space and time are used to assess corresponding changes in sediment supply and channel stability using Schumm's (1981, 1985) conceptual framework as modified by Church (1992, 2006); **Figs. 5 and 10**). Small 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) (**Fig. 11**). The three channel types are further divided based on grain size (gravel, cobble, boulder) and 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.

To further address physical and biological connectivity in riverine ecosystems (Hynes, 1975), Stanford and Ward (1993) developed a hierarchical classification based on river corridors in Montana that considers stream order, valley type (canyon vs. floodplain), slope, and channel pattern (**Fig. 12**). Their framework emphasizes ecological process domains in terms of longitudinal, lateral, and vertical connectivity between the channel, floodplain/riparian zone, and hyporheic zone, with unconfined floodplain rivers being the most diverse and ecologically productive (e.g., Hauer et al., 2016). Such environments are relatively rare, typically comprising $<$10% of the stream length in mountain basins (e.g., Buffington et al., 2004; May and Lisle, 2012; Goode et al., 2013), but receive considerable attention due to their ecological value and the competing human use of floodplains for agriculture, industry, and municipal development (e.g., Sedell and Froggatt, 1984; Tockner and Stanford, 2002; Hauer et al., 2016). The Stanford and Ward (1993) approach also emphasizes temporal dynamics of physical processes and associated habitat availability/quality, referred to as "the shifting habitat mosaic" (Malard et al., 2002; Stanford et al., 2005; Brennan et al., 2019). Although their framework is process-based, it is largely conceptual, with subsequent studies further quantifying the processes occurring in their channel types, particularly with regard to geomorphic and fluvial controls on hyporheic exchange at different spatial scales (e.g., Baxter and Hauer, 2000; Poole et al., 2002, 2006; Lorang et al., 2005; Stanford et al., 2005; Buffington and Tonina, 2009; Bean et al., 2014; Helton et al., 2014). An important aspect of the Stanford and Ward (1993) classification is the recognition of spatial and temporal connectivity of processes in structuring system behavior at multiple scales; a concept that is receiving renewed interest in geomorphology and hyporheic studies (e.g., Harvey and Gooseff, 2015; Magliozzi et al., 2018; Harvey et al., 2019; Ward and Packman, 2019; Wohl et al., 2019).

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 number of channels (single vs. multithread), entrenchment (ratio of floodplain width to channel width; a measure of channel confinement), width-to-depth ratio, and sinuosity (**Fig. 13**). 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., Savery et al., 2001; Epstein, 2002; Beardsley, 2011), as well as inclusion of island types (Wyrick and Klingeman, 2011). Channel characteristics in the Rosgen (1994, 1996b) approach are measured using classic field techniques adapted from Dunne and Leopold (1978), but with specific methods and parameter definitions (Shelley

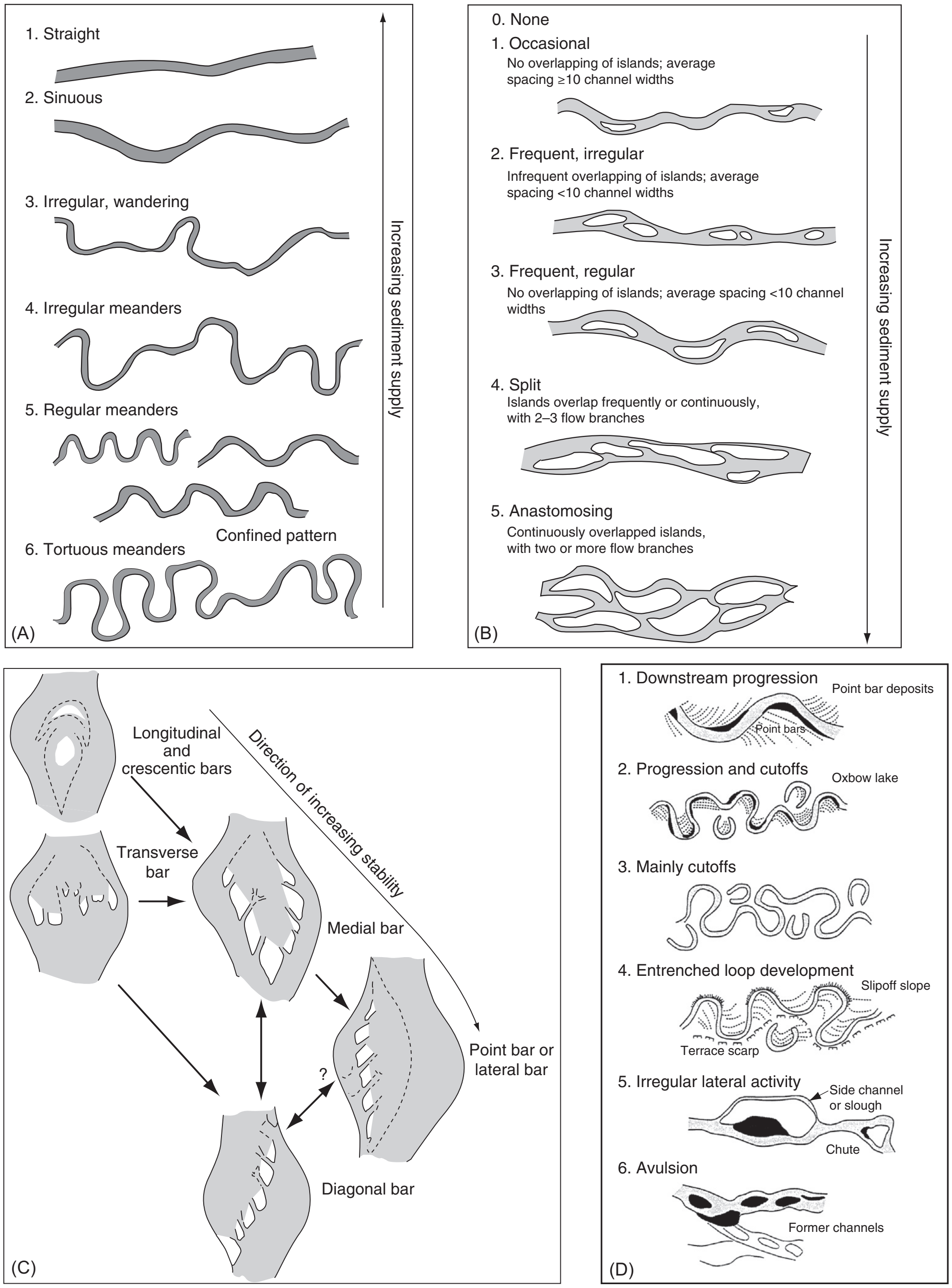


Fig. 10 Classification of the planform characteristics of large alluvial rivers from aerial photographs (Kellerhals et al., 1976): (A) channel pattern/sinuosity, (B) frequency of islands, (C) bar types (Church and Jones, 1982) and (D) lateral activity of the channel and floodplain. Channel response to increasing sediment supply is shown for panels (A) and (B). In panel (C), increasing bar stability is associated with decreasing sediment supply. Panel (C) redrafted from Fig. 11.4 in Church M and Jones D (1982) Channel bars in gravel-bed rivers. In: Hey RD, Bathurst JC, and Thorne CR (eds.) *Gravel-bed Rivers: Fluvial Processes, Engineering and Management*, pp. 291–338. Chichester, UK: Wiley, with permission from the authors. Panels (A), (B), and (D) redrafted from Figs. 8–10 in Hogan DL, Bird SA, and Wilford DJ (1996) Channel Conditions and Prescriptions Assessment (interim methods). Victoria, BC: British Columbia Ministry of Environment, Lands and Parks and Ministry of Forests, Watershed Restoration Technical Circular no. 7, 42 pp., with permission from the Province of British Columbia; which were modified from Fig. 1 in Kellerhals R and Church M (1989) The morphology of large rivers: Characterization and management. In: Dodge DP (ed.) *Proceedings of the International Large River Symposium*. Ottawa, ON: Department of Fisheries and Oceans Canada, Canadian Special Publication of Fisheries and Aquatic Sciences 106, pp. 31–48, with permission from Fisheries and Oceans Canada; and from Figs. 2, 3, and 5 in Kellerhals R, Church M, and Bray DI (1976) Classification and analysis of river processes. *Journal of the Hydraulics Division, American Society of Civil Engineers* 102: 813–829, with permission from ASCE.

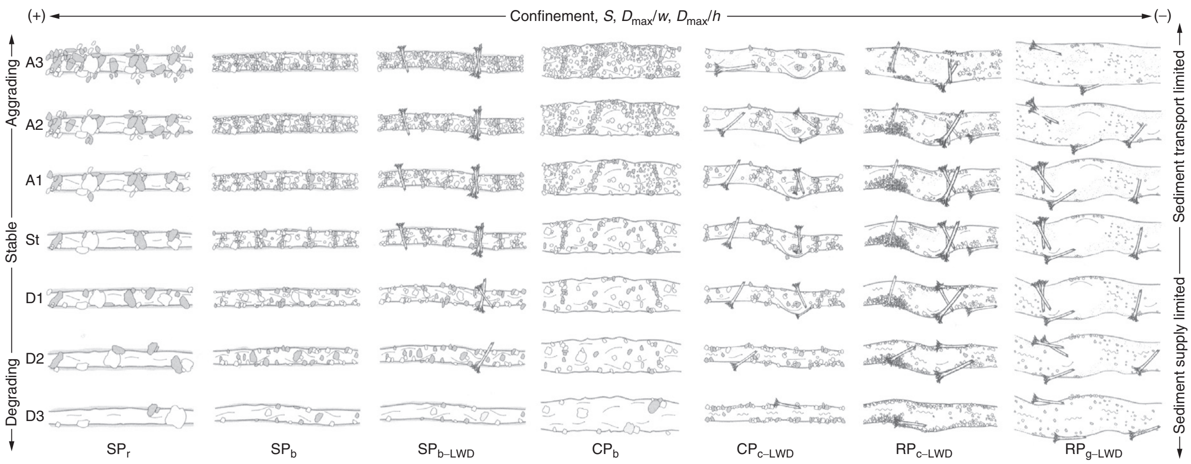


Fig. 11 FPC (1996b) classification of small and intermediate channels (bankfull width < 20–30 m), showing potential wood loading and surface grain-size characteristics as a function of disturbance (degradation/aggradation, left side of figure) and the corresponding supply- vs. transport-limited conditions (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.* Vancouver, BC: British Columbia Ministry of Forests, Forest Practices Code, 95 pp., with permission from the Province of British Columbia.

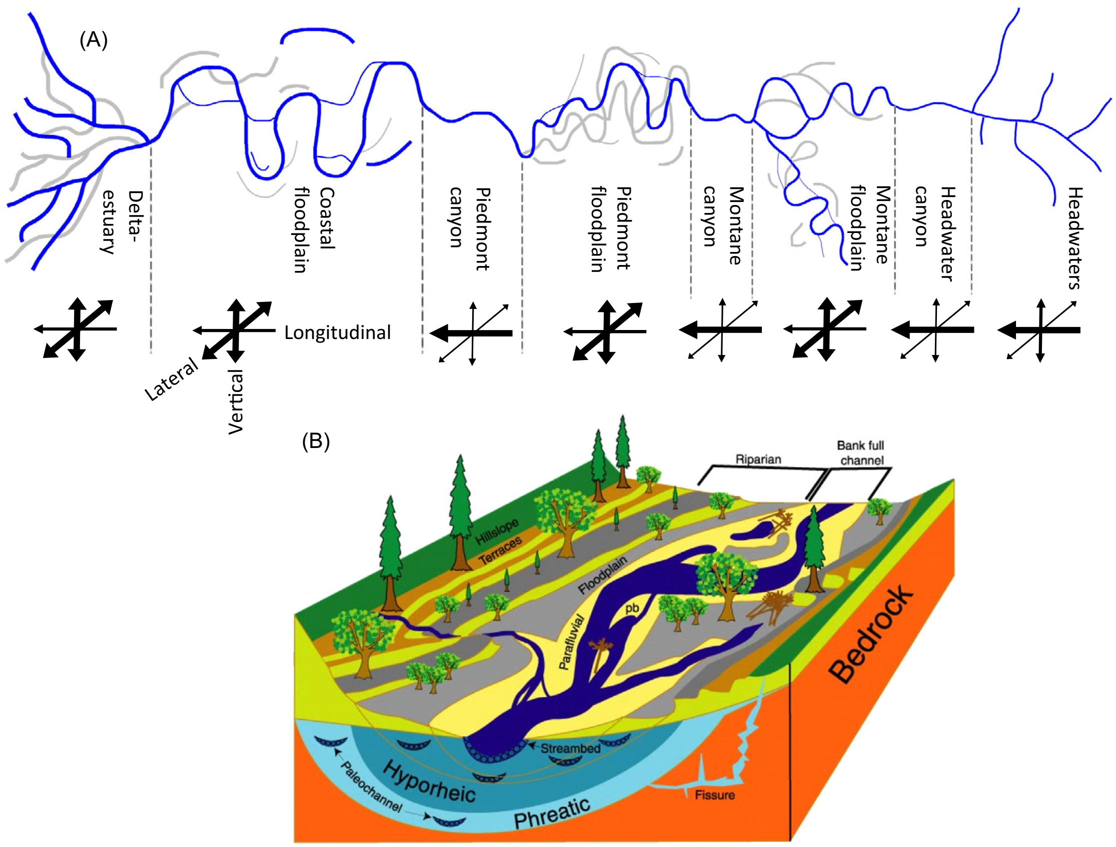


Fig. 12 Stanford and Ward (1993) classification of (A) river corridors, distinguishing stream order (location within the stream network), valley type (canyon vs. floodplain), slope, and channel pattern. The degree of longitudinal (horizontal arrow), lateral (oblique arrow), and vertical (downward/upward arrow) connectivity between the channel, floodplain/riparian zone, and hyporheic zone is indicated by respective arrow size, with each zone illustrated in (B) for an unconfined floodplain channel. Modified from Stanford JA, Lorang MS, and Hauer FR (2005) The shifting habitat mosaic of river ecosystems. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 29: 123–137, with permission from Taylor & Francis Ltd, http:/www.tandfonline.com; Ward JV, Tockner K, Arscott DB and Claret C (2002) Riverine landscape diversity. *Freshwater Biology* 47: 517–539, with permission from Wiley; Stanford JA (1998) Rivers in the landscape: Introduction to the special issue on riparian and groundwater ecology. *Freshwater Biology* 40: 402–406, with permission from Wiley; and Stanford JA and Ward JV (1993) An ecosystem perspective of alluvial rivers: Connectivity and the hyporheic corridor. *Journal of the North American Benthological Society* 12(1): 48–60, with permission from the University of Chicago Press.

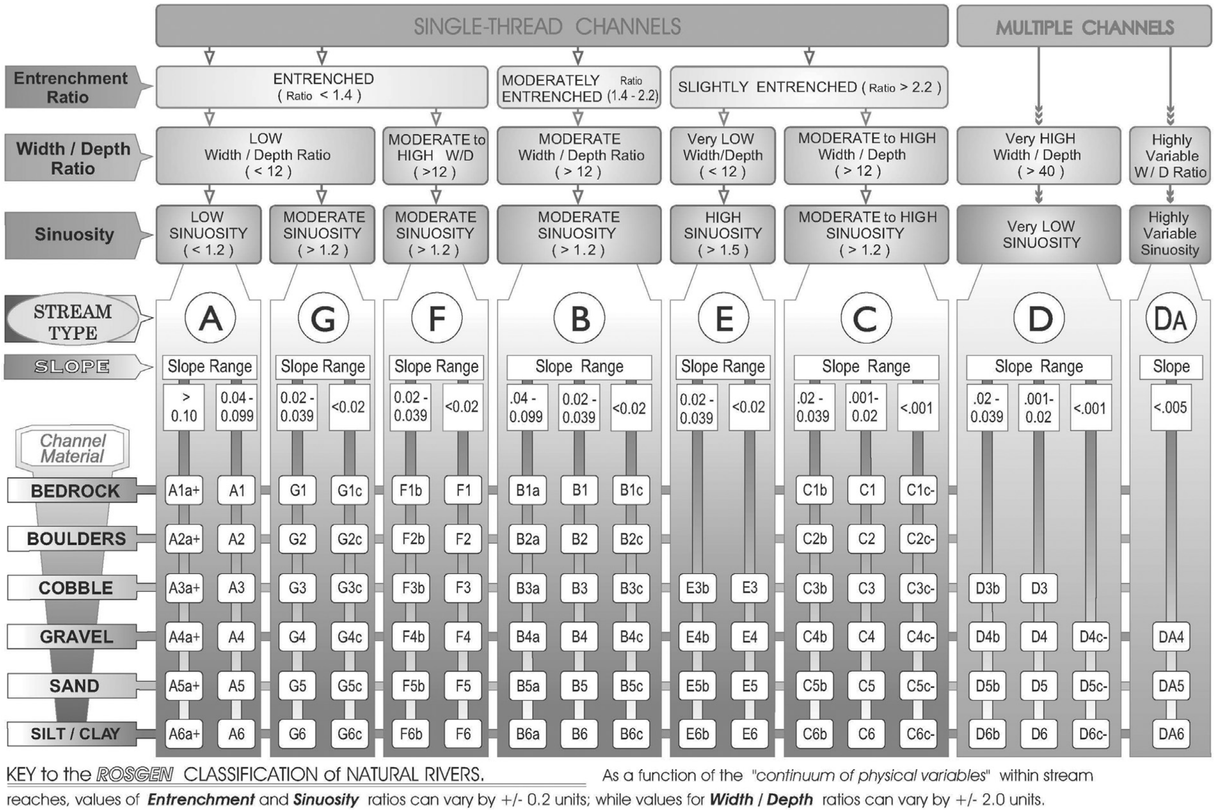


Fig. 13 Rosgen (1994, 1996b) stream type classification. Reprinted with permission from Fig. 5.3 in Rosgen DL (1996b) *Applied River Morphology*, 378 pp. Pagosa Springs, CO: Wildland Hydrology.

et al., 2010) that, if not followed, can alter results of the classification (Roper et al., 2008; Buffington et al., 2009; Rosgen, 2009). A primary goal of the Rosgen (1994, 1996b) method is identifying stable channel morphologies that provide reference conditions for use in stream restoration; an approach referred to as "natural channel design" in which reaches that are judged to be in dynamic equilibrium provide a blueprint for restoring physical and ecological function of impaired reaches (Rosgen, 1996b, 2011; Lave, 2014). Subsequent work modified the classification 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, **Fig. 14**A; Rosgen, 2006b). Similar genetic models are used by Nanson and Croke (1992) and Brierley and Fryirs (2005). Sub-reach variability of width and depth also have been examined for Rosgen stream types and were found to have more explanatory power for stream classification than the standard suite of channel characteristics used in the Rosgen approach (Lane et al., 2017). The Rosgen (1996b, 2006b) methods are widely used by consultants and state and federal land managers (see reviews by Johnson and Fecko, 2008; Wilkerson, 2008; Lave, 2008, 2009, 2014; Lave et al., 2010), but are largely descriptive and controversial within the geomorphic community (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, 2016; 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). Furthermore, the efficacy of stream restoration using natural channel design has shown mixed results ecologically. For example, in some cases fish habitat and water quality have improved following restoration using Rosgen's natural channel design (Baldigo et al., 2010; Richardson et al., 2011), while in other cases post-restoration water quality and macroinvertebrate conditions are no different from degraded urban streams (Sudduth et al., 2011; Violin et al., 2011), in part, due to the use of heavy machinery and removal of riparian vegetation during restoration. However, poor ecological outcomes such as this plague many stream restoration efforts and are not unique to Rosgen's natural channel design (Beschta et al., 1994; Roni et al., 2005; Albertson et al., 2013; Haase et al., 2013; Lave, 2014). This points to the need for improved restoration approaches that explicitly address ecological goals and biophysical interactions (Castro and Thorne, 2019; Johnson et al., 2019), rather than assuming that restoration of physical function will produce healthy ecosystems; i.e., succumbing to the "field of dreams" belief (Palmer et al., 1997; Sudduth et al., 2011). Successful restoration should also consider larger-scale conditions beyond the stream reach being restored to avoid "band aid" solutions that do not address the root cause(s) of stream impairment.

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 of channel morphology. Their approach recognizes nested physical scales of processes and controls on channel

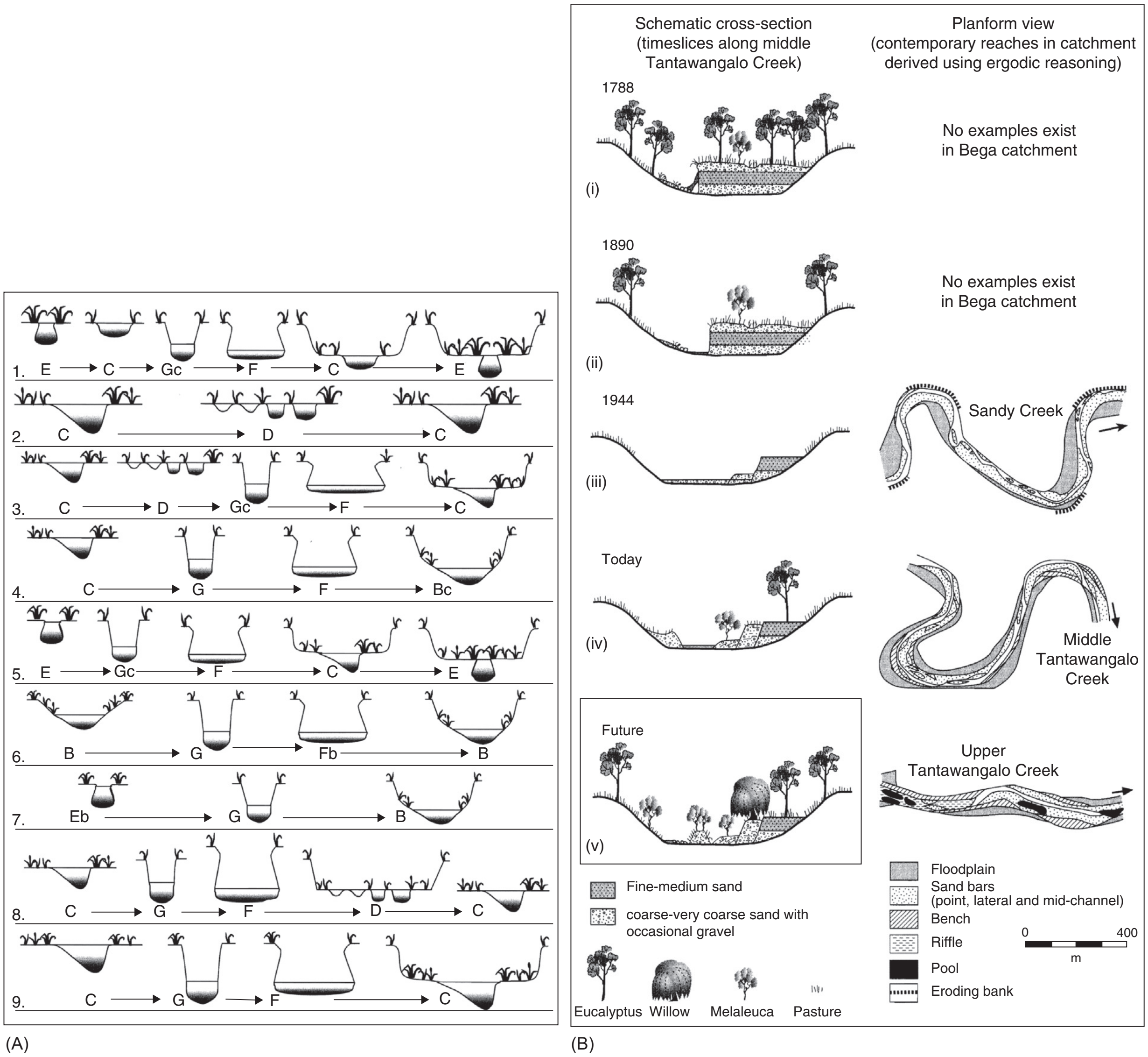


Fig. 14 Examples of descriptive stream succession (evolutionary) models developed by (A) Rosgen (2006b) and (B) Brierley and Fryirs (2005). Letters in (A) correspond with Rosgen stream types given in **Fig. 13**. Panel (A) reprinted with permission from Fig. 2.38 in Rosgen DL (2006b) *Watershed Assessment of River Stability and Sediment Supply (WARSSS)*, 648 pp. Fort Collins, CO: Wildland Hydrology. Panel (B) reproduced from Brierley GJ and Fryirs KA (2005) *Geomorphology and River Management: Applications of the River Styles Framework*, 398 pp. Oxford, UK: Blackwell, with permission from Blackwell (Wiley).

morphology, including geomorphic province, watershed, valley segment, channel reach, and channel unit (Montgomery and Buffington, 1998). Three valley types are distinguished (colluvial, bedrock, and alluvial), within which eight reach-scale morphologies are recognized based on visual identification (Fig. 15, **Table 2**), with transitional morphologies also possible (Montgomery and Buffington, 1997; Gomi et al., 2003; Vianello and D'Agostino, 2007; Cianfrani et al., 2009; Addy et al., 2011, 2014). 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 in the development of their classification was the synthesis of prior geomorphic literature to explain morphogenic processes and response potential associated with each channel type. At larger spatial scales, channels are grouped into source, transport, and response reaches (Schumm, 1977), as well as process domains for the dominance of fluvial versus debris-flow processes in controlling valley form and channel morphology (**Figs. 2**b and **6**; Montgomery and Buffington, 1997, 1998; Buffington et al., 2003; Buffington, 2012). Their approach also recognizes 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 fish habitat and macroinvertebrate assemblages at local (Inoue et al., 1997; Moir et al., 2002, 2004,

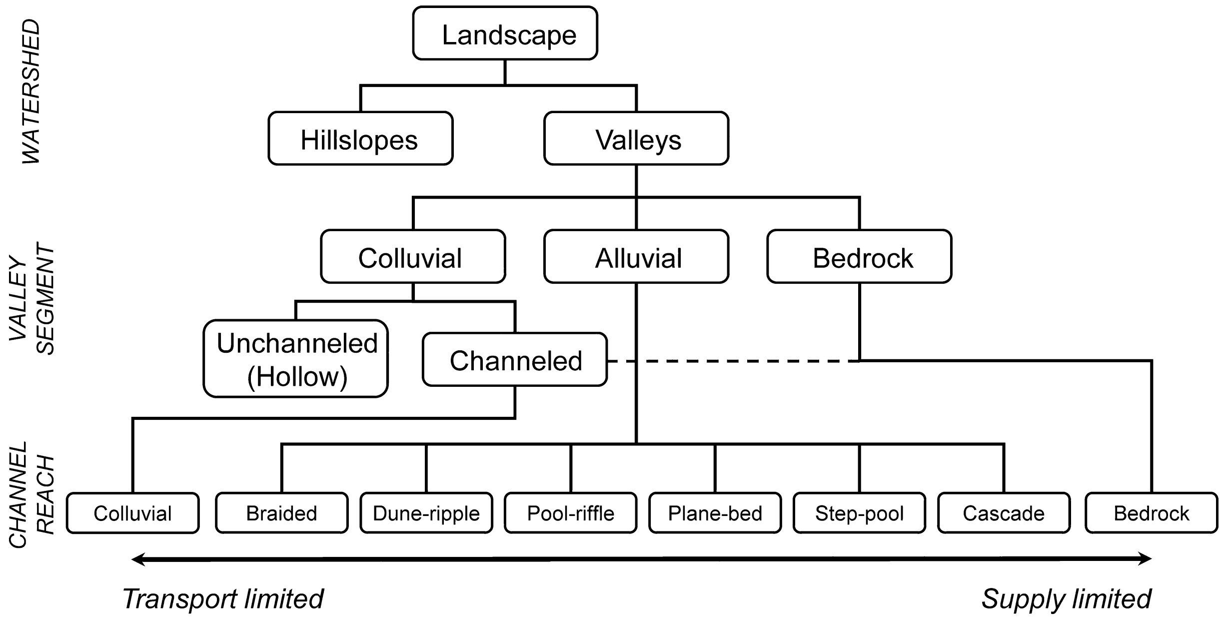


Fig. 15 Montgomery and Buffington's (1997) hierarchical subdivision of watersheds into valley segments and channel reaches, with reaches arrayed in terms of supply- vs. transport-limited conditions. Modified from Bisson PA, Montgomery DR, and Buffington JM (2017) Valley segments, stream reaches, and channel units. In: Hauer FR and Lamberti GA (eds.) *Methods in Stream Ecology. Vol. 1: Ecosystem Structure*, 3rd edn., pp. 21–47. San Diego, CA: Academic Press/Elsevier; and Montgomery DR and Buffington JM (1997) Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109: 596–611.

2006; Sullivan et al., 2006; Cianfrani et al., 2009; Milner et al., 2015) and basin scales (Montgomery et al., 1999; Buffington et al., 2004; Addy, 2009; May and Lisle, 2012; Pfeiffer and Finnegan, 2017), 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; Wondzell and Gooseff, 2013; Magliozzi et al., 2018; Wondzell et al., 2022). 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; Milner, 2010; Addy et al., 2011, 2014), underscoring the control of geomorphic history and lithology on channel morphology (Fitzpatrick et al., 2006; 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; Golden and Springer, 2006; Thompson et al., 2006; Vianello and D'Agostino, 2007; Addy et al., 2011, 2014; Livers and Wohl, 2015).

Another popular 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 geomorphic-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 (**Fig. 14**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. Subsequent modifications of the method also have been proposed to reduce subjectivity/expert-opinion in determining classification input parameters (Nardini et al., 2020). 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 resurgence in using successional models, in this case for application to current land management problems (also see Piégay and Schumm, 2003; Rosgen, 2006b; Cluer and Thorne, 2014).

Table 2 Montgomery and Buffington (1997) stream types.

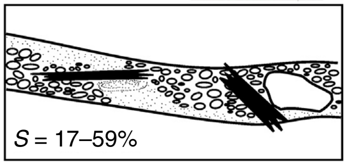
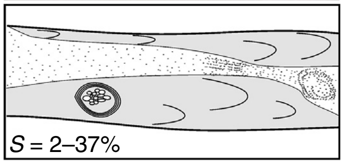
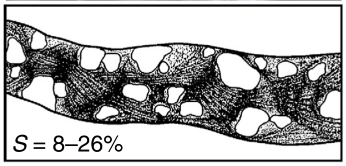
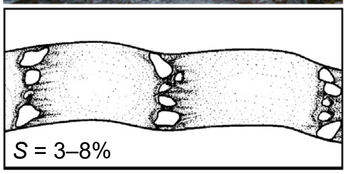
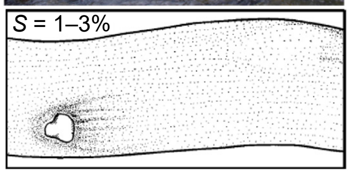
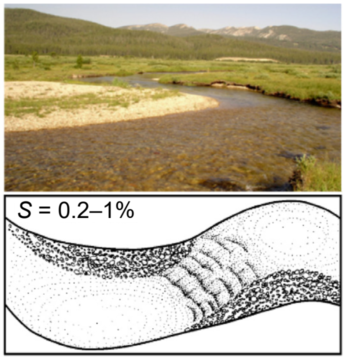
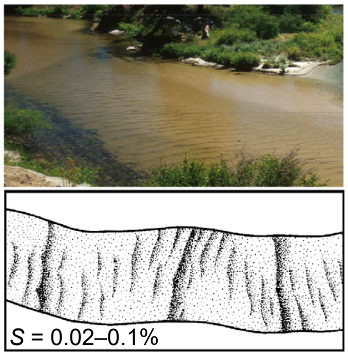
Channel type[a,b]	
  	*Colluvial*—First-order channels incised into colluvial valleys by overland flow and seepage erosion. Streamflow may be perennial or ephemeral, with streambeds characterized by poorly sorted sand- to boulder-sized sediment, and bed morphology that is strongly controlled by stochastically 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 rates 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. Moderate to high mobility of the median grain size (D_{50}) at bankfull flow, as indexed by the excess Shields stress ($1.6 < \tau^*_{bf}/\tau^*_{r50} < 2.9$)[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 channels, typically confined, 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 mobility of D_{50} at bankfull flow ($0.9 < \tau^*_{bf}/\tau^*_{r50} < 2.2$). 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.
 	*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 ($1 < \tau^*_{bf}/\tau^*_{r50} < 1.9$). 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.

Table 2 Montgomery and Buffington (1997) stream types.—cont'd

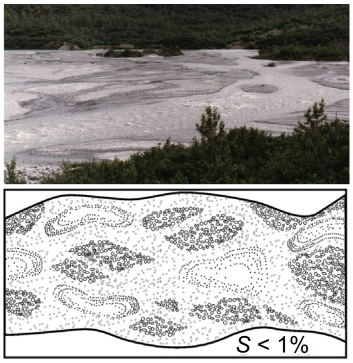
Channel type [a,b]



Pool-riffle—Alternating pool and bar topography caused by laterally oscillating flow that forces complimentary 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} ($1.1 < \tau^*_{bf}/\tau^*_{r50} < 2.6$), 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.



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 ($26 < \tau^*_{bf}/\tau^*_{r50} < 90$). Low roughness due to large width-to-depth ratios ($12 < w/h < 47$) and large relative submergence ($3000 < h/D_{50} < 32{,}000$), but bed form roughness may be significant. Extensive sediment storage in bed forms and floodplain. Photo used with permission, courtesy of Carter Borden.



Braided—Multithread rivers with large width-to-depth ratios and dynamic beds prone to rapid avulsion. Bed material may be gravel/cobble or sand, with correspondingly different values of slope ($0.2 < S < 1\%$, gravel; $0.02 < S < 0.1\%$, sand), width-to-depth ($34 < w/h < 84$, gravel; $61 < w/h < 377$, sand), relative submergence ($14 < h/D_{50} < 64$, gravel; $5000 < h/D_{50} < 11{,}000$, sand) and bed mobility at bankfull flow ($1.4 < \tau^*_{bf}/\tau^*_{r50} < 3$, gravel; $18 < \tau^*_{bf}/\tau^*_{r50} < 61$, 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, while bar deposition promotes flow division. 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 (Montgomery and Buffington, 1997; Gomi et al., 2003). 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 co-vary 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^*_{r50}) are from data compiled by Buffington (2012) and Bisson et al. (2017). Reported values represent inner quartile ranges of compiled data distributions for each channel type. Values may vary regionally (e.g., McDavitt, 2004; Wohl and Merritt, 2005; Flores et al., 2006; Golden and Springer, 2006; Thompson et al., 2006; Vianello and D'Agostino, 2007; Addy et al., 2011, 2014; Livers and Wohl, 2015).

[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. The reference Shields stress (τ^*_{r50}) is determined from the Mueller et al. (2005) and Pitlick et al. (2008) equations matched at $S = 0.01$ ($\tau^*_{r50} = 0.021 + 2.18S$, $S < 0.01$; $\tau^*_{r50} = 0.36S^{0.46}$, $S \geq 0.01$), except for dune-ripple channels and sand-bed braided streams, where the original Shields (1936) curve was used, as fit by Brownlie (1981).

Modified from Buffington JM, Woodsmith RD, Booth DB, and Montgomery DR (2003) Fluvial processes in Puget Sound rivers and the Pacific Northwest. In: Montgomery DR, Bolton S, Booth DB, and Wall L (eds.) *Restoration of Puget Sound Rivers*, pp. 46–78. Seattle, WA: University of Washington Press; and Buffington JM and 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.

More recently, Gurnell et al. (2016) developed a hierarchical channel classification to address environmental laws enacted by the European Union (Water Framework Directive, 2000). The classification includes eight, nested, spatiotemporal scales (ecoregion, catchment, landscape unit, river segment, channel reach, geomorphic unit (including in-channel, bank, and floodplain facies), hydraulic unit, and river element (individual patches of sediment/vegetation/wood)). Twenty-three channel types are distinguished in terms of confinement, channel pattern, bed material composition, flow regime, and groundwater–surface water interactions, as

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-bedrock-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 and 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 floodplain 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 boulder 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 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.

Reproduced from Brierley GJ and Fryirs KA (2005) *Geomorphology and River Management: Applications of the River Styles Framework*, 398 pp. Oxford, UK: Blackwell, with permission from Blackwell (Wiley).

well as 10 floodplain types based on definitions of Nanson and Croke (1992) (further detailed by Rinaldi et al. (2016), who emphasize that the channel typing in their approach is open-ended, allowing modification and site-specific tailoring, as needed). The approach combines field measurements and database analyses to assess current biophysical conditions, document past responses, and determine future response trajectories at the channel-reach scale. Overall, the Gurnell et al. (2016) classification is a mixture of descriptive cataloging and process-based interpretations, ranging from morphodynamic modelling to documenting historic channel conditions to inference based on channel metrics such as confinement, channel pattern, and stream power. It was developed specifically for river management and application by non-geomorphologists (Rinaldi et al., 2016), although geomorphic expertise is needed to interpret the processes underlying channel metrics and to understand causes for observed historic responses.

A variety of other hierarchical classifications have been developed for managing riverine ecosystems (e.g., Maxwell et al., 1995; Petts and Amoros, 1996; Habersack, 2000; Poole, 2002; Snelder and Biggs, 2002; Thorp et al., 2006, 2010; Dollar et al., 2007; Olivero Sheldon et al., 2015). 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 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 micro-habitat 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 (1) valley-scale changes in channel confinement, alluvial volume, slope, and sinuosity, (2) mesoscale changes in bed topography and sediment permeability, and (3) local changes in hydraulic pressure caused by turbulence and flow obstructions (e.g., LWD, boulders, vegetation, redds, and other biotic mounds) (e.g., Baxter and Hauer, 2000; Greig et al., 2007; Buffington and Tonina, 2009; Bean et al., 2014). 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 re-set 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). In steep river segments, the ecological effects of debris-flow inputs tend to be transient as the pulse of debris-flow sediment and wood disperses downstream over time (Benda et al., 2003; Lewicki et al., 2006), accumulating in lower-gradient, unconfined reaches that may be long-term core habitats.

6.51.3.8 Spatial analysis and statistical classifications

Spatial analysis of topography offers a means for objective classification of channel morphology. For example, spectral analysis and spatial autocorrelation have been used to objectively identify a broad range of topographic features, including scales of bed roughness (e.g., grains, particle clusters, and small bedforms; Robert, 1988), overlapping scales of sand bedforms (Gutierrez et al., 2013), different types of channel units and their spacing (e.g., pools, riffles, steps; Richards, 1976; Carling and Orr, 2000; Chin, 2002; McKean et al., 2008; Molnar et al., 2010; Trevisani et al., 2010; Duffin et al., 2021), reach morphology (e.g., plane-bed vs. pool-riffle channels; McKean et al., 2009; Marzadri et al., 2014), variation of channel width, slope, and sinuosity (e.g., Ferguson, 1975; Nakamura and Swanson, 1993), valley-scale sediment waves (McKean et al., 2008), and the response of river profiles and drainage networks to tectonic evolution over geologic time scales (e.g., Danesh-Yazdi et al., 2017; Roberts et al., 2019). Similarly, the fractal dimension of channel topography can be used to objectively classify reach morphology (e.g., Guillon et al., 2020). In many cases, interpretation of the above spatial analyses relies on visual inspection of the results to identify thresholds of response and domains of different topographic features, making the analysis subjective or reliant on user-defined rules. This problem can be remedied through formal statistical testing. 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) and statistical tests have been used to identify significant scales of pool and riffle topography to better understand their morphogenesis and temporal response to floods and sediment pulses (Richards, 1976; Madej, 1999, 2001).

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; Altunkaynak and Strom, 2009; Milner, 2010; Beechie and Imaki, 2014; Guillon et al., 2020). Over the last several decades, proliferation of high-resolution geospatial datasets and GIS tools for analyzing spatially continuous data (e.g., McKean et al., 2009; Alber and Piégay, 2011; Roux et al., 2015; Golly and Turowski, 2017; Thoms et al., 2018; Nardini and Brierley, 2021) have spawned an increasing number of statistical channel classifications, as well as landscape-scale statistical analyses of biophysical interactions (e.g., Brenden et al., 2008; Leathwick et al., 2011; Isaak et al., 2017; Troia and McManamay, 2020; Denison et al., 2021; Jacobs et al., 2021;

Tsang et al., 2021). Bottom-up statistical approaches, such as cluster or diversity analyses, also can be used to classify channel types based on distinct ranges and combinations of channel attributes (e.g., slope, grain size, channel dimensions, and confinement) that, in turn, can be related to driving variables, such as discharge, stream power, and sediment supply (e.g., Newson et al., 1998; Elliott and Jacobson, 2006; Schmitt et al., 2007; Elliott et al., 2009, 2014; Bizzi and Lerner, 2012; Splinter, 2013; Vaughan et al., 2013; Phillips and Desloges, 2015; Kasprak et al., 2016; Horacio et al., 2017; Lane et al., 2017; Levick et al., 2018; McManamay et al., 2018; Thoms et al., 2018; McManamay and DeRolph, 2019; Ouellet Dallaire et al., 2019; Brinkerhoff et al., 2020; Henshaw et al., 2020; De Cortes et al., 2021; Erwin et al., 2021). Similar methods have been used to objectively identify channel units within a given reach type (Helm et al., 2020). The above statistical approaches are frequently empirical, requiring interpretation of the underlying physical processes and assessment of whether the division of reach types is geomorphically meaningful, 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. Furthermore, it has been suggested that cluster analysis may provide a statistical means for identifying different process domains (Phillips and Desloges, 2015; Thoms et al., 2018).

The above statistical approaches tend to involve complex multi-parameter analyses for classifying channels. In contrast, a recent analysis by Jha and Diplas (2017) advocates simplicity. Using probability distributions of dimensionless channel characteristics (width-to-depth ratio, slope, and sinuosity), Jha and Diplas (2017) showed that modal values of those characteristics vary systematically with elevation for alluvial rivers in North America and the United Kingdom, suggesting that elevation could be used as a simple and consistent means for classifying alluvial rivers. Mechanistically, they proposed that channel morphology is controlled by potential energy (as measured by elevation above sea level) and that elevation can be used as a surrogate for other driving factors (climate, tectonics, geology, and watershed characteristics) that covary with it. However, we note that elevation is an imperfect proxy for specific controls on channel morphology (i.e., discharge, sediment supply, slope, confinement, vegetation, and disturbance regime). For example, downstream changes in channel morphology are driven, in part, by corresponding changes in channel slope and, thus, basin curvature, not absolute elevation. Basin curvature is controlled by geomorphic history and local base-level features such as lakes, grabens, large-scale knickpoints that perch sub-basins (e.g., Adams et al., 2016), and glacial topography (hanging valleys, troughs, and terminal moraines; e.g., Brardinoni and Hassan, 2007; Addy et al., 2014), rather than sea level per se. Jha and Diplas (2017) recognized this to some degree, noting that high-elevation plateaus and local downstream discontinuities in physical features would modulate the control of elevation on channel morphology. However, we caution that elevation is best used as a rapid, reconnaissance-level assessment of channel morphology when information on the actual underlying controls (discharge, sediment supply, slope, confinement, vegetation, and disturbance regime) is unavailable.

6.51.4 Use and compatibility of channel classifications

The Appendix summarizes the above classification approaches, the physical environment for which each classification was developed, the 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) or grain-size sampling techniques (e.g., Kellerhals and Bray, 1971; Bunte et al., 2009), 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 to another, similar to what has been done for bed material sampling (Kellerhals and Bray, 1971), but with limitations due to differences in classification criteria, methods, scale of analysis, and purpose of each classification, as discussed above. Such comparisons can be done theoretically using parameters common to each method, or empirically by conducting multiple classifications at a given set of field sites (e.g., Kasprak et al., 2016).

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 (**Fig. 16**). 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 reach-scale 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 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

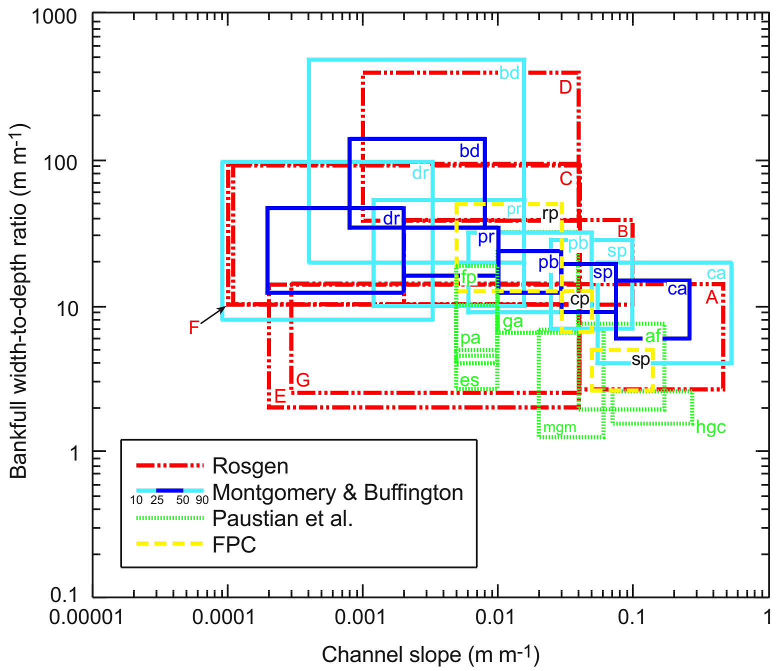


Fig. 16 Comparison of typical channel slopes (*S*) and bankfull width-to-depth ratios (*w*/*h*) for several channel classifications developed for mountain rivers in western North America. Values for Rosgen A-G stream types were determined from his Fig. 5-3 (Rosgen, 1996b), including allowable variation of classification parameters (see **Fig. 13** footnote); values not reported in his Fig. 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 inner quartile ranges of *S* and *w*/*h* distributions of data compiled by Buffington (2012), while cyan lines represent 10–90th percentile ranges. 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 if 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).

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 et al., 2011, 2014). 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**).

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

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

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 two classifications generally match the **Table 4** expectations of correspondence between reach-scale morphologies, but some of the discrepancies between the classifications are striking. 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), while 40% of the pool-riffle channels are classified as Rosgen B and G stream types (plane-bed and step-pool/cascade morphologies, respectively). Data from a subsequent study in the same watershed (Kasprak et al., 2016) showed further mismatches; 67% of pool-riffle channels were classified as Rosgen B and G stream types (plane-bed and step-pool/cascade morphologies), and 33% of plane-bed channels were classified as Rosgen C stream types (pool-riffle morphology), although sample size was even smaller (**Table 5**). 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 insight for the user (a matter of user-specific goals and objectives).

In a more comprehensive investigation, Kasprak et al. (2016) empirically compared four classification approaches in southeastern Oregon: (1) the river styles framework (Brierley and Fryirs, 2000, 2005); (2) a modified version of Beechie and Imaki's (2014) method for predicting channel pattern, in which smaller channels (bankfull width < 8 m) were assigned Montgomery and Buffington (1997) stream types based on reach slope; (3) the Rosgen (1994, 1996b) approach; and (4) a cluster analysis of channel attributes (bottom-up statistical classification). Results showed that stream types between approaches could be grouped in terms of underlying channel characteristics (e.g., reach slope, sinuosity, confinement, bankfull width-to-depth ratio, and grain size), but with imperfect correspondence of reach morphologies, similar to that shown by **Fig. 16**. For example, as with the empirical studies discussed above, 60% of the predicted pool-riffle channels were classified as Rosgen B and G stream types (plane-bed and step-pool morphologies), while 50% of the predicted plane-bed channels were classified as Rosgen C and A streams (pool-riffle and step-pool/cascade morphologies).

Kasprak et al. (2016) further argue that the form–process paradigm is inherent in the above approaches in terms of their descriptions of valley setting, morphology, and measured channel characteristics. For example, confinement implicitly indicates the potential for hillslope sediment inputs and channel pattern indicates the potential for lateral adjustment, while slope, channel geometry, and grain size can be used to quantify relative values of stream power, resistance, and channel competence between stream types. However, those factors do not explain reach morphogenesis per se, particularly where similar values of confinement, slope, and grain size yield different reach-scale morphologies (e.g., gravel-bed pool-riffle (Rosgen C) vs. plane-bed (Rosgen B) channels). Specification of the processes giving rise to each morphology in a given classification is needed for users not trained in geomorphology to understand the processes associated with a given channel form. Nevertheless, analysis of channel characteristics can be informative. For example, Lane's (1955) balance can be formalized to predict how channel characteristics (slope, grain size, bankfull geometry, and sediment mobility) adjust to imposed conditions of discharge and sediment supply (**Fig. 17** inset), with domains for different channel types empirically overlain on those values (**Fig. 17**). Using this framework, one can predict how channel characteristics and reach morphology may respond to altered discharge and sediment supply due to natural and anthropogenic disturbances (Buffington et al., 2003; Buffington, 2012). The framework also shows that, while slope is the dominant factor controlling the occurrence of Montgomery and Buffington (1997) channel types (**Fig. 17**), reach morphology arises from complex interactions of multiple factors that covary with slope (e.g., Palucis and Lamb, 2017; Khan et al., 2021;); specifically, the slope covariates in **Fig. 17** are relative submergence, excess shear stress, discharge, and equilibrium transport rate (bedload transport equal to sediment supply), all of which are predicted simultaneously using a linked series of equations (Buffington, 2012) that inherently captures interactions. Interaction and competition between multiple factors reinforces Kasprak et al.'s (2016) conclusion that classifications which implicitly account for such interactions may avoid biases inherent in hierarchical approaches that impose a top-down structure on the importance of successive factors and that do not formally address interactions (e.g., Rosgen, 1994, 1996b; Brierley and Fryirs, 2000, 2005; Orr et al., 2008).

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		
Southeastern Oregon (Kasprak et al., 2016; CHaMP)[c, d]							
A		1	/3	/1			
B			2/1	2/4	9/2		
C				1/3	5/1		1
E					/1		
G					1/1		
Northern Idaho (Whiting et al., 1999)[c]							
A				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 of reach morphology, while light shading indicates 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 Fig. 13 footnote), and if the latter resulted in multiple stream types (see Roper et al., 2008; Buffington et al., 2009 for further detail).

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

[d]Rosgen channel types are from Kasprak et al. (2016). Montgomery and Buffington (1997) channel types are from (1) field observations made by multiple crews in 2011-2012 (Columbia Habitat Monitoring Program—CHaMP, https://www.champmonitoring.org), values before the slash mark and (2) predicted as a function of reach slope (Kasprak et al., 2016), values after the slash mark.

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

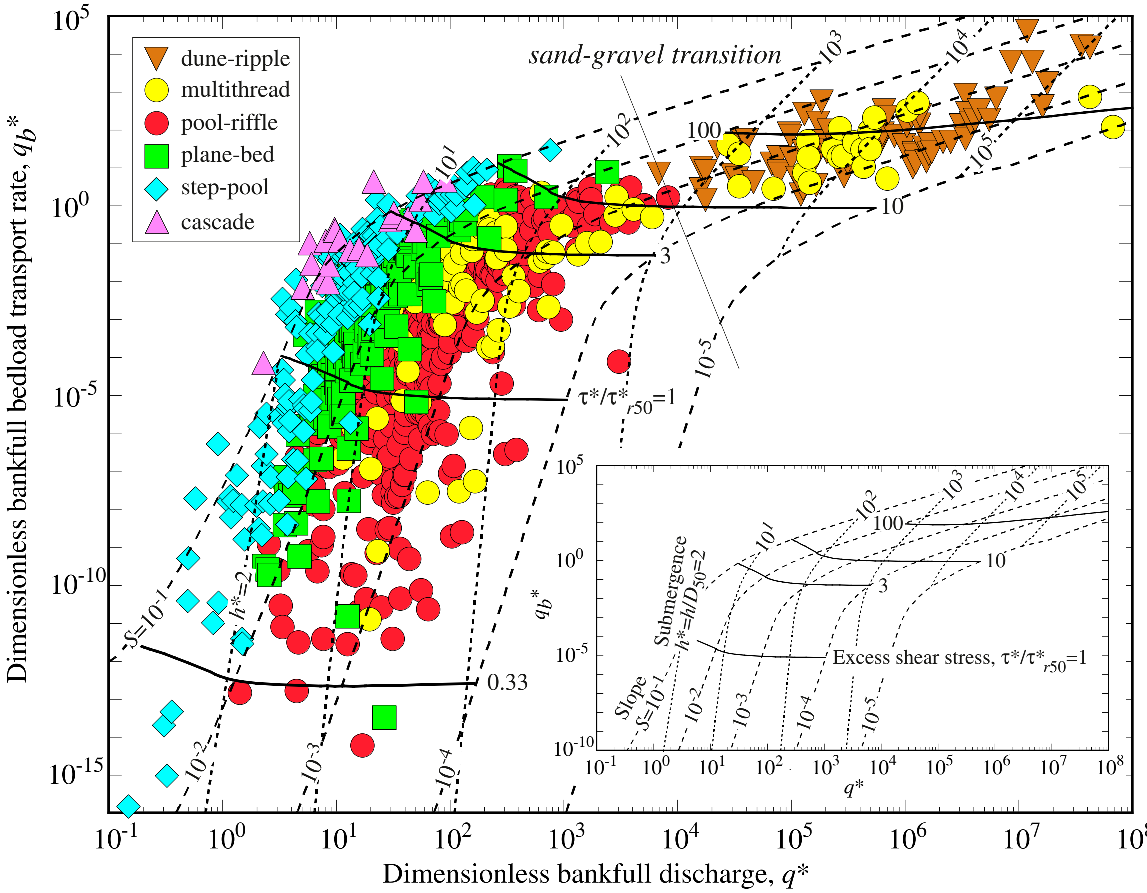


Fig. 17 Lane's (1955) balance formalized as a state diagram for alluvial rivers, showing (inset panel) predicted contours of equilibrium channel slope (S), relative submergence ($h^* = h/D_{50}$, where h is flow depth and D_{50} is the median surface grain size), and excess Shields stress (τ^*/τ^*_{r50}, a measure of sediment mobility, where τ^* is the applied Shields stress and τ^*_{r50} is the reference Shields stress for a low transport rate of D_{50}) as functions of dimensionless discharge (q^*) and dimensionless equilibrium transport rate (q_b^*, bedload transport rate = sediment supply), both per unit width. The larger panel populates the figure with field data for different reach-scale channel types using predicted values of q^* and q_b^* evaluated at bankfull stage. Here, multithread rivers include wandering/divided, braided, and anastomosing channels. Methods and data sources are detailed by Buffington (2012), but with (1) q_b^* predicted from the Parker et al. (1982) equation, as modified by Parker (1990), (2) τ^*_{r50} for coarse-grained channels ($D_{50} \geq 2$ mm) predicted from the Mueller et al. (2005) and Pitlick et al. (2008) equations matched at $S = 0.01$ ($\tau^*_{r50} = 0.021 + 2.18S$, $S < 0.01$; $\tau^*_{r50} = 0.36S^{0.46}$, $S \geq 0.01$), and (3) τ^*_{r50} for fine-grained channels ($D_{50} < 2$ mm) predicted from the Shields (1936) curve, as fit by Brownlie (1981). Modified from Buffington JM (2012) Changes in channel morphology over human time scales. In: Church M, Biron PM, and Roy AG (eds.) *Gravel-bed Rivers: Processes, Tools, Environments*, pp. 435–463. Chichester: Wiley, U.S. public domain; and Buffington JM, Woodsmith RD, Booth DB, and Montgomery DR (2003) Fluvial processes in Puget Sound rivers and the Pacific Northwest. In: Montgomery DR, Bolton S, Booth DB, and Wall L (eds.) *Restoration of Puget Sound Rivers*, pp. 46–78. Seattle, WA: University of Washington Press. After Parker G (1990) Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research* 28: 417–436.

6.51.5 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 (Fig. 18). This may be linked to changing scientific and societal needs, such that the purpose or underlying philosophy of a given classification has a limited time of being in vogue (Kondolf, 1995; Kondolf et al., 2003, 2016). For example, hierarchical channel classifications are currently in vogue because they address a need for holistic, basin-wide studies of physical and biological processes in response to recent environmental laws and calls for interdisciplinary collaboration among scientists, managers, and stakeholders. In contrast, genetic classifications were popular in the late 1800s and early 1900s following Darwin's work on evolution (Kondolf, 1995), but have begun making a recent comeback as a means of contextualizing observed morphologies and associated habitats (i.e., interpreting morphologic/ecological states and trajectories in response to natural and anthropogenic disturbances as a function of space and time) (e.g., Brierley and Fryirs, 2005; Rosgen, 2006b; Cluer and Thorne, 2014; Rinaldi et al., 2015; Gurnell et al., 2016).

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 (Fig. 18), despite the fact that the approach has a strong process basis.

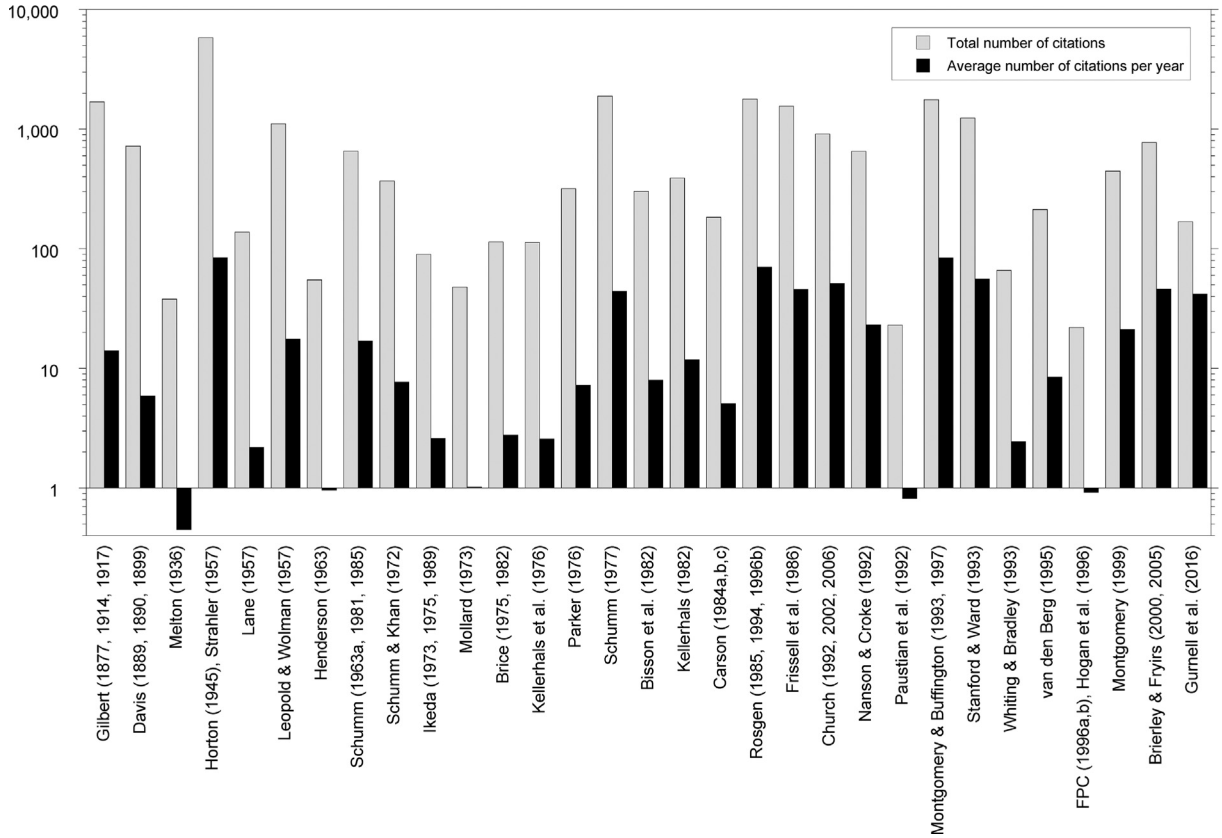


Fig. 18 Number of total citations and average citations per year since publication for select channel classifications as of 2020 according to Scopus. The number of citations is assumed to be correlated with use of a given classification, but is not an exact measure of use, since citations may also include criticism or discussion of the publication, without actual use of the related classification. Furthermore, these statistics may not include citation within grey literature and contract reports, which may be a more relevant index for use by practitioners. 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); 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 (1993, 1997) include Bisson and Montgomery (1996), Montgomery and Buffington (1998), Buffington et al. (2003), and Bisson et al. (2006, 2017); values for Stanford and Ward (1993) include Ward and Stanford (1995), Stanford (1996, 2006), and Stanford et al. (2005, 2017); values for Brierley and Fryirs (2000, 2005) include Fryirs and Brierley (2000), Brierley et al. (2002), and Fryirs (2003); and values for Gurnell et al. (2016) include González del Tánago et al. (2016) and Rinaldi et al. (2016).

One of the strongest factors governing 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 desired goals (i.e., detailed research vs. reconnaissance-level measurements for rapid, practical application). Conflict arises when reconnaissance-level measurements are extended beyond their limitations and are used to make indefensible assessments of channel condition or to plan unjustified restoration activities (e.g., see Gillian, 1996; Kondolf, 1998; Kondolf et al., 2001; Smith and Prestegaard, 2005; 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 non-experts.

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, 2014; 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.

6.51.6 Future needs and directions

6.51.6.1 Standardization and sample size

The proliferation and incompatibility of channel classifications begs the question of whether the geomorphic community should standardize 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., Raven et al., 1998; 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 one should sample in conducting grain-size analyses (Wolman, 1954; Church et al., 1987; Rice and Church, 1996), but similar rules have not been developed for determining requisite sample sizes for accurately representing the mean and variance of other channel characteristics (e.g., width, depth) in any one channel type, let alone across different channel morphologies. Recent work provides some insight to this question. In forested gravel-bed rivers, reach lengths of at least 15 bankfull widths may be needed to characterize the spatial heterogeneity of channel units in pool-riffle streams (Helm et al., 2020), which is half the reach length (30 channel widths) advocated by Dunne and Leopold (1978) for pool-riffle channels having low wood loading and a pool spacing of 5-7 channel widths (i.e., a sample size of 4-6 pools as a minimum estimate of topographic variability). In terms of constructing reliable DEMs from surveyed cross sections, a cross-section spacing of 0.5–1 bankfull widths may be needed to produce accurate 2D hydraulic models in pool-riffle and plane-bed channels, while a coarser cross-section spacing of 3 widths may suffice for determining mean values of bankfull depth and slope from interpolated DEMs (Conner and Tonina, 2014; Glenn et al., 2016). DEM interpolation allows bulking of otherwise sparse topographic information that can analytically reduce uncertainty, but it remains an open question of how many individual field measurements of channel width and depth are needed for simple statistics performed on those values in the absence of interpolated DEMs; this is important because DEMs are not typically constructed for purposes of channel classification. 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. Nevertheless, insufficient sampling of channel characteristics will likely result in large uncertainties in channel typing and monitoring of physical conditions, and may hinder data sharing between groups collecting such information (Roper et al., 2008, 2010).

6.51.6.2 Remote sensing

Using DEMs, one can make first-order predictions of channel type, stream characteristics (width, depth, grain size, channel pattern, confinement), and associated aquatic habitat as functions of slope and drainage area (e.g., Lunetta et al., 1997; Montgomery et al., 1998, 1999; Buffington et al., 2004; Beechie et al., 2006; Benda et al., 2007; Hall et al., 2007; Orr et al., 2008; Addy, 2009; Gorman et al., 2011; Wilkins and Snyder, 2011; Buffington, 2012; Goode et al., 2012; May and Lisle, 2012; Nagel et al., 2014; Pfeiffer and Finnegan, 2017; O'Brien et al., 2019). These approaches require field verification and process-based interpretation of differences between observed and predicted values (e.g., Dietrich et al., 1996; Buffington and Montgomery, 1999b), but nonetheless offer a rapid means for remote sensing of basin features. However, recent advances in LiDAR (Light Detection and Ranging) have the potential to radically change our 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 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 banks and 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). However, shallow flow depths (<10–20 cm), turbidity, turbulence, water-surface waves, and poor reflectivity of the streambed (a function of sediment properties and flow depth) can limit the use of bathymetric LiDAR (McKean and Isaak, 2009; Legleiter and Harrison, 2019). 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 our 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.

A variety of other instruments and measurement techniques for remote sensing can fill the above data gaps and provide additional information about flow conditions (velocity, depth, temperature), sediment transport, and associated aquatic habitat. These include synthetic aperture radar, multispectral and hyperspectral imagery, infrared thermal imagery, high-resolution photography/videography, acoustic Doppler, and echo sounders (see reviews by Carbonneau and Piégay (2012), Bizzi et al. (2016), Gilvear and Bryant (2016), Gilvear et al. (2016), Legleiter and Harrison (2019), Tomsett and Leyland (2019), Piégay et al. (2020), and references therein). In addition, a variety of techniques have recently been developed for remotely sensing grain size on both exposed and submerged surfaces using lasers and different types of imagery, with structure-from-motion techniques being particularly promising for quantifying grain-size variation from high-resolution photography/videography (Woodget and Austrums, 2017; Woodget et al., 2017). Platforms for deploying the above instruments range from ground- and river-based systems to satellites. Advances in the availability of unmanned platforms for airborne instruments (i.e., drones) allow rapid and extensive collection of field data in remote areas that can be used to quantify channel type and monitor channel condition/response over time to natural and anthropogenic disturbances. In addition, online availability of remotely-sensed data (e.g., aerial photography and Landsat imagery in Google Earth) is increasingly being used to quantify channel characteristics at basin, regional, and global scales (e.g., Gleason et al., 2014; Ferguson et al., 2015; Hou et al., 2019; Boothroyd et al., 2021).

6.51.7 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 taken to select 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 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 (Stevens et al., 1975; Carling, 1988a; Hoey, 1992; Montgomery and Bolton, 2003; Kondolf et al., 2001; Brierley and Fryirs, 2005; Rosgen, 2006b; Cluer and Thorne, 2014; Rinaldi et al., 2015). 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. In this regard, an important future challenge is to couple process-based classification with dynamic models of system response at spatial and temporal scales the are ecologically relevant and meaningful to problems faced by land managers (Fausch et al., 2002). Although mechanistic models linking physical and biological processes can be applied to entire stream networks and used to predict past/future conditions (Buffington et al., 2004; May and Lisle, 2012; Goode et al., 2013; Wheaton et al., 2018), most such models are not dynamic, despite the recognized importance of watershed dynamics in structuring physical conditions, riverine habitat, and metapopulation response (Benda et al., 2004). Advances in GIS modelling and the increased availability of spatially continuous datasets have dramatically expanded the spatial scale of watershed analysis over the last several decades, but dynamic models of system response that mechanistically describe nested interactions over space and time are needed to contextualize physical and biological conditions within and between basins for effective management and restoration efforts.

6.51.8 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 (Fig. 1)	Any river network	River network		✓
Orr et al. (2008): Nested subdivision of stream order, specific stream power, slope, and floodplain width (confinement)	Small channels, with gravel to boulder beds, and moderate to steep slopes (NW England), but applicable to any river network	River network		✓
Process domain				
Schumm (1977): Sediment production, transfer and deposition zones (Fig. 2A)	Source to sink (headwaters to lowland depositional zone); generally applicable to any river environment	Basin	✓	
Montgomery (1999): Interaction between disturbance processes, channel morphology and aquatic habitat (Fig. 2B)	Mountain rivers of the Pacific Northwest (headwaters to alluvial plains), but concepts applicable to any environment	Valley	✓	
Land type/valley segment (implicit process domain):				
Platts (1974): Relates channel morphology and fish habitat to land types, associated process domains, and stream order	Small, steep to very steep, alluvial rivers, with boulder to sand beds, and variable floodplain extent; US Rocky Mountains (Idaho)	Reach		✓
Cupp (1989): Recognizes 7 land types and 19 subordinate valley types, noting valley slope, confinement, channel pattern, and geomorphic features bounding the channel	Small to large rivers, from steep headwaters to moderate-gradient coastal areas of western Washington; boulder to sand beds; concepts applicable to other environments	Valley		✓
Alexander et al. (2009): Valley segments distinguished by confinement, channel pattern, width variation, and bar type	Small to large alluvial rivers, with gravel to silt beds, moderate to low slopes (10^{-3}–10^{-4}), and variable floodplain extent; Great Plains	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, and limited analysis of gravel/cobble-bed rivers, of various size, with moderate to low slopes (10^{-2}–10^{-5}); select data from moderate-slope, sand-bed laboratory channels; data compilation from conterminous United States and select rivers in central Canada (Manitoba), Mexico, China, Turkey and Egypt	Reach to valley		✓
Leopold and Wolman (1957): *S*–*Q* threshold for braided vs. meandering channels (Fig. 3)	Small to large rivers, with cobble to sand beds, and moderate to low slopes (10^{-2}–10^{-5}); data compilation from US Rocky Mountains, Interior/Great Plains, Appalachians, central Alaska and India	Reach to valley		✓
Bray (1982): *S*–*Q* threshold for braided vs. meandering channels, with degree of sinuosity and frequency of islands indicated	Small to large, gravel/cobble-bed rivers, with moderate to low slopes (10^{-2}–10^{-4}); Canadian Rocky Mountains and Interior Plains (Alberta)	Reach to valley		✓
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}–10^{-4}); data compilation from western North America (Canada and United States), Columbia and Australia	Reach to valley		✓
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, and steep to low slopes (10^{-1}–10^{-4}); Pacific Northwest (Cascade and Olympic mountains, western Washington)	Reach to valley	✓	✓

Slope–discharge–grain size (*S*–*Q*–*D*):	Alluvial floodplain rivers (unconfined to partly confined):			
Henderson (1963): *S*–*QD* threshold for braided vs. meandering and straight channels (latter two share a common space)	Re-analysis of Leopold and Wolman (1957)	Reach to valley	✓	✓
Osterkamp (1978): *S*–*Q* domains for braided vs. meandering channels, stratified by grain size and sinuosity	Sand- to gravel-bed rivers of various size, with moderate to low slopes (10^{-3}–10^{-4}) (Kansas); supplemental data compilation of laboratory channels and sand to cobble rivers of various size, with moderate slopes (10^{-2}–10^{-3}), western United States	Reach to valley		✓
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, and steep to low slopes (10^{-1}–10^{-4}); unpublished data compilation by M. Church for western North America (United States and Canada), Interior and Great Plains (United States), southwestern United States, Canadian Arctic Archipelago, Iceland, Norway, Russia, India and New Zealand	Reach to valley		✓
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 and worldwide compilation	Reach to valley	✓	✓
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}–10^{-3}); data compilation for western North America (conterminous United States and Canada), United Kingdom and New Zealand	Reach to valley	✓	
Other discriminators:				
Schumm and Khan (1972), Schumm et al. (1972): Straight, meandering and braided channels as a continuous function of *S* vs. bed load transport rate, or shear stress	Moderate-slope (10^{-2}–10^{-3}), laboratory sand-bed channels	Reach to valley		✓
Anderson et al. (1975), Parker (1976): Domains for straight, meandering, and braided channels as a function of bankfull Froude number and channel form index (product of channel slope and width-depth ratio, *Sw*/*h*) developed from stability analysis; includes transitional types and braiding intensity	Data compilation, using laboratory sand-bed channels, sand and gravel irrigation canals (US Rocky Mtns and Great Plains) and sand to cobble, floodplain rivers of various size and slope (conterminous United States, central Alaska and select rivers in China, Norway and India)	Reach to valley	✓	
Fredsøe (1978): Thresholds for straight, meandering, and braided channels as a function of *w*/*h*, Shields stress, and stability analysis	Laboratory sand-bed channels and small to large, floodplain rivers, with sand to gravel beds, and low to moderate slopes (10^{-3}-10^{-4}); Midwestern United States, California central coast, Australia, and Denmark	Reach	✓	
Excess shear velocity (u^*/u_c^*) and 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 and small to large, floodplain rivers, with cobble to sand beds, moderate to low slopes (10^{-2}–10^{-5}) and variable confinement; Japan	Reach to valley		✓
Florsheim (1985): Extension of Ikeda framework to bar formation and 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 and steep to moderate slopes (10^{-1}–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}–10^{-4}) and variable confinement; data compilation from conterminous western United States, Alaska, Scotland and Norway	Reach to valley		✓

(Continued)

Classification approach	*Environment*[a]	*Scale of application*[b]	*Process-based*[c]	*Descriptive*
van den Berg (1995), Kleinhans and van den Berg (2011): Stream power–grain size threshold for braided vs. meandering channels; later combined with bar theory predictions (i.e., existence, extent, and pattern of bars)	Small to large, floodplain rivers, with cobble to sand beds, moderate to low slopes (10^{-2}–10^{-4}) and variable confinement; worldwide compilation	Reach to valley	✓	✓
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 (Fig. 17)	Small to large rivers, with boulder to sand beds, steep to low slopes (10^{0}–10^{-4}) and variable confinement; worldwide data compilation	Reach to valley	✓	✓
Métivier et al. (2017): Domains for braided vs. single-thread channels using Lacey's law (dimensionless channel width as a function of dimensionless discharge, both scaled by grain size)	Data compilation for laboratory sand-bed channels	Reach	✓	✓
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 and stability arrayed as functions of mode of sediment transport, ratio of bed load to suspended load (a function of sediment supply, caliber and stream power), channel gradient and width-to-depth ratio (Fig. 4)	Small to large rivers, with gravel to sand beds, and moderate to low slopes (10^{-2}–10^{-4}); data synthesis from Great Plains; concepts generally applicable to floodplain rivers	Reach to valley	✓	✓
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 and tortuous meandering) and 17 minor types; channel type and stability arrayed as functions of sediment supply, caliber, ratio of bed load to suspended load, channel gradient and discharge (as modified by river regulation)	Medium to large rivers, with cobble to silt beds and various slopes; some confined, non-alluvial rivers; western and 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 and bed load supply relative to transport capacity	Small to large rivers, with cobble/gravel beds, and moderate slopes (10^{-2}–10^{-3}); New Zealand; concepts generally applicable	Reach to valley	✓	
Church (1992, 2006): Synthesis and generalization of above conceptual frameworks by Schumm and Mollard (Fig. 5)	Applicable to most types of alluvial rivers (boulder to silt beds, confined headwaters to unconfined lowlands)	Reach to valley	✓	✓
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 United States and Canada	Reach to valley	✓	✓
Nanson and Croke (1992), Brierley and Fryirs (2005): Genetic sequences (Figs. 7 and 14b)	Synthesis of alluvial floodplain rivers from around the world; silt- to boulder-bed rivers of various size, confinement, and slope	Reach to valley	✓	✓
Aerial photographs and GIS:				
Mollard (1973): Same as Mollard (1973) above	Same as Mollard (1973) above	Reach to valley	✓	✓
Brice (1975): Recognizes 67 channel types as a function of the degree and character of sinuosity, braiding and anabranching	Medium to large alluvial rivers of various slope, grain size and floodplain extent; conterminous United States, central Alaska and select international rivers (unspecified locations)	Reach to valley		✓

Brice and Blodgett (1978a,b), Brice (1982): Describes alluvial rivers in terms of 14 factors, and recognizes 4 major channel types as a function of variability in channel width, nature of point bars, and degree of braiding; channel type correlated with long-term lateral and vertical stability, and short-term bed scour/fill	Same as above	Reach to valley	✓	✓
Kellerhals et al. (1976), Kellerhals and Church (1989): Classification of planform features (sinuosity, frequency of channel islands, bar type and lateral activity of the channel and floodplain; Fig. 10)	Medium to large alluvial rivers, with cobble to sand beds, moderate to low slopes (10^{-2}–10^{-5}) and variable floodplain extent; Canadian Rocky Mountains and Interior Plains (Alberta)	Reach to valley	✓	✓
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 and bedrock rivers, with very steep to moderate slopes (10^{0}–10^{-3}) and variable confinement; western United States (southern Utah, northern California, western Washington); concepts generalizable to any environment	Reach to valley	✓	
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) and small to large, floodplain rivers (same as Leopold and Wolman, 1957); concepts generally applicable to most sand- and gravel/cobble-bed rivers	Reach to valley	✓	
Church (2002, 2006): Recognizes 6 channel types as a function of bankfull Shields stress, grain size, mode of transport, reach morphology and 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 and worldwide compilation of Shields values	Reach to valley	✓	✓
Whiting and Bradley (1993): Classifies channel type in terms of risk of debris-flow disturbance, mobility of input material and mode of transport (Fig. 8)	Small to medium-sized headwater channels, with boulder to gravel beds and variable confinement; mountain basins of the Pacific Northwest; applicable to mountain basins prone to mass wasting, but concepts generalizable to other types, frequencies and magnitudes of sediment input (pulse vs. press)	Reach to valley	✓	
Channel/geomorphic units				
Bisson et al. (1982), Sullivan (1986), Bryant et al. (1992), Church (1992), Hawkins et al. (1993), Wood-Smith and Buffington (1996), Padmore et al. (1998): Hierarchical classification, recognizing two major channel unit types (pools vs. "shallows"), four or more secondary types (subdivision of pools into scour vs. backwater types and subdivision of "shallows" into various steep vs. low-gradient types; e.g., cascade, riffle, glide) and a variety of tertiary types (e.g., different types of scour pools) using visual assessment of channel topography, hydraulics, grain size, water-surface slope, and water-surface topography; excludes exposed bars; generally descriptive, but some studies more process-based than others; approach has been expanded to include new unit types (e.g., Beechie et al., 2005; Erskine et al., 2005; Moir and Pasternack, 2008)	Moderate-gradient (10^{-2}–10^{-3}), small to medium-sized, gravel/cobble-bed rivers of western North America and the United Kingdom, typically hosting salmonids; concepts generalizable to other environments	Channel unit	✓	✓

(Continued)

Classification approach	*Environment*[a]	*Scale of application*[b]	*Process-based*[c]	*Descriptive*
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}–10^{-2}), cobble- and boulder-bed channels of the Pacific Northwest, with moderate to high confinement; concepts generalizable to other environments	Channel unit	✓	✓
Church and Jones (1982): Visual classification of bar types and processes	Large, gravel/cobble, floodplain rivers of various slope, with unconfined to partially-confined valleys; synthesis of Canadian rivers and select United Kingdom and New Zealand rivers; concepts generally applicable to any coarse-grained, bar-form river	Channel unit	✓	✓
Osterkamp (1998), Wyrick and Klingeman (2011): Visual classification of island types, morphogenesis, age, and stability	Alluvial and bedrock rivers of various size and slope, with examples drawn from rivers around the world	Channel unit	✓	✓
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}–10^{-3}) and unconfined to partially-confined valleys; northern California, southern Oregon and southeastern Alaska; concepts generalizable to other pool-forming rivers	Channel unit	✓	✓
Brierley et al. (2013), Wheaton et al. (2015), Belletti et al. (2017): Visual classification of in-channel, bank, and floodplain units based on factors such as location, shape, topography, water-surface slope, hydraulics, grain size/relative roughness, vegetation, and activity (modern vs. relict); generally descriptive, but some approaches provide morphogenic interpretations	Alluvial and bedrock rivers of various size, slope, substrate and confinement (headwaters to lowlands); mountain basins of Australia, New Zealand, northern California, and Europe, but concepts are generalizable to other environments	Geomorphic unit	✓	✓
Hierarchical				
Frissell et al. (1986): Describes physical conditions and processes across multiple spatial and temporal scales to assess aquatic habitat (Fig. 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}–10^{-2}), boulder to gravel beds and variable confinement; concepts generalizable to other environments and basin sizes	Micro to reach, viewed within a basin context	✓	✓
Paustian et al. (1992): Recognizes process domains, associated reach types, aquatic habitats and sensitivity to landscape disturbance; see text for further explanation	Alluvial and bedrock rivers spanning a broad range of headwater to lowland process domains; small to large rivers, with steep to moderate slopes (10^{-1}–10^{-3}), boulder to sand beds, and variable confinement; mountain basins of southeastern Alaska; some concepts generalizable, but process domains are region specific	Reach, viewed within a valley and basin context	✓	✓
Stanford and Ward (1993), Stanford et al. (2005): Classifies river corridors in terms of stream order, valley type, and ecological process domains (longitudinal, lateral, and vertical connectivity between the channel, floodplain/riparian zone, and hyporheic zone), emphasizing nested spatial and temporal scales of interactions (Fig. 12)	Small headwater streams to large lowland estuaries, although mainly focused on steep- to moderate-sloped channels (10^{-1}–10^{-3}), with boulder to gravel beds and variable confinement in glaciated basins of the US Rocky Mountains (Montana)	Micro to valley, viewed within a valley segment and basin context	✓ (ecologically)	✓
FPC (1996a,b), Hogan et al. (1996): Uses channel morphology to assess channel condition and stability as a function of sediment supply (Figs. 10 and 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}–10^{-5}) and variable confinement; mountain basins of British Columbia; concepts and classification parameters generally applicable to other environments	Reach, viewed within a valley and basin context	✓	✓

Rosgen (1985, 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 (Fig. 13); employs empirical genetic models to predict channel response to disturbance (Fig. 14A); see text for further discussion	Alluvial and bedrock rivers from headwaters to lowlands; small to large rivers, with steep to low slopes (10^{-1}–10^{-4}), boulder to silt beds and variable confinement; mountain basins of the western United States; 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 3 valley types, within which 8 channel morphologies and their response potential are described within the context of associated fluvial processes, process domains, bed load supply relative to transport capacity, external factors (e.g., LWD) and geomorphic history (Table 2, Figs. 2B and 6); designed for academic and management purposes; see text for further discussion	Alluvial, bedrock and colluvial channels from headwaters to lowlands; small to large rivers, with steep to low slopes (10^{0}– $< 10^{-3}$), boulder to sand beds and variable confinement; mountain basins of the western United States, 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 (Fig. 14B) to assess channel condition and to inform restoration actions; see text for further explanation	Broad range of process domains for alluvial and bedrock rivers of various size, slope, substrate and confinement (headwaters to lowlands); mountain basins of Australia and New Zealand, but concepts are generalizable to other environments	Reach to valley, viewed within a basin context	✓	✓
Fitzpatrick et al. (2006, 2016): Recognizes 15 stream-segment types based on slope, confinement, valley type, network position, geology, and process domains; supplemented by reach-scale field measurements of Montgomery and Buffington (1997) channel types, floodplain and riparian conditions, and disturbance/response potential	Alluvial and bedrock rivers, with variable confinement, steep to low slopes, and boulder to sand beds; north shore of Lake Superior, Midwestern US; concepts broadly applicable, but process domains are region specific	Reach to valley segment, within a basin context	✓	✓
Gurnell et al. (2016), Rinaldi et al. (2016): Eight hierarchical scales of analysis, recognizing 23 channel types and 10 floodplain types, emphasizing assessment of current, past, and future conditions at reach scales; see text for further explanation	Alluvial, bedrock, and colluvial channels of various size, slope, confinement, and grain size (headwaters to lowlands); European rivers and associated historical context; concepts and classification parameters generalizable to other environments	Reach viewed within the context of seven other scales of analysis	✓	✓
Other				
Erskine et al. (2005, 2017): Recognizes 12 reach types based on channel pattern, confinement, substrate, process domain, and associated channel units.	Tropical rivers of northern Australia; bedrock and alluvial channels, with steep to low slopes, small to large width, and boulder to mud beds in mountain to estuarine environments. Includes lake, wetland, and unchanneled "reaches"	Reach within a valley context	✓	✓
Sutfin et al. (2014): Five reach types based on channel pattern, confinement, confining material (bedrock vs. alluvium), extent of streambed alluvium, and process domain, with implications for riparian habitat (Shaw et al., 2014)	Ephemeral channels in arid mountain basins; bedrock and alluvial rivers, with steep to moderate slopes, small to medium width, and sand to cobble beds; southern Arizona	Reach, viewed within a valley and basin context	✓	✓

[a]Channel slopes (S) are described as very steep ($S \geq 10^{-1}$), steep ($3 \times 10^{-2} < S < 10^{-1}$), moderate ($10^{-3} < S < 3 \times 10^{-2}$), 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 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}–10^{0} w), reach (10^{1}–10^{2} w), valley ($> 10^{2}$ w). Larger spatial scales are expressed in terms of network and basin structure: network link, sub-basin, and basin.

[c]Multiple check marks indicate a mixture of both process-based and descriptive approaches, with small check marks indicating a subordinate category.

Acknowledgments

We thank Gary Brierley and Jaime Goode for constructive comments on the first edition of this manuscript. JMB dedicates this work to John Mason Buffington V (1945–2010) for his steadfast encouragement and inspiring love of history and nature.

References

Adams, B.A., Whipple, K.X., Hodges, K.V., Heimsath, A.M., 2016. In situ development of high-elevation, low-relief landscapes via duplex deformation in the Eastern Himalayan hinterland, Bhutan. Journal of Geophysical Research: Earth Surface 121, 294–319.

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.

Addy, S., Soulsby, C., Hartley, A.J., Tetzlaff, D., 2011. Comparison of channel reach morphology and associated controls in deglaciated montane catchments in the Cairngorms, Scotland. Geomorphology 132, 176–186.

Addy, S., Soulsby, C., Hartley, A.J., 2014. Controls on the distribution of channel reach morphology in selectively glaciated catchments. Geomorphology 211, 121–133.

Alabyan, A.M., Chalov, R.S., 1998. Types of river channel patterns and their natural controls. Earth Surface Processes and Landforms 23, 467–474.

Alber, A., Piégay, H., 2011. Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France). Geomorphology 125, 343–360.

Albertson, L.K., Koenig, L.E., Lewis, B.L., Zeug, S.C., Harrison, L.R., Cardinale, B.J., 2013. How does restored habitat for Chinook salmon (*Oncorhynchus tshawytscha*) in the Merced River in California compare with other Chinook streams? River Research and Applications 29, 469–482.

Alexander, J.S., Zelt, R.B., Schaepe, N.J., 2009. Geomorphic segmentation, hydraulic geometry, and hydraulic microhabitats of the Niobrara River, Nebraska—Methods and initial results. US Geological Survey. Scientific Investigations Report 2009-5008, 51 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.

Anderson, A.G., Parker, G., Wood, A., 1975. The flow and stability characteristics of alluvial river channels. Minneapolis, MN: University of Minnesota, St. Anthony Falls Hydraulic Laboratory. Project Report no. 161 116 pp.

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. In: Stream Corridors: Adaptive Management and Design. Proceedings of the Second International Conference on Natural Channel Systems, *CD-ROM. March 1-4, Niagara Falls, ON*.

Baldigo, B.P., Ernst, A.G., Warren, D.R., Miller, S.J., 2010. Variable response of fish assemblages, habitat, and stability to natural-channel-design restoration in Catskill mountain streams. Transactions of the American Fisheries Society 139, 449–467.

Bangen, S.G., Kramer, N., Wheaton, J.M., Bouwes, N., 2017. The GUTs of the geomorphic unit tool: What is under the hood. American Geophysical Union Fall Meeting, New Orleans, LA, Abstract EP31D-1901. https://doi.org/10.13140/RG.2.2.31118.66884.

Barry JJ (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.

Bean, J.R., Wilcox, A.C., Woessner, W.W., Muhlfeld, C.C., 2014. Multiscale hydrogeomorphic influences on bull trout (*Salvelinus confluentus*) spawning habitat. Canadian Journal of Fisheries and Aquatic Sciences 72, 514–526.

Beardsley, M., 2011. DB: A proposed new stream type class for the Rosgen classification system to account for stream channels controlled by beaver activity. GreenLine Blog, Colorado Riparian Association 22 (3). https://coloradoriparian.org/2011/09/29/stream-classification-beavers/.

Beechie, T., Imaki, H., 2014. Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. Water Resources Research 50, 39–57.

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., Pess, G.R., Buffington, J.M., Moir, H.J., Roni, P., Pollock, M.M., 2010. Process-based principles for restoring river ecosystems. BioScience 60, 209–222.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A.M., Mao, L., Nardi, L., Vezza, P., 2017. Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. Geomorphology 283, 143–157.

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., 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.

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., Miller, D., Andras, K., Bigelow, P., Reeves, G., Michael, D., 2007. NetMap: A new tool in support of watershed science and resource management. Forest Science 53 (2), 206–219.

Beschta, R.L., Platts, W.S., Kauffman, J.B., Hill, M.T., 1994. Artificial stream restoration—Money well spent or an expensive failure?. In: Environmental Restoration, Universities Council on Water Resources Annual Conference, Big Sky, MT, pp. 76–104.

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, 1st edn. Academic Press, San Diego, CA, pp. 23–52.

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.
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, 2nd edn. Academic Press/Elsevier, San Diego, CA, pp. 23–49.
Bisson, P.A., Montgomery, D.R., Buffington, J.M., 2017. Valley segments, stream reaches, and channel units. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology, 3rd edn., Vol. 1: Ecosystem Structure. Academic Press/Elsevier, San Diego, CA, pp. 21–47.
Bizzi, S., Lerner, D.D., 2012. Characterizing physical habitats in rivers using map-derived drivers of fluvial geomorphic processes. Geomorphology 169–170, 64–73.
Bizzi, S., Demarchi, L., Grabowski, R.C., Weissteiner, C.J., Van de Bund, W., 2016. The use of remote sensing to characterise hydromorphological properties of European rivers. Aquatic Sciences 78, 57–70.
Bledsoe, B.P., Watson, C.C., 2001. Logistic analysis of channel pattern thresholds: Meandering, braiding, and incising. Geomorphology 38, 281–300.
Boothroyd, R.J., Williams, R.D., Hoey, T.B., Barrett, B., Prasoio, O.A., 2021. Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. WIREs Water 8, e21496.
Bradley, J.B., Whiting, P.J., 1992. A process-based stream classification system for small streams in Washington. Timber, Fish, and Wildlife Agreement Report TFW-SH11-91-001. Washington State Department of Natural Resources, Olympia, WA, 70 pp.
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.
Brenden, T.O., Wang, L., Seelbach, P.W., 2008. A river valley segment classification of Michigan streams based on fish and physical attributes. Transactions of the American Fisheries Society 137, 1621–1636.
Brennan, S.R., Schindler, D.E., Cline, T.J., Walsworth, T.E., Buck, G., Fernandez, D.P., 2019. Shifting habitat mosaics and fish production across river basins. Science 364, 783–786.
Brice, J.C., 1975. Airphoto interpretation of the form and behavior of alluvial rivers. Final Report to the US Army Research Office, Durham, NC. Washington University, St. Louis, MO, 10 pp.
Brice, J.C., 1982. Stream channel stability assessment. US Department of Transportation, Washington, DC. Federal Highway Administration Report FHWA/RD-82/021, 42 pp.
Brice, J.C., Blodgett, J.C., 1978a. Countermeasures for hydraulic problems at bridges, Vol. 1, Analysis and Assessment. In: Federal Highway Administration Report FHWA/RD-78-162, Washington, DC, 184 pp.
Brice JC and Blodgett JC (1978b) Countermeasures for hydraulic problems at bridges, Vol. 2, Case Histories for Sites 1-283. Washington, DC: Federal Highway Administration Report FHWA/RD-78-163, 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, pp. 13–71. Special Publication 75.
Brierley, G., 1996. Channel morphology and element assemblages: A constructivist approach to facies modelling. In: Carling, P.A., Dawson, M.R. (Eds.), Advances in Fluvial Dynamics and Stratigraphy. Wiley, Chichester, UK, pp. 263–298.
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.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell, Oxford, UK, 398 pp.
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., Fryirs, K., Cullum, C., Tadaki, M., Huang, H.Q., Blue, B., 2013. Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understanding of river systems. Progress in Physical Geography 37, 601–621.
Brinkerhoff, C.B., Gleason, C.J., Feng, D., Lin, P., 2020. Constraining remote river discharge estimation using reach-scale geomorphology. Water Resources Research 56 e2020WR027949.
Brownlie, W.R., 1981. Prediction of flow depth and sediment discharge in open channels. California Institute of Technology, Pasadena, CA. W.M. Keck Laboratory of Hydraulics and Water Resources Report KH-R-43A, 232 pp.
Bryant, M.D., 1980. Evolution of large, organic debris after timber harvest: Maybeso Creek, 1949–1978. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. General Technical Report PNW-GTR-101, 30 pp.
Bryant, M.D., 1985. Changes 30 years after logging in large woody debris, and its use by salmonids. In: Johnson, R.R., Ziebell, C.D., Patton, D.R., Ffolliott, P.F., Hamre, R.H. (Eds.), Riparian Ecosystems and Their Management. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 329–334. General Technical Report RM-GTR-120.
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, pp. 435–463.
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., 2013. Geomorphic classification of rivers. Schroder J. (ed. in Chief) and Wohl E. (vol. ed.). In: Treatise on Geomorphology vol. 9. Academic Press, San Diego, CA, pp. 730–767.
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., 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., 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.
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.
Bunte, K., Abt, S.R., Swingle, K.W., Potyondy, J.P., 2009. Comparison of three pebble count protocols (EMAP, PIBO, and SFT) in two mountain gravel-bed streams. Journal of the American Water Resources Association 45 (5), 1209–1227.

Bunte, K., Abt, S.R., Swingle, K.W., Potyondy, J.P., 2010. Bankfull mobile particle size and its prediction from a Shields-type approach. In: 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/.

Bunte, K., Abt, S.R., Swingle, K.W., Cenderelli, D.A., Schneider, J.M., 2013. Critical Shields values in coarse-bedded steep streams. Water Resources Research 49, 7427–7447.

Butt AZ (1999) *Stream channel morphology in the Lake Tahoe basin within a hierarchical framework: A geomorphic perspective*. Ph.D. dissertation, University of Nevada, Reno, NV, 355 pp.

Candel, J., Kleinhans, M., Makaske, B., Wallinga, J., 2021. Predicting river channel pattern based on stream power, bed material and bank strength. Progress in Physical Geography 45 (2), 253–278.

Carbonneau, P.E., Piégay, H., 2012. Fluvial remote sensing for science and management. Chichester: Wiley 440 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.

Carling, P.A., Orr, H.G., 2000. Morphology of riffle-pool sequences in the River Severn, England. Earth Surface Processes and Landforms 25, 369–384.

Carling, P., Jansen, J., Meshkova, L., 2014. Multichannel rivers: Their definition and classification. Earth Surface Processes and Landforms 39, 26–37.

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.

Castro, J.M., Thorne, C.R., 2019. The stream evolution triangle: Integrating geology, hydrology, and biology. River Research and Applications 35, 315–326.

Charlton, F.G., Brown, P.M., Benson, R.W., 1978. The hydraulic geometry of some gravel rivers in Britain. Hydraulics Research Station Report IT 180, Wallingford, UK, 48 pp.

Chin, A., 2002. The periodic nature of step-pool mountain streams. American Journal of Science 302, 144–167.

Chin, A., 2006. Urban transformation of river landscapes in a global context. Geomorphology 79, 460–487.

Church, M., 1983. Pattern of instability in a wandering gravel bed channel. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. Blackwell, Oxford, UK, pp. 169–180.

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. John Wiley & Sons, 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.

Cianfrani, C.M., Sullivan, S.M.P., Hession, W.C., Watzin, M.C., 2009. Mixed stream channel morphologies: Implications for fish community diversity. Aquatic Conservation: Marine and Freshwater Ecosystems 19, 147–156.

Cluer, B., Thorne, C., 2014. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications 30, 135–154.

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.

Comiti, F., 2012. How natural are Alpine mountain rivers? Evidence from the Italian Alps. Earth Surface Processes and Landforms 37, 693–707.

Connell, J.H., 1978. Diversity in tropical rain forests and coral reefs. Science 199, 1302–1310.

Conner, J.T., Tonina, D., 2014. Effect of cross-section interpolated bathymetry on 2D hydrodynamic model results in a large river. Earth Surface Processes and Landforms 39, 463–475.

Cupp, C.E., 1989. Valley segment type classification for forested lands of Washington. Washington State Department of Natural Resources, Olympia, WA. Timber, Fish, and Wildlife Agreement Report TFW-AM-89-001, 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.

Danesh-Yazdi, M., Tejedor, A., Foufoula-Georgiou, E., 2017. Self-dissimilar landscapes: Revealing the signature of geologic constraints on landscape dissection via topologic and multi-scale analysis. Geomorphology 295, 16–27.

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.

De Cortes, J.P.S., de Fraga, R., Pupim, F.N., Luvizott, G.L., 2021. A statistical-based reach scale classification for the lower Tapajós river channel, eastern Amazonia. Progress in Physical Geography 45, 600–620.

Demarchi, L., Bizzi, S., Piégay, H., 2016. Hierarchical object-based mapping of riverscape units and in-stream mesohabitats using LiDAR and VHR imagery. Remote Sensing 8, 97.

Denison, C.D., Scott, M.C., Kubach, K.M., Peoples, B.K, 2021. Incorporating network connectivity into stream classification frameworks. Environmental Management 67, 291–307.

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., 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.

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.

Dollar, E.S.J., James, C.S., Rogers, K.H., Thoms, M.C., 2007. A framework for interdisciplinary understanding of rivers as ecosystems. Geomorphology 89, 147–162.

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.

Duffin, J., Carmichael, R.A., Yager, E.M., Benjankar, R., Tonina, D., 2021. Detecting multi-scale riverine topographic variability and its influence on Chinook salmon habitat selection. Earth Surface Processes and Landforms 46, 1026–1040.

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., Giles, T.R., 2009. Assessing the effect of vegetation-related bank strength on channel morphology and stability in gravel-bed streams using numerical models. Earth Surface Processes and Landforms 34, 712–724.

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.

Elliott, C.M., Jacobson, R.B., 2006. Geomorphic classification and assessment of channel dynamics in the Missouri National Recreation River, South Dakota and Nebraska. US Geological Survey. Scientific Investigations Report 2006-5313, 66 pp.

Elliott, C.M., Huhmann, B.L., Jacobson, R.B., 2009. Geomorphic classification of the Lower Platte River, Nebraska. US Geological Survey. Scientific Investigations Report 2009–5198, 29 pp.

Elliott, C.M., Jacobson, R.B., Freeman, M.C., 2014. Stream classification of the Apalachicola-Chattahoochee-Flint river system to support modeling of aquatic habitat response to climate change. US Geological Survey. Scientific Investigations Report 2014–5080, 79 pp.

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

Erskine, W.D., Saynor, M.J., Erskine, L., Evans, K.G., Moliere, D.R., 2005. A preliminary typology of Australian tropical rivers and implications for fish community ecology. Marine and Freshwater Research 56, 253–267.

Erskine, W., Saynor, M., Lowry, J., 2017. Application of a new river classification scheme to Australia's tropical rivers. Singapore Journal of Tropical Geography 38, 167–184.

Erwin, S.O., Jacobson, R.B., Jones, J.C., 2021. Stream classification and gravel-bar inventory for Buffalo National River and Ozark National Scenic Riverways. US Geological Survey. Scientific Investigations Report 2020-5122, 42 pp.

Fausch, K.D., Torgersen, C.E., Baxter, C.V., Li, H.W., 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. BioScience 52 (6), 1–16.

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., 1975. Meander irregularity and wavelength estimation. Journal of Hydrology 26, 315–333.

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.

Ferguson, R.I., Church, M., Rennie, C.D., Venditti, J.G., 2015. Reconstructing a sediment pulse: Modeling the effect of placer mining on Fraser River, Canada. Journal of Geophysical Research: Earth Surface 120, 1436–1454.

Fitzpatrick, F.A., Peppler, M.C., DePhilip, M.M., Lee, K.E., 2006. Geomorphic characteristics and classification of Duluth-area streams, Minnesota. US Geological Survey. Scientific Investigations Report 2006-5029, 54 pp.

Fitzpatrick, F.A., Ellison, C.A., Czuba, C.R., Young, B.M., McCool, M.M., 2016. Geomorphic response of Duluth-area streams to the June 2012 flood, Minnesota. US Geological Survey. Scientific Investigations Report 2016–5104, 53 pp.

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 JL (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.

Fredsøe, J., 1978. Meandering and braiding of rivers. Journal of Fluid Mechanics 85, 609–624.

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 GK (1877) *Report on the geology of the Henry Mountains*, 1st edn. Washington, DC: US Geographical and Geological Survey of the Rocky Mountain Region, 160 pp.

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

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

Gillian S (1996) Use and misuse of channel classification, USDA Forest Service, Stream Systems Technology Center, Stream Notes October 1996, 4–5.

Gilvear, D.J., Bryant, R., 2016. Analysis of remotely sensed data for fluvial geomorphology and river science. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology, 2nd edn. Wiley, Chichester, pp. 103–132.

Gilvear, D.J., Hunter, P., Stewardson, M., 2016. Remote sensing: Mapping natural and managed river corridors from the micro to the network scale. In: Gilvear, D.J., Greenwood, M.T., Thoms, M.C., Wood, P.J. (Eds.), River Science: Research and Management for the 21st Century. Wiley Blackwell, Chichester, UK, pp. 171–196.

Gleason, C.J., Smith, L.C., Lee, J., 2014. Retrieval of river discharge solely from satellite imagery and at-many-stations hydraulic geometry: Sensitivity to river form and optimization parameters. Water Resources Research 50, 9604–9619.

Glenn, J., Tonina, D., Morehead, M., Friedler, F., Benjankar, R., 2016. Effect of transect location, transect spacing, and interpolation methods on river bathymetry accuracy. Earth Surface Processes and Landforms 41, 1185–1198.

Golden, L.A., Springer, G.S., 2006. Channel geometry, median grain size, and stream power in small mountain streams. Geomorphology 78, 64–76.

Golly, A., Turowski, J.M., 2017. Deriving principal channel metrics from bank and long-profile geometry with the R package cmgo. Earth Surface Dynamics 5, 557–570.

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.

González del Tánago, M., Gurnell, A.M., Belletti, B., García de Jalón, D., 2016. Indicators of river system hydromorphological character and dynamics: Understanding current conditions and guiding sustainable river management. Aquatic Sciences 78, 35–55.

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.

Goode, J.R., Buffington, J.M., Tonina, D., Isaak, D.J., Thurow, R.F., Wenger, S., Nagel, D., Luce, C., Tetzlaff, D., Soulsby, C., 2013. Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. Hydrological Processes 27, 750–765.

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.

Gorman, A.M., Whiting, P.J., Neeson, T.M., Koonce, J.F., 2011. Channel substrate prediction from GIS for habitat estimation in Lake Erie tributaries. Journal of Great Lakes Research 37, 725–731.

Graf, W.L., 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35 (4), 1305–1312.

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.

Greig, S.M., Sear, D.A., Carling, P.A., 2007. A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. Hydrological Processes 21 (3), 323–334.

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.

Guillon, H., Byrne, C.F., Lane, B.A., Sandoval Solis, S., Pasternack, G.B., 2020. Machine learning predicts reach-scale channel types from coarse-scale geospatial data in a large river basin. Water Resources Research 56 e2019WR026691.

Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., Garcia de Jalon, D., Gonzalez del Tanago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A.J., Klosch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martinez-Fernandez, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences 78, 1–16.

Gutierrez, R.R., Abad, J.D., Parsons, D.R., Best, J.L., 2013. Discrimination of bed form scales using robust spline filters and wavelet transforms: Methods and application to synthetic signals and bed forms of the Río Paraná, Argentina. Journal of Geophysical Research: Earth Surface 118, 1400–1419.

Haase, P., Hering, D., Jähnig, S.C., Lorenz, A.W., Sundermann, A., 2013. The impact of hydromorphological restoration on river ecological status: A comparison of fish, benthic invertebrates, and macrophytes. Hydrobiologia 704, 475–488.

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

Hall, J.E., Holzer, D.M., Beechie, T.J., 2007. Predicting river floodplain and lateral channel migration for salmon habitat conservation. Journal of the American Water Resources Association 43 (3), 1–12.

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.

Harvey, J., Gooseff, M., 2015. River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins. Water Resources Research 51, 6893–6922.

Harvey, J., Gomez-Velez, J., Schmadel, N., Scott, D., Boyer, E., Alexander, R., Eng, K., Golden, H., Kettner, A., Konrad, C., Moore, R., Pizzuto, J., Schwarz, G., Soulsby, C., Choi, J., 2019. How hydrologic connectivity regulates water quality in river corridors. Journal of the American Water Resources Association 55 (2), 369–381.

Hassan, M.A., Bird, S.A., Reid, D., Ferrer-Boix, C., Hogan, D., Brardinoni, F., Chartrand, S., 2018. Variable hillslope-channel coupling and channel characteristics of forested mountain streams in glaciated landscapes. Earth Surface Processes and Landforms 44, 736–751.

Hauer, F.R., Locke, H., Dreitz, V., Hebblewhite, M., Lowe, W., Muhlfeld, C., Nelson, C., Proctor, M., Rood, S., 2016. Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Science Advances 2, e16000026.

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

Hawkins, C.P., Kershner, J.L., Bisson, P.A., Bryant, M.D., Decker, L.M., Gregory, S.V., McCullough, D.A., Overton, C.K., Reeves, G.H., Steedman, R.J., Young, M.K., 1993. A hierarchical approach to classifying stream habitat features. Fisheries 18, 3–12.

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.

Helm, C., Hassan, M.A., Reid, D., 2020. Characterization of morphological units in a small, forested stream using close-range remotely piloted aircraft imagery. Earth Surface Dynamics 8, 913–929.

Helton, A.M., Poole, G.C., Payn, R.A., Izurieta, C., Stanford, J.A., 2014. Relative influences of the river channel, floodplain surface, and alluvial aquifer on simulated hydrologic residence time in a montane river floodplain. Geomorphology 205, 17–26.

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

Henshaw, A.J., Sekarsari, P.W., Zolezzi, G., Gurnell, A.M., 2020. Google Earth as a data source for investigating river forms and processes: Discriminating river types using form-based process indicators. Earth Surface Processes and Landforms 45, 331–344.

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., 1986. Channel morphology of unlogged, logged, and debris torrented streams in the Queen Charlotte Islands. BC Ministry of Forests and Lands. Land Management Report no. 49, 94 pp.

Hogan, D.L., 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. In: Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G., Swanson, F.J. (Eds.), Erosion and Sedimentation in the Pacific Rim. International Association of Hydrological Sciences Publication 165, Wallingford, UK, pp. 343–353.

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, Victoria, BC. Watershed Restoration Technical Circular no. 7, 42 pp.

Hogan, D.L., Bird, S.A., Hassan, M., 1998. Spatial and temporal evolution of small coastal gravel-bed streams: Influence of forest management on channel morphology and fish habitats. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B. (Eds.), Gravel-bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, CO, pp. 365–392.

Horacio, J., Ollero, A., Pérez-Alberti, A., 2017. Geomorphic classification of rivers: A new methodology applied in an Atlantic region (Galica, NW Iberian Peninsula). Environmental Earth Sciences 76, 746.

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.

Hou, J., van Dijk, A.I.J.M., Renzullo, L.J., Vertessy, R.A., Mueller, N., 2019. Hydromorphological attributes for all Australian river reaches derived from Landsat dynamic inundation remote sensing. Earth System Science Data 11, 1003–1015.

Hynes, H.B.N., 1975. The stream and its valley. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 19, 1–15.

Ikeda, H., 1973. A study on the formation of sand bars in an experimental flume. Geographical Review 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 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 Sciences 54, 1331–1341.

IPCC, 2021. Technical Summary. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 150 pp.

Isaak, D.J., Wenger, S.J., Young, M.K., 2017. Big biology meets microclimatology: Defining thermal niches of ectotherms at landscape scales for conservation planning. Ecological Applications 27 (3), 977–990.

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.

Jacobs, G.R., Thurow, R.F., Buffington, J.M., Isaak, D.J., Wenger, S.J., 2021. Climate, fire regime, geomorphology, and conspecifics influence the spatial distribution of Chinook salmon redds. Transactions of the American Fisheries Society 150, 8–23.

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.

Jha, R., Diplas, P., 2017. Elevation: A consistent and physically-based framework for classifying streams. Journal of Hydraulic Research 56 (3), 299–312.

Johnson, M.F., Thorne, C.R., Castro, J.M., Kondolf, G.M., Mazzacano, C.S., Rood, S.B., Westbrook, C., 2019. Biomic river restoration: A new focus for river management. River Research and Applications 36, 3–12.

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.

Kasprak, A., Hough-Snee, N., Beechie, T., Bouwes, N., Brierley, G., Camp, R., Fryirs, K., Imaki, H., Jensen, M., O'Brien, G., Rosgen, D., Wheaton, J., 2016. The blurred line between form and process: A comparison of stream channel classification frameworks. PLoS One 11 (3), e0150293.

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.

Keller, E.A., MacDonald, A., Tally, T., Merritt, N.J., 1995. Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. Washington, DC: US Geological Survey Professional Paper 1454-P, 29 pp.

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.

Khan, S., Fryirs, K., Ralph, T.J., 2021. Geomorphic controls on the diversity and patterns of fluvial forms along longitudinal profiles. Catena 203, 105329.

Kleinhans, M.G., 2011. Sorting out river channel patterns. Progress in Physical Geography 34 (3), 287–326.

Kleinhans, M.G., van den Berg, J.H., 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surface Processes and Landforms 36, 721–738.

Knighton, A.D., Nanson, G.C., 1993. Anastomosis and the continuum of channel pattern. Earth Surface Processes and Landforms 18, 613–625.

Knighton, D., 1998. *Fluvial Forms and Processes: A New Perspective*. London: Arnold 383 pp.

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., 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.

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, 1st edn. Wiley, Chichester, UK, pp. 171–204.

Kondolf, G.M., Piégay, H., Schmitt, L., Montgomery, D.R., 2016. Geomorphic classification of rivers and streams. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology, 2nd edn. Wiley, Chichester, UK, pp. 133–158.

Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings of the American Society of Civil Engineers 81 (745), 1–17.

Lane, E.W., 1957. A study of the shape of channels formed by natural streams flowing in erodible material. US Army Engineer Division, Missouri River, Corps of Engineers. MRD Sediment Series no. 9, Omaha, NE, 106 pp.

Lane, B.A., Pasternack, G.B., Dahlke, H.E., Sandoval-Solis, S., 2017. The role of topographic variability in river channel classification. Progress in Physical Geography 41 (5), 570–600.

Lave R (2008) *The Rosgen wars and the shifting political economy of expertise.* Ph.D. dissertation, University of California, Berkeley, CA, 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., 2014. Freedom and constraint: Generative expectations in the US stream restoration field. Geoforum 52, 236–244.

Lave, R., Doyle, M., Robertson, M., 2010. Privatizing stream restoration in the US. Social Studies of Science 40, 677–703.

Leathwick, J.R., Snelder, T., Chadderton, W.L., Elith, J., Julian, K., Ferrier, S., 2011. Use of generalised dissimilarity modelling to improve the biological discrimination of river and stream classifications. Freshwater Biology 56, 21–38.

Legleiter, C.J., Harrison, L.R., 2019. Remote sensing of river bathymetry: Evaluating a range of sensors, platforms, and algorithms on the upper Sacramento River, California, USA. Water Resources Research 55, 2142–2169.

Leopold, L.B., Wolman, M.G., 1957. River channel patterns: Braided, meandering, and straight. US 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.

Levick, L., Hammer, S., Lyon, R., Murray, J., Birtwistle, A., Guertin, P., Goodrich, D., Bledsoe, B., Laituri, M., 2018. An ecohydrological stream type classification of intermittent and ephemeral streams in the southwestern United States. Journal of Arid Environments 155, 16–35.

Lewicki, M., Buffington, J.M., Thurow, R.F., Isaak, D.J., 2006. Numerical model of channel and aquatic habitat response to sediment pulses in mountain rivers of central Idaho. Eos, Transactions of the American Geophysical Union 87 (52). Fall Meeting Supplement, Abstract H51B-0481.

Lewin, J., 1978. Floodplain geomorphology. Progress in Physical Geography 2, 408–437.

Li, C., Czapiga, M.J., Eke, E.C., Parker, G., 2015. Variable Shields number model for river bankfull geometry: Bankfull shear velocity is viscosity-dependent but grain-size independent. Journal of Hydraulic Research 53 (1), 36–48.

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 of the American Geophysical Union 86 (Joint Assembly Supplement). Abstract B44B-01.

Livers, B., Wohl, E., 2015. An evaluation of stream characteristics in glacial versus fluvial process domains in the Colorado Front Range. Geomorphology 231, 72–82.

Lotspeich, F.B., Platts, W.S., 1982. An integrated land-aquatic classification system. North American Journal of Fisheries Management 2, 138–149.

Lunetta, R.S., Cosentino, B.L., Montgomery, D.R., Beamer, E.M., Beechie, T.J., 1997. GIS-based evaluation of salmon habitat in the Pacific Northwest. Photogrammetric Engineering and Remote Sensing 63 (10), 1219–1229.

Madej, M.A., 1999. Temporal and spatial variability in thalweg profiles of a gravel-bed river. Earth Surface Processes and Landforms 24, 1153–1169.

Madej, M.A., 2001. Development of channel organization and roughness following sediment pulses in single-thread, gravel bed rivers. Water Resources Research 37 (8), 2259–2272.

Madsen SW (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.

Magliozzi, C., Grabowski, R.C., Packman, A.I., Krause, S., 2018. Toward a conceptual framework of hyporheic exchange across spatial scales. Hydrology and Earth System Sciences 22, 6163–6185.

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.

Marzadri, A., Tonina, D., McKean, J.A., Tiedemann, M.G., Benjankar, R.M., 2014. Multi-scale streambed topographic and discharge effects on hyporheic exchange at the stream network scale in confined streams. Journal of Hydrology 519, 1997–2011.

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 of the 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, St. Paul, MN. General Technical Report NC-176, 72 pp.

May, C.L., Lisle, T.E., 2012. River profile controls on channel morphology, debris flow disturbance, and the spatial extent of salmonids in steep mountain streams. Journal of Geophysical Research: Earth Surface 117, F00A03.

McDavitt WN (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 of the 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.

McManamay, R.A., DeRolph, C.R., 2019. A stream classification system for the conterminous United States. Scientific Data 6, 190017.

McManamay, R.A., Troia, M.J., DeRolph, C.R., Olivero Sheldon, A., Barnett, A.R., Kao, S.-C., Anderson, M.G., 2018. A stream classification system to explore the physical habitat diversity and anthropogenic impacts in riverscapes of the eastern United States. PLoS One 13 (6), e0198439.

Melles, S.J., Jones, N.E., Schmidt, B., 2012. Review of theoretical developments in stream ecology and their influence on stream classification and conservation planning. Freshwater Biology 57, 415–434.

Melton, F.A., 1936. An empirical classification of flood-plain streams. Geographical Review 26, 593–609.

Métivier, F., Lajeunesse, E., Devauchelle, O., 2017. Laboratory rivers: Lacey's law, threshold theory, and channel stability. Earth Surface Dynamics 5, 187–198.

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, J.R., Ritter, J.B., 1996. An examination of the Rosgen classification of natural rivers. Catena 27, 295–299.

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.

Milner VS (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.

Milner, V.S., Willby, N.J., Gilvear, D.J., Perfect, C., 2015. Linkages between reach-scale physical habitat and invertebrate assemblages in upland stream. Marine and Freshwater Research 66, 438–448.

Moir, H.J., Pasternack, G.B., 2008. Relationships between mesoscale morphological units, stream hydraulics and Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat on the Lower Yuba River, California. Geomorphology 100, 527–548.

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.

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., 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.

Mollard, J.D., 1973. Air Photo Interpretation of Fluvial Features, Fluvial Processes and Sedimentation. National Research Council of Canada, Ottawa, ON, pp. 341–380.

Molnar, P., Densmore, A.L., McArdell, B.W., Turowski, J.M., Burlando, P., 2010. Analysis of changes in the step-pool morphology and channel profile of a steep mountain stream following a large flood. Geomorphology 124, 85–94.

Montgomery, D.R., 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35, 397–410.

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, Olympia, WA. Timber, Fish, and Wildlife Agreement Report TFW-SH10-93-002, 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., Foufoula-Georgiou, E., 1993. Channel network source representation using digital elevation models. Water Resources Research 29, 3925–3934.
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., 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., 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., 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., 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.
Morisawa, M.E., 1957. Accuracy of determination of stream lengths from topographic maps. Transactions of the 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.
Mueller, E.R., Pitlick, J., Nelson, J.M., 2005. Variation in the reference Shields stress for bed load transport in gravel-bed streams and rivers. Water Resources Research 41. W04006.
Nagel, D.E., Buffington, J.M., Parkes, S.L., Wenger, S., Goode, J.R., 2014. A landscape scale valley confinement algorithm: Delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. General Technical Report RMRS-GTR-321, 42 pp.
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.
Nakamura, F., Swanson, F.J., 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms 18, 43–61.
Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology 4, 459–486.
Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: Their cause, character and classification. Earth Surface Processes and Landforms 21, 217–239.
Nardini, A., Brierley, J.G., 2021. Automatic river planform identification by a logical-heuristic algorithm. Geomorphology 375, 107558.
Nardini, A., Yepez, S., Zuniga, L., Gualtieri, C., Bejarano, M.D., 2020. A computer aided approach for River Styles-inspired characterization of large basins: The Magdalena River (Columbia). Water 12, 1147.
Newson, M.D., Newson, C.L., 2000. Geomorphology, ecology and river channel habitat: Mesoscale approaches to basin-scale challenges. Progress in Physical Geography 24 (2), 195–217.
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.
O'Brien, G.R., Wheaton, J.M., Fryirs, K., Macfarlane, W.W., Brierley, G., Whitehead, K., Gilbert, J., Volk, C., 2019. Mapping valley bottom confinement at the network scale. Earth Surface Processes and Landforms 44, 1828–1845.
Olivero Sheldon, A., Barnett, A., Olivero Anderson, M.G., 2015. A stream classification for the Appalachian region. Boston, MA: The Nature Conservancy, Eastern Regional Office 162.
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.
Orr, H.G., Large, A.R.G., Newson, M.D., Walsh, C.L., 2008. A predictive typology for characterising hydromorphology. Geomorphology 100, 32–40.
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.
Osterkamp, W.R., 1998. Processes of fluvial island formation, with examples from Plum Creek, Colorado and Snake River, Idaho. Wetlands 18 (4), 530–545.
Ouellet Dallaire, C., Lehner, B., Sayre, R., Thieme, M., 2019. A multidisciplinary framework to derive global river reach classifications at high spatial resolution. Environmental Research Letters 14, 024003.
Padmore, C.L., Newson, M.D., Charlton, E., 1998. Instream habitat in gravel-bed rivers: Identification and characterization of biotopes. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B. (Eds.), Gravel-Bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, CO, pp. 345–364.
Palmer, M.A., Ambrose, R.F., Poff, N.L., 1997. Ecological theory and community restoration ecology. Restoration Ecology 5 (4), 291–300.
Palucis, M.C., Lamb, M.P., 2017. What controls channel form in steep mountain streams? Geophysical Research Letters 44, 7245–7255.
Parfit, M., 1993. Restoration: New ideas, new understanding, new hope. National Geographic Magazine 184 (5), 108–119. Special Edition, Water: The power, promise, and turmoil of North America's fresh water.
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., 1990. Surface-based bedload transport relation for gravel rivers. Journal of Hydraulic Research 28, 417–436.
Parker, G., Klingeman, P.C., McLean, D.G., 1982. Bedload and size distribution in paved gravel-bed streams. Journal of the Hydraulics Division 108, 544–571. American Society of Civil Engineers.
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.
Pasternack, G.B., Baig, D., Weber, M.D., Brown, R.A., 2018. Hierarchically nested river landform sequences. Part 2: Bankfull channel morphodynamics governed by valley nesting structure. Earth Surface Processes and Landforms 43, 2519–2532.
Paustian, S.J., Anderson, K., Blanchet, D., Brady, S., Cropley, M., Edgington, J., Fryxell, J., Johnejack, G., Delliher, D., Kuehn, M., Maki, S., Olson, R., Seesz, J., Wolanek, M., 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.
Petts, G.E., Amoros, C., 1996. The fluvial hydrosystem. In: Petts, G.E., Amoros, C. (Eds.), pp. 1–12. Fluvial Hydrosystems, London: Chapman & Hall.
Petts, G.E., Möller, H., Roux, A.L., 1989. Historical Change of Large Alluvial Rivers: Western Europe. Chichester: Wiley 355 pp.
Pfeiffer, A.M., Finnegan, N.J., 2017. Basin-scale methods for predicting salmonid spawning habitat via grain size and riffle spacing, tested in a California coastal drainage. Earth Surface Processes and Landforms 42, 941–955.
Pfeiffer, A.M., Finnegan, N.J., Willenbring, J.K., 2017. Sediment supply controls equilibrium channel geometry in gravel rivers. Proceedings of the National Academy of Sciences 114 (13), 3346–3351.
Phillips, R.T.J., Desloges, J.R., 2015. Alluvial floodplain classification by multivariate clustering and discriminant analysis for low-relief glacially conditioned river catchments. Earth Surface Processes and Landforms 40, 756–770.
Phillips, CB., Jerolmack, DJ, 2019. Bankfull transport capacity and the threshold of motion in coarse-grained rivers. Water Resources Research 55 (11), 316–330.
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.
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., Arnaud, F., Belletti, B., Bertrand, M., Bizzi, S., Carbonneau, P., Dufour, S., Liébault, F., Ruiz-Villanueva, V., Slater, L., 2020. Remotely sensed rivers in the Anthropocene: State of the art and prospects. Earth Surface Processes and Landforms 45, 157–188.
Pitlick, J., Mueller, E.R., Segura, C., Cress, R., Torizzo, M., 2008. Relation between flow, surface-layer armoring and sediment transport in gravel-bed rivers. Earth Surface Processes and Landforms 33, 1192–1209.
Platts, W.S., 1974. Geomorphic and aquatic conditions influencing salmonids and stream classification. USDA Forest Service, Billings, MT. Surface Environment and Mining Program, 199 pp.
Pollen-Bankhead, N., Simon, A., 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? Geomorphology 116, 353–362.
Poole, G.C., 2002. Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. Freshwater Biology 47, 641–660.
Poole, G.C., Stanford, J.A., Frissell, C.A., Running, S.W., 2002. Three-dimensional mapping of geomorphic controls on flood-plain hydrology and connectivity from aerial photos. Geomorphology 48, 329–347.
Poole, G.C., Stanford, J.A., Running, S.W., Frissell, C.A., 2006. Multiscale geomorphic drivers of groundwater flow paths: Subsurface hydrologic dynamics and hyporheic habitat diversity. Journal of the North American Benthological Society 25 (2), 288–303.
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.
Praskievicz, S., 2018. River classification as a geographic tool in the age of big data and global change. Geographical Review 108 (1), 120–137.
Raven, P.J., Boon, P.J., Dawson, F.H., Ferguson, A.J.D., 1998. Towards an integrated approach to classifying and evaluating rivers in the UK. Aquatic Conservation: Marine and Freshwater Ecosystems 8, 383–393.
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.
Richards, K.S., 1976. The morphology of riffle-pool sequences. Earth Surface Processes 1, 71–88.
Richardson, C.J., Flanagan, N.E., Ho, M., Pahl, J.W., 2011. Integrated stream and wetland restoration: A watershed approach to improved water quality on the landscape. Ecological Engineering 37, 25–39.
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.
Rinaldi, M., Gurnell, A.M., González del Tánago, M., Bussettini, M., 2016. Classification of river morphology and hydrology to support management and restoration. Aquatic Sciences 78, 17–33.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). Geomorphology 180–181, 96–108.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology 251, 122–136.
Robert, A., 1988. Statistical properties of sediment bed profiles in alluvial channels. Mathematical Geology 20 (3), 205–225.
Roberts, G.G., White, N., Lodhia, B.H., 2019. The generation and scaling of longitudinal river profiles. Journal of Geophysical Research: Earth Surface 124, 137–153.
Roni, P., Fayram, A.H., Miller, M.A., 2005. Monitoring and evaluating instream habitat enhancement. In: Roni, P. (Ed.), Monitoring Stream and Watershed Restoration. American Fisheries Society, Bethesda, MD, pp. 209–236.
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., Lanigan, S.H., Archer, E., Downie, S., Faustini, J., Hillman, T.W., Hubler, S., Jones, K., Jordan, C., Kaufmann, P.R., Merritt, G., Moyer, C., Pleus, A., 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, Fort Collins, CO, pp. 91–95. RM-120.
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, 378 pp.
Rosgen DL (2003) *Applied River Morphology.* Ph.D. based on existing publications, 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, 648 pp.
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.
Rosgen, D.L., 2011. Natural channel design: Fundamental concepts, assumptions, and methods. In: Simon, A., Bennett, S.J., Castro, J.M. (Eds.), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools, Geophysical Monograph 194. American Geophysical Union, Washington, DC, pp. 69–93.
Roux, C., Alber, A., Bertrand, M., Vaudor, L., Piégay, H., 2015. "FluvialCorridor": A new ArcGIS toolbox package for multiscale riverscape exploration. Geomorphology 242, 29–37.
Rubin, Z.K., Kondolf, G.M., Carling, P.A., 2015. Anticipated geomorphic impacts from Mekong basin dam construction. International Journal of River Basin Management 13 (1), 105–121.
Savery, T.S., Belt, G.H., Higgins, D.A., 2001. Evaluation of the Rosgen stream classification system in Chequamegon-Nicolet National Forest, Wisconsin. Journal of the American Water Resources Association 37, 641–654.
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. US Geological Survey Professional Paper 352-B, Washington, DC, pp. 17–30.
Schumm, S.A., 1963a. A tentative classification of alluvial river channels. US Geological Survey. Circular 477, 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., 1969. River metamorphosis. Journal of the Hydraulics Division, American Society of Civil Engineers 95 (1), 255–274.
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 Ancient Nonmarine Depositional Environments. Society of Economic Paleontologists and Mineralogists, Tulsa, OK, pp. 19–29. Special Publication 31.
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., 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.
Schumm, S.A., Khan, H.R., Winkley, B.R., Robbins, L.B., 1972. Variability of river patterns. Nature 237 (May 29), 75–76.
Schwartz, J.S., 2016. Use of ecohydraulic-based mesohabitat classification and fish species traits for stream restoration design. Water 8, 520.
Schwart, J.S., Herricks, E.D., 2008. Fish use of ecohydraulic-based mesohabitat units in a low-gradient Illinois stream: Implications for stream restoration. Aquatic Conservation: Marine and Freshwater Ecosystems 18, 852–866.
Seaber, P.R., Kapinos, F.P., Knapp, G.L., 1987. Hydrologic unit maps. US Geological Survey, Denver, CO. Water-Supply Paper 2294, 63 pp.
Sedell, J.R., Froggatt, J.L., 1984. Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verhandlungen - Internationale Vereinigung für Theoretische und Angewandte Limnologie 22, 1828–1834.
Seelbach, P.W., Wiley, M.J., Baker, M.E., Wehrly, K.E., 2006. Initial classification of river valley segments across Michigan's lower peninsula. 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. 25–48.
Shaw, J.R., Cooper, D.J., Sutfin, N.A., 2014. Applying a hydrogeomorphic channel classification to understand spatial patterns in riparian vegetation. Journal of Vegetation Science 29, 550–559.
Shelley, J.E., Young, C.B., McEnroe, B.M., 2010. The Rosgen Rosetta Stone: Translating Rosgen terminology. In: Palmer, R.N. (Ed.), World Environmental and Water Resources Congress 2010: Challenges of Change. American Society of Civil Engineers, New York, pp. 1788–1796.
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).
Sidorchuk, A., 2003. Floodplain sedimentation: Inherited memories. Global and Planetary Change 39, 13–29.
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 responses. 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.
Simon, A., Pollen-Bankhead, N., Thomas, R.E., 2011a. Development and application of a deterministic bank stability and toe erosion model for stream restoration. In: Simon, A., Bennett, S.J., Castro, J.M. (Eds.), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. American Geophysical Union, Washington, DC, pp. 453–474.
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.
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 of the American Geophysical Union 90, 45–46.
Southerland WB (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.
Splinter, D.K., 2013. Clustering and classifying channel morphology in Eastern Oklahoma ecoregions using dissimilarity coefficients. Physical Geography 34 (6), 512–528.
Stanford, J.A., 1996. Landscapes and catchment basins. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology, 1st edn. Elsevier/Academic Press, San Diego, pp. 3–22.
Stanford, J.A., 2006. Landscapes and riverscapes. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology, 2nd edn. Elsevier/Academic Press, San Diego, pp. 3–21.
Stanford, J.A., Ward, J.V., 1993. An ecosystem perspective of alluvial rivers: Connectivity and the hyporheic corridor. Journal of the North American Benthological Society 12 (1), 48–60.
Stanford, J.A., Lorang, M.S., Hauer, F.R., 2005. The shifting habitat mosaic of river ecosystems. Verhandlungen - Internationale Vereinigung für Theoretische und Angewandte Limnologie 29, 123–137.
Stanford, J.A., Alexander, L.C., Whited, D.C., 2017. Riverscapes. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology, 3rd edn., Vol. 1: Ecosystem Structure. Elsevier/Academic Press, San Diego, pp. 3–19.
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 of the American Geophysical Union 38, 913–920.
Sudduth, E.B., Hassett, B.A., Cada, P., Bernhardt, E.S., 2011. Testing the field of dreams hypothesis: Functional responses to urbanization and restoration in stream ecosystems. Ecological Applications 21 (6), 1972–1988.
Sullivan K (1986) *Hydraulics and fish habitat in relation to channel morphology*. Ph.D. dissertation, Johns Hopkins University, Baltimore, MD, 407 pp.
Sullivan, S.M.P., Watzin, M.C., Hession, W.C., 2006. Influence of stream geomorphic condition on fish communities in Vermont, U.S.A. Freshwater Biology 51, 1811–1826.
Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326.
Sutfin, N.A., Shaw, J., Wohl, E.E., Cooper, D., 2014. A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona, USA. Geomorphology 221, 164–175.
Tadaki, M., Brierley, G., Cullum, C., 2014. River classification: Theory, practice, politics. WIREs Water 1, 349–367.
Talling, P.J., 2000. Self-organization of river networks to threshold states. Water Resources Research 36 (4), 1119–1128.
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.

Thoms, M., Scown, M., Flotemersch, J., 2018. Characterization of river networks: A GIS approach and its applications. Journal of the American Water Resources Association 54 (4), 899–913.
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.
Thorne, C.R., Hey, R.D., Newson, M.D., 1997. Applied Fluvial Geomorphology for River Engineering and Management. Wiley, Chichester, UK, 376 pp.
Thorp, J.H., Flotemersch, J.E., Delong, M.D., Casper, A.F., Thoms, M.C., Ballantyne, F., Williams, B.S., O'Neill, B.J., Haase, C.S., 2010. Linking ecosystem services, rehabilitation, and river hydrogeomorphology. BioScience 60, 67–74.
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.
Tockner, K., Stanford, J.A., 2002. Review of Riverine Floodplains: Present State and Future Trends. In: Biological Sciences Faculty Publications, 166. University of Montana, 23 pp.
Tomsett, C., Leyland, J., 2019. Remote sensing of river corridors: A review of current trends and future directions. River Research and Applications 35, 779–803.
Trampush, S.M., Huzurbazar, S., McElroy, B., 2014. Empirical assessment of theory for bankfull characteristics of alluvial channels. Water Resources Research 50, 9211–9220.
Trevisani, S., Cavalli, M., Marchi, L., 2010. Reading the bed morphology of a mountain stream: A geomorphometric study on high-resolution topographic data. Hydrology and Earth System Sciences 14, 393–405.
Trimble, S.W., 1997. Stream channel erosion and change resulting from riparian forests. Geology 25, 467–469.
Troia, M.J., McManamay, R.A., 2020. Biogeographic classification of streams using fish community- and trait-environment relationships. Diversity and Distributions 26, 108–125.
Tsang, Y., Infante, D.M., Wang, L., Krueger, D., Wieferich, D., 2021. Conserving stream fishes with changing climate: Assessing fish responses to changes in habitat over a large region. Science of the Total Environment 755, 142503.
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, Washington, DC, pp. 20–47. Special Report 29.
Vaughan, I.P., Merrix-Jones, F.L., Constantine, J.A., 2013. Successful predictions of river characteristics across England and Wales based on ordination. Geomorphology 194, 121–131.
Vianello, A., D'Agostino, V., 2007. Bankfull width and morphological units in an alpine stream of the dolomites (Northern Italy). Geomorphology 83, 266–281.
Violin, C.R., Cada, P., Sudduth, E.B., Hassett, B.A., Penrose, D.L., Bernhardt, E.S., 2011. Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. Ecological Applications 21 (6), 1932–1949.
Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319, 299–304.
Ward, A.S., Packman, A.I., 2019. Advancing our predictive understanding of river corridor exchange. WIREs Water 6, e1327.
Ward, J.V., Stanford, J.A., 1995. The serial discontinuity concept: Extending the model to floodplain rivers. Regulated Rivers: Research and Management 10, 159–168.
Water Framework Directive, 2000. Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy. Official Journal of the European Communities L327, 1–72.
Wheaton, J.M., Fryirs, K.A., Brierley, G., Bangen, S.G., Bouwes, N., O'Brien, G., 2015. Geomorphic mapping and taxonomy of fluvial landforms. Geomorphology 248, 273–295.
Wheaton, J.M., Bouwes, N., Mchugh, P., Saunders, C., Bangen, S., Bailey, P., Nahorniak, M., Wall, E., Jordan, C., 2018. Upscaling site-scale ecohydraulic models to inform salmonid population-level life cycle modeling and restoration actions - Lessons from the Columbia River Basin. Earth Surface Processes and Landforms 43, 21–44.
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.
Wilkerson, G.V., Parker, G., 2011. Physical basis for quasi-universal relationships describing bankfull hydraulic geometry of sand-bed rivers. Journal of Hydraulic Engineering 137 (7), 739–753.
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.
Williams, G.P., 1978. The case of the shrinking channels—the North Platte and Platte Rivers in Nebraska. US Geological Survey. Circular 781, 48 pp.
Williams, R.D., Bangen, S., Gillies, E., Kramer, N., Moir, H., Wheaton, J., 2020. Let the river erode! Enabling lateral migration increases geomorphic unit diversity. Science of the Total Environment 715, 136817.
Wohl, E., 2000. Mountain Rivers. In: American Geophysical Union, Washington, DC. Water Resources Monograph 14, 320 pp.
Wohl, E., 2019. Forgotten legacies: Understanding and mitigating historical human alteration of river corridors. Water Resources Research 55, 5181–5201.
Wohl, E., Merritt, D., 2005. Prediction of mountain stream morphology. Water Resources Research 41, W08419.
Wohl, E., Merritts, D.J., 2007. What is a natural river? Geography Compass 1 (4), 871–900.
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., Brierley, G., Cadol, D., Coulthard, T.J., Covino, T., Fryirs, K.A., Grant, G., Hilton, R.G., Lane, S.N., Magilligan, F.J., Meitzen, K.M., Passalacqua, P., Poeppl, R.E., Rathburn, S.L., Sklar, L.S., 2019. Connectivity as an emergent property of geomorphic systems. Earth Surface Processes and Landforms 44, 4–26.
Wolman, M.G., 1954. A method of sampling coarse bed material. Transactions of the 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.
Wondzell, S.M., Gooseff, M.N., 2013. Geomorphic controls on hyporheic exchange across scales: Watersheds to particles. Schroder J. (ed. in Chief) and Wohl E. (vol. ed.). In: Treatise on Geomorphology, vol. 9. Academic Press, San Diego, CA, pp. 203–218.
Wondzell, S.M., Herzog, S.P., Gooseff, M.N., Ward, A.S., Schmadel, N., 2022. Geomorphic controls on hyporheic exchange across scales–Watersheds to particles. Schroder J (ed. in Chief) and Wohl E (vol. ed.). In: Treatise on Geomorphology. vol. 6. Academic Press, San Diego, CA, pp. 409–429.
Woodget, A.S., Austrums, R., 2017. Subaerial gravel size measurement using topographic data derived from a UAV-SfM approach. Earth Surface Processes and Landforms 42, 1434–1443.
Woodget, A.S., Austrums, R., Maddock, I.P., Habit, E., 2017. Drones and digital photogrammetry: From classifications to continuums for monitoring river habitat and hydromorphology. WIREs Water 4, e1222.
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.
Wyrick, J.R., Klingeman, P.C., 2011. Proposed fluvial island classification scheme and its use for river restoration. River Research and Applications 27, 814–825.
Wyrick, J.R., Pasternack, G.B., 2014. Geospatial organization of fluvial landforms in a gravel-cobble river: Beyond the riffle-pool couplet. Geomorphology 213, 48–65.
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.