



Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange

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Abstract

We propose that the mechanisms driving hyporheic exchange vary systematically with different channel morphologies and associated fluvial processes that occur in mountain basins, providing a framework for examining physical controls on hyporheic environments and their spatial variation across the landscape. Furthermore, the spatial distribution of hyporheic environments within mountain catchments represents a nested hierarchy of process controls. Large-scale process drivers (geology, climate, fire, and land use) impose a suite of watershed conditions (topography, streamflow, sediment supply, and vegetation) on the fluvial system. Different combinations of imposed watershed conditions result in different reach-scale channel morphologies (e.g. step-pool, pool-riffle, and braided) that, in turn, structure hyporheic processes (e.g. pressure divergence, spatial variation of hydraulic conductivity) and resultant hyporheic environments (scales and rates of hyporheic exchange). Consequently, a holistic view of natural and anthropogenic drivers over a range of spatial and temporal scales is needed for understanding hyporheic ecosystems.

1 Introduction

Hyporheic exchange is the mixing of river water with shallow groundwater across the porous sediment surrounding alluvial rivers. The mechanics and environmental effects of hyporheic exchange are discussed by Tonina and Buffington (2009). Here, we explore how these mechanisms vary across the landscape and the types of hyporheic environments that may result.

The effects of hyporheic exchange on aquatic and riparian ecosystems depend largely on scales and rates of exchange, which, in turn, depend on the processes causing exchange and on the physical boundary conditions imposed by the local environment (e.g. the depth and lateral extent of alluvium). The mechanisms causing exchange include spatial and temporal

changes in: streambed pressure, bed mobility, the volume of sedimentary material surrounding a river, and its hydraulic conductivity (Tonina and Buffington 2009). We propose that these mechanisms vary systematically with different channel morphologies and associated fluvial processes in mountain basins. Although it is recognized that hyporheic exchange differs with local channel characteristics (Gooseff et al. 2003, 2007; Harvey and Bencala 1993; Kasahara and Wondzell 2003), these differences have not been systematized by channel type, except at very broad scales (Stanford and Ward 1993; White 1993) or in limited comparisons (Anderson et al. 2005; Gooseff et al. 2007; Kasahara and Wondzell 2003). Doing so may help organize the exponentially growing body of hyporheic literature (Dahm et al. 2006; Valett et al. 1993) and the identification of relevant geomorphic processes that influence hyporheic exchange and associated aquatic and terrestrial habitats in different parts of the channel network.

2 Hyporheic Exchange and the Landscape

Mechanisms driving hyporheic exchange occur over multiple, nested, spatial scales, resulting in successive scales of hyporheic circulation (Figure 1). The multiple scales and rates of exchange collectively define a distribution of hyporheic residence times (the amount of time that river water spends traversing the subsurface sediment before re-emerging into the stream). The residence time is an important property of the hyporheic zone because chemical and biological reactions taking place within the sediment depend on the amount of time that river water is in contact with the groundwater environment (Duff and Triska 2000; Hendricks and White 1991; Mulholland and DeAngelis 2000).

Previous studies have proposed that at landscape scales hyporheic exchange is influenced by broad-scale changes in channel confinement, valley slope, and morphologic complexity of the channel and floodplain (Gooseff et al. 2007; Hauer et al. 2003; Malard et al. 2002; White 1993; Wondzell 2006; Wörman et al. 2006). In particular, Stanford and Ward (1993) proposed the concept of a hyporheic corridor that varies continuously downstream through a watershed, analogous to Vannote et al.'s (1980) river continuum concept. The corridor and intensity of hyporheic flux, expands and shrinks with spatio-temporal changes in channel and floodplain characteristics and with changes in discharge, providing a 'shifting mosaic' of surface–subsurface exchange and associated aquatic habitats (Malard et al. 2002; Stanford 2006). The hyporheic corridor concept recognizes discrete typological environments (e.g. headwaters, montane floodplain, coastal plain; Stanford and Ward 1993), but the associated geomorphic processes and their spatio-temporal extent across the landscape are not recognized, except at very broad scales.

In contrast, we propose that the mechanisms and characteristics of hyporheic exchange vary systematically with different reach-scale channel

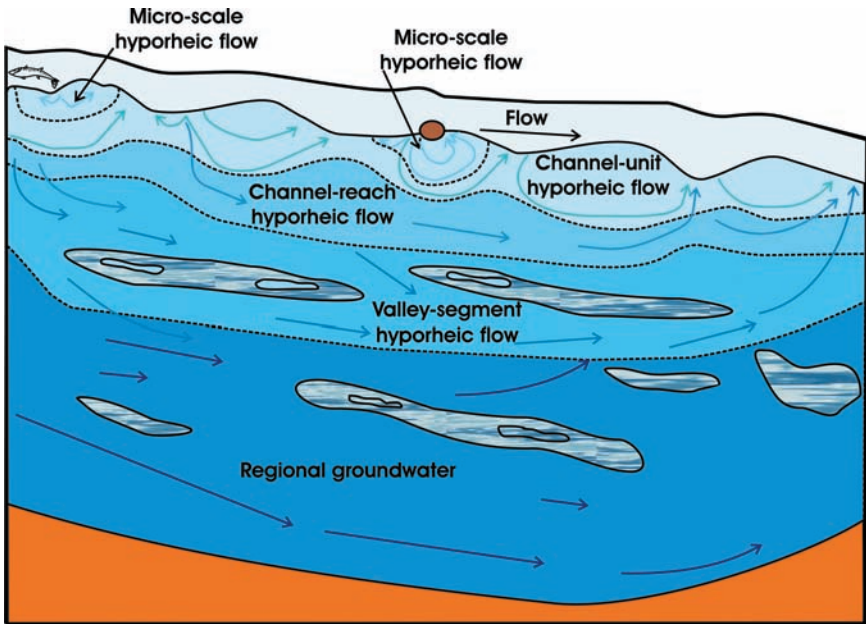


Fig. 1. Nested scales of hyporheic exchange: (1) micro [e.g. variation of head around wood debris, salmon redds, or protruding streambed particles; scale of exchange is up to a channel width (W) in length], (2) channel unit (head variations around individual bedforms (pools, bars, steps); up to several W), (3) channel reach (e.g. changes in reach slope, meso-scale changes in alluvial volume, flow through the floodplain between meander bends, or cross-valley head differences between the main channel and secondary channels; tens of W), and (4) valley segment scales (e.g. changes in valley confinement, alluvial volume, or underlying bedrock topography; hundreds to thousands of W) (Baxter and Hauer 2000; Dent et al. 2001; Edwards 1998; Malard et al. 2002). Boundaries between scales indicated by dashed lines. Note that impervious clay layers (horizontally shaded lenses) can alter the extent and direction of hyporheic exchange. Modified from Alley et al. (1999).

types. The effects of different channel types have been recognized in previous studies in terms of differences in bed topography and corresponding influences on head variations (Anderson et al. 2005; Gooseff et al. 2006; Harvey and Bencala 1993; Kasahara and Hill 2006a,b; Malard et al. 2002), but there has been no systematic examination of these effects across the range of channel types present in mountain basins.

Mountain basins are characterized by a variety of reach-scale channel morphologies (FPC 1996; Montgomery and Buffington 1997; Rosgen 1994; Schumm 1985). Different channel types result from different combinations of watershed conditions (slope, confinement, stream flow, sediment supply, and vegetation; Mollard 1973; Montgomery and Buffington 1997; Schumm 1985), with each channel type representing different physical regimes (Buffington et al. 2003). Typical reach-scale channel types found in mountain basins are shown in Figure 2 using the Montgomery and Buffington (1997) classification. Characteristics of hyporheic exchange expected for each channel

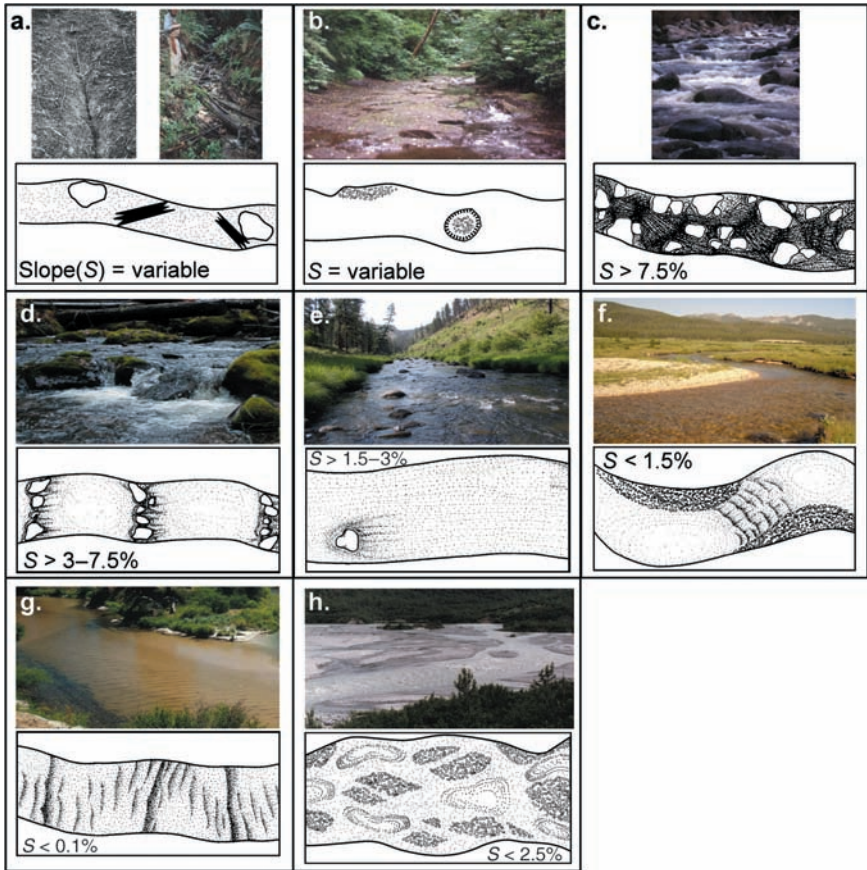


Fig. 2. Reach-scale channel types typical of mountain rivers: (a) colluvial, (b) bedrock, (c) cascade, (d) step-pool, (e) plane-bed, (f) pool-riffle, (g) dune-ripple, and (h) braided. S is channel slope. Modified from Montgomery and Buffington (1997). Slope ranges are from Buffington et al. (2004), but values may vary regionally (Wohl and Merritt 2005). Transitional morphologies may also occur (Gomi et al. 2003; Montgomery and Buffington 1997). Note that the Montgomery and Buffington (1997) approach is a visual classification of channel morphology; each channel type has characteristic ranges of channel slope, grain size, relative roughness, etc. that co-vary with basin discharge and sediment supply (Buffington et al. 2003), but those features are not used to classify channel type. Further discussion of the geomorphic processes and factors controlling these different channel types can be found elsewhere (Buffington et al. 2003; Montgomery and Bolton 2003; Montgomery and Buffington 1997, 1998).

type are examined below in terms of the exchange mechanisms discussed by Tonina and Buffington (2009), followed by a synthesis of the results.

2.1 COLLUVIAL CHANNELS

Colluvium is unconsolidated hillslope material chiefly deposited by gravitational processes (creep, rockfall), but with some deposition from slope wash (sheetflow or minor rilling) and mass wasting (minor slope avalanches,

slumps, or debris flows). Colluvial channels are streams incised into valleys filled by colluvium, and typically occur in headwater areas as first-order channels (those that constitute the beginning of the channel network; Montgomery and Buffington 1997).

Colluvial channels are formed by overland flow and groundwater seepage. They are confined by hillslopes, which are their source of sediment and water input. Streamflow in these channels may be perennial or ephemeral, with streambeds characterized by poorly sorted sediment and channel morphology that is strongly controlled by stochastically occurring obstructions (boulders, wood, in-channel vegetation; Gomi et al. 2002; Gooderham et al. 2007). Although colluvial channels have steep bed slopes, they have little scouring energy because of shallow stream flows and in-channel obstructions that are large relative to channel size.

Hillslope confinement limits lateral hyporheic exchange in colluvial channels, but steep stream slopes and high head gradients may drive hyporheic flow through channel banks and footslopes of confining hillsides. Furthermore, hillslope groundwater may upwell into the channel or seep through channel banks, depending on regional groundwater gradients and seasonal groundwater flow. We suspect that hyporheic exchange in colluvial channels is primarily caused by head variations associated with in-channel obstructions and by spatial variations in colluvial volume due to shallow, irregular depths to bedrock and frequent, small-scale changes in lateral confinement. However, hyporheic exchange is expected to be fairly shallow because of modest colluvial depths (Schmidt et al. 2001) and steep slopes that promote strong groundwater underflow and compression of hyporheic circulation cells (Tonina 2005). Hyporheic exchange in colluvial channels may also arise from spatial variations in sediment composition and hydraulic conductivity, depending on the characteristics of hillslope sediment supply and colluvial stratigraphy. Weak rates of bedload transport in colluvial channels will preclude turnover as a mechanism for hyporheic flow, and near-bed turbulence may be damped by shallow flows, in-channel vegetation, and flow obstructions that are large relative to channel size.

2.2 BEDROCK CHANNELS

Bedrock channels are typically confined, steep reaches lacking a persistent or continuous alluvial bed due to transport rates greater than the sediment supply (Gilbert 1877; Montgomery et al. 1996), or due to the occurrence of recent debris-flow scour (Benda 1990). Pools and flow obstructions like log jams may occasionally retain alluvial pockets of irregular extent and depth in these channels through which limited hyporheic flow may occur. Similarly, bedrock fractures and fissures may allow some hyporheic exchange, depending on their degree of connectivity. Otherwise, hyporheic exchange will be limited to isolated locations where alluvial pockets occur and will be driven by: spatial changes in the volume of these pockets; near-bed turbulence

and head gradients over them; and mechanical mixing (scour/deposition) of the alluvial patches and their associated pore water during floods and debris flows.

2.3 CASCADE CHANNELS

Cascade channels are characterized by a disorganized boulder bed of tumbling, turbulent flow, steep slopes ($> 7.5\%$), and a high degree of valley-wall confinement, with little to no floodplain (Montgomery and Buffington 1997). Tumbling flow over boulders, as well as jet-and-wake flows around them, create substantial pressure gradients that are likely the primary mechanism for hyporheic exchange in these channels. Near-bed turbulence may enhance this exchange because of the presence of coarse, porous bed material. However, lateral hyporheic flow is inhibited by valley confinement and steep bed slopes that tend to direct hyporheic exchange in a predominantly downstream direction. Irregular alluvial volumes due to shallow depths to bedrock and frequent lateral hillslope projections may also generate hyporheic exchange in cascade channels, whereas mechanical mixing via turnover does not occur; the boulder-forming substrate moves only during infrequent (50–100 year) flows (Grant et al. 1990). Cascade channels that are within the debris-flow domain (Montgomery 1999) may flow through heterogeneous debris-flow deposits, the spatial variation of which may trigger additional hyporheic flow.

2.4 STEP-POOL CHANNELS

Step-pool channels are characterized by longitudinally repeating sequences of boulder and wood steps separated by pools containing finer material (sand to cobbles) (Chin and Wohl 2005). They differ from cascade channels in that they exhibit organized bedforms and spatial sorting of bed material. Step-pool channels typically occur at somewhat lower slopes than cascade channels ($> 3\text{--}7.5\%$), but are similarly confined, with shallow and irregular depths to bedrock, and limited floodplains. Step-pool topography strongly interacts with the flow in these channels, with hyporheic exchange predominantly driven by longitudinal changes in pressure head across the step topography (Anderson et al. 2005; Gooseff et al. 2006; Harvey and Bencala 1993; Hester and Doyle 2008; Hill and Lymburner 1998; Kasahara and Hill 2006a,b). Turbulent losses due to plunging flow over the steps likely enhances these head gradients and may also drive hyporheic exchange via near-bed turbulent fluctuations. Rates of hyporheic exchange are rapid due to coarse porous sediment and strong head gradients, resulting in very low residence times (Kasahara and Wondzell 2003). Like cascade channels, spatial variations in alluvial volume and hydraulic conductivity may also trigger hyporheic exchange, but flow paths are expected to be shallow and predominantly two-dimensional overall, with lateral flow limited by hillslope

confinement and steep channel slopes. Mobility of the finer bed material (sand to cobble) occurs on an annual basis (Schmidt and Ergenzinger 1992), but hyporheic exchange from mechanical mixing of the bed material is of limited extent, and bedform turnover does not occur except during rare floods or debris flows (Sawada et al. 1983); however, in some environments, step-forming boulders may be more mobile (Warburton 1992).

2.5 PLANE-BED CHANNELS

Plane-bed channels are gravel- and cobble-bed rivers that exhibit a predominantly planar topography (long riffles). They typically have moderate bed slopes (1.5–3%) and may or may not be confined by valley walls (Montgomery and Buffington 1997).

Because bedforms are generally lacking in these channels, flow is fairly uniform and head variations for driving hyporheic exchange are limited to isolated obstructions (boulders, wood, bank projections; Cooper 1965; Hutchinson and Webster 1998) and occasional river bends. The general lack of bedforms may cause near-bed turbulence from boulders and particle clusters to play a relatively more important role for hyporheic exchange in these channels (Packman et al. 2004).

Because plane-bed channels may be either confined or unconfined, the degree of lateral hyporheic exchange through the floodplain may vary. However, their lack of bedforms and lack of significant channel sinuosity may limit advective exchange with the floodplain. The role of spatial changes in the volume of alluvium as a mechanism for hyporheic exchange is similarly uncertain. Bed material in plane-bed channels tends to be homogeneous (Buffington and Montgomery 1999a), limiting the occurrence of hyporheic exchange from spatial variations in hydraulic conductivity. However, buried paleochannels and relict sedimentary deposits from prior geomorphic regimes may create sediment heterogeneity that influences hyporheic exchange through the floodplain (Sophocleous 1991; Stanford and Ward 1993).

Bed material in plane-bed channels typically moves during near-bankfull floods, which occur frequently (every 1–3 years), but are of limited duration (several hours to days each year) (Wolman and Miller 1960). Consequently, hyporheic exchange via mechanical mixing of bed material is minimal.

2.6 POOL-RIFFLE CHANNELS

Pool-riffle channels exhibit a regular downstream sequence of pool, riffle, and bar topography, with riffles providing the local hydraulic control for upstream pools, and pool and bar units commonly alternating from one side of the channel to the other. Pool-riffle channels have moderate slopes (< 1.5–2%), with pools composed of finer material (sand, gravel) and riffles composed of coarser sediment (gravel, cobble). These channels are

commonly unconfined, with variable sinuosity (straight to meandering; Leopold and Wolman 1957) and may be single-thread or divided around occasional islands and medial bars (Schumm 1985).

Hyporheic exchange in pool-riffle channels is predominantly driven by spatial variations of pressure head (Hill et al. 1998; Vaux 1962; White et al. 1987). Because pool-riffle bedforms are large relative to flow depths, they exert a strong influence on channel hydraulics, water-surface elevation, and head gradients, creating complex three-dimensional flow, both within the river and in the hyporheic zone (Figure 3 of Tonina and Buffington 2009; also see Cardenas and Zlotnik 2003; Kasahara and Hill 2007; Marzadri et al. 2006; Tonina and Buffington 2007). Furthermore, pool-riffle topography may be self-formed through interactions between streamflow and sediment transport or forced by external flow obstructions (wood, bedrock projections; Buffington et al. 2002; Montgomery et al. 1995), resulting in greater channel complexity, more variable head gradients, and potentially greater hyporheic exchange (Mutz et al. 2007).

The unconfined valleys in which pool-riffle channels typically occur promote lateral hyporheic exchange and a more complex three-dimensional structure than in steeper, confined channels (colluvial, cascade and step-pool morphologies). For example, hyporheic exchange may occur across meander bends (Kasahara and Hill 2007; Wroblicky et al. 1998), between divided channels (Kasahara and Wondzell 2003), between the main channel and floodplain bodies of water (side channels, ponds, oxbow lakes; Stanford et al. 2005), and through a complex network of paleochannels buried within the floodplain (Sophocleous 1991; Stanford and Ward 1993; Triska et al. 1989). Coarse bed material within pool-riffle channels creates rapid rates of hyporheic exchange (Stanford and Ward 1993; Tonina and Buffington 2007), but larger alluvial volumes surrounding these channels allow development of deeper and longer flow paths, broadening residence time distributions and time scales for biochemical reactions compared to steeper, confined channels. Although pool-riffle channels generally occupy broad, deep, alluvial valleys, spatial variations in alluvial depth and valley confinement can trigger hyporheic flow at multiple scales (reach to valley segment; Baxter and Hauer 2000).

Pool-riffle channels can also exhibit strong spatial variation of grain size (textural patches), resulting from spatio-temporal variations in channel hydraulics, sediment supply and bedload transport (Buffington and Montgomery 1999a,b; Dietrich and Smith 1984; Dietrich et al. 1989, 2006). Channel migration and overbank flooding also create a complex sedimentary stratigraphy within the surrounding floodplain deposits, which is further enhanced by the local geologic history (e.g. glacial deposits, volcanic detritus, paleoclimates and associated hydrologic regimes). Pockets of sand, silt, and organic material of low hydraulic conductivity are common, as well as zones of well-sorted gravels and cobbles of high hydraulic conductivity; each of which are of limited spatial extent, promoting textural

heterogeneity within the channel and floodplain that can drive or enhance hyporheic flow (Salehin et al. 2004; Sophocleous 1991).

The three-dimensional topography, channel sinuosity, and flow obstructions in pool-riffle channels create multiple scales of turbulence and near-bed pressure fluctuations, but turbulence-induced hyporheic exchange is likely minor; although pool-riffle channels tend to have a coarse, porous surface layer, the subsurface material is typically finer, with pore spaces filled by sands and silts (Church et al. 1987) that will likely damp turbulent pressure fluctuations within short distances from the bed surface (Detert et al. 2007). The effectiveness of near-bed pressure fluctuations in generating hyporheic exchange will also vary with spatial variations in sediment patches and their grain-size composition (sorting and percentage of fine material).

Bedload transport in pool-riffle channels is similar to that of plane-bed reaches, with significant sediment motion occurring only during near-bankfull flows of limited duration. Moreover, bedforms in pool-riffle channels are relatively stable during these events and do not migrate downstream. Hence bedform turnover does not occur, and hyporheic exchange due to mechanical mixing of bed material is limited to local scour and fill, which tends to be stochastic and spatially limited (Haschenburger 1999; Hassan 1990).

2.7 DUNE-RIPPLE CHANNELS

Dune-ripple channels are sand-bed rivers characterized by multiple bed forms (ripples, dunes, antidunes) that are highly mobile and change morphology (type, size, frequency) with discharge (Gilbert 1914; Middleton and Southard 1984; Shields 1936). These channels are typically unconfined and have low slopes ($< 0.1\%$).

Hyporheic processes in dune-ripple channels are similar to pool-riffle channels, with several important exceptions. Pressure-head variations are the dominant mechanism for hyporheic exchange, but because flow depths are typically large compared to bedform size, head variations largely result from changes in velocity head (dynamic pressure), rather than changes in water-surface elevation (static pressure) (Elliott and Brooks 1997a,b; Packman and Brooks 2001; Savant et al. 1987; Thibodeaux and Boyle 1987). Consequently, pressure variations within dune-ripple channels generally follow a two-dimensional sinusoidal pattern in the downstream direction due to deep flow over two-dimensional bedforms (Elliott and Brooks 1997b; Raudkivi 1963) similar to Figure 5 of Tonina and Buffington (2009). This contrasts with relatively shallower flows in pool-riffle channels, where pressure-head variations are a complex result of both dynamic and static variations that change seasonally with discharge (Buffington and Tonina 2008).

Laboratory experiments show that sand clusters that protrude into the flow only a few centimeters, like ripple formations, can generate head gradients strong enough to drive in-stream flow through sand beds despite

their low permeability (Elliott and Brooks 1997a,b; Marion et al. 2002). However, rates of hyporheic exchange are considerably lower in dune-ripple channels due to their sand beds and consequently lower permeability compared to coarser-grained channels (pool-riffle, step-pool; Tonina and Buffington 2007). Field and laboratory studies show that spatial variability of sediment composition in sand-bed channels can also generate hyporheic exchange (Salehin et al. 2004), but this mechanism is typically secondary to head variations resulting from channel topography and sinuosity (Cardenas et al. 2004; Sophocleous 1991).

Dune-ripple channels also differ from the other channel types in that they exhibit active bedload transport at most streamflows, with bedform migration and active hyporheic exchange via turnover processes. Changes in bedform shape, size, and spacing with discharge also suggest that pumping exchange is spatially and temporally dynamic in these channels. However, exchange due to turbulent fluctuations is likely minor in dune-ripple channels due to their fine bed material composition; turbulent fluctuations cannot propagate rapidly enough through these hydraulically resistant sediments (Packman et al. 2004; Vollmer et al. 2002).

As with pool-riffle channels, extensive three-dimensional hyporheic flow can occur in dune-ripple channels due to their unconfined valleys and associated complexities (channel meandering, floodplain water bodies, paleochannels, heterogeneity of alluvial deposits). Furthermore, because valley slopes are low, horizontal groundwater velocities are small, allowing hyporheic flows to penetrate deeper into the alluvium, unless deflected by sedimentary facies of low hydraulic conductivity (Figure 1). These longer flow paths together with the lower permeability of sand-bed rivers will lead to broader residence time distributions than steeper, coarse-grained channel types.

2.8 BRAIDED CHANNELS

Braided rivers are multi-thread channels, with moderate slopes ($< 2.5\%$) and large width-to-depth ratios. Individual braid threads can have either a pool-riffle morphology or a bar-riffle morphology lacking pools. Braiding results from high sediment loads that overwhelm channel transport capacity (glacial outwash, landslide pulses, volcanic eruptions) or as a result of weak, erodible banks (loss of riparian root strength after clear-cutting, livestock trampling, or in semiarid regions with naturally sparse riparian vegetation) (Buffington et al. 2003; Millar 2000). Bed material in braided rivers ranges from large cobble to sand, depending on the caliber of the sediment supply and local valley slope.

Processes of hyporheic exchange in braided rivers are likely similar to those of pool-riffle channels, but with greater spatial variability of head across the river valley due to multiple channels. Furthermore, braided rivers tend to be more dynamic, exhibiting greater rates of bedload transport, bedform movement, and channel avulsion (Fahnestock 1963), causing

Table 1. Hyporheic mechanisms and their importance by reach type (+ = likely; p = possible; - = unlikely)

Channel type	Mechanisms for hyporheic exchange				
	Head variation	Alluvial volume variation	Hydraulic conductivity variation	Near-bed turbulence	Mechanical mixing/turnover
Confined					
Colluvial	+	p	p	p	p/-
Bedrock	-	-	-	-	-/-
Cascade	+	p	p	+	-/-
Step-pool	+	p	p	+	p/-
Plane-bed*	p	p	p	p	p/-
Unconfined					
Braided	+	+	+	p, - [†]	p/p
Pool-riffle	+	+	+	p	p/-
Dune-ripple	+	+	+	-	+/+

*May be confined or unconfined.

[†]Possible in braided rivers with gravel or cobble beds, unlikely in sand-bedded ones.

stronger temporal variability of hyporheic exchange and associated aquatic habitats (Malard et al. 2002; Ward and Stanford 1995). More frequent bedload movement also suggests increased relevance of mechanical mixing of bed material as a source of hyporheic exchange compared to pool-riffle channels. Complex, three-dimensional hyporheic flow paths are expected in these broad, unconfined channels, but residence times may be shorter than in pool-riffle channels because of a lack of finer-grained floodplain deposits and a more extensive network of paleochannels. Turnover exchange can occur in sand-bedded braided channels.

3 Synthesis and Conclusion

3.1 MECHANICS OF HYPORHEIC EXCHANGE

Table 1 summarizes the relative importance of different mechanisms for generating hyporheic exchange in the above channel types. In general, the range of mechanisms causing hyporheic exchange increases as one moves from steep, confined channels to lower-gradient, unconfined ones. Each mechanism is examined in turn.

We first consider pressure-head variations. Because the divergence of streambed pressure is influenced by flow-boundary interactions, we expect that different channel types, with characteristically different channel topographies, will have different pressure-head profiles and different potentials for hyporheic exchange (Figure 3). In particular, characteristic differences in the amplitude and wavelength of bed topography may have a strong

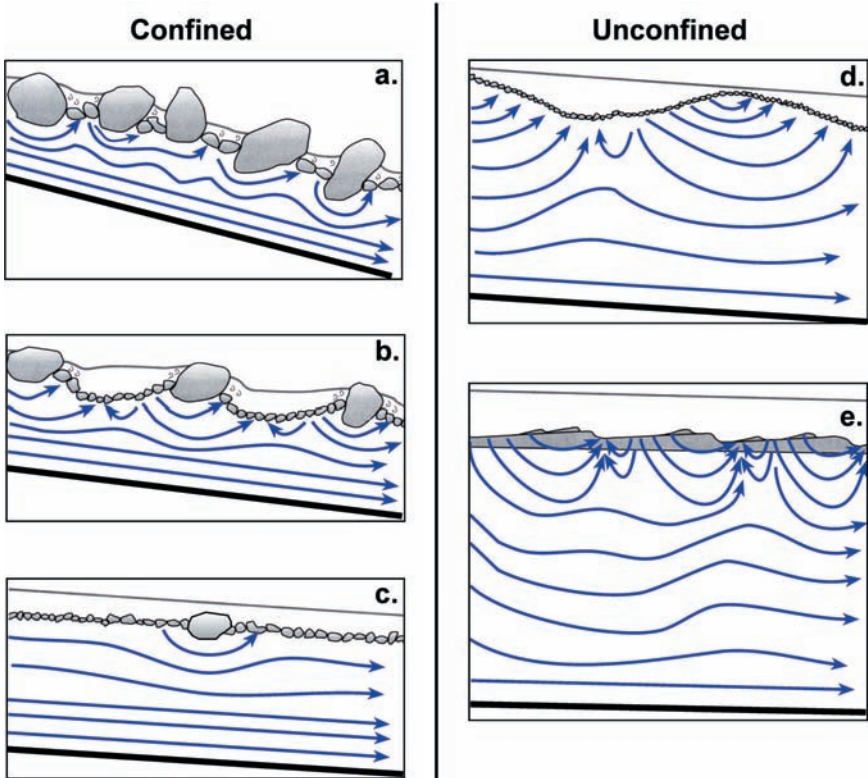


Fig. 3. Hypothesized patterns of hyporheic exchange for different reach-scale channel types: (a) cascade, (b) step-pool, (c) plane-bed, (d) pool-riffle and (e) dune-ripple. Modified from Montgomery and Buffington (1997). Plane-bed channels may be either confined by valley walls or unconfined.

influence on the divergence of streambed pressure and consequent hyporheic circulation (Anderson et al. 2005; Gooseff et al. 2006; Vaux 1968). For example, bed topography in cascade channels is characterized by frequent boulder obstructions that likely cause short, fast hyporheic circulation cells under each boulder obstruction. Hyporheic circulation is likely similar in step-pool channels, but with longer circulation cells due to a broader spacing between topographic obstructions (boulder or log steps; Anderson et al. 2005; Harvey and Bencala 1993; Kasahara and Wondzell 2003). Because plane-bed channels have essentially featureless topography, hyporheic exchange due to pressure variations is limited to local circulation around occasional obstructions (boulders, wood, bank projections) and obstruction-forced pools. In contrast, pool-riffle channels are characterized by well-formed hyporheic circulation cells caused by regular downstream pressure variations that are a function of the spacing and size of pool and bar topography (Tonina and Buffington 2007). Hyporheic circulation in

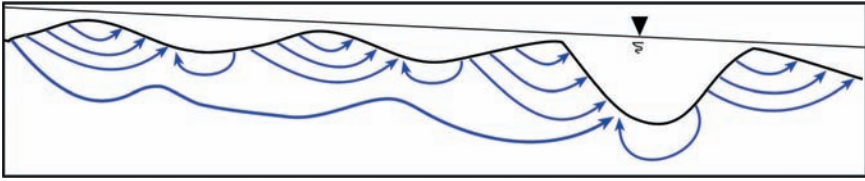


Fig. 4. Nested scales of hyporheic exchange created by topographic irregularity. Topographic lows cause larger-scale circulation that captures and envelopes smaller-scale circulation cells (Elliott and Brooks 1997a).

dune-ripple channels is similar, but depends more strongly on dynamic head variations (spatial and temporal changes in velocity) due to greater submergence of bedforms and stronger flow separation in the lee of bedforms. In any of these channel types, topographic irregularity and the occurrence of deeper bedforms within a sequence of channel units will cause nested flow paths that capture deeper circulation of upstream topography (Figure 4). The gravel and cobble bed material of plane-bed and pool-ripple channels also make them appealing spawning sites for salmonids (Montgomery et al. 1999), which alter head gradients and hydraulic conductivity in the process of constructing their nests, thereby generating hyporheic exchange through biotic activity (Tonina 2005).

Hyporheic exchange is also influenced by systematic changes in channel slope and depth of alluvium across these channel types. Shallow depths of alluvium in cascade and step-pool channels likely limit the vertical extent of hyporheic exchange, resulting in short, fast, flow paths, while steep valley slopes should cause greater hyporheic underflow (hyporheic water that does not exchange with surface water), resulting in an overall smaller volume of exchange (Figure 3a–b). Strong hyporheic underflow also limits the vertical extent and residence time distribution of overlying hyporheic exchange (Storey et al. 2003; Tonina 2005). In contrast, pool-ripple and dune-ripple channels are characterized by lower valley slopes and deeper alluvial deposits, allowing the development of deeper hyporheic exchange, with a range of short to long flow paths and a correspondingly broad distribution of residence times (Figure 3d–e). Lower valley slopes in these channels also likely result in relatively less underflow.

Characteristic differences in channel confinement across these morphologies (Figure 3) also create differences in lateral complexity of the river valley that affect head gradients and hyporheic exchange (Figure 5). Unconfined valleys allow channel meandering and the development of cross-channel hyporheic exchange between meanders, side channels, paleochannels, and other floodplain water bodies. In contrast, confined channels force relatively straight rivers with little opportunity for the development of meanders and cross-channel exchange.

Hyporheic exchange caused by spatial variations in alluvial volume may also be correlated with channel confinement (Table 1). The larger sediment

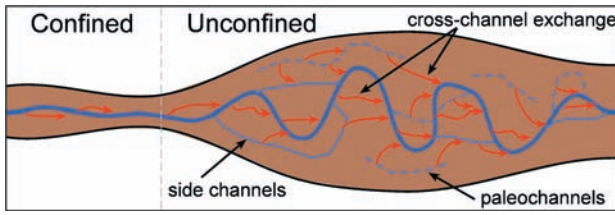


Fig. 5. Differences in lateral complexity of head gradients and hyporheic exchange in confined versus unconfined alluvial valleys.

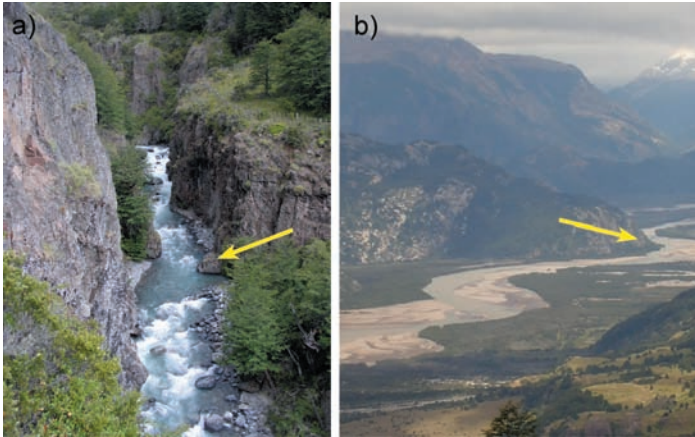


Fig. 6. Photographs of (a) confined and (b) unconfined channels. Arrows indicate bedrock projections that locally constrict alluvial area.

volumes in unconfined channels (pool-riffle, dune-ripple, braided) may allow greater spatial variability of lateral confinement and depth of alluvium, driving stronger hyporheic exchange via this mechanism than in steeper channels (colluvial, cascade, step-pool) (Figure 6). However, small, frequent changes in alluvial volume are common in confined channels due to irregular bedrock projections or hillslope projections (Figure 6a). Larger, but less frequent, projections occur in unconfined valleys (Figure 6b). Hence, it is unclear which of these environments has the largest spatial variation in alluvial volume; it becomes an issue of frequency versus magnitude of changes in alluvial volume. To our knowledge, this issue has not been studied and warrants further examination. In general, the spatial variation of confinement depends largely on geologic history (e.g. structural controls on valley shape or glacial legacies).

Spatial variations in hydraulic conductivity among different channel types can also be grouped by confinement (Table 1). Pool-riffle and dune-ripple channels tend to occur in unconfined alluvial valleys, with the alluvium representing a complex depositional history and strong spatial

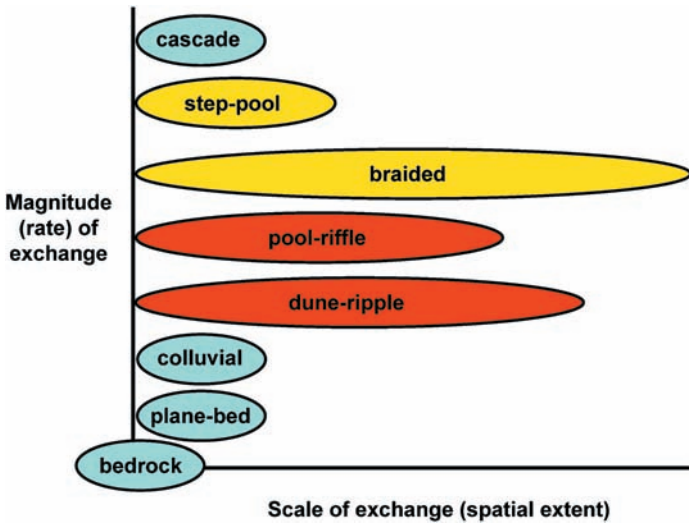


Fig. 7. Relative magnitudes and scales of hyporheic exchange for different channel types. Colors indicate the current extent of knowledge concerning hyporheic exchange in these different channel types (warmer colors indicate more knowledge). In general, more is known about hyporheic exchange in pool-riffle and dune-ripple channels (from field, laboratory, and numerical studies), less about step-pool and braided channels, and least about cascade, colluvial, plane-bed, and bedrock channels.

changes in depositional facies and hydraulic conductivity. Consequently, these channels have a higher potential for hyporheic exchange being driven by spatial variation of sediment facies and hydraulic conductivity.

We hypothesize that hyporheic exchange from turbulent mixing will be more pronounced in coarser-grained (more porous) channels (cascade, step-pool), and progressively less important as bed material becomes finer (less porous and stronger damping of turbulence) as one moves from cobble- and gravel-bed morphologies (plane-bed, pool-riffle, braided) to sand-bed ones (dune-ripple and some braided channels) (Table 1). Hyporheic exchange from mechanical mixing during bedload transport is limited to channels that regularly mobilize all or some portion of their bed (step-pool, plane-bed, pool-riffle, braided, and dune-ripple), while turnover exchange is exclusive to sand-bed rivers (dune-ripple and some braided channels).

3.2 MAGNITUDE AND SCALE OF HYPORHEIC EXCHANGE

Figure 7 shows a conceptual plot of the magnitudes and scales (rates and spatial extent) of hyporheic exchange for different channel types. Cascade and step-pool channels are expected to have high magnitudes of exchange due to large head gradients and porous sediment (high hydraulic conductivity), but steep valley slopes and small alluvial volumes will limit the

scale of exchange for these channels. In contrast, braided, pool-riffle, and dune-ripple channels are expected to have moderate magnitudes of hyporheic exchange due to more moderate head gradients and finer bed material (cobble to sand sizes, with a range of high to low hydraulic conductivities), but will be characterized by a broader array of hyporheic mechanisms (Table 1) and larger scales of exchange due to these channel types occurring in unconfined valleys with extensive alluvial deposits. Scales of hyporheic exchange are expected to be fairly limited in colluvial channels because of steep slopes and shallow valley fill, but head gradients may be substantial due to frequent, obstructions and shallow, ephemeral flow depths. Plane-bed channels are underlain by thicker alluvial packages, but lack of bed topography will limit the magnitude and scale of hyporheic exchange that can be developed. Finally, bedrock channels should have the smallest magnitudes and scales of hyporheic exchange due to the limited occurrence of alluvial patches.

In terms of biological significance, the scale of hyporheic exchange and consequent connectivity of landscape elements is correlated with the extent and diversity of habitats available to fish, macroinvertebrates, and riparian vegetation (Amoros and Bornette 2002; Malard et al. 2002; Stanford and Ward 1988; Ward and Tockner 2001; Ward et al. 2002). But, the magnitude of exchange is also important in terms of ecosystem vigor. Residence time, which is the convolution of both the magnitude and scale of hyporheic exchange, controls the development of biochemical gradients and available habitats. Biochemical gradients will be limited in channel types characterized by short, rapid hyporheic flow paths (cascade, step-pool channels), resulting in more uniform biochemical conditions and more uniform habitats compared to channels characterized by a broad range of hyporheic path lengths and travel times (dune-ripple, pool-riffle). We suspect that pool-riffle channels provide the best mix of magnitude and scale of hyporheic exchange, particularly those that occur in broad alluvial valleys (Stanford et al. 2005), and are more stable environments than braided channels (Malard et al. 2002).

Another factor that is important for water quality and stream metabolism is the length scale for complete mixing between surface and hyporheic waters (L_m), or turnover length (Harvey and Wagner 2000; Harvey et al. 1996; Kasahara and Wondzell 2003). L_m depends on the river discharge (Q), the wetted channel perimeter (P), and the rate of exchange (q_h , the average downwelling flux per unit streambed area, which varies with channel morphology and the exchange mechanisms discussed above)

$$L_m = \frac{Q}{q_h P} \quad (1)$$

This equation indicates that mixing lengths should be shorter for low discharges (small Q), rapid rates of exchange (large q_h), or wide channels (large P).

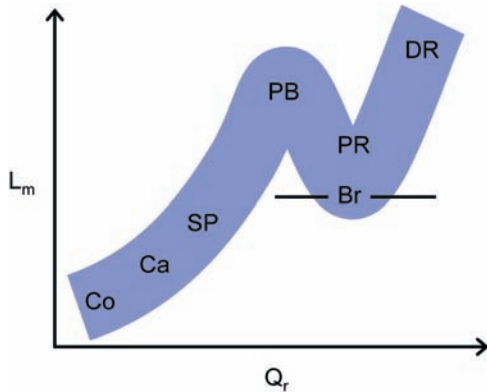


Fig. 8. Conceptual plot of length scales for complete mixing of river and hyporheic waters (L_m) as a function of river discharge (Q_r) and channel type (Co = colluvial, Ca = cascade, SP = step-pool, PB = plane-bed, PR = pool-riffle, BR = braided, DR = dune-ripple).

The general downstream progression of channel types (Montgomery and Buffington 1997), together with downstream increases in discharge and channel size (Leopold and Maddock 1953), allows us to develop a conceptual plot of expected mixing lengths for different channel types (Figure 8). Because discharge increases faster than channel size with increasing drainage area (Emmett 1975; Dunne and Leopold 1978), we expect L_m to increase as one moves downstream through a basin (Kasahara and Wondzell 2003), but with values modulated by specific channel types and their associated rates of hyporheic exchange. Stronger temporal variation of discharge in headwater areas (typically colluvial, bedrock, cascade, and step-pool channels) should also cause greater variability of L_m compared to mainstem portions of the channel network (typically plane-bed, pool-riffle, and dune-ripple morphologies). Specific values of L_m are not known for these channel types, but Kasahara and Wondzell (2003) report length scales on the order of 100 m (about 50 channel widths) for complete mixing in two second-order step-pool channels during summer low flow, compared to $L_m \approx 1.7$ km (about 200 channel widths) for a fifth-order pool-riffle channel.

3.3 SPATIAL DISTRIBUTION OF CHANNEL TYPES AND RIVERINE HABITATS

In conclusion, we might ask 'How does all of this play out on the landscape and where are the ecological hotspots for hyporheic habitat in a river network?' To address this question, we can predict channel type and associated hyporheic exchange as a function of slope using digital elevation models (Figure 9). From this we can think about the spatial patterns and distributions of channel types and hyporheic environments. Predictions of this sort indicate that nearly 90% of the stream length in mountain basins is composed of steep channels (step-pool, cascade,

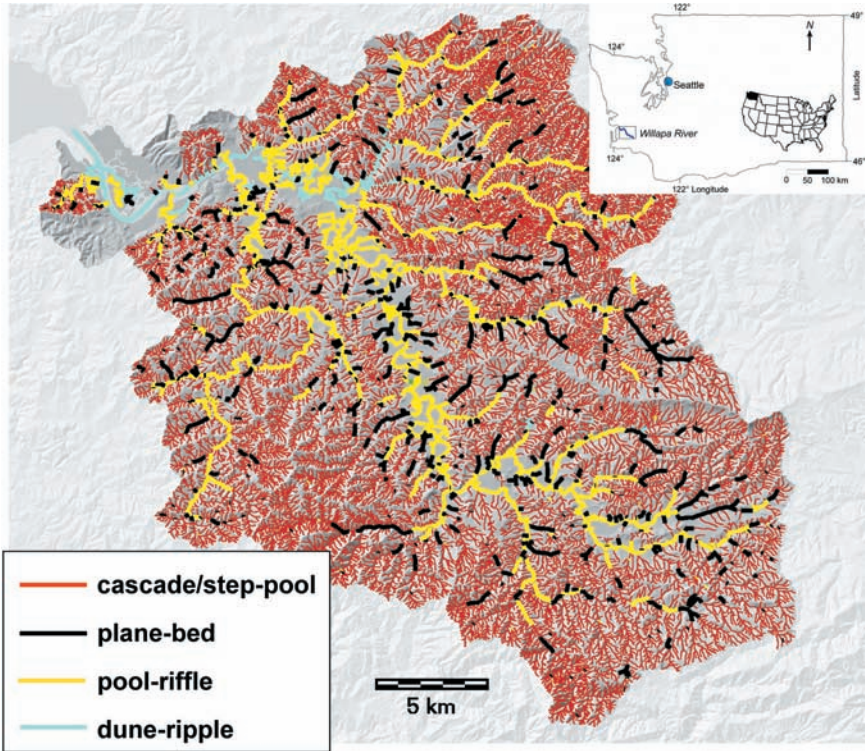


Fig. 9. Predicted spatial distribution of channel types and associated hyporheic environments in the Willapa basin, western Washington, USA. Modified from Buffington et al. (2004).

bedrock and colluvial morphologies; Buffington et al. 2004; Stock and Dietrich 2003), indicating that most hyporheic exchange throughout the river network is rapid and shallow. The remaining 10% of the river network is composed of lower-gradient, less confined channels (plane-bed, pool-riffle, dune-ripple and braided morphologies) where hyporheic exchange is expected to be slower, deeper and more complex. These lower-gradient unconfined channels typically correspond with greater abundance and diversity of aquatic and riparian organisms (Malard et al. 2002; Stanford and Ward 1988; Stanford et al. 2005). Hence, critical and or productive habitats in mountain basins are of limited extent in terms of the total length of the river network.

However, the spatial pattern of channel types and hyporheic environments is region- and basin-specific, depending on a nested hierarchy of process controls (Figure 10). Large-scale process drivers (geology, climate, fire, and land use) impose a suite of watershed conditions (topography, streamflow, sediment supply, and vegetation) on the fluvial system. Different combinations of imposed watershed conditions result in different reach-scale channel types (e.g. cascade, pool-riffle, braided; Buffington et al. 2003)

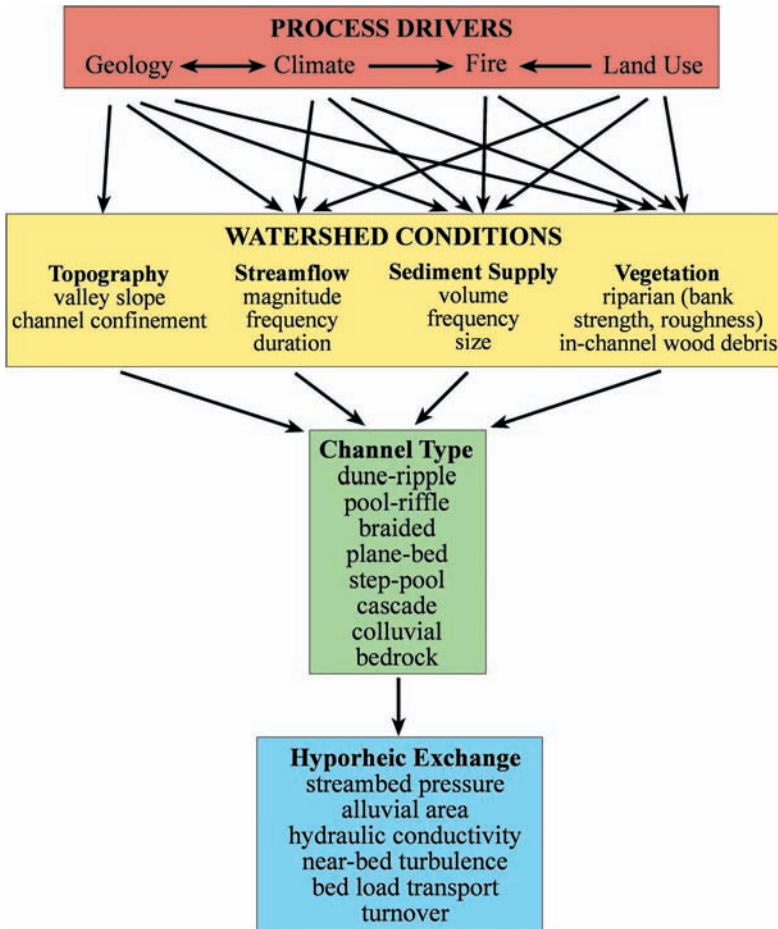


Fig. 10. Nested hierarchy of process controls in mountain basins. Modified from Buffington et al. (2003).

that, in turn, structure hyporheic processes (e.g. pressure divergence, spatial variation of hydraulic conductivity) and resultant hyporheic environments (scales and rates of hyporheic exchange). Hence, a holistic understanding of natural and anthropogenic drivers across multiple spatial and temporal scales is needed for assessing the occurrence of hyporheic environments across a landscape.

Although mountain basins exhibit a general downstream sequence of channel types, representing systematic downstream changes in slope, discharge, and sediment supply (Montgomery and Buffington 1997), this sequence can be locally reset or spatially discontinuous due to a variety of factors (structural or glacial controls on slope, changes in lithology and rock strength, pulsed sediment inputs from debris flows, wood jams, tributary confluences; Benda et al. 2004; Brardinoni and Hassan 2007; Martin et al.

2004; Montgomery and Bolton 2003; Rice 1998). Consequently, physical factors that influence hyporheic exchange (confinement, substrate, and bedforms) can vary either gradually or rapidly downstream through a river network, depending on local and basin-scale characteristics (Figure 9).

Acknowledgements

We thank Dr. Markus Stoffel and an anonymous reviewer for constructive comments that improved the manuscript.

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