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Chapter 2

Valley Segments, Stream Reaches, and Channel Units

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2.1 INTRODUCTION

Valley segments, stream reaches, and channel units are three hierarchically nested subdivisions of the drainage network within watersheds (Frissell et al., 1986; Table 2.1; Fig. 2.1). These three subdivisions compose the habitat for large, mobile aquatic organisms such as fishes. Within the hierarchy of spatial scales (Table 2.1), valley segments, stream reaches, and channel units represent the largest physical subdivisions that can be directly altered by human activities. As such, it is useful to understand how they respond to anthropogenic disturbance, but to do so requires classification systems and quantitative assessment procedures that facilitate accurate, repeatable descriptions and convey information about biophysical processes that create, maintain, and destroy channel structure.

The location of different types of valley segments, stream reaches, and channel units within a watershed exerts a powerful influence on the distribution and abundance of aquatic plants and animals by governing the characteristics of surface and shallow subsurface water flow and the capacity of streams to store sediment and transform organic matter (Hynes, 1970; Pennak, 1979; Vannote et al., 1980; O'Neill et al., 1986; Statzner et al., 1988; Montgomery et al., 1999; Baxter and Hauer, 2000; Stanford et al., 2005; Beechie et al., 2008a; Miller et al., 2008; Bean et al., 2014). The first biologically based classification systems were proposed for European streams. They were based on zones marked by shifts in dominant aquatic species, such as fishes, from a stream's headwaters to its mouth (Huet, 1959; Illies, 1961; Hawkes, 1975). Characterizations of biologically based zones have included the effects of physical processes and disturbance types on changes in faunal assemblages (Zalewski and Naiman, 1985; Statzner and Higler, 1986). Hydrologists and fluvial geomorphologists, whose objectives for classifying streams may differ from those of aquatic biologists, have based classification of stream channels on a variety of physical factors, including the structure of the stream network, morphology (shape) of the channel, size and mobility of streambed material, and sediment transport zones (e.g., erosional headwaters vs. depositional lowlands) (see review by Buffington and Montgomery (2013) and references therein). Other approaches for classifying stream types and channel units have combined hydraulic or geomorphic properties with explicit assessment of the suitability of a channel for certain types of aquatic organisms (Pennak, 1971; Bovee and Cochnauer, 1977; Binns and Eiserman, 1979; Bisson et al., 1982; Beschta and Platts, 1986; Sullivan et al., 1987; Hawkins et al., 1993).

There are several reasons why stream ecologists classify and measure valley segments, stream reaches, and channel units. The first may simply be to describe physical changes in stream channels over time, whether in response to human impacts or to natural disturbances (Gordon et al., 1992). A second reason for stream classification may be to group sampling areas into like physical units for purposes of comparison. This is often desirable when conducting stream surveys in different drainages (e.g., Wohl et al., 2007). Classification of reach types and channel units enables investigators to extrapolate results to other areas with similar features (Hankin and Reeves, 1988; Dolloff et al., 1993). A third objective for classification may be to determine the suitability of a stream for some type of deliberate channel alteration. Habitat restoration in streams and rivers with histories of environmental degradation is currently being undertaken in many

Methods in Stream Ecology. http://dx.doi.org/10.1016/B978-0-12-416558-8.00002-0
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TABLE 2.1 Hierarchical levels of channel classification, each with a typical size range and temporal scale of persistence.

Classification Level	Spatial Scale (order of magnitude)	Temporal Scale (years)
Geomorphic province	>1000 km^2	>10,000
Watershed	50–1000 km^2	>10,000
Valley segment Colluvial valleys Bedrock valleys Alluvial valleys	100–10,000 m	1000–10,000
Channel reaches Colluvial reaches Bedrock reaches Free-formed alluvial reaches Cascade Step-pool Plane-bed Pool-riffle Braided Dune-ripple Forced alluvial reaches Forced step-pool Forced pool-riffle	10–1000 m	1–1000
Channel/habitat units Fast water Rough Smooth Slow water Scour pools Dammed pools Bars	1–10 m	<1–100

After Frissell et al. (1986); Montgomery and Buffington (1998).

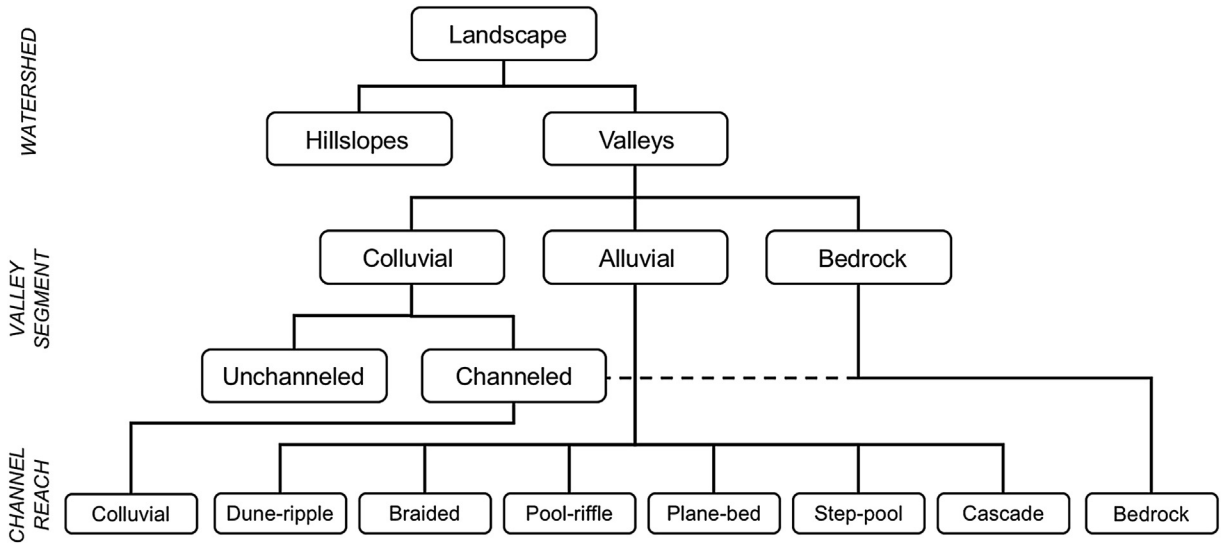

FIGURE 2.1 Hierarchical subdivision of watersheds into valley segments and stream reaches. *After Montgomery and Buffington (1997).*

locations, and some restoration procedures may be inappropriate for certain types of stream channels (National Research Council, 1992; Pess et al., 2003; Beechie et al., 2008b). Successful rehabilitation requires that approaches be consistent with the natural hydraulic and geomorphic conditions of different reach types (Gordon et al., 1992; Buffington et al., 2003; Beechie et al., 2010) and do not impede disturbance and recovery cycles (Reice, 1994; Reeves et al., 1995). Finally, accurate description of stream reaches and channel units often is an important first step in describing the microhabitat requirements of aquatic organisms during their life histories, or in studying the ecological processes that influence their distribution and abundance (Hynes, 1970; Schlosser, 1987; Wiens, 2002).

Geomorphically based stream reach and channel-unit classification schemes continue to undergo refinement. Stream ecologists will do well to heed the advice of Balon (1982), who cautioned that nomenclature itself is less important than detailed descriptions of the meanings given to terms. Thus, it is important for investigators to be as precise as possible when describing what is meant by the terms of the classification scheme they have chosen. Although a number of stream reach and channel-unit classification systems have been put forward, none has yet been universally accepted (Buffington and Montgomery, 2013; Kasprak et al., 2016). In this chapter, we focus on two classification schemes that can provide stream ecologists with useful tools for characterizing aquatic habitat at intermediate landscape scales: the Montgomery and Buffington (1997) model for valley segments and stream reaches, and the Hawkins et al. (1993) model for channel ("habitat") units. Both systems are based on hierarchies of topographic and fluvial characteristics, and both employ descriptors that are measurable and ecologically relevant. The Montgomery and Buffington (1997) classification provides a geomorphic, process-based method of identifying valley segments and stream reaches, while the Hawkins et al. (1993) classification deals with identification and measurement of different types of channel units within a given reach. After describing the classification schemes, we outline methods for their application. The methods described herein begin with a laboratory examination of maps, photographs, and electronic databases for preliminary identification of valley segments and stream reaches, and conclude with a field survey of channel units in one or more reach types.

2.1.1 Valley Segment Classification

Hillslopes and valleys are the principal topographic subdivisions of watersheds (Fig. 2.1). Valleys are areas of the landscape where water converges and where eroded material accumulates. Valleys can be subdivided into segments possessing distinctive geomorphic characteristics (Cupp, 1989). In general, three types of valley segments can be identified: *colluvial*, *alluvial*, and *bedrock* (Fig. 2.1). Colluvial valleys are further subdivided into those with and without recognizable stream channels.

Valley-segment classification describes valley form based on the dominant processes of sediment input and transport. The term sediment here includes both large and small inorganic particles eroded from hillslopes. Valleys can be filled primarily with *colluvium* [sediment and organic matter delivered to the valley floor from adjacent hillslopes by slow gravitational motion or sudden mass wasting (landslides)] or *alluvium* [sediment delivered to the valley floor by streamflow or debris flows (rapidly moving slurries of water, sediment, and organic debris)] (see also Chapter 5). A third condition includes valleys that have little accumulated sediment and are dominated by bedrock floors. In addition to the nature of the material on the valley floor, valley segments distinguish portions of the valley system in which sediment movement is transport- or supply-limited (Fig. 2.2). In transport-limited valley segments, sediment movement is controlled primarily by the frequency of floods and debris flows capable of mobilizing streambed material; in such environments, the sediment supply exceeds the river's capacity to carry sediment, causing net deposition of alluvium along the valley floor in the long term. In supply-limited valley segments, sediment movement is controlled primarily by the rate and availability of sediment delivered to the segment by inflowing water, adjacent hillslopes, and streambank

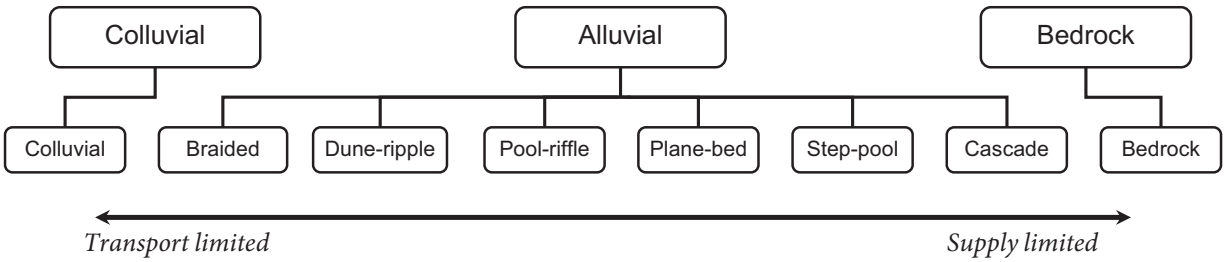

FIGURE 2.2 Arrangement of valley segment and stream-reach types according to whether they are limited by the supply of sediment delivered to the channel or by fluvial transport of the available supply. *After Montgomery and Buffington (1997).*

erosion; here the supply is less than the river's capacity for sediment transport, resulting in a net, long-term deficit of alluvium that, in extreme cases, can lead to exposure of the underlying bedrock.

2.1.1.1 Colluvial Valleys

Colluvial valleys serve as temporary repositories for sediment and organic matter eroded from the surrounding hillslopes. In colluvial valleys, fluvial (waterborne) transport is relatively ineffective at removing materials deposited on the valley floor. Consequently, sediment and organic matter gradually accumulate in headwater valleys until periodically flushed by debris flows in steep terrain, or excavated by periodic hydrologic expansion of the alluvial channel network in low-gradient landscapes. After removal of accumulated sediment by large disturbances, colluvial valleys begin refilling (Dietrich et al., 1986).

Unchanneled colluvial valleys are headwater valley segments lacking recognizable stream channels. They possess soils eroded from adjacent hillslopes, a property which distinguishes them from steep headwater valleys of exposed bedrock. The depth of colluvium in unchanneled colluvial valleys is related to the rate at which material is eroded from hillslopes and the time since the last valley-excavating disturbance. The cyclic process of emptying and refilling occurs at different rates in different geoclimatic regions and depends on patterns of precipitation, geological conditions, and the nature of hillslope vegetation (Dietrich et al., 1986). Unchanneled colluvial valleys do not possess defined streams (Montgomery and Dietrich, 1988), although seasonally flowing seeps and small springs may serve as temporary habitat for some aquatic organisms that are present in these areas.

Channeled colluvial valleys contain low-order streams immediately downslope from unchanneled colluvial valleys, commonly forming the uppermost portions of the stream network. Flow in colluvial channels tends to be shallow and ephemeral due to small drainage areas that do not support sustained streamflow. Colluvial channels may also result from upwelling of subsurface flow (seepage channels or springs). Because shear stresses (see Chapters 4 and 5) generated by streamflows are incapable of substantially moving and sorting deposited colluvium, channels in these valley segments tend to be characterized by a wide range of sediment and organic matter sizes, with channel morphology controlled by stochastically occurring obstructions (boulders, wood, in-channel vegetation) that are large relative to channel size (Gomi et al., 2002; Gooderham et al., 2007). Episodic scour of channeled colluvial valleys by debris flows often governs the degree of channel incision in steep terrain and, like unchanneled colluvial valleys, cyclic patterns of sediment excavation periodically reset the depth of colluvium. Consequently, the frequency of sediment-mobilizing discharge or debris flows regulates the amount of sediment stored in colluvial valleys.

Seasonal habitat may be available for some aquatic organisms in channeled colluvial valleys, but the ephemeral nature of flow can limit completion of full life cycles if the organisms cannot survive desiccation. Instead, the main ecological role of colluvial valleys is the long-term storage and periodic flushing of organic matter and accumulated colluvium by debris flows. Such events are rare, but colluvial valleys may comprise a substantial percentage of the drainage network in mountain basins, collectively providing an important source of organic material and sediment for lower gradient alluvial habitats.

2.1.1.2 Alluvial Valleys

Alluvial valleys are supplied with sediment from upstream sources and adjacent hillslopes, and the streams within them are capable of moving and sorting the sediment at erratic intervals. The sediment transport capacity of an alluvial valley is insufficient to scour the valley floor to bedrock, resulting in an accumulation of valley fill primarily of fluvial origin. Alluvial valleys are the most common type of valley segment in many landscapes and usually contain the streams of greatest interest to aquatic ecologists. They range from confined, a condition in which hillslopes or abandoned stream terraces narrowly constrain the active valley floor with little or no floodplain development, to unconfined, with a well-developed floodplain. A variety of stream-reach types and associated aquatic habitats occur in alluvial valleys, depend-ing on the degree of confinement, valley gradient, discharge regime, and sediment supply (Fig. 2.3). Unconfined alluvial valleys are ecologically the most productive and diverse locations in the river network (Stanford and Ward, 1993; Malard et al., 2002; Stanford et al., 2005; Hauer et al., 2016), but generally comprise a small percentage of the stream length in mountain basins (see Chapter 1).

2.1.1.3 Bedrock Valleys

Bedrock valleys have little valley fill material and usually possess confined channels lacking a continuous alluvial bed. Two types of bedrock valleys can be distinguished: those sufficiently steep to have a transport capacity greater than the sediment

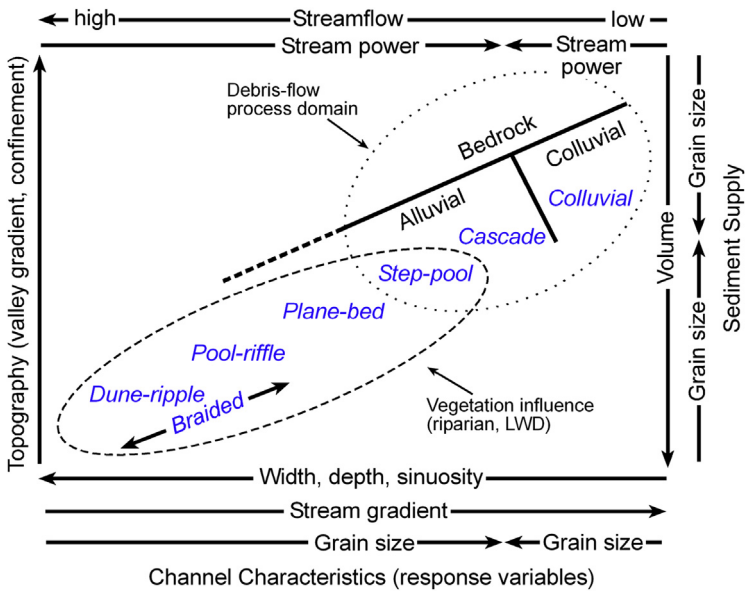

FIGURE 2.3 Influence of watershed conditions (topography, streamflow, and sediment supply) on stream-reach types (blue text) and associated channel characteristics (width, depth, sinuosity, stream gradient, grain size). Process domains are shown for debris flows and the influence of vegetation (*dashed ellipses*), and valley-segment types are indicated (colluvial, alluvial, bedrock). *Modified from Buffington (2012); based on concepts of Schumm (1977, 1985).*

supply, thereby remaining predominantly bedrock-floored, and those associated with low-order streams recently excavated to bedrock by debris flows.

2.1.1.4 Response Potential

The form and function of valley segments can be altered by large-scale natural or human-caused disturbances, such as volcanic eruptions, dams, and levee construction. However, valley-segment classification generally reflects long-term geologic conditions and does not allow forecasting of how the characteristics of the valley will change in response to short-term alterations of streamflow or sediment supply that occur over timescales relevant to humans and aquatic populations. Consequently, stream reach classification is more useful for characterizing response to such changes.

2.1.2 Stream-Reach Classification

Stream reaches consist of repeating sequences of specific types of channel units (e.g., pool-riffle-bar sequences) and specific ranges of channel characteristics (slope, hydraulic geometry (width, depth), sediment size and mobility), which distinguish them in certain aspects from adjoining reaches (Table 2.2). In the Montgomery and Buffington (1997) approach, stream reaches are visually classified based on observed morphology and patterns of stream flow. Channel characteristics (slope, grain size, etc.) can be subsequently measured, but those values are not formally used to classify reach type. Transition zones between adjacent reaches may be gradual or sudden, and exact upstream and downstream reach boundaries may be a matter of some judgment. Colluvial valley segments can possess colluvial and bedrock-reach types, and bedrock valleys can host bedrock and discontinuous alluvial-reach types, but alluvial valleys typically exhibit a broad variety of stream-reach types (Fig. 2.1). Reach morphology in alluvial valleys is related to the characteristics of the sediment supply (grain size and rate of input), the power of the stream to mobilize its bed (a function of stream flow and topographic gradient), and the degree of channel confinement by valley walls (Fig. 2.3). Specifically, six alluvial-reach types can be recognized (Fig. 2.4), although intermediate types also can occur (e.g., Gomi et al., 2003; Thompson et al., 2006).

2.1.2.1 Cascade Reaches

Cascade reaches are the steepest alluvial channels, with stream gradients typically ranging from 8-26%. A few small, turbulent pools may be present in cascade reaches, but the majority of flowing water tumbles over and around closely

TABLE 2.2 Characteristics of different types of stream reaches.

Feature	Dune-Ripple	Braided	Pool-Riffle	Plane-Bed	Step-Pool	Cascade	Bedrock	Colluvial
Predominant bed material	Sand	Variable (sand to cobble)	Gravel	Gravel/cobble	Gravel/cobble/ boulder	Boulder	Bedrock	Variable
Bedform pattern	Multilayered	Laterally oscillatory	Laterally oscillatory	None	Vertically oscillatory	Chaotic	Variable	Variable
Dominant roughness elements	Sinuosity, bedforms (dunes, ripples, bars), banks, large wood	Bedforms (bars, pools), streambed	Bedforms (bars, pools), streambed, large wood, sinuosity, banks	Streambed, banks	Bedforms (steps, pools), stream-bed (boulders), large wood, banks	Streambed (boulders), banks	Streambed (sculpted bedrock), banks	Banks, streambed, large wood
Dominant sediment sources	Fluvial, bank erosion, inactive channels	Fluvial, bank erosion, debris flows, glaciers	Fluvial, bank erosion, inactive channels, debris flows	Fluvial, bank erosion, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Hillslope, debris flows
Typical slope (%)[a]	0.02–0.1	0.02–0.1 (sand) 0.2–1 (gravel/ cobble)	0.2–1	1–3	3–8	8–26	2–37	17–59
Typical confinement	Unconfined	Variable	Unconfined	Variable	Moderately confined	Strongly confined	Strongly confined	Strongly confined
Pool spacing (channel widths)	5–7	Variable	5–7	High if pools present	1–4	<1	Variable	Variable
Typical bankfull width-to-depth ratio (w/h)[a]	12–47	34–102	15–33	12–24	9–19	6–14	4–19	3–5
Typical bankfull depth-to-median grain size ratio (h/D_{50})[a]	3000–32,000	5000–11,000 (sand) 14–64 (gravel/ cobble)	13–40	5–11	3–7	3–7	10–53	3–24
Typical bankfull bed mobility (ratio of applied-to-critical shear stress for median grain size, τ/τ_{c50})[a]	26–90	23–68 (sand) 1.2–2.7 (gravel)	0.9–2.2	1–2	1.1–3	2.3–4	1.6–13	6–9
Typical bankfull/effective discharge recurrence interval (years)[b]	1–2/1–2	Variable	1–2/1–2	1–2/1–2	2/1-3	Unknown	Unknown	Unknown

[a] *The reported values of slope and bankfull ratios of width-to-depth (w/h), depth-to-median grain size (h/D_{50}), and applied-to-critical shear stress (τ/τ_{c50}) represent inner quartile ranges for worldwide data compiled by Buffington (2012). Full distributions show significant overlap among reach types (e.g., Buffington et al., 2004) and values may vary regionally (e.g., McDavitt, 2004; Wohl and Merritt, 2005). Data for colluvial reaches are from Montgomery and Buffington (1997, unpublished) and Vianello and D'Agostino (2007). Although bankfull values of τ/τ_{c50} are high in colluvial reaches, such events are likely rare and/or of short duration, as colluvial channels generally lack sustained streamflow. Data for bedrock reaches are from Montgomery et al. (1996a), Montgomery and Buffington (1997, unpublished), Wohl and David (2008), and Goode and Wohl (2010).*

[b] *The effective discharge is that which transports the most sediment over time (Wolman and Miller, 1960) and corresponds with near-bankfull flows in both low- and high-gradient alluvial channels (e.g., Andrews, 1980; Whiting et al., 1999). Values for plane-bed and step-pool reaches are inner quartile ranges for data reported by Whiting et al. (1999), Zimmermann and Church (2001), Marion and Weirich (2003), and Lenzi et al. (2006). Recurrence interval for mobilizing step-forming boulders is typically 25–100 years (Grant et al., 1990; Chin, 1998; Lenzi et al., 2006).*

Modified from Montgomery and Buffington (1997).

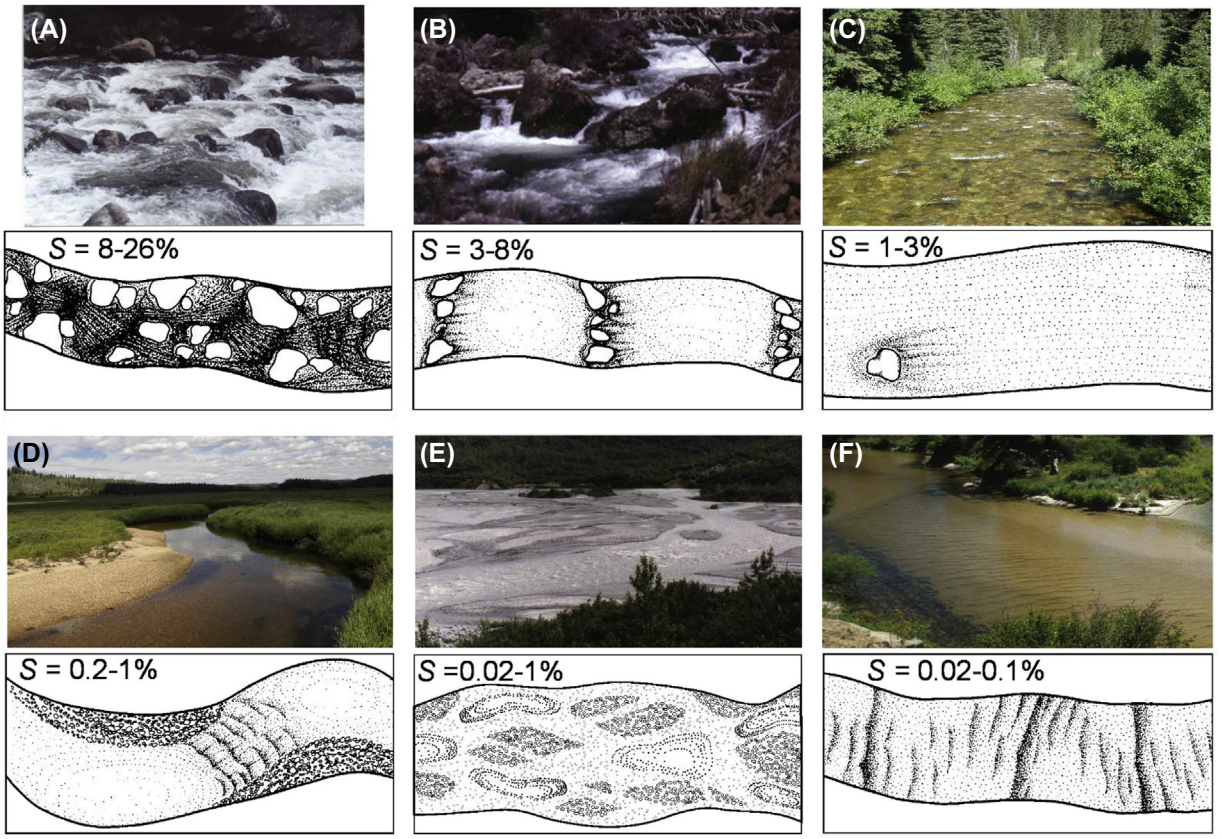

FIGURE 2.4 Photographs and plan-view sketches of alluvial stream-reach types (A) cascade, (B) step-pool, (C) plane-bed, (D) pool-riffle, (E) braided, and (F) dune-ripple. *After Montgomery and Buffington (1997).*

spaced boulders and large wood (Fig. 2.4A). The boulders are supplied from adjacent hillslopes or from periodic debris-flow deposition. This stream type typically occurs in headwater areas, is strongly confined by valley walls, and therefore has small width-to-depth ratios (Table 2.2). Although cascade reaches may experience debris flows, sediment movement is predominantly fluvial. The cascading nature of water movement in this reach type is usually sufficient to remove all but the largest bed material (cobbles and boulders) and organic matter on an annual basis. What little fine sediment and organic matter that remains is trapped behind boulders and logs, or is stored in a few pockets where reduced velocity and tur-bulence permit deposition.

The rapid flushing of fine sediment from cascade reaches during moderate to high flows suggests that transport from this reach type is supply-limited (Fig. 2.2). This is further supported by sediment mobility calculations, indicating that the bankfull shear stress (see Chapters 4 and 5) is typically two to four times greater than that needed to mobilize the median size of the streambed material (Table 2.2); that is to say, the median grain size is predicted to be highly mobile at bankfull flow. Bankfull is defined as the flow that just begins to spill onto the floodplain. In steep, confined channels that lack well-developed floodplains, such as cascade reaches, other high-flow indicators are used as surrogates for bankfull stage (e.g., vegetation extent, rock staining, moss line, or bank soil extent).

Despite the overall high transport capacity of cascade stream reaches, the bed-forming boulders rarely move because flow depths are shallow relative to the size of the boulders even during annual floods; rare high-magnitude floods or debris flows are required to mobilize boulders in cascade reaches. Although the boulders provide a stable environment, cascade reaches offer relatively limited aquatic habitat due to fast turbulent flow and insufficient extent of gravel and sand patches (e.g., Halwas et al., 2005).

2.1.2.2 Step-Pool Reaches

Step-pool reaches possess discrete channel-spanning accumulations of boulders and logs that form a series of vertical steps alternating with pools containing finer substrata (Fig. 2.4B). These channels tend to be relatively straight and have high

gradients (typically 3–8%), coarse but heterogeneous substrata (gravel to boulder), small width-to-depth ratios, and moderate confinement by valley walls (Table 2.2). Pools typically occur at a spacing of every one-to-four channel widths in step-pool reaches, although step spacing increases with decreasing channel slope (Grant et al., 1990; Chartrand et al., 2011). The regular spacing of boulder steps may be the result of (1) kinematic waves and particle congestion (i.e., periodic traffic jams of boulders among smaller, more mobile particles), (2) periodic locations of near-critical flow that favor boulder deposition, or (3) a roughness configuration that stabilizes the bed on steep slopes (see review by Montgomery and Buffington (1997) and references therein). Steps can also form where boulders jam against streambanks, particularly where bedrock or trees protrude into the channel (Zimmermann et al., 2010).

The capacity of step-pool reaches to temporarily store fine sediment and organic matter generally exceeds that of cascade reaches, which lack well-defined pools. Flow thresholds necessary to transport sediment and mobilize channel substrata are complex in step-pool reaches. As with cascade reaches, large bed-forming structures (boulders and large wood) are relatively stable and move only during extreme flows (25e100-year events; Grant et al., 1990; Lenzi et al., 2006). During such events, the channel may lose its stepped profile, but step-pool morphology becomes reestablished on the falling limb of the hydrograph (see Chapter 3, Whittaker, 1987). In contrast, during more typical annual floods, fine sediment and organic matter in pools are rapidly transported over the stable, bed-forming steps, while the median grain size on the bed (typically cobble-sized material) is predicted to have low-to-moderate mobility (Table 2.2). Like cascade reaches, aquatic habitat is limited in step-pool channels, but pools and gravel patches dammed by boulder and log steps can offer seasonal habitat to macroinvertebrates, juvenile fish, and smaller-bodied adult fish, such as trout (Inoue et al., 1997; Montgomery et al., 1999; Halwas et al., 2005).

2.1.2.3 Plane-Bed Reaches

Plane-bed stream reaches lack a stepped longitudinal profile and instead are characterized by long, relatively straight channels of uniform depth that typically have moderate slopes (1e3%) and streambeds composed predominantly of gravel and cobble (Fig. 2.4C). In many cases, plane-bed reaches occupy transitional locations in the stream network between steep, confined stream reaches (step-pool, cascade) and lower-gradient, unconfined stream types (pool-riffle, dune-ripple). As such, plane-bed reaches usually exhibit intermediate values of stream gradient, width-to-depth ratio, and relative submergence (the ratio of flow depth to median particle size) (Table 2.2). Similarly, plane-bed reaches may or may not be confined by valley walls and can show more extensive floodplain development than step-pool and cascade reaches, although not as extensive as lower gradient pool-riffle and dune-ripple reaches.

At low-to-moderate flows, plane-bed stream reaches may possess large boulders extending above the water surface, forming mid-channel eddies. However, the absence of channel-spanning structures or significant constrictions by streambanks generally inhibits pool development. In addition, plane-bed reaches typically exhibit armored streambeds that are characterized by a coarse surface layer of sediment that limits the transport of finer-grained subsurface material. Surface grains are mobilized at discharges near bankfull, a commonly occurring flood that happens every 1e2 years on average in plane-bed reaches (Table 2.2). During such events, movement of the armor layer is sporadic and transport distances are short, with low-to-moderate mobility predicted for the median grain size (Table 2.2).

Plane-bed reaches can host a variety of macroinvertebrates and fishes due to abundant gravel and cobble substrata and relatively lower stream gradients and slower flows than cascade and step-pool reaches (e.g., Montgomery et al., 1999; Halwas et al., 2005). Moreover, animal activities including foraging, fighting, and nest-building can have a substantial effect on physical channel characteristics and fluvial processes in gravel-bed rivers, which include plane-bed, pool-riffle, and braided reach types. For example, silk-spinning caddisflies bind substrata, reducing their mobility and the overall rate of sediment transport in such environments (Statzner et al., 1999; Albertson et al., 2014). In contrast, foraging and fighting by crayfish directly moves bed material, alters small-scale bed topography and roughness, removes biofilms and algae, and stirs up fine sediments from the streambed that increase turbidity and can be the dominant source of suspended sediment transport during certain times of the year (Statzner et al., 2000; Rice et al., 2016). Streambank burrowing by crayfish also adds to the sediment load of the stream and may destabilize streambanks (Rice et al., 2016). Like crayfish, fish that forage along the streambed can loosen the substrata, which may increase its mobility (Pledger et al., 2014, 2016). Similarly, redd excavation (nest building) by salmonids loosens substrata, coarsens the streambed and creates small-scale mounds that alter stream velocity and hyporheic exchange (the cycling of streamflow into and out of the alluvium surrounding the stream; also see Chapters 1 and 5 and reviews by Tonina and Buffington (2009a), Wondzell and Gooseff (2013) and references therein). These physical changes to the stream during redd excavation can have both positive and negative effects on the survival of salmonid offspring; streambed coarsening decreases the probability that nests will be scoured during high flows (Montgomery et al., 1996b) and mound topography forces oxygenated river water and marine-derived nutrients into salmon redds via hyporheic exchange (see Chapter 8), enhancing the habitat quality (Bjornn and Reiser, 1991; Greig et al., 2007; Tonina and Buffington, 2009b; Buxton et al., 2015a), but also elevates shear stresses over the redd

which, combined with bed loosening during redd excavation, can make redds more susceptible to erosion (Buxton et al., 2015b). However, the subsurface egg pocket is typically coarse-grained, which may reduce sediment mobility and loss of incubating eggs despite overall higher mobility of the redd (Rennie and Millar, 2000). During redd excavation, salmonids also move large quantities of gravel that in some cases may be comparable to the annual sediment transport accomplished by the river (Hassan et al., 2008). In summary, aquatic animals can actively modify gravel-bed rivers, having a substantial effect on channel morphology and fluvial processes that frequently benefit these animals and the surrounding ecosystem. These activities are respectively termed *zoogeomorphology* (Butler, 1995) and *ecosystem engineering* (e.g., Moore, 2006).

2.1.2.4 Pool-Riffle Reaches

Pool-riffle reaches are commonly associated with small to mid-sized streams and are prevalent in alluvial valleys of low-to-moderate gradient (0.2–1%). They are frequently sinuous and are characterized by a regular sequence of pools, riffles, and bars that form an undulating streambed (Fig. 2.4D). Pools are topographic depressions in the stream bottom caused by local flow convergence and scour, while bars are complimentary areas of flow divergence and deposition that form the high points of the channel. Riffles are located at crossover areas from pools to bars. At low streamflow, the water meanders around bars and through pools and riffles that commonly alternate from one side of the river to the other. The spacing between pools is typically five to seven channel widths (Keller and Melhorn, 1978), but can be modulated by wood debris (Nakamura and Swanson, 1993; Montgomery et al., 1995; Buffington et al., 2002; Segura and Booth, 2010), which anchors the location of pools and associated riffles and bars (Lisle, 1986b; Bisson et al., 1987). Streams rich in large wood tend to have erratic and complex channel morphologies (Bryant, 1980; Montgomery et al., 2003).

Channel substrata in pool-riffle reaches are mobilized annually during freshets. At bankfull flows, pools and riffles are inundated to such an extent that the channel appears to have a uniform gradient, but local pool-riffle-bar features emerge as flows recede. Movement of bed material at bankfull flow is sporadic and discontinuous, with mobility of the median grain size exhibiting a near-bankfull threshold (Table 2.2). As portions of the surface armor layer are mobilized, finer sediment underneath is flushed dpmk rfc qrpc_k `cb, creating pulses of scour and deposition and removal of fine sediment that can be detrimental to aquatic organisms (Reiser et al. 1985). Furthermore, pool-riffle topography bpgtcq spatial variation in shear stress (see Chapter 4) and sediment transport that sort bed material into textural patches (grain-size facies), creating complex streambed surfaces and habitats (Kinerson, 1990; Wolcott and Church 1991; Lisle and Madej, 1992; Buffington and Montgomery, 1999; Dietrich et al. 2006; Nelson et al. 2009, 2010). Bankfull events are common in pool-riffle channels (occurring every 1–2 years on average) and correspond with the effective discharge (that which transports the most sediment in the long term, Wolman and Miller, 1960, Table 2.2). Pool-riffle reaches typically exhibit well-developed floodplains that provide "relief valves" for flooding, limiting in-channel shear stress and transport rates to near-bankfull values, and providing lateral connection with floodplain and riparian ecosystems (see Chapter 1). Broad floodplains also indicate a general lack of channel confinement.

Like plane-bed channels, pool-riffle reaches commonly host many aquatic animals and are typically ecological hotspots of diversity and productivity due to greater complexity of channel characteristics [topography, textural patches, depth, velocity], and more extensive floodplains offering diverse riparian vegetation (shade, cover, terrestrial inputs of food and nutrients) and off-channel habitats (floodplain ponds and sloughs), in stark contrast to channel and floodplain characteristics in steeper gradient channels. This complexity promotes complex food webs between the aquatic and terrestrial systems, enhancing productivity and diversity (Baxter et al., 2005; Bellmore et al., 2013). Pool-riffle reaches and their adjacent floodplains also typically exhibit extensive hyporheic exchange over nested spatial and temporal scales, creating a variety of habitats for hyporheic organisms (see Chapters 1 and 8, and reviews by Greig et al. 2007; Buffington and Tonina, 2009; Wondzell and Gooseff, 2013). At watershed scales, salmonids show a strong preference for pool-riffle and plane-bed reaches, structuring the spatial distribution of these fish and their associated risks to natural and anthropogenic disturbance (Montgomery et al., 1999; May and Lisle, 2012; Goode et al., 2013). Despite the ecological importance of floodplain rivers (pool-riffle, braided, dune-ripple reaches), they are typically of limited spatial extent (constituting less than 15% of the stream network in many mountain basins, Buffington et al., 2004) and are commonly in conflict with human use of floodplains (Hauer et al., 2016).

2.1.2.5 Braided Reaches

Braided reaches possess multithread channels with low-to-moderate gradients (typically 0.02–1%), and are characterized by very large width-to-depth ratios (commonly 34–102) and numerous bars scattered throughout the channel (Fig. 2.4E and Table 2.2). Individual braid threads typically have a pool-riffle morphology, with pools commonly formed at the confluence of two braids. Bed material varies from sand to cobble and boulder depending on channel gradient and local sediment supply. Braided channels commonly occur in glacial outwash zones and other locations overwhelmed by high sediment supply (e.g., downstream of massive landslides, or volcanic eruptions) or in places with weak, erodible banks (e.g., river corridors that have lost vegetative root strength because of riparian cattle grazing

or riparian clear cutting, or in semi-arid regions where riparian vegetation is naturally sparse). In braided reaches the location of bars changes frequently and the channel containing the main flow can often move laterally over short periods of time. In terms of gradient, grain size, and bed mobility, braided reaches appear to span conditions between dune-ripple and pool-riffle streams and may exhibit streambeds that are either predominately sand or gravel and cobble (Table 2.2). Aquatic and hyporheic habitats can be extensive in braided reaches, with strong lateral and vertical connectivity, but are spatially and temporally dynamic due to the frequent shifting of flow paths and the seasonal expansion and contraction of the braid network (see Chapter 1, Ward and Stanford, 1995; Malard et al., 2002).

2.1.2.6 Dune-Ripple Reaches

Dune-ripple stream reaches consist of low gradient (0.02–0.1%), meandering channels with predominantly sand substrata (Fig. 2.4F). This reach type generally occurs in higher-order channels within unconstrained valley segments and exhibits less turbulence than high-gradient reach types. Shallow- and deep-water areas are present, and point bars and pools may occur at meander bends. As current velocity increases over the fine-grained substrata of dune-ripple reaches, the streambed is molded into a predictable succession of bedforms, from small ripples to various types of large dunes. Sediment movement occurs at nearly all flows and is strongly correlated with discharge, indicating transport-limited conditions. The streambed is highly mobile at bankfull stage, with typical shear stresses up to 100 times greater than the critical value for sediment motion, in contrast to bankfull shear stresses that are commonly one to two times the critical value in plane-bed and pool-riffle reaches (Table 2.2). Similarly, bankfull submergence (ratio of flow depth to median grain size) is commonly quite high (on the order of 1000 to 10,000) in dune-ripple streams and is several orders of magnitude larger than that of plane-bed and pool-riffle stream reaches (Table 2.2). A well-developed floodplain typically is present, with strong lateral connectivity during overbank floods (see Chapter 1). Like pool-riffle reaches, bankfull flow is a common occurrence (every 1–2 years on average) and typically corresponds with the effective discharge (Table 2.2). However, dune-ripple channels are distinguished from pool-riffle reaches by their low-gradient sandy streambed, nearly continuous transport of sediment, and presence of ripples and dunes. Aquatic and hyporheic habitats can be extensive for those species adapted to sandy substrata, frequent bed mobility, and turbid flow.

2.1.2.7 Forced Reaches

Flow obstructions such as large wood debris and bedrock projections can locally force some of the above reach morphologies. For example, wood debris introduced to a plane-bed channel may create local pool scour and bar deposition that forces a pool-riffle morphology (Table 2.1). Similarly, wood in cascade or bedrock channels may dam upstream sediment and create downstream plunge pools, forming a step-pool morphology. Flow obstructions anchor the location of forced pools (Lisle, 1986b), but the size and occurrence of pools additionally depend on channel characteristics (slope, width-to-depth ratio, relative submergence (ratio of flow depth to grain size), local hydraulics, and the size and rate of bed material supply relative to stream flow) (Buffington et al., 2002; Woodsmith and Hassan, 2005; Borg et al. 2007; Thompson and Wohl, 2009; Hawley et al., 2013).

Forced stream reaches can be particularly important ecologically, creating habitats that might not otherwise occur. For example, wood debris extracts energy from the flow, decreasing the size of sediment that a river can carry, which may result in more extensive spawning habitats for salmonids at both reach and watershed scales (Buffington et al., 2004). Similarly, wood and boulders that force pools in an otherwise plane-bed reach can dramatically alter the available aquatic and hyporheic habitats.

2.1.2.8 Hyporheic Exchange

The above reach types exhibit specific physical characteristics (sediment size, bed topography, sinuosity, confinement) that not only structure surface habitat, but likely exert strong controls on patterns and rates of hyporheic exchange (see Chapters 1 and 8; Stanford and Ward, 1993; White, 1993; Baxter and Hauer, 2000; Buffington and Tonina, 2009; Wondzell and Gooseff, 2013). In particular, differences in the spacing and height of bed topography provide first-order controls on streambed pressure gradients and patterns of hyporheic flow (Fig. 2.5) that are further modulated by (1) sediment size [affecting the porosity and hydraulic conductivity (rate) of subsurface flow] and (2) the vertical and lateral extent of alluvium within a given valley. Collectively, these features structure rates and spatial scales of hyporheic exchange and the associated metabolism of the surface–subsurface ecosystem (Fig. 2.6). Hence, reach types can provide a window on subsurface processes that may not be readily apparent from our terrestrial perspective of the river system, as well as providing a framework for systematically describing the mechanics of hyporheic exchange within and between watersheds (Buffington and Tonina, 2009; Wondzell and Gooseff, 2013).

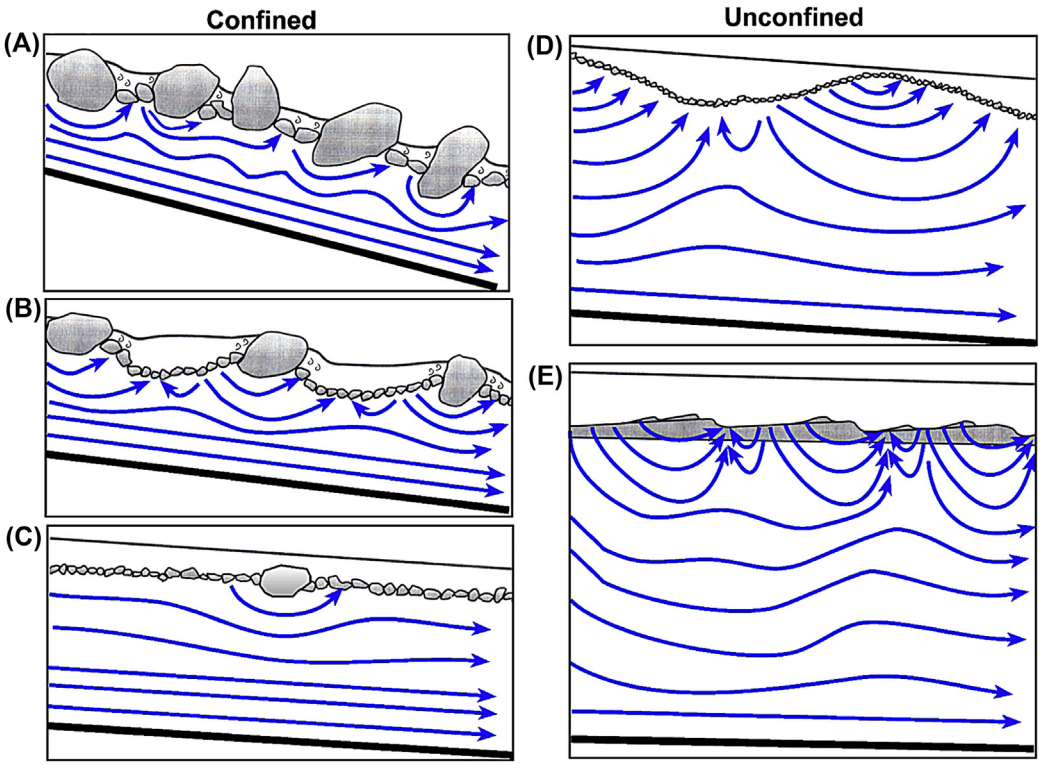

FIGURE 2.5 Hypothesized longitudinal patterns and depths of hyporheic exchange for different reach-scale channel types: (A) cascade, (B) step-pool, (C) plane-bed, (D) pool-riffle and (E) dune-ripple. Unconfined channels additionally will exhibit lateral hyporheic exchange (see Chapter 1). *From Buffington and Tonina (2009).*

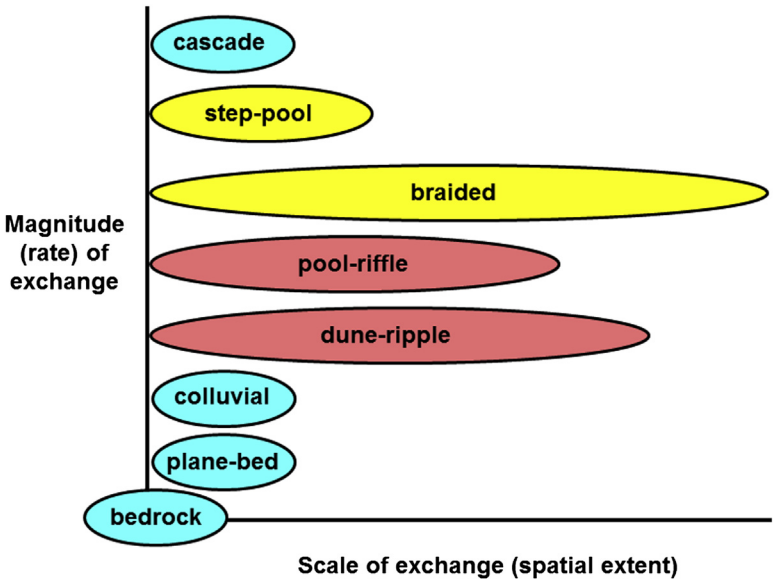

FIGURE 2.6 Conceptual diagram of the relative scales and magnitudes of hyporheic exchange for different stream-reach types. Colors indicate the current extent of knowledge concerning hyporheic exchange in these different reach types (*warmer* colors indicate more knowledge). In general, more is known about hyporheic exchange in pool-riffle and dune-ripple channels (from field, laboratory, and numerical studies), less is known about step-pool and braided channels, and least known about cascade, colluvial, plane-bed, and bedrock channels. *From Buffington and Tonina (2009).*

2.1.2.9 Response Potential and Disturbance Regime

Channel response to changes in streamflow and sediment supply depends on stream reach type and associated degrees of freedom [i.e., extent of confinement, size of bed and bank material relative to stream power, and supply- vs. transport-limited conditions]. In general, bedrock channels have fewer degrees of freedom for morphologic response than alluvial channels. In turn, steep, confined alluvial channels (e.g., step-pool and cascade reaches) are less responsive than lower-gradient unconfined channels (e.g., pool-riffle, braided, and dune-ripple reaches), which may exhibit multiple, and sometimes competing, responses to a given disturbance (Montgomery and Buffington, 1997). Although step-pool and cascade reaches are resilient to moderate changes in discharge and sediment supply, these high-energy, confined streams offer little refuge to aquatic organisms during disturbance events. In contrast, pool-riffle, braided, and dune-ripple reaches can exhibit extensive, dynamic response to changes in sediment and water inputs, making them unstable environments, but their topographic diversity, complex off-channel habitats, and floodplain connectivity can provide a variety of refugia for aquatic organisms during disturbance events.

In addition, disturbance regimes typically vary with stream-reach type. Montgomery (1999) proposed that characteristic geomorphic processes occurring in different portions of the landscape control the spatial and temporal patterns of disturbance that, in turn, structure riverine ecosystems and their dynamicsdreferred to as process domains. In mountain basins, alluvial stream reaches can be broadly grouped into two process domains: (1) steep, confined channels (cascade and step-pool reaches) that are governed by a combination of debris flows and flooding and (2) low-gradient channels (pool-riffle, braided, and dune-ripple reaches) governed by flooding that, in unconfined settings, fosters lateral mobility (channel migration and avulsion) and temporal expansion/contraction of the stream network and its connection to off-channel and floodplain habitats (see Chapters 1 and 5). In forested basins, extensive riparian vegetation and wood inputs can further modify channel processes, responses, and disturbance regimes.

2.1.3 Channel Unit Classification

Channel units are relatively homogeneous localized areas of the channel that differ in morphology, depth, velocity, and substrata characteristics from adjoining areas, and they are the building blocks for the larger stream reaches discussed above (Bisson et al., 1982; Sullivan, 1986; Church, 1992; Halwas and Church, 2002). The most generally used channel unit terms for small to mid-size streams are riffles and pools. Individual channel units are created by interactions between flow and roughness elements of the streambed at meso (subreach) scales. Definitions of channel units usually apply to conditions at low discharge. At high discharge, channel units are often indistinguishable from one another and their hydraulic properties differ greatly from those at low flows. Although channel unit dimensions and relative extent can vary with discharge, channel-unit types are generally constant across a broad range of low flows.

Different types of channel units in close proximity to one another provide organisms with a choice of habitat, particularly in small streams possessing considerable physical heterogeneity (Hawkins et al., 1993; Halwas et al., 2005). Channel-unit classification is therefore quite useful for developing an understanding of the distribution and abundance of aquatic plants and animals in patchy stream environments. Channel units are known to influence nutrient exchanges (Triska et al., 1989; Aumen et al., 1990), algal abundance (Tett et al., 1978; Murphy, 1998), production of benthic invertebrates (Huryn and Wallace, 1987), invertebrate diversity (Hawkins, 1984), and the distribution of fishes (Angermeier, 1987; Bisson et al., 1988; Schlosser, 1991; Beechie et al., 2005). The frequency and location of different types of channel units within a reach can be affected by a variety of disturbances, including anthropogenic disturbances that remove structural roughness elements such as large wood (Lisle, 1986a; Sullivan et al., 1987; Woodsmith and Buffington, 1996; Elosegi and Johnson, 2003) or impede the ability of a stream to interact naturally with its adjacent riparian zone and floodplain (Beschta and Platts, 1986; Pinay et al., 1990). Channel-unit classification is a useful tool for understanding the relationships between anthropogenically induced habitat alterations and aquatic organisms.

Hawkins et al. (1993) modified an earlier channel-unit classification system (Bisson et al., 1982) and proposed a 3-tiered system of classification (Fig. 2.7) in which investigators could select the level of habitat resolution appropriate to the question being addressed. The first level was subdivided into fast water ("*riffle*") and slow water ("*pool*") units. The second level distinguished fast water units having rough ("turbulent") versus smooth ("non-turbulent") water surfaces, and slow-water units formed by scour from slow-water units formed by dams. Strictly speaking, nearly all river flows are turbulent (as opposed to laminar or "nonturbulent") according to hydraulic principles. Consequently, we use the terms "rough" and "smooth" to describe the water surface of channel units, rather than the "turbulent" and "nonturbulent" terms proposed by Hawkins et al. (1993) (Fig. 2.7). The third level of classification further subdivided each type of fast and slow water unit based on characteristic hydraulic properties and the principal kind of habitat-forming structure or process.

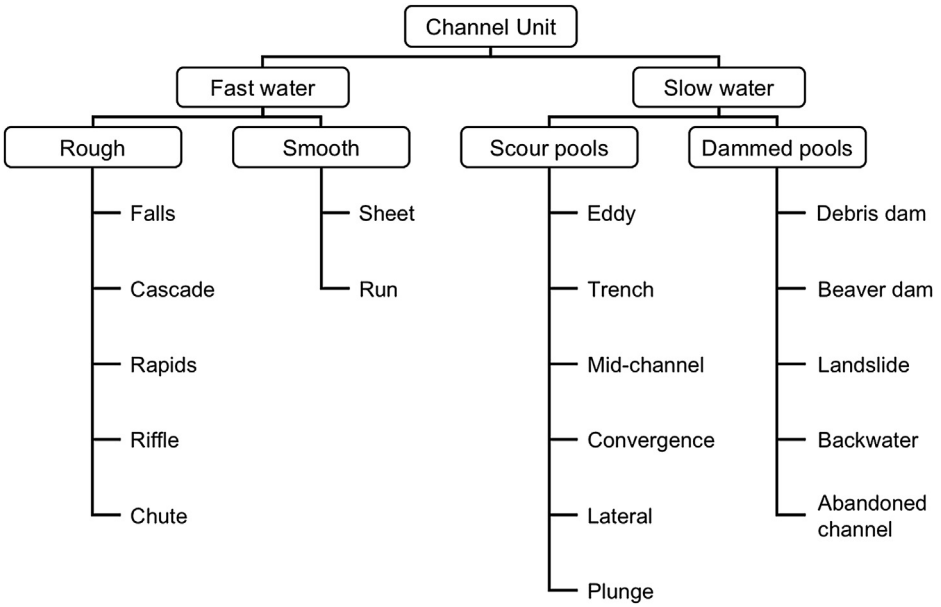

FIGURE 2.7 Hierarchical subdivision of channel units in streams. *After Hawkins et al. (1993).*

2.1.3.1 Rough Fast-Water Units

The term "fast water" is a relative term that describes current velocities observed at low-to-moderate flows and is meant only to distinguish this class of channel unit from other units in the same stream with "slow water". Most of the time, but not always, slow-water units will be deeper than fast-water units at a given discharge. The generic terms *riffle* and *pool* are frequently applied to fast- and slow-water channel units, respectively, although these terms convey limited information about geomorphic or hydraulic characteristics of a stream. Current velocity and depth are the main criteria for separating riffles from pools in low- to mid-order stream channels. Although there are no absolute values of velocity or depth that identify riffles and pools, they are by definition separated by depth. Pools are not shallow and riffles are not deep. However, pools can contain fast or slow waters, while riffles are only fast.

TABLE 2.3 **Types of rough and smooth fast-water channel units and the relative rankings of variables used to distinguish them. Rankings are in descending order of magnitude where a rank of one denotes the highest value of a particular parameter. Step development is ranked by the abundance and size of hydraulic jumps within a channel unit.**

	Gradient	Supercritical Flow	Bed Roughness	Mean Velocity	Step Development
Rough					
Falls	1	n/a	n/a	1	1
Cascade	2	1	1	2	2
Chute	3	2	4	3	5
Rapids	4	3	2	4	3
Riffle	5	4	3	5	4
Smooth					
Sheet	Variable	6	6	6	5
Run	6	5	5	7	5

From Hawkins et al. (1993).

Hawkins et al. (1993) recognized five types of rough fast-water channel units (Table 2.3). Channel units are classified as rough as Froude number increases (see Chapters 4 and 5). Hydraulic jumpsdsufficient to entrain air bubbles and create localized patches of white waterdapproach and can exceed critical flow. In contrast, the appearance of the flow is much more uniform in smooth fast-water units. Rough fast-water channel units are listed in Table 2.3 in approximate descending order of gradient, bed roughness, current velocity, and abundance of hydraulic steps.

Falls are essentially vertical drops of water and are commonly found in bedrock, cascade, and step-pool stream reaches. *Cascade* channel units consist of a highly turbulent series of short falls and small scour basins, frequently characterized by very large sediment sizes and a stepped longitudinal profile. They are prominent features of bedrock and cascade reaches. *Chute* channel units are typically narrow, steep slots in bedrock. They are common in bedrock reaches and also occur in cascade and step-pool reaches. *Rapids* are moderately steep channel units with coarse substrata, but unlike cascades possess a somewhat planar (vs. stepped) longitudinal profile. Rapids are the dominant fast-water channel unit of steeper gradient plane-bed stream reaches. *Riffles* are the most common type of rough fast water in low-gradient (<3%) alluvial channels and may be found in plane-bed, pool-riffle, dune-ripple, and braided reaches. The particle size of riffles tends to be somewhat finer than that of the other rough fast-water units, since riffles are shallower than rapids and generally have lower tractive force to mobilize the streambed (see Chapters 4 and 5).

2.1.3.2 Smooth Fast-Water Units

Hawkins et al. (1993) recognized two types of smooth fast-water units. Sheet-channel units are rare in many watersheds but may be common in valley segments dominated by bedrock. Sheets occur where shallow water flows uniformly over smooth bedrock of variable gradient; they may be found in bedrock, cascade, or step-pool reaches, but are generally isolated, as true sheet flow is highly rare in stream systems. Run-channel units are fast-water units of shallow gradient, typically with substrata ranging in size from sand to cobbles. They are characteristically deeper than riffles and because of their smaller substrata have little if any supercritical flow, giving their water surface a smooth appearance. Runs are common in pool-riffle, dune-ripple, and braided stream reaches, usually in mid- and higher-order channels.

2.1.3.3 Scour Pools

There are two general classes of slow-water channel units: pools created by scour that forms a depression in the streambed and pools created by the impoundment of water upstream from an obstruction to flow (Table 2.4). Scour pools can be created when discharge is sufficient to mobilize the substrata at a particular site at a rate that exceeds the upstream supply of sediment, while dammed pools can be formed under any flow condition. Hawkins et al. (1993) recognized six types of scour pools.

Eddy pools are the result of large flow obstructions along the edge of the stream or river. These pools are located on the downstream side of the structure and are usually proportional to the size of the obstruction. Eddy pools are often associated with large wood deposits or rock outcrops and boulders and can be found in virtually all reach types.

Trench pools, like chutes, are usually located in tightly constrained, bedrock-dominated reaches. They are characteristically U-shaped in cross-sectional profile and possess highly resistant, nearly vertical banks. Trench pools can be among the deepest of the slow-water channel units created by scour, and their depth tends to be rather uniform throughout much of their length, unlike other scour pool types. Although often deep, trench pools may possess relatively high current velocities.

Mid-channel pools are formed by flow constrictions that focus scour along the main axis of flow in the middle of the stream. Mid-channel pools are deepest near the head. This type of slow-water channel unit is very common in cascade, step-pool, and pool-riffle reaches. Flow constriction may be caused by laterally confined, hardened banks (bridge abutments are good examples), or by large flow obstructions such as boulders or woody debris, but an essential feature of mid-channel pools is that the direction of water movement around an obstruction is not diverted toward an opposite bank.

Convergence pools result from the confluence of two streams of somewhat similar size. In many respects convergence pools resemble mid-channel pools except that there are two main water entry points, which may result in a pattern of substrata particle sorting in which fines are deposited near the head of the pool in the space between the two inflowing channels. Convergence pools can occur in any type of alluvial stream reach, but are common in braided stream reaches.

Lateral scour pools occur where the channel encounters a resistant streambank or other flow obstruction near the edge of the stream. Typical obstructions include bedrock outcrops, boulders, large wood, or gravel bars. Many lateral scour pools form next to or under large, relatively immovable structures such as accumulations of logs or along a streambank that has been armored with rip-rap or other material that resists lateral channel migration. Water is deepest adjacent to the

TABLE 2.4 Characteristics of slow-water channel units. Location denotes whether the unit is likely to be associated with the thalweg of the channel (the main part of the flow) or adjacent to a bank. Longitudinal and cross-sectional profiles refer to the deepest point in the unit relative to the head, middle, or tail region of the unit. Substrata characteristics refer to the extent of particle sorting (i.e., particle uniformity) and resistance to scour. The channel unit-forming constraint describes the feature most likely to cause pooling.

	Location	Longitudinal Profile	Cross-Sectional Profile	Substrate Features	Forming Constraint
Scour Pools					
Eddy	Bank	Middle	Middle	Surface fines, not resistant to scour	Flow obstruction causing lateral deflection
Trench	Thalweg	Uniform	Uniform	Bedrock or sorted, resistant to scour	Bilateral resistance
Mid-channel	Thalweg	Middle	Middle	Sorted, variable resistance to scour	Constriction at upstream end
Convergence	Thalweg	Middle	Middle	Sorted, variable resistance to scour	Convergence of two channels
Lateral	Thalweg	Head or middle	Side	Sorted, variable resistance to scour	Flow obstruction causing lateral deflection
Plunge	Thalweg	Head	Upstream or middle	Sorted, variable resistance to scour	Full-spanning obstruction causing waterfall
Dammed Pools					
Debris dam	Thalweg	Tail	Highly variable	Usually sorted, not resistant to scour	Large woody debris dam of fluvial origin
Beaver dam	Thalweg	Tail	Highly variable	Surface fines, not resistant to scour	Beaver dam
Landslide dam	Thalweg	Tail	Highly variable	Often unsorted, variable resistance to scour	Organic and inorganic matter delivered by mass wasting from adjacent hillslope
Backwater	Bank	Tail	Highly variable	Unsorted with surface fines, not resistant to scour	Obstruction at tail impounding water along margin of main channel
Abandoned channel	Floodplain	Highly variable	Highly variable	Unsorted with surface fines, not resistant to scour	Lateral meander bars that isolate an overflow channel from the main channel

Modified from Hawkins et al. (1993).

streambank containing the flow obstruction and shallowest next to the opposite bank. Lateral scour pools are very common in step-pool, pool-riffle, dune-ripple, and braided reaches. In pool-riffle and dune-ripple reaches, lateral scour pools form naturally at meander bends even without large roughness elements (Leopold et al., 1964; Yang, 1971; Dietrich et al., 1979; Caamaño et al., 2012).

Plunge pools result from the vertical fall of water over a full-spanning obstruction onto the streambed. The full-spanning obstruction creating the plunge pool is located at the head of the pool and the waterfall can range in height from less than a meter to hundreds of meters, as long as the force of the fall is sufficient to scour the bed and entrain sediment over the downstream lip of the resultant pool (see reviews by Buffington et al. (2002) and Scheingross and Lamb (2016, 2017) and references therein). A second, far less common type of plunge pool occurs in higher-order channels, where the stream passes over a sharp geological discontinuity such as the edge of a plateau, forming a large falls with a deep pool at the base. Depending on the height of the waterfall and the composition of the substrata, plunge pools can be quite deep (Scheingross and Lamb, 2017). Overall, plunge pools are most abundant in small, steep headwater streams, especially those with bedrock, cascade, and step-pool reaches, but are also common in forested pool-riffle channels where logs create plunge-pool steps.

2.1.3.4 Dammed Pools

Dammed pools are created by the impoundment of water upstream from a flow obstruction, rather than by scour downstream from the obstruction. They are distinguished by the type of material causing the water impoundment and by their location in relation to the thalweg (Table 2.4). The rate at which sediment fills dammed pools depends on sediment generation from source areas and fluvial transport from upstream reaches. Due to their characteristically low current velocities, dammed pools often have more surface fines than scour pools, and fill with sediment at a much more rapid rate. However, some types of dammed pools tend to possess more structure and cover for aquatic organisms than scour pools because of the complex arrangement of material forming the dam. Additionally, dammed pools can be very large, varying with the height of the dam and the extent to which it blocks the flow. Highly porous dams result in little impoundment. Well-sealed dams usually fill to the crest of the dam, creating a spill.

Hawkins et al. (1993) identified five types of dammed pools, three of which occur in the main channel of streams. Debris-dam pools are typically formed at the terminus of a debris flow or where large pieces of wood float downstream at high discharge and lodge against a channel constriction. The characteristic structure of debris dams consists of one or a few large key pieces that hold the dam in place and that trap smaller pieces of wood and sediment that comprise the matrix (e.g., Nakamura and Swanson, 1993; Abbe and Montgomery, 2003).

Beaver-dam pools, the only channel unit of natural biogenic origin, are unlike debris-dam pools in that they usually lack very large key pieces but instead consist of tightly woven smaller pieces sealed on the upstream surface with fine sediment. Some beaver dams may exceed 2 m in height, but most dams in stream systems are about a meter or less high (Pollock et al., 2015). In watersheds with high seasonal runoff, beaver dams may breach and be rebuilt annually. In such instances, fine sediments stored above the dam are flushed when the dam breaks.

Landslide-dam pools form when mass wasting from an adjacent hillslope or a tributary debris flow block a stream, causing an impoundment. Dam material consists of a mixture of coarse and fine sediments and, in forested terrain, woody debris. When landslides occur, some or most of the fine sediment in the landslide deposit may be rapidly transported downstream, leaving behind structures too large to be moved by the flow. Main channel-landslide pools are located primarily in laterally constrained reaches of relatively small streams. They are most abundant in confined reaches (step-pool and cascade reaches) where hillslopes are directly coupled to the channel, although some are found in moderately confined pool-riffle and plane-bed reaches of larger-order streams, particularly where steep tributary basins have deposited debris-flow fans in the mainstem river (Benda et al., 2003). Dammed pools are nearly always less abundant than scour pools in alluvial channels, due both to the rapidity with which they fill with sediment and to the temporary nature of most dams.

Two types of dammed pools located away from the main channel are found primarily at low flows. *Backwater* pools occur along the bank of the main stream at the downstream end of an upstream disconnected floodplain channel. Backwater pools often appear as a diverticulum from the main stream and possess water flowing slowly in an eddy pattern. Pool-riffle, dune-ripple, and braided reaches are most likely to possess this type of channel unit.

Abandoned-channel pools have no surface water connections to the main channel. They are formed by bar deposits in secondary channels that are isolated at low flow. Abandoned channel pools are floodplain features of pool-riffle, dune-ripple, and braided reaches that may be ephemeral or maintained by subsurface flow (see Chapters 5 and 8).

2.2 GENERAL DESIGN

2.2.1 Site Selection

It is generally impossible to locate examples of every type of valley segment, stream reach, and channel unit in one watershed due to regional differences in geology and hydrologic regimes. Instead, it is likely that potential study sites will consist of certain commonly occurring local reach types. In the laboratory, maps and photographs can be used to determine approximate reach boundaries based on changes in stream gradient, degree of valley confinement, channel meander patterns, or significant changes in the predominant rock type (e.g., Rosgen, 1996; Montgomery and Buffington, 1998). The main goal of the laboratory portion of this chapter is to practice map skills and to locate two or more distinctive stream-reach types.

2.2.2 General Procedures

While it is possible to infer valley segment and reach types from maps and photographs, preliminary classification should be verified by a visit to the sites. Identification of channel units from low elevation aerial photographs, especially for small streams enclosed within a forest canopy, is virtually impossible and always requires a field survey. In the laboratory, the stream of interest can be divided into sections based on average gradient and apparent degree of valley confinement (e.g., Rosgen, 1996; Montgomery and Buffington, 1998). Topographic changes in slope can provide important information regarding reach boundaries (e.g., Baxter and Hauer, 2000). The scale of topographic maps (including USGS 7.5 min series maps) may or may not allow identification of key changes in stream gradient and valley confinement that mark reach transitions in very small streams. Maps may or may not provide accurate information on the sinuosity of the stream or the extent of channel braiding, depending on the size of the stream one is studying and the age and resolution of the map with which one is working. Nonetheless, topographic maps are essential for plotting changes in the elevational profile of a stream, as well as changes in valley confinement.

Aerial photographs are often available from natural resource management agencies and online resources such as Google Earth and should be used to supplement information extracted from maps. Aerial photographs can be used to accurately locate changes in channel shape in streams not obscured by forest canopies. Orthographic photographs provide a three-dimensional, if somewhat exaggerated, perspective of landscape relief but require stereoscopic map reading equipment that optically superimposes offset photos. This equipment can range from pocket stereoscopes costing $20 to mirror reflecting stereoscopes costing over $2000. Low-altitude aerial photographs (1:12,000 scale or larger) are most useful and should be examined whenever available. Geological and soils maps of the area will help identify boundaries between geological formations, another important clue to the location of different reach types. Vegetative maps or climatological maps (e.g., rainfall or runoff), if available, provide additional information about the setting of the stream. Landsat imagery can be helpful at large landscape scales but does not provide the resolution needed for designation of reach boundaries in small streams. Shaded relief images made from laser altimetry, or LiDAR (Light Detection and Ranging) data, provide highly detailed views of topographic relief and can help establish reach transitions and channel migration history (e.g., National Center for Airborne Laser Mapping, 2016).

For advanced users, geographic information system (GIS) analysis of digital elevation models (DEMs) can also be used to predict valley and reach types, as well as hydraulic geometry (channel width, depth), floodplain extent, and channel confinement (e.g., Buffington et al., 2004; Benda et al., 2007; Hall et al., 2007; Clarke et al., 2008; Fernandez et al., 2012; Nagel et al., 2014). If bathymetric LiDAR data are available (derived from blue-green lasers that can penetrate water), one can determine hydraulic geometry, sinuosity, confinement, and basic channel units (riffle, pool) using programs such as the River Bathymetry Toolkit (McKean et al., 2009; USFS and ESSA, 2010). The first approach discussed above of coupling DEMs with hydraulic geometry equations (e.g., Clarke et al., 2008) is useful for making basinwide predictions of channel characteristics, but can contain considerable error that requires careful ground-truthing and/or calibration. The second approach of measuring reach- and valley-segment characteristics from local LiDAR data (USFS and ESSA, 2010) is more accurate, but also requires a certain degree of field verification because all topographic models contain errors, and each instrument platform for remotely sensing topography has specific, inherent limitations.

Once the stream has been subdivided into provisional reach boundaries in the laboratory, contrasting sites are visited and all or part of the reaches of interest are surveyed on foot using the criteria in Tables 2.3 and 2.4 to identify channel units. This is often a time-consuming process, depending on the accessibility of the reach, its length and riparian characteristics, and the level of detail used in inventorying channel units. Surveys of channel units in small- to mid-size

streams typically involve teams of two to three people covering 1–5 km day^{-1}. Representative sections of a reach can be studied, provided the sections include examples of each type of channel unit present in the reach as a whole (Dolloff et al., 1993). A useful rule of thumb is that reach subsamples should be at least 20–50 channel-widths long; for example, a survey of channel units in a reach with an average channel width of 10 m should be at least 200–500 m long. During the survey, the team should verify that the preliminary laboratory classification of valley segment and reach type was correct. Any significant changes in reach character should be noted, particularly if the stream changes from one reach type to another. The valley-segment types most often surveyed by stream ecologists will be alluvial and bedrock (colluvial reaches also are easily recognized). Stream-reach characteristics are given in Table 2.2 as a guide and for predicting likely reach types before going to the field. Ultimately, however, stream type should be classified visually, in the field, based on understanding of differences in reach morphology (Fig. 2.4) and associated processes, not based on the specific values given in Table 2.2. For example, when in the field, one does not measure channel characteristics (slope, width-depth ratio, grain size) and then "look up" the associated reach type in Table 2.2. Rather, one visually identifies reach morphology from the descriptions, photographs, and drawings presented in this chapter and then makes field measurements, as desired, to further quantify the physical characteristics of the observed stream-reach type.

Surveys of channel unit composition can be used simply to determine the presence and number of each type of unit in the reach. More often, however, investigators wish to establish the percent of total wetted area or volume in each channel-unit type on the date the stream was surveyed. Simple counts of the number and type of channel units can be completed almost as fast as it takes to walk the reach, but estimates of surface area or volume can require considerable time, depending on the complexity of the channel and size of the units. Highly accurate estimates of area and volume involve many length, width, and depth measurements of each unit, increasingly measured in large channels with precise surveying equipment [Real Time Kinematic Global Positioning System (RTK GPS) or digital theodolites (total station)]. Visual estimation of the surface area of individual channel units has proven to be a reasonably accurate and much less time-consuming technique (Hankin and Reeves, 1988; Dolloff et al., 1993). However, visual estimates must be periodically calibrated by comparing them with careful measurements of the same channel units. Part of this exercise will involve performing such a comparison.

In conducting channel unit surveys, the question inevitably arises "What is the relative size of the smallest possible unit to be counted?" For channels with complex topographic features and considerable hydraulic complexity, this is a challenging question. Fast-water units possess some areas of low current velocity and slow-water units usually have swiftly flowing water in them at some point. Location of channel unit boundaries for survey purposes is almost always subjective. Except for waterfalls, transitions from one unit to the next can be gradual. In general, an area should be counted as a separate unit if (1) its overall physical characteristics are clearly different from those of adjacent units, and (2) its size is significant relative to the size of the wetted channel. A guideline for what constitutes "significant" is that the greatest dimension of the channel unit should equal or exceed the average wetted width of the reach for units in the stream's thalweg, and one-half the average wetted width of the reach for units along the stream's margin. It is quite possible (and should be expected) that channel units will not all be arranged in a linear fashion along the reach, but that some units will be located next to each other, depending on the presence of flow obstructions and channel braiding. If time permits, one should measure all channel units (including those smaller than what may be "significant" as defined above); measuring the full distribution of channel units provides maximum flexibility for subsequent analysis of the data (i.e., one can decide how best to truncate the data for a given research topic or management question, both for the issue at hand and for future queries of the data).

Channel unit surveys challenge investigators to balance the accuracy of characterizing stream conditions over an entire reach against the precision obtained by carefully mapping a limited subsection of the reach (Poole et al., 1997). The greater the desired precision, the more time will be required for the survey and the less the area that can be covered within a given time. Rapid techniques for visually estimating channel-unit composition in stream reaches exist (Hankin and Reeves, 1988) as well as precise survey methods for mapping the fine details of channel structure at a scale of one to several units (Gordon et al., 1992). What technique is appropriate will be governed by the nature of the research topic. In all cases, investigators must keep in mind that variations in discharge and wetted channel dimensions can strongly influence the relative abundance of different channel unit types in terms of the total stream area or volume of the wetted channel; therefore, it is often desirable to repeat the survey at a variety of flows to quantify this potential source of uncertainty. Observer bias may also occur (e.g., Poole et al. 1997; Roper et al., 2010), so if time permits, channel-unit surveys should be repeated on the same day by a separate team to assess this source of error.

Although inventories of channel units in reaches of small streams can be conducted by one person, it is much easier and safer for surveys to be carried out by teams of at least two to three people. Because it is necessary to measure lengths and widths repeatedly, each crew member can be assigned a different task. Although practiced survey crews become proficient at identifying channel unit boundaries and maximizing the data-gathering efficiency, it is important to work slowly and

deliberately. It is far better to take time to collect accurate data than to be in a hurry to complete the reach survey; further, the risk of accidents declines with careful planning and time management, and cautious attention to detail. Work safely.

2.3 SPECIFIC METHODS

2.3.1 Basic Method: Valley Segment, Stream Reach, and Channel Unit Classification

2.3.1.1 Laboratory Protocols

1. Select a watershed. Assemble topographic maps, aerial photographs, and other information pertinent to the area. Identify watershed boundaries. Within the watershed, select a stream or streams of interest.
2. With the aid of the topographic map, construct a longitudinal profile of the channel beginning at the mouth of the stream and working toward the headwaters. Use a map wheel (also called a curvimeter or map measure) or a planimeter to measure the distance along the blue line that marks the stream. If a map wheel or planimeter is not available, a finely graduated ruler may be substituted. In either case, be sure to calibrate the graduations on the map wheel, planimeter, or ruler against the map scale. Record the elevation and distance from the mouth each time a contour line intersects the channel. Plot the longitudinal profile of the stream with the stream source nearest the vertical axis (Fig. 2.8). If GIS coverage of the area is available, use the appropriate data queries to determine channel length and longitudinal profile. Advanced GIS users may wish to additionally predict hydraulic geometry and channel confinement or measure those features along with basic channel unit characteristics (riffle and pool dimensions) if bathymetric LiDAR coverage is available, as discussed above.
3. Visually locate inflection points on the stream profile (Fig. 2.8). These points often mark important reach transitions. Compute the average channel slope in each segment according to the following formula:

$$S = \frac{E_u - E_d}{L} \tag{2.1}$$

where S = average slope, E_u = elevation at the upstream end of the stream reach, E_d = elevation at the downstream end of the stream reach, and L = reach length. Remember to use common distance units for both numerator and denominator.

4. Examine the shape of the contour lines intersecting the stream to determine the approximate level of valley confinement in each segment. The width of the channel will not be depicted on most topographic maps, but the general shape and width of the valley floor will indicate valley confinement (Fig. 2.9).
5. With the aid of a stereoscopic map reader, magnifying lens, dissecting microscope, or onscreen computer image, examine photographs of the stream segments identified on the topographic map. If it is possible to see the exposed (unvegetated) channel in the photographs, estimate the width of the exposed channel and compare it to the estimated

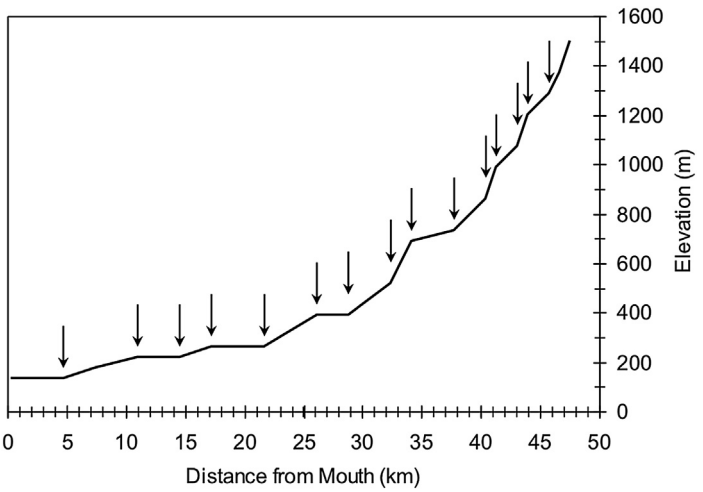

FIGURE 2.8 Hypothetical example of a stream profile constructed from a topographic map. Arrows denote changes in gradient that may mark reach boundaries.

width of the flat valley floor. Use the following guidelines to determine the approximate degree of confinement for the reach:

Valley floor width <2 channel widths	Strongly confined
Valley floor width = 2−4 channel widths	Moderately confined
Valley floor width >4 channel widths	Unconfined

6. Compare average gradients and valley-floor widths of each segment on the longitudinal stream profile with geological, soils, vegetation, and/or climatological maps of the watershed (as available). Changes in the boundaries shown on these maps may help in more precisely locating reach boundaries and in forming hypotheses about reach conditions that can be evaluated during visits to the sites. From all available evidence, determine the most likely valley segment and reach type (or range of types) for each segment based on the features summarized in Table 2.2. Select one or more reaches for site surveys to verify laboratory classification of valley segments and stream-reach types and to inventory channel units, which generally cannot be determined through the above remote-sensing techniques.

2.3.1.2 Field Protocols

It may be possible to combine certain aspects of the field survey in this exercise with field methods discussed in other chapters in this book. One reach may be surveyed on one field trip and a second reach surveyed on a different field trip.

Valley-Segment and Stream-Reach Classifications

1. Upon arrival at the site, inspect the stream channel, adjacent valley floor, and hillslopes to verify the accuracy of preliminary valley segment and reach classification(s). Refer to Table 2.2 and Fig. 2.4 as guides for field identification of stream-reach types, but remember that reach classification relies on visual identification, not looking up results in Table 2.2 after measuring the channel characteristics. If it is possible to do so (for example, from a vantage point that permits a panoramic view of the valley floor), locate landmarks that mark reach boundaries and that are easily visible from the stream itself. In some cases, the segment and reach type(s) can be easily classified from a vantage point above the stream valley or from standing on the banks of the river, while in other cases one must walk the reach, partic-ularly where the channel is obscured by riparian vegetation.

Channel-Unit Inventory

1. If the reach is too long to complete the exercise within 2–4 h (e.g., >500 m), select a representative section of the reach for the channel unit survey. Location of representative sections may be based on ease of access, but the section should typify the reach as a whole and be long enough to likely contain all types of channel units in the reach (20–50 channel widths). Use the descriptions of channel-unit types in Tables 2.3 and 2.4 to identify the units. If reference photographs or schematic drawings of different types of channel units are available (e.g., Bisson et al., 1982), refer to them when necessary.

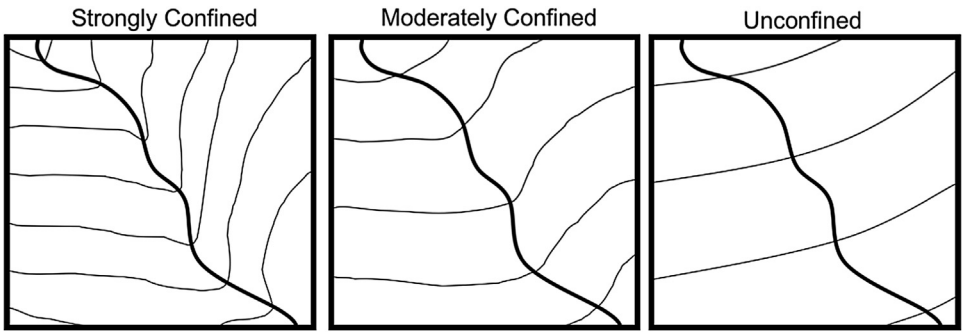

FIGURE 2.9 Appearance of strongly confined, moderately confined, and unconfined channels on topographic maps.

2. Most channel-unit surveys progress in an upstream direction, but this is not essential. It is necessary, however, to be able to recognize channel-unit boundaries. These boundaries are often marked by abrupt gradient transitions, which tend to be more easily visible looking upstream than downstream. Begin at a clearly monumented starting point, using GPS if available to establish geospatial coordinates. Starting points are usually located at reach boundaries but may consist of a man-made structure such as a bridge or some other permanent feature of the landscape. If semipermanent markers are used (e.g., a stake or flag tied to a tree), the location of the marker should be precisely referenced.
3. Divide into teams of two or more individuals. Moving along the stream away from the starting point, the team should identify and record each channel unit as it is encountered (Table 2.5). Units located side-by-side relative to the thalweg (e.g., a pool in the main channel and an adjacent backwater) should be so noted.
4. Record the distance from the starting point of the reach survey to the beginning of each channel unit. This can be accomplished with a measuring tape (or hip chain), rangefinder, hand-held GPS, or survey equipment (auto level, total station, or RTK GPS). Smartphones can also be used, offering a variety of "apps" for measuring GPS coordinates, compass direction, slope (digital clinometer), and distance; and they take adequate photographs. Unless GPS or survey equipment are used, it will most likely be necessary to measure distances from intermediate reference points along the channel because bends in the channel or riparian vegetation will obscure the view of the starting point. For small streams, it may be helpful to locate intermediate distance reference points at short intervals (e.g., 50 m). If optical or laser rangefinders will be used to measure distances (recommended for all but the smallest streams), calibrate them at the beginning of each field trip by measuring the distance between two points with a tape and adjusting the readings on the rangefinders to match the known distance. Optical rangefinders, in particular, can become misaligned if dropped and should be recalibrated frequently.
5. For each channel unit, visually estimate the wetted surface area and note it on the data form (Table 2.5). For these estimates, it may be helpful to calibrate the "eye" of the observer by placing several rectangles or circles of plastic of known area on the ground before beginning the survey. The pieces of plastic (e.g., old tarps) should approximate the sizes of typical channel units at the site.

TABLE 2.5 An example of a field data form for conducting channel unit surveys (channel units can be identified by an acronym or alphanumeric designation).

Location_____ Date_____ Surveyors_____

Stream_____ Discharge_____ _____

Quad Map_____ Time_____ _____

Starting Point/GPS_____ Water Temp_____ _____

Ending Point/GPS_____ Reach Type_____ _____

Channel Unit	Distance from Start	GPS Location	Area (estim.)	Greatest Length	Widths					Depths									
					1	2	3	4	5	1	2	3	4	5	6	7	8	9	10

Modified from Dolloff et al. (1993).

6. Periodically (e.g., every 10 channel units), use the techniques illustrated in Advanced Method 1, below, to measure the length and width of a channel unit after its area has been visually estimated. Record these measurements on the data form, as they will be used to determine any systematic bias in the visual area estimates, and will make it possible to calculate a correction factor.

2.3.2 Advanced Method: Detailed Measurements of Channel Units

1. Perform steps one to four from the above visual method of inventorying channel units.
2. For each channel unit, use a range finder, measuring tape, or telescoping surveyor's rod to measure its greatest length in any direction and record this length on the data form (Table 2.5). Widths should be measured at right angles to the line defining the greatest length. For more detailed measurements, channel dimensions can be surveyed with an auto level, total station, or RTK GPS.
3. Measure the wetted width at regular intervals along the length of the channel unit. Although five width measurements are shown on Table 2.5, the number can vary at the discretion of the investigators. Geomorphically, simple units require fewer width measurements than units with complex margins, but in general more is better.
4. If the volume of each channel unit is to be estimated in addition to the area, record the depth of the stream at regular intervals across the channel unit at each width transect. If the stream is wadeable, depths are usually measured with a telescoping fiberglass surveyor's rod, graduated wading staff, or meter stick (for very small streams). For very large streams, an electronic depthfinder operated from a boat may be appropriate. At a minimum, depth should be determined at one-third and two-thirds the distance from one side of the channel unit to the other at each width transect, yielding two depth measurements for each width measurement (Table 2.5). Once again, complex channel units require more depth measurements for accurate volume estimates than geomorphically simple units.
5. From your measurements (Table 2.5), calculate the average dimensions of each channel unit (width, depth, surface area, volume) and the percentage of wetted stream area and volume occupied by each unit type using the below equations:

$$\text{Average width} = \frac{\text{Sum of width measurements}}{\text{Number of measurements}} \tag{2.2}$$

$$\text{Average depth} = \frac{\text{Sum of depth measurements}}{\text{Number of measurements}} \tag{2.3}$$

$$\text{Area} = \text{Length} \times \text{Average width} \tag{2.4}$$

$$\text{Volume} = \text{Length} \times \text{Average width} \times \text{Average depth} \tag{2.5}$$

$$\%\ \text{of Area} = \frac{\text{Area of channel unit type}}{\text{Total area of reach}} \times 100 \tag{2.6}$$

$$\%\ \text{of Volume} = \frac{\text{Volume of channel unit type}}{\text{Total volume of reach}} \times 100 \tag{2.7}$$

2.4 QUESTIONS

1. Were preliminary determinations of valley segment and reach types from maps and photographs correct when sites were visited in the field? What types of valley segments and stream reaches would be easy to identify from maps and aerial photographs? What types would be difficult to identify?
2. What would likely happen if each reach type were to experience a very large precipitation event, such as a flood with a 100–200-year recurrence interval? Would the effects be similar to other large disturbances such as inputs of massive volumes of fine sediment?
3. Give a few examples of situations where a stream reach might change from one type to another.
4. How does riparian vegetation influence the characteristics of different reach types? For one or two types, describe how alteration of the riparian plant community could affect channel features.
5. If the channel unit survey compared visual estimates of surface area with estimates derived from actual length and width measurements, was there a tendency for visual estimates to over- or underestimate the area? Were errors more apparent for certain types of channel units than for others? Explain why, and suggest a way to correct for systematic bias in the visual estimates.

6. Describe several ways of displaying channel unit frequency data.
7. Describe how the properties of different types of channel units might change with increasing streamflow.
8. Based on your knowledge of the habitat preferences of a certain taxon of aquatic organism (e.g., an aquatic insect or fish species), suggest how that organism would likely be distributed among the channel units within the reach or reaches that were surveyed.
9. How would the frequency of different types of channel units in a reach likely change in response: to removal of large wood; to extensive sediment inputs; to destruction of riparian vegetation; and to a project involving channelization of the reach?

2.5 MATERIALS AND SUPPLIES

Basic Field Materials
- 100-m fiberglass tape or hip chain
- Flagging
- Hand-held GPS
- Optical or laser rangefinder
- Surveyor's rod, graduated wading staff, or meter stick
- Waterproof data forms
- Camera

Advanced Field Materials
- Surveying equipment (auto level, total station, or RTK GPS)
- Survey stakes and rebar for monumenting the site

Basic Laboratory Materials
- Aerial photographs
- Geologic, soils, climate, and vegetation maps (as available)
- Graph paper
- Map wheel (map measure), planimeter, or digitizer
- Stereoscope
- Topographic maps

Advanced Laboratory Materials
- Computer
- GIS databases, including digital versions of the above maps and photographs
- DEM (30-m resolution or better)
- Algorithms (computer programs) for querying GIS databases and predicting valley and channel characteristics, some of which may require user development using published approaches (e.g., Hall et al., 2007; Clarke et al., 2008; Fernandez et al., 2012), while others are "canned" (user ready) and freely available (e.g., Benda et al., 2007; USFS and ESSA, 2010; Nagel et al., 2014).

REFERENCES

Abbe, T.B., Montgomery, D.R., 2003. Patterns and process of wood debris accumulation in the Queets river basin, Washington. Geomorphology 51, 81-107.

Albertson, L.K., Sklar, L.S., Pontau, P., Dow, M., Cardinale, B.J., 2014. A mechanistic model linking insect (Hydropsychidae) silk nets to incipient sediment motion in gravel-bedded streams. Journal of Geophysical Research: Earth Surface 119, 1833-1852.

Andrews, E.D., 1980. Effective and bankfull discharges of streams in the Yampa river basin, Colorado and Wyoming. Journal of Hydrology 46, 311-330.

Angermeier, P.L., 1987. Spatiotemporal variation in habitat selection by fishes in small Illinois streams. In: Matthews, W.J., Heins, D.C. (Eds.), Community and Evolutionary Ecology of North American Stream Fishes. University of Oklahoma Press, Norman, OK, pp. 52-60.

Aumen, N.G., Hawkins, C.P., Gregory, S.V., 1990. Influence of woody debris on nutrient retention in catastrophically disturbed streams. Hydrobiologia 190, 183-192.

Balon, E.K., 1982. About the courtship rituals in fishes, but also about a false sense of security given by classification schemes, comprehensive reviews and committee decisions. Environmental Biology of Fishes 7, 193-197.

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.

Baxter, C.V., Fausch, K.D., Saunders, W.C., 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater Biology 50, 201–220.

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.

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., Moir, H., Pess, G., 2008a. Hierarchical physical controls on salmonid spawning location and timing. In: Sear, D.A., DeVries, P. (Eds.), Salmonid Spawning Habitat in Rivers: Physical Controls, Biological Responses, and Approaches to Remediation, American Fisheries Society Symposium, vol. 65, pp. 83-101. Bethesda, MD.

Beechie, T., Pess, G., Roni, P., Giannico, G., 2008b. Setting river restoration priorities: a review of approaches and a general protocol for identifying and prioritizing actions. North American Journal of Fisheries Management 28, 891-905.

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.

Bellmore, R.J., Baxter, C.V., Martens, K., Connolly, P.J., 2013. The floodplain food web mosaic: a study of its importance to salmon and steelhead with implications for their recovery. Ecological Applications 23, 189-207.

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., 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, 206-219.

Beschta, R.L., Platts, W.S., 1986. Morphological features of small streams: significance and function. Water Resources Bulletin 22, 369-379.

Binns, N.A., Eiserman, F.M., 1979. Quantification of fluvial trout habitat in Wyoming. Transactions of the American Fisheries Society 108, 215-228.

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.), Acquisition and Utilization of Aquatic Habitat Inventory Information. Symposium Proceedings, October 28e30, 1981, Portland, Oregon. The Hague Publishing, Billings, MT, pp. 62-73.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K.V., Sedell, J.R., 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In: Salo, E.O., Cundy, T.W. (Eds.), Streamside Management: Forestry and Fishery Interactions. Institute of Forest Resources, University of Washington, Seattle, WA, pp. 143-190. Contribution Number 57.

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.

Bjornn, T.C., Reiser, D.W., 1991. Habitat requirements of salmonids in streams. In: Meehan, W.R. (Ed.), Influence of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication 19, Bethesda, MD, pp. 83-138.

Borg, D., Rutherfurd, I., Stewardson, M., 2007. The geomorphic and ecological effectiveness of habitat rehabilitation works: Continuous measurement of scour and fill around large logs in sand-bed streams. Geomorphology 89, 205-216.

Bovee, K.D., Cochnauer, T., 1977. Development and Evaluation of Weighted Criteria Probability of Use Curves for Instream Flow Assessments: Fisheries. Instream Flow Information Paper Number 3. Cooperative Instream Flow Service Group, Fort Collins, CO.

Bryant, M.D., 1980. Evolution of Large, Organic Debris after Timber Harvest: Maybeso Creek, 1949 to 1978. United States Forest Service, General Technical Report PNW-101. Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Buffington, J.M., 2012. Changes in channel morphology over human time scales. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), Gravel-Bed Rivers: Processes, Tools, Environments. Wiley, Chichester, UK, pp. 435-463.

Buffington, J.M., Lisle, T.E., Woodsmith, R.D., Hilton, S., 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18, 507-531.

Buffington, J.M., Montgomery, D.R., 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35, 3507-3522.

Buffington, J.M., Montgomery, D.R., 2013. Geomorphic classification of rivers. In: Schroder, J., Wohl, E. (Eds.), Treatise on Geomorphology. Academic Press, San Diego, CA, pp. 730-767.

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., Tonina, D., 2009. Hyporheic exchange in mountain rivers II: effects of channel morphology on mechanics, scales and rates of exchange. Geography Compass 3, 1038-1062.

Buffington, J.M., Woodsmith, R.D., Booth, D.B., Montgomery, D.R., 2003. Fluvial processes in Puget Sound rivers and the Pacific Northwest. In: Montgomery, D.R., Bolton, S., Booth, D.B., Wall, L. (Eds.), Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA, pp. 46-78.

Butler, D.R., 1995. Zoogeomorphology: Animals as Geomorphic Agents. Cambridge University Press, Cambridge, UK.

Buxton, T.H., Buffington, J.M., Tonina, D., Fremier, A.K., Yager, E.M., 2015a. Modeling the influence of salmon spawning on hyporheic exchange of marine-derived nutrients in gravel streambeds. Canadian Journal of Fisheries and Aquatic Sciences 72, 1146-1158.

Buxton, T.H., Buffington, J.M., Yager, E.M., Hassan, M.A., Fremier, A.K., 2015b. The relative stability of salmon redds and unspawned streambeds. Water Resources Research 51, 6074-6092.

Caamaño, D., Goodwin, P., Buffington, J.M., 2012. Flow structure through pool-riffle sequences and a conceptual model for their sustainability in gravel-bed rivers. River Research and Applications 28, 377-389.

Chartrand, S.M., Jellinek, M., Whiting, P.J., Stamm, J., 2011. Geometric scaling of step-pools in mountain streams: observations and implications. Geomorphology 129, 141-151.

Chin, A., 1998. On the stability of step-pool mountain streams. Journal of Geology 106, 59-69.

Church, M., 1992. Channel morphology and typology. In: Carlow, P., Petts, G.E. (Eds.), The Rivers Handbook. Blackwell Scientific Publications, Oxford, UK, pp. 126-143.

Clarke, S.E., Burnett, K.M., Miller, D.J., 2008. Modeling streams and hydrogeomorphic attributes in Oregon from digital and field data. Journal of the American Water Resources Association 44, 459-477.

Cupp, C.E., 1989. Valley Segment Type Classification for Forested Lands of Washington. Timber, Fish, and Wildlife Agreement Report TFW-AM-89-001. Washington State Department of Natural Resources, Olympia, WA.

Dietrich, W.E., Nelson, P.A., Yager, E., Venditti, J.G., Lamb, M.P., Collins, L., 2006. Sediment patches, sediment supply and channel morphology. In: Parker, G., Garcia, M.H. (Eds.), River, Coastal and Estuarine: Morphodynamics. Taylor and Francis/Balkema, The Netherlands, pp. 79-90.

Dietrich, W.E., Smith, J.D., Dunne, T., 1979. Flow and sediment transport in a sand bedded meander. Journal of Geology 87, 305-315.

Dietrich, W.E., Wilson, C.J., Reneau, S.L., 1986. Hollows, colluvium and landslides in soil-mantled landscapes. In: Abrahams, A.D. (Ed.), Hillslope Processes. Allen and Unwin, Boston, MA, pp. 361-388.

Dolloff, C.A., Hankin, D.G., Reeves, G.H., 1993. Basinwide Estimation of Habitat and Fish Populations in Streams. United States Forest Service. General Technical Report SE-83. Southeastern Forest Experiment Station, Asheville, NC.

Elosegi, A., Johnson, L.B., 2003. Wood in streams and rivers in developed landscapes. In: Gregory, S.V., Boyer, K.L., Gurnell, A.M. (Eds.), The Ecology and Management of Wood in World Rivers, American Fisheries Society Symposium, pp. 337-353. Bethesda, MD.

Fernández, D., Barquín, J., Álvarez-Cabria, M., Peñas, F.J., 2012. Quantifying the performance of automated GIS-based geomorphological approaches for riparian zone delineation using digital elevation models. Hydrology Earth System Science 16, 3851-3862.

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.

Gomi, T., Sidle, R.C., Richardson, J.S., 2002. Understanding processes and downstream linkages of headwater systems. BioScience 52, 905-916.

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

Goode, J.R., Wohl, E., 2010. Substrate controls on the longitudinal profile of bedrock channels: Implications for reach-scale roughness. Journal of Geophysical Research 115, F03018. http://dx.doi.org/10.1029/2008JF001188.

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.

Gooderham, J.P.R., Barmuta, L.A., Davies, P.E., 2007. Small headwater streams: physically heterogeneous systems structured by a lack of competence? Journal of the North American Benthological Society 26, 365-374.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., 1992. Stream Hydrology: An Introduction for Ecologists. John Wiley and Sons, Chichester, UK.

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, 323-334.

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, 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.

Hankin, D.G., Reeves, G.H., 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Canadian Journal of Fisheries and Aquatic Sciences 45, 834-844.

Hawley, R.J., MacMannis, K.R., Wooten, M.S., 2013. Bed coarsening, riffle shortening, and channel enlargement in urbanizing watersheds, northern Kentucky, USA. Geomorphology 201, 111-126.

Hassan, M.A., Gottesfeld, A.S., Montgomery, D.R., Tunnicliffe, J.F., Clarke, G.K.C., Wynn, G., Jones-Cox, H., Poirier, R., MacIsaac, E., Herunter, H., Macdonald, S.J., 2008. Salmon-driven bed load transport and bed morphology in mountain streams. Geophysical Research Letters 35, L04405.

Hauer, F.R., Locke, H., Dreitz, V.J., Hebblewhite, M., Lowe, W.H., Muhlfeld, C.C., Nelson, C.R., Proctor, M.F., Rood, S.B., 2016. Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Science Advances 2 (6), e1600026.

Hawkes, H.A., 1975. River zonation and classification. In: Whitton, B.A. (Ed.), River Ecology. Blackwell Scientific, Oxford, UK, pp. 312-374.

Hawkins, C.P., 1984. Substrate associations and longitudinal distributions in species of Ephemerellidae (Ephemeroptera: Insecta) from western Oregon. Freshwater Invertebrate Biology 3, 181-188.

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.

Huet, M., 1959. Profiles and biology of western European streams as related to fish management. Transactions of the American Fisheries Society 88, 155-163.

Huryn, A.D., Wallace, J.B., 1987. Community structure of Trichoptera in a mountain stream: spatial patterns of production and functional organization. Freshwater Biology 20, 141-156.

Hynes, H.B.N., 1970. The Ecology of Running Waters. University of Toronto Press, Toronto, Ontario, Canada.

Illies, J., 1961. Versuch einer allgemein biozönotishen Gliederung der Fliessegewässer. Internationale Revue gesamten. Hydrobiologie 46, 205-213.

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.

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, e0150293.

Keller, E.A., Melhorn, W.N., 1978. Rhythmic spacing and origin of pools and riffles. Geological Society of America Bulletin 89, 723-730.

Kinerson, D., 1990. Bed Surface Response to Sediment Supply (M.S. thesis). University of California Berkeley, Berkeley, CA.

Lenzi, M.A., Mao, L., Comiti, F., 2006. Effective discharge for sediment transport in a mountain river: computational approaches and geomorphic effectiveness. Journal of Hydrology 326, 257-276.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. W. H. Freeman, San Francisco, CA.

Lisle, T.E., 1986a. Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska. North American Journal of Fisheries Management 6, 538-550.

Lisle, T.E., 1986b. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. Geological Society of America Bulletin 97, 999-1011.

Lisle, T.E., Madej, M.A., 1992. Spatial variation in armouring in a channel with high sediment supply. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), Dynamics of Gravel-bed Rivers. John Wiley, New York, pp. 277-293.

Malard, F., Tockner, K., Dole-Oliver, M.-J., Ward, J.V., 2002. A landscape perspective of surfaceesubsurface hydrological exchanges in river corridors. Freshwater Biology 47, 621-640.

Marion, D.A., Weirich, F., 2003. Equal-mobility bed load transport in a small, step-pool channel in the Ouachita Mountains. Geomorphology 55, 139-154.

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, W.N., 2004. Application of a Stream Channel Classification in a Mountainous Setting (M.S. thesis). Utah State University, Logan, UT.

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.

Miller, D.J., Burnett, K., 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: Physical Controls, Biological Responses, and Approaches to Remediation, American Fisheries Society Symposium, vol. 65, pp. 103-120. Bethesda, MD.

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

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: Lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York, NY, pp. 13-42.

Montgomery, D.R., Dietrich, W.E., 1988. Where do channels begin? Nature 336, 232-234.

Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M., Stock, J.D., 1996a. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381, 587-589.

Montgomery, D.R., Buffington, J.M., Peterson, N.P., Schuett-Hames, D., Quinn, T.P., 1996b. Streambed scour, egg burial depths and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences 53, 1061-1070.

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., 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., Abbe, T.B., Buffington, J.M., 2003. Geomorphic effects of wood in rivers. In: Gregory, S.V., Boyer, K.L., Gurnell, A. (Eds.), The Ecology and Management of Wood in World Rivers, American Fisheries Society Symposium, vol. 37, pp. 21-47. Bethesda, MD.
Moore, J.W., 2006. Animal ecosystem engineers in streams. BioScience 56, 237-246.
Murphy, M.L., 1998. Primary production. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York, NY, pp. 144-168.
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. General Technical Report RMRS-GTR-321. US Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
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.
National Center for Airborne Laser Mapping http://calm.geo.berkeley.edu/ncalm/ddc.html.
National Research Council, 1992. Restoration of Aquatic Ecosystems. National Academy Press, Washington, DC.
Nelson, P.A., Dietrich, W.E., Venditti, J.G., 2010. Bed topography and the development of forced bed surface patches. Journal of Geophysical Research: Earth Surface 115, F04024, doi:10.1029/2010JF001747.
Nelson, P.A., Venditti, J.G., Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., Sklar, L.S., 2009. Response of bed surface patchiness to reductions in sediment supply. Journal of Geophysical Research: Earth Surface 114, F02005, doi:10.1029/2008JF001144.
O'Neill, R.V., DeAngelis, D.L., Waide, J.B., Allen, T.F.H., 1986. A Hierarchical Concept of Ecosystems. Princeton University Press, Princeton, NJ.
Pennak, R.W., 1971. Toward a classification of lotic habitats. Hydrobiologia 38, 321-334.
Pennak, R.W., 1979. The dilemma of stream classification. In: Classification, Inventory and Analysis of Fish and Wildlife Habitat. Report FWS/OBS-78/76. United States Fish and Wildlife Service, Biological Services Program, Washington, DC, pp. 59-66.
Pess, G.R., Montgomery, D.R., Beechie, T.J., Holsinger, L., 2003. Anthropogenic alterations to the biogeography of Puget Sound salmon. In: Montgomery, D.R., Bolton, S., Booth, D.B., Wall, L. (Eds.), Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA, pp. 129-154.
Pinay, G., Decamps, H., Chauvet, E., Fustec, E., 1990. Functions of ecotones in fluvial systems. In: Naiman, R.J., Decamps, H. (Eds.), The Ecology and Management of Aquatic-Terrestrial Ecotones. United Nations Educational Scientific and Cultural Organization, Paris and Parthenon Publishing Group, Carnforth, UK, pp. 141-170.
Pledger, A.G., Rice, S.P., Millett, J., 2014. Reduced bed material stability and increased bedload transport caused by foraging fish: a flume study with juvenile Barbel (Barbus barbus). Earth Surface Processes and Landforms 39, 1500-1513.
Pledger, A.G., Rice, S.P., Millett, J., 2016. Bed disturbance via foraging fish increases bedload transport during subsequent high flows and is controlled by fish size and species. Geomorphology 253, 83-93.
Pollock, M.M., Lewallen, G., Woodruff, K., Jordan, C.E., Castro, J.M., 2015. The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains. United States Fish and Wildlife Service, Portland, OR.
Poole, G.C., Frissell, C.A., Ralph, S.C., 1997. In-stream habitat unit classification: inadequacies for monitoring and some consequences for management. Journal of the American Water Resources Association 33, 879-896.
Reeves, G.H., Benda, L.E., Burnett, K.M., Bisson, P.A., Sedell, J.R., 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. In: American Fisheries Society Symposium, vol. 17, pp. 334-349.
Reice, S.R., 1994. Nonequilibrium determinants of biological community structure. American Scientist 82, 424-435.
Reiser, D.W., Ramey, M.P., Lambert, T.R., 1985. Review of Flushing Flow Requirements in Regulated Streams. Research and Development Report Z19-5-120-84, Pacific Gas and Electric Company, San Ramon, CA.
Rennie, C.D., Millar, R.G., 2000. Spatial variability of stream bed scour and fill: A comparison of scour depth in chum salmon (Oncorhynchus keta) redds and adjacent bed. Canadian Journal of Fisheries and Aquatic Sciences 57, 928-938.
Rice, S.P., Johnson, M.F., Mathers, K., Reeds, J., Extence, C., 2016. The importance of biotic entrainment for base flow fluvial sediment transport. Journal of Geophysical Research: Earth Surface 121. http://dx.doi.org/10.1002/2015JF003726.
Roper, B.B. et al., 2010. A comparison of the performance and compatibility of protocols used by seven monitoring groups to measure stream habitat in the Pacific Northwest. North American Journal of Fisheries Management 30, 565–587.
Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO.
Scheingross, J.S., Lamb, M.P., 2016. Sediment transport through self-adjusting, bedrock-walled waterfall plunge pools. Journal of Geophysical Research: Earth Surface 121. http://dx.doi.org/10.1002/2015JF003620.
Scheingross, J.S., Lamb, M.P., 2017. A mechanistic model of waterfall plunge pool erosion into bedrock. Journal of Geophysical Research: Earth Surface 122, https://doi.org/10.1002/2017JF004195.
Schlosser, I.J., 1987. A conceptual framework for fish communities in small warmwater streams. In: Matthews, W.J., Heins, D.C. (Eds.), Community and Evolutionary Ecology of North American Stream Fishes. University of Oklahoma Press, Norman, OK, pp. 17-24.
Schlosser, I.J., 1991. Stream fish ecology: a landscape perspective. BioScience 41, 704-712.
Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York, NY.
Schumm, S.A., 1985. Patterns of alluvial rivers. Annual Review of Earth and Planetary Sciences 13, 5-27.
Segura, C., Booth, D.B., 2010. Effects of geomorphic setting and urbanization on wood, pools, sediment storage, and bank erosion in Puget Sound streams. Journal of the American Water Resources Association 46, 972-986, DOI: 10.1111/j.1752-1688.2010.00470.x.
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, 48-60.
Stanford, J.A., Lorang, M.S., Hauer, F.R., 2005. The shifting habitat mosaic of river ecosystems. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 29, 123-136.
Statzner, B., Higler, B., 1986. Stream hydraulics as a major determinant of benthic invertebrate zonation patterns. Freshwater Biology 16, 127-139.
Statzner, B., Gore, J.A., Resh, V.H., 1988. Hydraulic stream ecology: observed patterns and potential applications. Journal of the North American Benthological Society 7, 307-360.
Statzner, B., Arens, M.-F., Champagne, J.-Y., Morel, R., Herouin, R., 1999. Silk-producing stream insects and gravel erosion: significant biological effects on critical shear stress. Water Resources Research 35, 3495-3506.
Statzner, B., Fièvet, E., Champagne, J.-Y., Morel, R., 2000. Crayfish as geomorphic agents and ecosystem engineers: biological behavior affects sand and gravel erosion in experimental streams. Limnology and Oceanography 45, 1030-1040.
Sullivan, K., 1986. Hydraulics and Fish Habitat in Relation to Channel Morphology (Ph.D. dissertation). Johns Hopkins University, Baltimore, MD.

Sullivan, K., Lisle, T.E., Dolloff, C.A., Grant, G.E., Reid, L.M., 1987. Stream channels: the link between forests and fishes. In: Salo, E.O., Cundy, T.W. (Eds.), Streamside Management: Forestry and Fishery Interactions. Institute of Forest Resources, University of Washington, Seattle, WA, pp. 39-97. Contribution Number 57.

Tett, P., Gallegos, C., Kelly, M.G., Hornberger, G.M., Cosby, B.J., 1978. Relationships among substrate, flow, and benthic microalgal pigment diversity in Mechams River, Virginia. Limnology and Oceanography 23, 785-797.

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, D.M., Wohl, E.E., 2009. The linkage between velocity patterns and sediment entrainment in a forced-pool and riffle unit. Earth Surface Processes and Landforms 34, 177-192,DOI: 10.1002/esp.1698.

Tonina, D., Buffington, J.M., 2009a. Hyporheic exchange in mountain rivers I: mechanics and environmental effects. Geography Compass 3, 1063-1086.

Tonina, D., Buffington, J.M., 2009b. A three-dimensional model for analyzing the effects of salmon redds on hyporheic exchange and egg-pocket habitat. Canadian Journal of Fisheries and Aquatic Sciences 66, 2153-2157.

Triska, F.J., Kennedy, V.C., Avazino, R.J., Zellweger, G.W., Bencala, K.E., 1989. Retention and transport of nutrients in a third order stream: hyporheic processes. Ecology 70, 1893-1905.

USFS, ESSA, 2010. River Bathymetry Toolkit (RBT). http://www.fs.fed.us/rm/boise/AWAE/projects/river_bathymetry_toolkit.shtml.

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.

Vianello, A., D'Agostino, V., 2007. Bankfull width and morphological units in an alpine stream of the dolomites (Northern Italy). Geomorphology 83, 266-281.

Ward, J.V., Stanford, J.A., 1995. The serial discontinuity concept: extending the model to floodplain rivers. Regulated Rivers Research & Management 10, 159-168.

Weins, J.A., 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47, 501-515.

White, D.S., 1993. Perspectives on defining and delineating hyporheic zones. Journal of the North American Benthological Society 12, 61-69.

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.

Whittaker, J.G., 1987. Sediment transport in step-pool streams. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel-Bed Rivers. John Wiley and Sons, New York, NY, pp. 545-579.

Wohl, E., David, G.C.L., 2008. Consistency of scaling relations among bedrock and alluvial channels. Journal of Geophysical Research 113, F04013.

Wohl, E., Merritt, D., 2005. Prediction of mountain stream morphology. Water Resources Research 41, W08419.

Wohl, E., Cooper, D., Poff, L., Rahel, F., Staley, D., Winters, D., 2007. Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming. Environmental Management 40, 284-302.

Wolcott, J., Church, M., 1991. Strategies for sampling spatially heterogeneous phenomena: the example of river gravels. Journal of Sedimentary Petrology 61, 534-543.

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. In: Schroder, J., Wohl, E. (Eds.), Treatise on Geomorphology. Academic Press, San Diego, CA, pp. 203-218.

Woodsmith, 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.

Woodsmith, R.D., Hassan, M.A., 2005. Maintenance of an obstruction-forced pool in a gravel-bed channel: streamflow, channel morphology, and sediment transport. In: Garcia, C., Batalla, R.J. (Eds.), Catchment Dynamics and River Processes: Mediterranean and Other Climate Regions, Developments in Earth Surface Processes 7. Elsevier, Amsterdam, The Netherlands, pp. 169-196.

Yang, C.T., 1971. Formation of riffles and pools. Water Resources Research 7, 1567-1574.

Zalewski, M., Naiman, R.J., 1985. The regulation of riverine fish communities by a continuum of abiotic-biotic factors. In: Alabaster, J.S. (Ed.), Habitat Modifications and Freshwater Fisheries. Butterworth, London, UK, pp. 3-9.

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., 2010. Step-pool stability: testing the jammed state hypothesis. Journal of Geophysical Research: Earth Surface 115, F02008, doi:10.1029/2009JF001365.