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The effect of macropores on bi-directional hydrologic exchange between a stream channel and riparian groundwater

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SUMMARY

Macropores and soil pipes in stream banks are common geomorphic features. Macropores and soil pipes that are open to the channel (i.e. "bank face-connected" macropores) are inundated when channel stage is elevated (e.g., from precipitation, snowmelt, dam release). However, previous studies have not investigated macropore impact on bi-directional water exchange between the channel and bank/riparian groundwater under variable hydrologic conditions. We monitored two transects of riparian groundwater wells perpendicular to the bank of a 2nd order stream for a year: one with bank face-connected macropores (M transect) and one without bank face-connected macropores (NM transect). Fluctuations in water level and temperature during storms in those wells closest to the channel were on average 139% and 29% higher, respectively, in the presence of macropores. Rising head tests in the same wells indicated that hydraulic conductivity was 61–140 times higher in the presence of macropores. Bank storage, indicated by gradient reversals between channel and riparian zone, occurred on two temporal scales. Bank storage during storms was more frequent in the M transect (occurred all year) than in the NM transect (occurred just in winter and spring). Smaller magnitude gradient reversals at the M transect are consistent with faster head equilibration and greater exchange volume. Bank storage also occurred on an annual basis, with channel water entering storage during summer and fall and returning to the channel during winter and spring. Taken together, these results suggest that macropores act as preferential flow paths that enhance the connectivity between channels and riparian groundwater that influences bank storage. Where bank macropores are present, conceptual models of hyporheic and groundwater flow should account for their effects.

1. Introduction

Floodplains and riparian zones can supply groundwater to stream channels, providing aquatic organisms with organic carbon and nutrients (McGlynn and McDonnell, 2003), and acting as a sink for pollutants such as excess nitrate (Groffman et al., 2002; Vidon et al., 2010).

In addition, bi-directional exchange of water between the channel and groundwater beneath and adjacent to stream channels (i.e. hyporheic exchange) can provide various functions from the perspective of the channel including temperature regulation, nutrient cycling, pollutant buffering, and habitat creation (Brunke and Gonser, 1997). Here we focus on this hyporheic zone, where flowpaths can be divided loosely into two categories known as the "gill" and "lung" models, respectively (Sawyer et al., 2009). In the gill model, flow directions can be similar during low flow and high flow conditions because of constraining background groundwater levels. By contrast, in the lung model there are notable flow reversals. When channel water levels are higher than the adjacent groundwater table, floodplain and riparian vadose zone pore spaces can fill with channel water. Once stream water levels fall below the adjacent groundwater table, water is released from pore spaces back to the stream. Lung model hyporheic exchange is known as bank storage during storm events (Pinder and Sauer, 1971), but also occurs due to daily snowmelt, evapotranspiration, hydropeaking, and tidal fluctuations (Arntzen et al., 2006; Francis et al., 2010; Loheide and Lundquist, 2009; Peterson and Connelly, 2001; Sawyer et al., 2009; Westbrook et al., 2005; Wondzell et al., 2010). Bank storage meets the hydrologic definition of hyporheic exchange as short flowpaths that leave and return to the channel within relatively short distances (bi-directional exchange) and is well-documented (Wondzell and Gooseff, 2013; Sawyer et al., 2009).

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Bank storage reduces peak channel flows during storm events and promotes groundwater recharge (Jung et al., 2004; Kondolf et al., 1987). Bank storage can also intercept and hold pulses of water quality constituents being transported downstream (Chen and Chen, 2003). Pollutants can enter banks during storm events and be slowly released at baseflow (Squillace et al., 1993). These pollutants can remain at elevated levels in riparian groundwater for months or years (McCallum et al., 2010). Bank storage is increasingly recognized as important to the overall heat and solute budget of streams. For example, bank storage can alter the stream heat budget by storing heat or acting as a thermal sink in urban areas (Anderson et al., 2011) and regulated rivers (Gerecht et al., 2011). Anderson et al. (2011) found that banks could store 72% of the heat stored within the stream. Bank storage can also facilitate biogeochemical conditions conducive to microbial activity in the floodplain/riparian zone (Burt et al., 2002; Gu et al., 2012). Peter et al. (2012) found >50% decline in nitrate in storm water that entered riparian groundwater zones. Gu et al. (2012) found a median nitrate removal rate by denitrification in bank storage of 2.1 g/d per m of stream length (max of 140 g/d/m) corresponding to a median nitrate uptake velocity of $2.7 \cdot 10^{-5}$ m/min. These studies suggest the importance of bank storage for nutrient budgets at the ecosystem level.

Flow rates through the saturated porous media of the hyporheic zone are often determined using Darcy's Law where $Q = KiA$ ("K" is the saturated hydraulic conductivity [m/s], "i" is the hydraulic gradient [m/m], "A" is the cross-sectional flow area [m^2]). K varies over more than 8 orders of magnitude near streams (Brassington, 2007; Calver, 2001) in both space and time (Genereux et al., 2008; Song et al., 2010), making it particularly important in determining hyporheic flow rates (Boulton et al., 2010; Hester and Doyle, 2008; Hester and Cranmer, 2014; Menichino and Hester, 2014). Regions where K is higher relative to surrounding media are preferential flow paths that dominate groundwater transport near streams (Fuchs et al., 2009; Heeren et al., 2010) and can control bank storage (Kondolf et al., 1987).

Macropores and soil pipes are a type of preferential flow path where connected void space exists in the porous media. Macropores and soil pipes have been shown to increase transport rates and dominate transport in the unsaturated zone in agricultural landscapes (Aubertin, 1971; Blake et al., 1973; Edwards et al., 1979), in forested hillslopes (Sidle et al., 2001; Nieber and Sidle, 2010), and in deeper groundwater situations (Qian et al., 2011). There have also been many studies of flow through fractured rock, where fracture flow similarly dominates transport where present (e.g., Rudolph et al., 1991; Cook et al., 1996; Matthai and Belayneh, 2004), although the geometry and connectivity can be quite different from macropores. Near streams, soil pipes have been shown to form by internal erosion along subsurface flowpaths toward the channel (Higgins and Coates, 1990; Fox and Wilson, 2010). Soil pipes can influence streamflow generation by increasing interflow or groundwater flow toward the channel (Higgins and Coates, 1990; Haught and van Meerveld, 2011).

By contrast, fewer studies have explored macropores for their capacity to facilitate bi-directional exchange between streams and riparian zone/floodplain groundwater. Nevertheless, an increasing number of studies suggest that such macropores are common (Bohlke et al., 2007; Gormally et al., 2011; Jones and Cottrell, 2007; Menichino et al., 2015; Newman and Keim, 2013). Some studies have explored the sediment scale impacts of macropores created by bioturbation (Mermillod-Blondin and Rosenberg, 2006; Mermillod-Blondin et al., 2004; Nogaro et al., 2006), however the bank storage effects of macropores remain poorly understood. Recent research does show that macropores within a meander bend act as preferential flow paths for solute transport through the meander (Menichino et al., 2014). Similarly, macropores may influence solute transport between stream channels and riparian groundwater zones (Angier and McCarty, 2008; Gormally et al., 2011; Newman and Keim, 2013). Macropores have been shown to exist in streams primarily between baseflow and bankfull water levels (Menichino et al., 2015). This suggests that most macropores will be inundated during storm events and may contribute to bank storage. However, we are unaware of any studies that quantify the importance of macropores on lung-model hyporheic exchange including bank storage.

Here we present a field study in which we evaluate the effect of bank macropores on bi-directional water exchange between a stream channel and riparian groundwater. We do this by comparing hydrologic response in bank sediments to flood waves in the channel in two locations: one with macropores that open to the bank ("bank face-connected macropores") and one without. Our specific objectives were to (1) evaluate macropore effects on the hydraulic gradient and direction of bi-directional exchange over a year of storm events, (2) evaluate macropore effects on lateral extent of bank storage in riparian sediments (lung model hyporheic zone size) over a year of storm events, (3) determine how items 1 and 2 above vary with seasonally changing hydrologic conditions.

2. Methods

Our site was a reach of Slate Branch, a 2nd order stream (based on 1:24000 USGS topographic map) in the Appalachian Province of southwest Virginia near Christiansburg. The contributing watershed is predominately urban, the average bankfull width is 5.2 m, average bankfull height is 0.69 m, stream gradient is 0.0098 m/m, and typical bank sediment type is sandy loam. Typical summer baseflow discharge was between 21 and 29 L/s.

Six naturally existing bank face-connected macropores were present in a cluster or grouping that measured 0.41 m long and 0.70 m tall. The openings of these macropores ranged from 14 to 28 cm (average of 18.7 cm) above the thalweg and ranged from 2 to 6 cm (average of 4.2 cm) in both height and width. The length that these macropores extended laterally into the bank, at least to the first bend in the macropore (i.e. what we could measure with a straight ruler) ranged from 9 to 51 cm (average of 29.7 cm).

We installed two rows (transects) of groundwater wells in the riparian zone/floodplain perpendicular to the stream channel at locations with (M transect) and without (NM transect) bank face-connected macropores (Fig. 1). We created boreholes with a 5.7 cm diameter augur. The boreholes ranged in depth from 1.67 to 1.74 m. The soil stratigraphy for all wells was fairly uniform silty clay, with some gravel locked in the silty clay matrix at depth. Roughly 15 cm of filter sand was added to the bottom of each borehole. The 4.22 cm outside diameter polyvinyl chloride wells were then added to the boreholes on top of the filter sand, leaving typically a 0.75 cm annulus or gap around them. This annulus was filled with additional filter sand to within 25 cm of the surface. Next, bentonite was used to fill the rest of the borehole. Water was added with the bentonite to ensure a watertight seal from surface flow. The site was inspected weekly or after every major storm event. During inspection we confirmed that the bentonite seal did not have cracks which would allow bypass flow down to the well screens (short circuiting). On the few occasions when minor surface cracks were observed in the bentonite, we repaired the seal. We also installed a stream stage gauge in between the two transects.

We monitored water levels and temperatures at 15-min intervals at the groundwater wells and stage gauge. Wells 0.5 m into the bank ("A") and 4.0 m into the bank ("D") of both transects housed Solinst Levelogger Juniors. Wells 1.0 and 2.0 m into the bank ("B" and "C", respectively) housed Onset Hobo Pressure