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Variation in reach-scale hydraulic conductivity of streambeds

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ABSTRACT

Streambed hydraulic conductivity is an important control on flow within the hyporheic zone, affecting hydrological, ecological, and biogeochemical processes essential to river ecosystem function. Despite many published field measurements, few empirical studies examine the drivers of spatial and temporal variations in streambed hydraulic conductivity. Reach-averaged hydraulic conductivity estimated for 119 surveys in 83 stream reaches across continental France, even of coarse bed streams, are shown to be characteristic of sand and finer sediments. This supports a model where processes leading to the accumulation of finer sediments within streambeds largely control hydraulic conductivity rather than the size of the coarse bed sediment fraction. After describing a conceptual model of relevant processes, we fit an empirical model relating hydraulic conductivity to candidate geomorphic and hydraulic drivers. The fitted model explains 72% of the deviance in hydraulic conductivity (and 30% using an external cross-validation). Reach hydraulic conductivity increases with the amplitude of bedforms within the reach, the bankfull channel width-depth ratio, stream power and upstream catchment erodibility but reduces with time since the last streambed disturbance. The correlation between hydraulic conductivity and time since a streambed mobilisation event is likely a consequence of clogging processes. Streams with a predominantly suspended load and less frequent streambed disturbances are expected to have a lower streambed hydraulic conductivity and reduced hyporheic fluxes. This study suggests a close link between streambed sediment transport dynamics and connectivity between surface water and the hyporheic zone.

1. Introduction

Hyporheic zones (HZs) are the saturated sediments beneath and adjacent to river channels through which surface water exchanges and mixes with groundwater (White, 1993; Boulton et al., 2010). The HZ is a unique ecotone that supports a variety of hydrological, ecological and biogeochemical processes essential to river ecosystem function (Gibert et al., 1990; Boulton et al., 2010). By regulating the transfer of heat and mass across the sediment–water interface, the HZs play a critical role in temperature buffering (Arrigoni et al., 2008) and biogeochemical cycling (Mulholland and Webster, 2010). They are also permanent habitats for many microbes and invertebrates (Brunke and Gonser, 1999), provide refugia for surface invertebrates or fish (Dole-Olivier, 2011; Kawanishi et al., 2013), and are used by some fish for spawning (Geist et al., 2002). The occurrence and magnitude of processes occurring in HZs largely depend upon the hydrological flux between surface and ground waters (Findlay, 1995; Fischer et al., 2005).

Most laboratory-, field-, and model-based research of hyporheic zone processes has been at the scale of a short river reach (up to several meander wavelengths) or smaller, but efforts to scale up this research to an entire river catchment are very rare (Kiel and Cardenas, 2014). Such efforts will require an understanding of catchment-scale variations in the hyporheic flow regimes including hyporheic flux, residence time, and geometry of flow paths. These are largely determined by variations in pressure at the sediment–water interface and hyporheic zone/groundwater boundary, by bed mobility, and by the variable hydraulic conductivity of porous boundary material (Blaschke et al., 2003). In turn, all these factors vary with river hydrology, channel morphology, and associated fluvial processes (Malard et al., 2002; Tonina and Buffington, 2009).

Although measurements of streambed conductivity have been reported from a broad range of stream types, few empirical studies link spatial (between sites) and temporal (with time) variations in streambed hydraulic conductivity to flow, catchment characteristics, and other geomorphic drivers. Point measurements of streambed hydraulic conductivity found in the literature vary between 10^{-10} and 10^{-2} m/s (Calver, 2001), and reach-average values are between 10^{-5} and 10^{-3} m/s (Genereux et al., 2008; Song et al., 2009; Chen, 2010; Cheng et al., 2010; Min et al., 2012; Taylor et al., 2013). This upper

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limit on reach-average values is an order of magnitude lower than might be expected for a uniform gravel [e.g., the Hazen formula (Hazen, 1892) estimates hydraulic conductivity of 0.04 m/s for particle size diameters of 2 mm]. This is because streambed sediments generally have a broad distribution of particle sizes and because hydraulic conductivity is largely determined by the smaller size fractions (Alyamani and Sen, 1993; Song et al., 2009; Descloux et al., 2010). Consequently, variation in hydraulic conductivity between reaches is likely the result of processes controlling presence of fine sediments in the streambed rather than the coarse fraction. Further, point-scale measurements vary considerably within a reach. In some rivers, sections of streambed may be effectively impermeable but the streambed is rarely impermeable throughout the river channel. The lowest reported value of 10^{-10} m/s, is five orders of magnitude smaller than the lowest reported reach-average value.

In this study we model spatial and temporal variations in hydraulic conductivity to support advances in our understanding of hyporheic processes and their ecological consequences at the catchment scale. After describing a conceptual model of streambed hydraulic connectivity, we use field data collected in 119 surveys of 83 stream reaches across continental France (Datry et al., 2014) to fit and cross-validate an empirical model of reach-scale conductivity as a function of candidate geomorphic and hydraulic controls.

2. Conceptual model of streambed hydraulic conductivity

Multiple processes likely influence the presence of fine sediments within the streambed and hence its hydraulic conductivity (Fig. 1). These processes drive fine sediment supply, retention on and within the streambed, and fine sediment removal. Fine sediment is supplied from scour of the upstream streambed or banks, and from erosion within the catchment (Wood and Armitage, 1997). Worldwide, land clearance, logging, and mining have increased catchment fine sediment supply whilst sediment control, sand mining, and trapping with dams offsets some of these increases (Walling, 2006; Descloux et al., 2010; Datry et al., 2014).

Fine sediments are normally deposited on the streambed contemporaneously with coarser- grained sediments (Lisle, 1989). In addition, suspended sediments may encounter the streambed through various processes including slackwater deposition, biofilm interception, and hyporheic exchange (Karwan and Saiers, 2012). Infiltrated fine sediment can be trapped just beneath an armour layer on the streambed surface or transported farther into the streambed by advection with downwelling pore water or through gravitational settling and then trapped by straining, settling, or chemical adhesion within the coarse sediment interstices (i.e., depth filtration) (Brunke, 1999; Blaschke et al., 2003; Cui et al., 2008; Nowinski et al., 2011; Karwan and Saiers, 2012). Depth filtration has been observed to extend into the streambed up to 0.5 m (Brunke, 1999; Blaschke et al., 2003; Olsen and Townsend, 2005). Many of these processes contribute to clogging (Blaschke et al., 2003) or colmation (Brunke, 1999), reducing the hydraulic conductivity and porosity of the streambed sediments, thereby altering hyporheic zone functions (Packman and MacKay, 2003; Datry et al., 2014).

For mobile streambeds, the effect of episodic scour-and-fill processes (or turnover) on clogging and the implications for hydraulic conductivity are not well understood (Packman and Brooks, 2001; Gartner et al., 2012). Bedload transport has been shown to inhibit clogging in flume experiments (Packman and Brooks, 2001; Rehg et al., 2005) and in streams (Evans and Wilcox, 2014). In contrast, streams with episodic bed mobilisation can exhibit a cyclical clogging behaviour initiated by a high flow event flushing fine sediments from the streambed (Genereux et al., 2008), followed by declining hydraulic conductivity with increased clogging in upper streambed layers over time (Schalchli, 1992; Hatch et al., 2010), and finally reaching a quasi-equilibrium state (Blaschke et al., 2003).

Although subject to little investigation, biological activity also influences streambed hydraulic conductivity (Statzner and Sagnes, 2008; Nogaro et al., 2009; Statzner, 2012). Biofilm growth is likely to enhance clogging (Mendoza-Lera and Mutz, 2013) and root growth and borrowing of biota may create preferential flow paths and increase conductivity (Battin and Sengschmitt, 1999; Mermillod-Blondin and Rosenberg, 2006). For example, tubificid worms can dig networks of galleries in fine sediment, creating preferential flow pathways and increasing hydraulic conductivity (Nogaro et al., 2006). As with clogging by fine sediments, these processes are likely to evolve over time but could be reduced or reset by scour of the streambed.

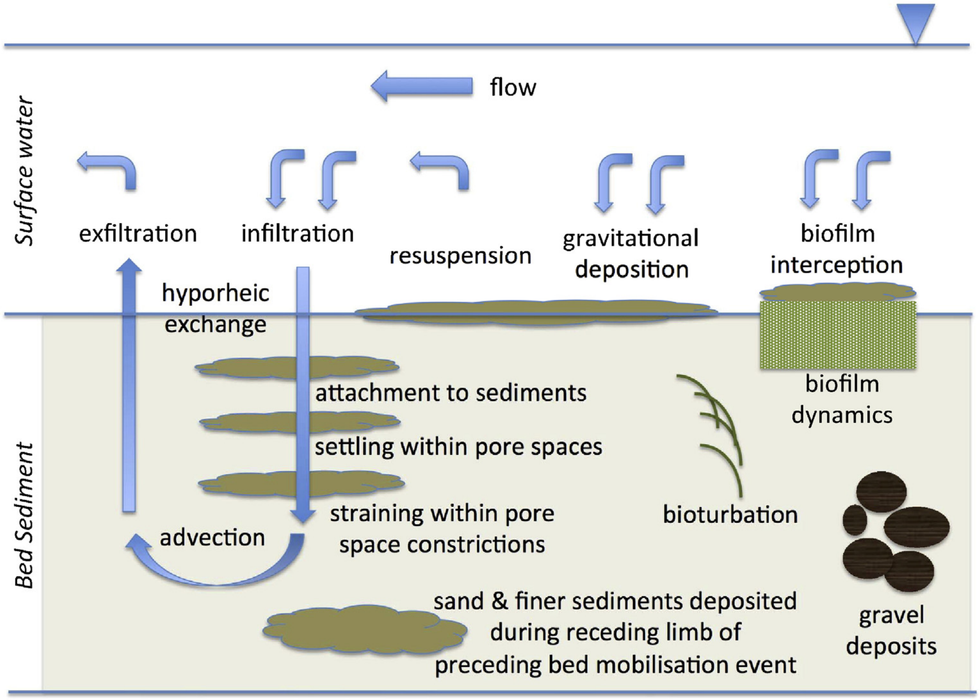

Fig. 1. Physical and biological processes affecting hydraulic conductivity of streambeds.