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Estimating spatial pattern of hyporheic water exchange in slack water pool

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Abstract: Hyporheic zone (HZ) influences hydraulic and biogeochemical processes in and alongside streams, therefore, investigating the controlling geographic factors is beneficial for understanding the hydrological processes in HZ. Slack water pool (SWP) is an essential micro-topographic structure that has an impact on surface water and groundwater interactions in the HZ during and after high flows. However, only a few studies investigate HZ surface water and groundwater exchange in the SWP. This study used the thermal method to estimate the HZ water exchange in the SWP in a segment of the Weihe River in China during the winter season. The findings show that on the flow-direction parallel to the stream, river recharge dominates the HZ water exchange, while on the opposing flow-direction bank groundwater discharge dominates the water exchange. The water exchange in the opposing flow-direction bank is about 1.6 times of that in the flow-direction bank. The HZ water exchange is not only controlled by flow velocity but also the location and shape of the SWP. Great water exchange amount corresponds to the shape with more deformation. The maximum water exchange within the SWP is close to the river bank where the edge is relatively high. This study provides some guidelines for water resources management during flooding events.

Keywords: hyporheic water exchange; thermal method; discharge; recharge; surface water-groundwater interactions

1 Introduction

Hyporheic zone (HZ), the saturated zone alongside and beneath the streambed where surface and groundwater interactions take place (Marzadri *et al.*, 2014), is a key component influ-

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encing hydraulic and biogeochemical processes (Fischer *et al*., 2005; Korbel and Hose, 2015; Stegen *et al*., 2018; Wang *et al*., 2018). Its function may have a significant effect on stream hydrological processes, water quality (Westhoff *et al*., 2011), and river ecosystem (Mendoza-Lera and Datry, 2017). Various factors can lead to the transport of water and flux through HZ (e.g., hydraulic conductivity (Trauth and Fleckenstein, 2017)). Micro-topography as one of an important factors (Frei *et al*., 2010; Zhang *et al*., 2016; Gualtieri *et al*., 2017; Ianniruberto *et al*., 2017), controlling fine-scale variability in hydraulic heads, is fundamental for the HZ water exchange at the habitat scale (~1 to 10 m) (Naiman and Latterell, 2005). The water exchange in the HZ is still less understood owing to the disparate environmental conditions (e.g., sediments structure and topography), it is a challenge to elucidate the effects of particular micro-topographic features on the interactions between surface water and groundwater (Boano *et al*., 2006; Tonina and Buffington, 2007).

HZ water exchange under various micro-topographic features has been investigated in many studies (e.g., hollows and hummocks (Frei *et al*., 2010), bedding orientation (Cheng *et al*., 2013), hillslope (Boulton *et al*., 2010; Dochartaigh *et al*., 2012), riffles (Storey *et al*., 2003), stream curvature (Cardenas *et al*., 2004) and confluence (Gualtieri *et al*., 2017; Ianniruberto *et al*., 2017)). Other authors publish the related findings at micro-topographies settings (see Table 1). The micro-topography is a vital driver leading to the spatial changes of hydrological processes in HZ. It affected the subsurface water exchange and nutrient transports (Frei *et al*., 2010; Caruso *et al*., 2016; Song *et al*., 2017), therefore, in turn, it has potential implications for the ecological habits (Stubbington, 2012). Moreover, there are high demands to understand the HZ water exchange in a specific micro-topography.

Table 1 Properties for some micro-topographies

Micro-topographic feature	Location in the HZ	HZ exchange patterns	Influencing factors	Analysis method	Reference
Hollows and hummocks	Floodplain	Frequent shifts	Runoff generation	Virtual modeling experiment	Frei *et al*. (2010)
Bank hillslope	Stream margin/floodplain	Mainly discharge	Groundwater head, soil permeability	3D geological model	Dochartaigh *et al*. (2012)
Pool-riffle	Riverbed	Complex interactions	Bedform–induced advection	Laboratory experiments and pumping exchange model	Tonina and Buffington (2007)
Riffle	Riverbed	Mixed [a]	Hydraulic conductivity, groundwater flux	MODFLOW, Numerical heat-transport model	Storey *et al*. (2003); Vogt *et al*. (2012)
Dunes and eddies	Riverbed	Differ in depths	Pressure gradient	Governing equations for fluid, tracer method	Fox *et al*. (2014); Chen *et al*. (2015)
Slack water pools	Stream margin/floodplain	Complex interaction	Flow velocity and shape	Thermal method	Present study

[a] Mixed, means the HZ water exchange in this condition is an interaction with spatial and diurnal variations at small scale.

Slack water pool (SWP) is a pool-like depression along the stream margin and on the floodplain that contains water only during high flow or after flood recede, it may hold water for only a few days or weeks (Dunster, 2011). It is characterized by low flow velocity and relatively static water level. Though SWP is a common feature in a river system, HZ water exchange within the SWP is poorly understood, and few studies have been reported (Kasahara and Wondzell, 2003; Cardenas *et al*., 2004). The HZ water exchange within the SWP is strongly influenced both by groundwater and streamflow due to close hydraulic connection with rivers, unlike other micro-topographies which are entirely nested in the riverbed.

Table 1 summarizes studies of micro-topographic effects on the HZ water exchange, influencing landscape elements and methods employed in their investigation. There are several methods (e.g., hydraulic conductivity (Chen *et al*., 2013), hydraulic gradient (Baxter *et al*., 2003), seepage meter (Isiorho and Meyer, 1999), isotope tracer (Darracq *et al*., 2009), numerical simulation (Lautz and Siegel, 2006) and heat tracers (Kalbus *et al*., 2006)) implemented to calculate the water exchange in the HZ. Among those methodologies, thermal method is widely used since point measurements of streambed temperatures can be efficiently detectable and obtained (Somogyvári *et al*., 2016), and analytical/numerical methods used in their interpretation can provide reliable exchange estimates when measurements were performed under the appropriate conditions (Schmidt *et al*., 2007).

This study uses the one-dimensional method to investigate the HZ water exchange in a relatively small (<20 m length) SWP in the Weihe River (Figures 1 and 2), a major tributary of the Yellow River, and to address the primary mechanism of water exchange between the stream and groundwater in the SWP.

2 Field site and measurements

The test site is located on the segment of the Weihe River in Meixian, the upstream where the river enters Shaanxi Province (Figure 1). The Weihe River is the first tributary of the Yellow River, which originates from Gansu Province, China. It runs across 818 km and joins the Yellow River in the city of Tongguan. The length in Shaanxi Province accounts for about 61% of the total length of the river. The annual rainfall is from 558 to 750 mm and with a mean approximately 610 mm. The drainage area, annual flow flux and annual sediment discharge of the river account for 17.9%, 16.9% and 2.5% of the total amount of the Yellow River Basin, respectively (Li *et al*., 2013).

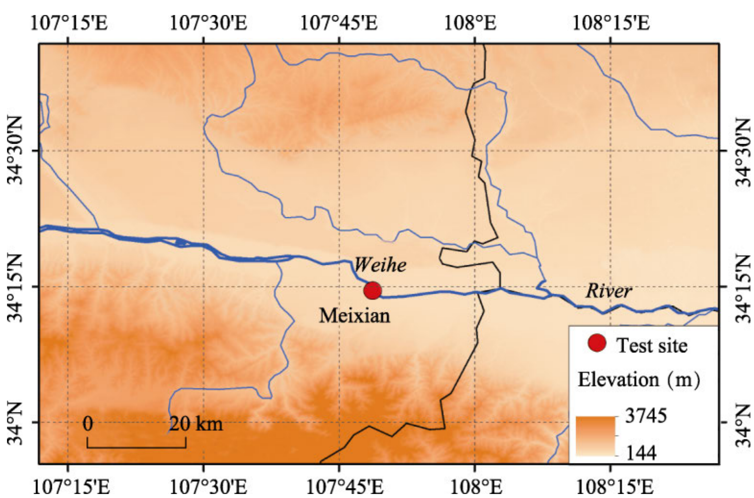

Figure 1 Map showing the location of the study area and the test site

The river has natural channel morphology with a width of 34 m and its course travels in a southwest direction in this reach, the SWP is situated in the southern river bank. The SWP is composed of three parts, the static part, the path belt and the main river channel. The streambed deposits consist primarily of loose, fluvial deposited, and gravel. The loose sediment and sand are distributed on the upper layer in the vicinity of the bank, and the gravel extensively occupies on this section of streambed. In the static part of the SWP, the sedimentary structure is mainly composed of the loose and coarse sand. The bank of the static part consists of fine to very fine sands with occasional silty areas. Fine sand extends from the surface to a depth of about 0.5 m where we found a discrete layer of sand and gravel in the bank of the river. The streambeds are relatively uniform in the upper layer of the sediment.

The experiment was carried out on 25 Jan 2015, from 11 am to 15 pm. In monitoring period, the air and water temperatures were 4.58 ± 1.70 (SD) and 5.03 ± 0.74 (SD)℃, respectively. The thermistor with the multiple depths has been used to record the sediment temperatures at the testing points (Figure 2). Temperature sensor (Heraeus, pt100) has been installed at 0.00 m, 0.10 m, 0.20 m, 0.30 m, 0.45 m, 0.60 m and 0.80 m, respectively. The measuring range of the sensor is from –50℃ to 200℃.

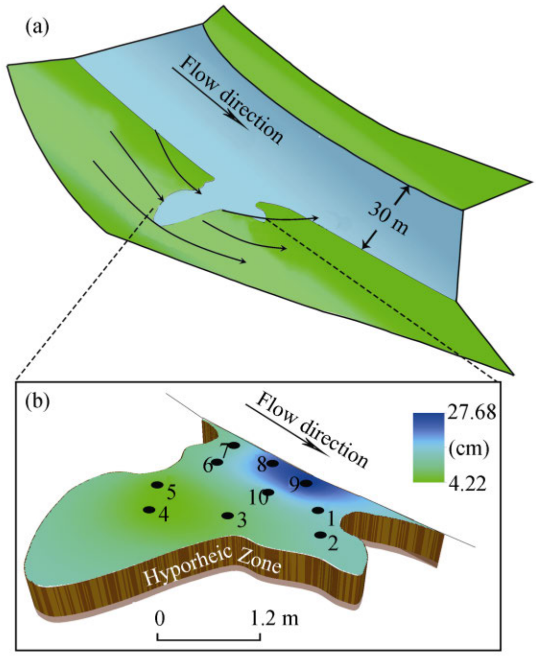

Figure 2 Map showing the measurements of the sediment temperature and water depth. (a. Position of the slack water pool; b. Description of water depth at the testing site

3 Methods

3.1 Thermal method

The one-dimensional method is a simple analytical solution that can provide an inexpensive, efficient approach to obtain accurate point estimates of HZ water exchange using streambed temperatures (Anibas *et al.*, 2009; Irvine *et al.*, 2015). The assumption of the HZ water exchange in SWP is just vertical directions (upward or downward), the water exchange rate can be expressed as following (Suzuki, 1960):

$$\frac{K}{\rho c}\frac{\partial^2 T(z)}{\partial z^2}-\frac{Q_v\rho_0 c_0}{\rho c}\frac{dT(z)}{dz}=\frac{\partial T(z)}{\partial t} \tag{1}$$

where $T(z)$ is the temperature (℃) of the streambed sediments at z depth; K is the heat conductivity (J s^{-1} m^{-1} K^{-1}); ρc is the volumetric heat capacity of saturated streambed system (J m^{-3} K^{-1}); $\rho_0 c_0$ is volumetric heat capacity of the water (J m^{-3} K^{-1}); and Q_v (mm/d) is the vertical water exchange through a unit area.

When in thermal steady state conditions, the right hand of Equation (1) tends to 0 and can be arranged as:

$$\frac{\partial^2 T(z)}{\partial z^2} - \frac{Q_v \rho_0 c_0}{K}\frac{dT(z)}{dz} = 0 \tag{2}$$

When $z = 0$, the T_z=T_0, and when $z\rightarrow\infty$, the T_z would be constant, then T_z=T_L. And the solution of equation (2) can be expressed as (Anibas *et al*., 2011):

$$Q_v = \left|\frac{K}{\rho_0 c_0}\ln\frac{T(z) - T_L}{T_0 - T_L}\right| \tag{3}$$

where Q_v is the water exchange at z depth, T_0 is the measurement of the temperature at the upper sediments; $\rho_0 c_0$ is the volumetric heat capacity of the fluid; and T_L is the constant groundwater temperature.

3.2 Determination of water exchange patterns

The water exchange pattern is determined using the conceptual diagram (Figure 3), and in this method the water-thermal transport is based on the steady state (Anibas *et al*., 2011). In present study, the upper sediment temperature varies with the testing sites, and the lower temperature is groundwater temperature which is constant. When the groundwater discharges the surface water, the heat would transport from deep depth to the interface between surface water and sediment, showing the upward flux. When the surface water recharges the groundwater, the heat would transport into the sediment, displaying the downward flux.

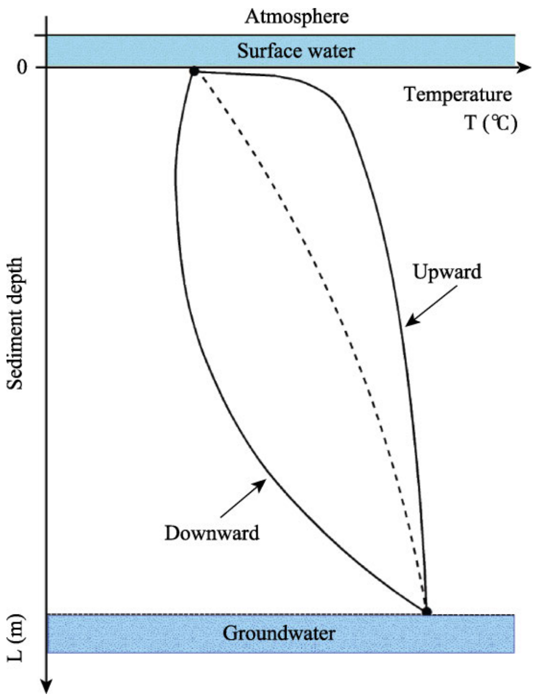

Figure 3 Conceptual diagram using vertical temperature distributional profile to determine hyporheic water exchange pattern (modified from the study by Anibas *et al*. (2011)

4 Results

4.1 Temperature profiles and water exchange patterns

Figure 4 summaries temperature profiles and water exchange patterns at the ten testing sites (points) within the SWP. The maximum of the sediment temperature is 8.7℃ in the 0.8 m depth at point 3; the minimum is 3.3℃ in the upper layer at the point 4. The average temperature of the upper layer and the deepest layer ranges from 5 to 8.3℃. There exists a strong upward flow from the groundwater to surface water at the points 1–3, especially at the point 1. Inversely, there exists a downward flow from the surface water to groundwater at points 5–9. However, at points 4 and 10, the water exchange pattern shows two patterns, meaning that water exchange patterns differ in depth.

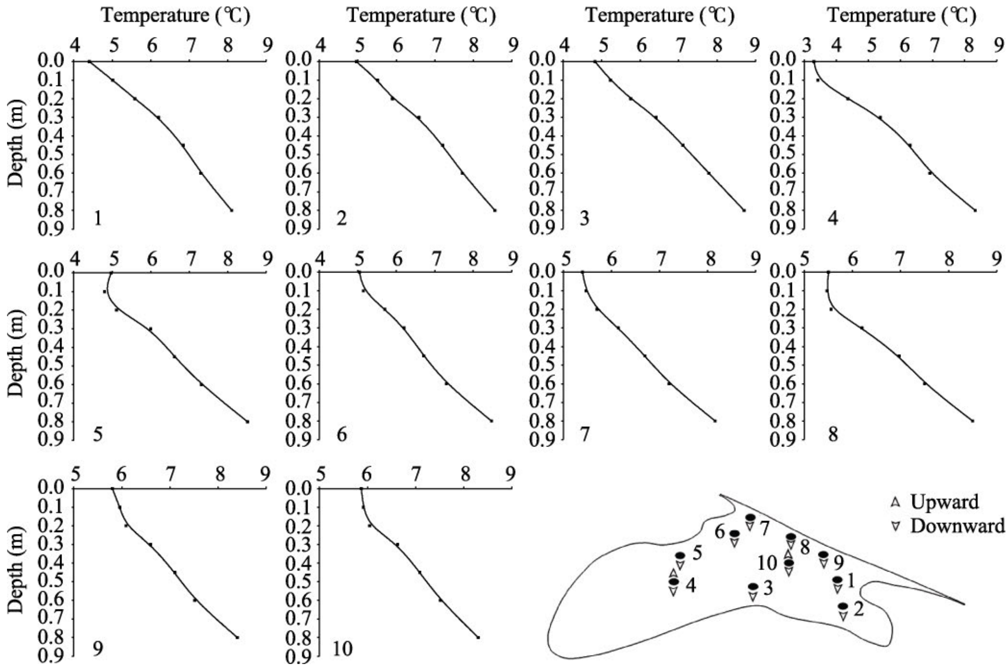

Figure 4 The analysis of the temperature of the sediments and schematic diagram of hyporheic water exchange patterns in the slack water pool

The belt (e.g., the points 7–9) connects the main river channel and the body of SWP (Figure 2b). The temperature-depth profiles would represent the interactions between groundwater and stream water, which oscilloscope apparently very flexible in certain depth (about at 0.2 m), and the temperature tends to the violation of the thermal steady state assumption in this range (Conant, 2004).

4.2 Hyporheic water exchange in the SWP

Figure 5a shows the water exchange magnitude in the SWP. The water exchange can be divided into three categories: high fluxes (including points 1, 2, 3 and 4), moderate fluxes (including points 5 and 6) and low fluxes (including 7, 8, 9 and 10).

There exists a significant relationship between surface water temperatures and the water exchange magnitudes (Figure 5b), indicated by $R^2 = 0.78$. The maximum water exchange is about 35.7 mm/d occurring at point 4, where the minimum surface water temperature of 3.7 ℃ is observed. The maximum surface water temperature is 5.8℃ at point 6 where the water exchange is 14.0 mm/d.

4.3 Spatial pattern of HZ water exchange within the SWP

Figure 6 shows the spatial pattern of water exchange within the SWP. There exists significant spatial pattern. Firstly, the water exchange close to the opposing flow-direction bank (points 1, 2 and 3) is stronger, and the mean of water exchange magnitude is 34.76 mm/d, about 1.6 times of the mean of 21.93 mm/d that close to the flow-direction bank (points 5, 6 and 7). Secondly, the water exchange becomes stronger when the location within the SWP is farther from the main channel.

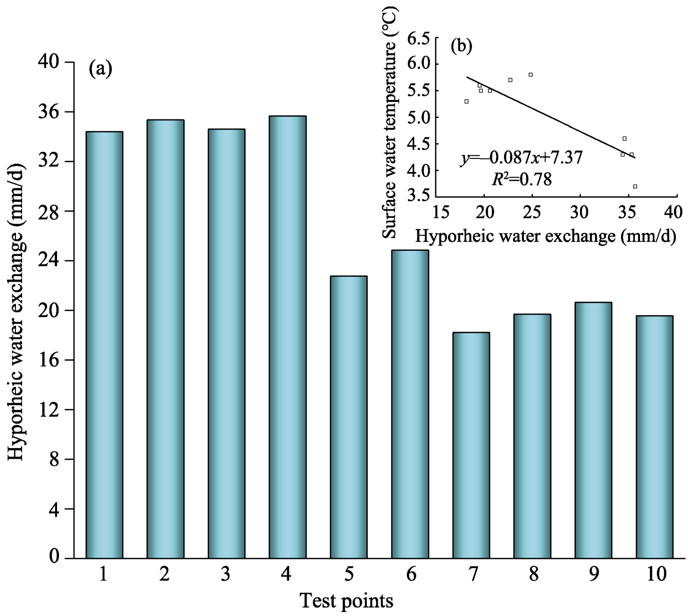

Figure 5 The hyporheic water exchange magnitude (a) and its relationship between surface water temperatures in different positions (b)

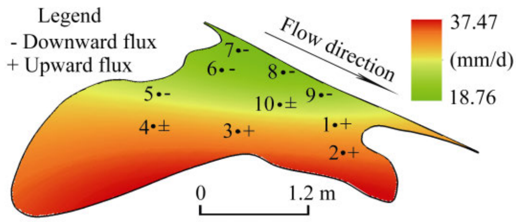

Figure 6 Spatial pattern of hyporheic water exchange within the slack water pool

5 Discussion

5.1 Temperature variations

Various elements can affect the temperature gradient changes due to the structural features of SWP, the main dynamics including spatiality of the runoff, hydraulic conductivity, and fluctuation from surface flow and wind. As an important characteristic link to the runoff, the spatial rainfall variability has impacts on the hydrogeological response (Sapriza-Azuri *et al*., 2015), and features directly affect the evolution of groundwater heads, and thereby influencing the surface-subsurface water exchanges (Trauth and Fleckenstein, 2017). In some regions, the intense precipitation over arid areas in a long time is associated with divergent flows (Kumar *et al*., 2015), when the flow merges in a catchment in a short time, and the water body in the micro-topography structures may be subject to intensive variations than normality. Meanwhile, the hydraulic gradient along the sediment-water interface is highly sensitive to the spatial structure of bedforms (Min *et al*., 2013; Chen *et al*., 2015), when the interface is influenced by the surface water flow, there would appear the fluctuation of pressure gradient, turbulent water flow from main river channel and the withdraw water into the river channel, which from the SWP edge would form a merging flow, this process would create the convection for the surface water. Furthermore, changes of minerals and grain sizes attributes in natural sediments (Rau *et al*., 2014) are combined with fluctuation from flow and wind, the heat rearrangement will take place within the SWP (Peralta-Maraver *et al*., 2018).

5.2 Drivers of water exchange pattern within the slack water pool

Two factors are potential contributors to exchange pattern in SWP: including that (1) the location in this system, and (2) the water status. There exists a series of the bends between the SWP and river bank. The water path in the subsurface can be more complicated than one direction river channel and have more direction changes, the groundwater discharge would be disturbed by this flow path. The meander bends of the stream can generate the near-stream flow paths according to their direction for the local groundwater network (Larkin and Sharp, 1992; Wroblicky *et al*., 1998). The location in the SWP has various meanders, hyporheic water exchange has the response to the flow variations resulted in topographic structures. For instance, some studies have revealed that the hydraulic properties of stream flow can induce the changing water exchange in the streambed and river banks (Malard *et al*., 2002; Tonina and Buffington, 2007; Zhang *et al*., 2016). The distribution of uniform groundwater flow leads to the dissolved substance variations in liquid phase and has relevance with the permeability (Koch and Nowak, 2015), so water exchange has feedback on the varieties of hydrological exchanges in river corridor.

Locations in the SWP influence the distribution of energy and create the changes of the properties in the sediment such as bubbles. Bubbles within porous media have an essential role in groundwater flow into the saturated zone (Ramirez *et al*., 2015). Conversely, in gaining river systems, the storm events can cause the changes of catchment size and shape, and form a temporary reversal of vertical hydraulic gradients, leading to surface water infiltration into the subsurface (Dudley-Southern and Binley, 2015), and then influence the groundwater discharge (Malcolm *et al*., 2006; Boano *et al*., 2008). However, the upwelling groundwater can block surface water infiltration (Gerecht *et al*., 2011), potentially reducing the nutrient attenuation capacity of the hyporheic zone (Rivett *et al*., 2008). The incomplete knowledge of aquifer properties under the surface water at few depths creates a problematic uncertainty (Josset *et al*., 2015). The groundwater table mainly influences the water body and the water flow from the river in HZ (Trauth and Fleckenstein, 2017). In the area close to the river bank, those two mechanisms would be separated by higher groundwater table generated from riparian. Another one, the flow velocity is relatively low and water status within the SWP is relatively steady. The water exchange in this condition is different from the flow individually controlled by main river channel or groundwater discharge. The water exchange gradient would be varied when the river water infiltrates this sediment system. In a period, the groundwater level is correlated to water volume and river recharge into this system. The flow of slightly compressible fluids through fractured rocks is of fundamental importance to groundwater (Kuhlman *et al*., 2015). The surface flow can propagate into the SWP; this may be associated with the system state and lateral sediments (Nazemi and Wheater, 2014; Wang *et al*., 2017).

Heterogeneity of the sediment and slope changes from the bank to the river channel would also lead to the spatial patterns of water exchange within the SWP. The complex sediment structure influences the water exchange greater than the homogeneous sediment structure (Conant Jr *et al*., 2004), the sediments with fine-sort particles are relatively uniform media and tend to have a good path. The sediment structure in the SWP is more heterogeneous than uniform riverbed, the sediment structure characterized by uneven spatial distribution and can drive the HZ water exchange pattern changes (Bellin *et al*., 2015). In the SWP, the element influencing the HZ water exchange is more variable than smooth river bank line. For instance, the vertical hydraulic conductivity is distributed spatially in different parts like in meandering riverbed (Jiang *et al*., 2015; Pozdniakov *et al*., 2016), the pore-scale processes and structures are the mechanisms leading to sediment structure changes (Schmeeckle *et al*., 2007). And from the distance the SWP to the main river channel, the HZ water exchange is strong near the river bank. This may be related to the pressure from the bank and the groundwater to the SWP. However, the mean particle friction does not vary systematically with bed slope in steep channels (Prancevic and Lamb, 2015). In the SWP, there exists a steep area with the rise of the river bank and forms a slop increase, the streambed sediments and the groundwater path would response to the slop within the SWP, pore in this streambed sediment subject to increase due to the decline of the water saturation degree. The water exchange process is characterized by complex spatial dynamics under the attributes of geomorphologic units (Boano *et al*., 2010; Doble *et al*., 2012), the characteristics of the sediment property and slope relative to the river bank are important for the spatiality of the HZ water exchange in the SWP (Gualtieri *et al*., 2017; Ianniruberto *et al*., 2017).

6 Implications

The challenge remaining for future work is to determine the extent to which pattern of the SWP can be most influenced by the water exchange and how to estimate this degree. Despite these compelling properties exhibited by SWP, several limitations may be attributed to the application of the one-dimensional equation. This method is more focused on the vertical exchange in this area, and the consideration for water exchange from the lateral zone is insufficient.

7 Conclusions

This study investigates the hyporheic water exchange in slack water pool using the thermal method. We found that hyporheic water exchange is mainly controlled by the location and water status in a slack water pool. There exists substantial spatial pattern on water exchange within slack water pool. River recharge dominates the water exchange in the area close to the flow-direction bank; while groundwater discharge dominates the water exchange in the area close to the opposing flow-direction bank. Furthermore, the exchange becomes stronger with the location farther from the main river channel.

The thermal approach provides an efficient method to determine the water exchange pattern, calculate the water exchange magnitude, and obtain the spatial information in some more complex geological structures. But for a slack water pool, there are some uncertainties due to the river flow and other artificial constructions such as a dam. The impact of constructions along the stream and the scale of slack water pool for the river channel have a very different influence on the results. In the future studies, care must be taken when comparing the data from the new conditions to probe more information driving the hyporheic water exchange.

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