

Study of heterogeneous vertical hyporheic flux via streambed temperature at different depths

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Abstract The hyporheic flux can be characterized using the heat-tracing method. Based on the analytical solution of the one-dimensional steady-state heat transport equation under vertical groundwater discharge conditions, hyporheic flux was obtained via a curve fitting method. The temperature data used was obtained from monitoring three different sections of the DaWen River, Shandong Province. The distribution of the depth of the hyporheic zone was analysed by a curve relating groundwater temperature and the depth of the hyporheic zone. The study results showed that the vertical hyporheic flux was significantly heterogeneous along the three sections. The hyporheic flux ranged from 99.61 to 356.25 L/m² per day. In the summer, the low temperature area on streambed profile was in accordance with the high value areas of hyporheic flux. There were several strong discharge zones within the same section and these flux values were normally distributed. The depth of the hyporheic zone was inversely proportional to the hyporheic flux and the hyporheic zone depth, also, presented great spatial heterogeneity.

Key words hyporheic flux; heterogeneity; heat transport equation; temperature profile; hyporheic zone depth

1 INTRODUCTION

As the interaction and transition zone of surface water and groundwater, the hyporheic zone plays an important role in the hydrological cycle (Brunke and Gonser 1997). Hyporheic exchange affects the constitution of water resources along the riverbank and ecological function of the transformation interface between river and groundwater (Wang *et al.* 2007). Having a clear understanding of the processes and characteristics of hyporheic exchange is of great significance in evaluating and exploiting water resources, as well as for maintaining and restoring the surface water-groundwater ecological system. Hydraulic characteristics of natural aquifer media have significant heterogeneity and spatial variability.

Research methods for hyporheic exchange flux include direct measurement, methods based on Darcy's laws and mass balance approaches (Kalbus *et al.* 2006). In recent years, the heat tracing method has become popular due to rapid development of temperature measurements in simulation methods. The heat tracing method involves burying a thermometer down a borehole or in water-bearing media to obtain continuous observed data that reveals the characteristics of water flow movement and heat transportation; hence, the hyporheic flux can be achieved easily, rapidly and accurately. The heat tracing method can be applied in analysing exchange of hyporheic flux, recharge and discharge rates from interactions between surface water and hydraulic conductivity of streambed sediments (Anderson 2005). Conant (2004) and Schmidt *et al.* (2006) measured the temperature profiles at specific depths of a streambed and calculated groundwater discharge. However, there is little accurate depiction and quantitative analysis of the heterogeneity characteristics of hyporheic flux in existing studies (Hatch *et al.* 2006, Ferguson 2007, Lautz *et al.* 2010), and the depth of the hyporheic zone is rarely mentioned.

This study, therefore, monitored the streambed temperature of DaWen River, which is a typical natural river in the Wenshang County of Shandong Province. The heterogeneity characteristics of the general hyporheic exchange process of this streambed was analysed by means of the heat tracing method. Also, spatial distribution patterns of the hyporheic flux and hyporheic zone depth were analysed.

2 METHODS OF HYPORHEIC FLOW CALCULATION

The basic assumption is that surface water and groundwater mainly exchange vertically within the riverbed. The governing equation for one-dimensional steady-state heat transport in the saturated

porous media (Bredehoeft and Papadopolus 1965) is:

$$\frac{K_{fs}}{gc} \frac{\partial^2 T(z)}{\partial z^2} - \frac{g_f c_f}{gc} \frac{\partial T(z)}{\partial z} q_z = \frac{\partial T(z)}{\partial t} \quad (1)$$

where $T(z)$ [$^{\circ}\text{C}$] is the streambed temperature at depth z ; t [s] is time; q_z [m/s] is vertical hyporheic flux, which is the hyporheic flux; rc [$\text{J}/(\text{m}^3\text{K})$] is the volumetric heat capacity of the solid-fluid system given as $rc = nr_f c_f + (1 - n) r_s c_s$ where $r_f c_f$ is the volumetric heat capacity of the fluid and $r_s c_s$ is the volumetric heat capacity of the solids; n [-] is the porosity; and K_{fs} [$\text{J}/(\text{s m})$] is the thermal conductivity of the saturated sediment.

If the upper and lower boundary conditions are $T = T_0$ for $z = 0$, and a fixed temperature T_L for $z = L$, where L is the depth of the hyporheic zone, the solution for equation (1) can be obtained:

$$\frac{T(z) - T_0}{T_L - T_0} = \frac{\exp(-\frac{q_z g_f c_f}{K_{fs}} z) - 1}{\exp(-\frac{q_z g_f c_f}{K_{fs}} L) - 1} \quad (2)$$

where T_0 is the temperature of the surface water and T_L is the temperature of the groundwater. The range of K_{fs} is 1.4 to 2.2 $\text{J}/(\text{s m})$. K_{fs} was set to 2.0 $\text{J}/(\text{s m})$ and $r_f c_f$ is equal to $4.2 \times 10^6 \text{ J}/(\text{m}^3\text{K})$, cited by Stonestrom and Constantz (2003).

The measured temperature of every vertical line varies with depth and satisfies:

$$T(z) = c + a \times \exp(-b \times z) \quad (3)$$

where a , b and c are unknown parameters. Through minimizing the sum of the squares of deviations between the measured and calculated temperatures via the curve fitting, the parameter q_z and T_0 of each line on the profile can be obtained. The process of curve fitting was accomplished using a Matlab code.

3 IN SITU TEMPERATURE MONITORING

3.1 Weather, hydrological and geological conditions

The test site is located in the DaWen River of Wenshang County in Jining City, Shandong Province, at about 2 km distance from the dam of the PiPa Mountain (Fig. 1). The type of climate in the DaWen watershed is from semi-humid to temperate continental monsoon. The average annual temperature is 12.9°C and the average annual rainfall is 694.0 mm. Most of the precipitation rains during the flood period. Runoff mainly occurs during the flooding period, with over 80% generated between June and September. Natural runoff is quite scarce in the dry season and therefore, most of the river segments tend to dry out. The streambed sediments were, mostly, composed of gravel from the grain size analyses tests.

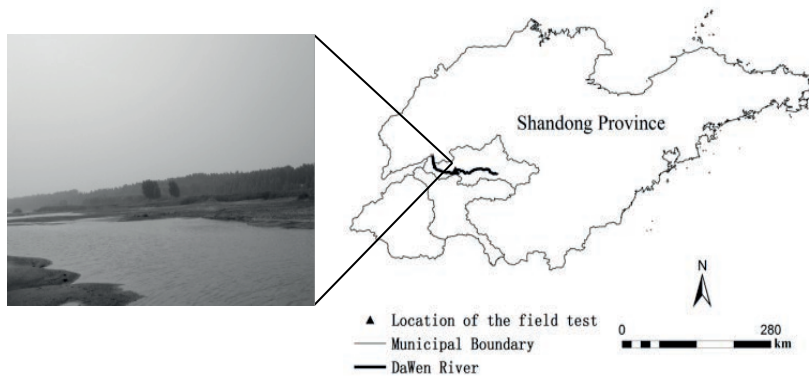


Fig. 1 Location of the test site in Shandong Province.

3.2 Schedule of streambed temperature monitoring

The *in situ* temperature monitoring was conducted from 4th to 7th June 2012. The thermodetector used for the test is made up of a probe, a thermometer and a sensor. Three sections were investigated on the south bank of the river. The space between each profile was 25 m. Sections A, B and C ranged from east to west along the river. Figure 2 shows the location of the test profiles and the distribution of monitoring points in one test profile. The space between each vertical line was 0.1 m, and five points were measured at each vertical line at an interval of 0.1 m. Owing to the small variation of water temperature, a steady temperature field was obtained at each section.

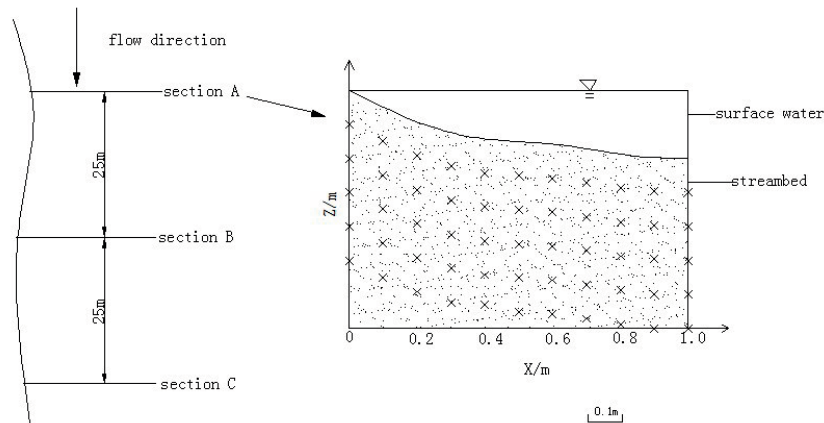


Fig. 2 Location of the test sections and the distribution of sampling points.

4 RESULTS AND DISCUSSION

4.1 Streambed temperature profile

Figure 3 shows the temperature profiles of sections A, B and C. The $x = 0$ m is the interface of the river and bank. The horizontal measurement range is 1 m for profiles A and C, and 1.4 m for profile B. The streambed temperatures of the three profiles ranged between 22.5 and 28.7°C. The

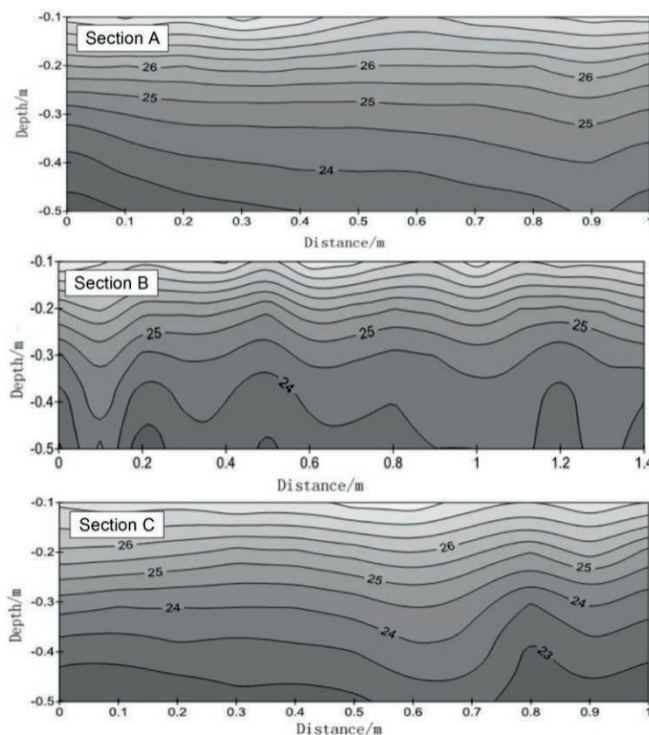


Fig. 3 Temperature profiles (°C) for the sections A, B and C.

temperature of profile B below 0.3 m from the streambed had high variability. The fluctuation tendency of streambed temperature was markedly different at 0.8 to 1 m from the bank of the river (Fig. 3). The gradient of temperature in each profile reduced gradually from the top to bottom of the streambed, illustrating that the deeper the streambed depth, the more stable the temperature.

In summer, major groundwater discharge zones are indicated by relatively low streambed temperature (Schmidt *et al.* 2006). The first and second discharge zones were located at between 0.2 to 0.5 m and 1.1 to 1.3 m in profile B.

4.2 Hyporheic exchange flux

The calculated flux was positive (Fig. 4), indicating that the flow direction is upward. Four comparisons of the observed and fitted results for the maximum and minimum hyporheic flux are presented in Fig. 4. When the hyporheic flux is larger, the temperature converges more rapidly with the depth. In other words, the larger the hyporheic flux, the shorter the distance from the streambed surface to the location with stable temperature.

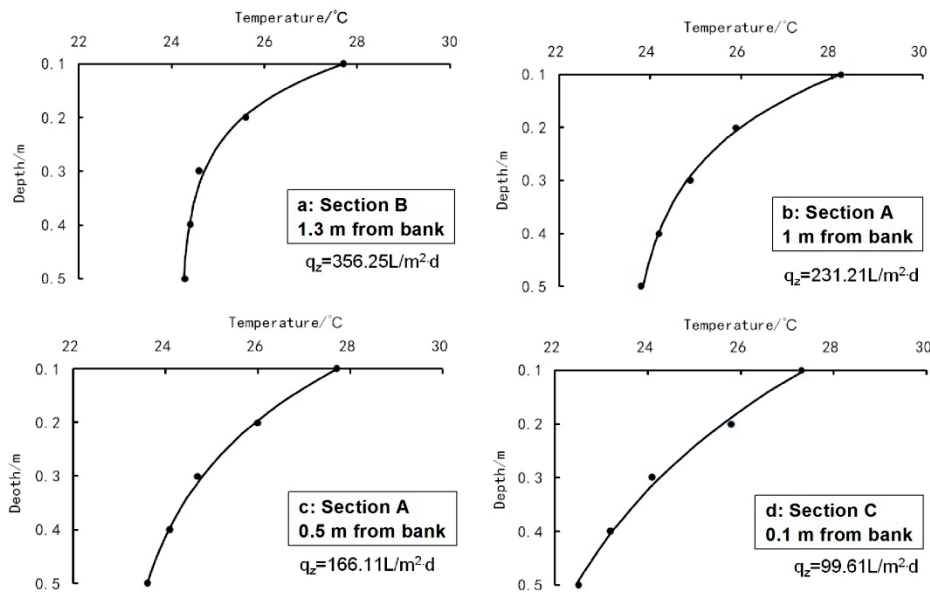


Fig. 4 Curve fitting of measured temperature at the test site.

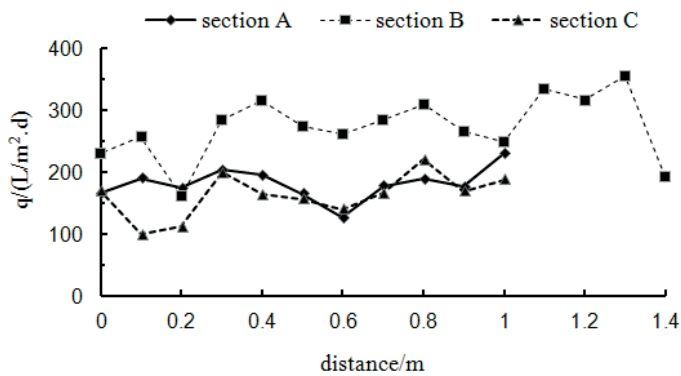
Table 1 summarizes the statistical characteristics of the hyporheic flux. The mean value was 213.23 L/(m²·d) and ranged from 99.61 to 356.25 L/(m²·d). The maximum value was 356.25 L/(m²·d) at 1.3 m distance from the bank of profile B, while the minimum was 99.61 L/(m²·d) at 0.1 m from the bank of profile C. In general, 50% of the total hyporheic flux ranged between 70 and 210 L/(m²·d). Samples of all and each of the profiles were normally distributed via a non-parameter single sample test.

The different profile distributions of the hyporheic fluxes are plotted in Fig. 5. Three high discharge zones ranging between 0.3 to 0.5 m, 0.7 to 0.9 m, and 1.1 to 1.3 m were confirmed as the major discharge zones from streambed temperature (Fig. 3). The hyporheic flux increased slightly from the bank to the river with high variability. The hyporheic flux varies with the quantity of flow, gradient, streambed topography, permeability of sediment and slope of the river (Harvey and Bencala 1993). The spatial variability is influenced by the heterogeneity of hyporheic zones under conditions of little change in topography and steady flow at one site. The homogeneous streambed might lead to less significant preferential flowpaths and, thus, lower maximum fluxes. Therefore, the more remarkable heterogeneity has a bigger flux (Schmidt *et al.* 2006).

Table 1 Hyporheic flux distribution statistics in the three sections.

$q_z / (L/m^2 \cdot d)$	A	B	C	All samples
Max	231.21	356.25	220.51	356.25
Min	127.23	161.22	99.61	99.61
Mean	182.06	273.17	162.65	213.23

Frequency histogram and normal distribution curve				
Normality test (K-S)	pass	pass	pass	pass

**Fig. 5** Hyporheic flux distribution of the different sections.

4.3 Temperature of groundwater and the depth of hyporheic flux zone

Generally, large hyporheic fluxes occur in places where connectivity between the surface water and groundwater is good, indicating that the depth of hyporheic flux was smaller. As illustrated in Fig. 6, the temperature of streambed attenuated rapidly under the surface of the streambed, within 1 m, and then become steady. The gradient of groundwater temperature was set to 0.01 and 0.001 °C/m, respectively. Determining the depth of the hyporheic zone was based on an increased sequence arrangement of groundwater temperature and joining the points smoothly. The depth of hyporheic zone was indicated by mean values of 1.65 and 2 m from the two temperature gradients. The minimal depth of the hyporheic zone was 0.95 m in the location where the maximum hyporheic flux occurred based on the gradient of 0.01 °C/m, as illustrated in Fig. 6(b). Similarly, the maximum depth of hyporheic zone was 2.95 m in the location where the minimal hyporheic flux occurred based on the first standard as illustrated in Fig. 6(c). The above was associated with the conclusion that the larger the hyporheic flux, the smaller the depth of the hyporheic zone. The temperature of groundwater ranged from 20 to 24 °C, which was approximately 10 °C below surface water temperature.

5 CONCLUSIONS

This study calculated hyporheic flux based on the governing equation for one-dimensional steady-state heat transport with the direction of groundwater discharge via a heat tracing method. There were major discharge zones in the measured profiles. The hyporheic flux had spatial heterogeneity,

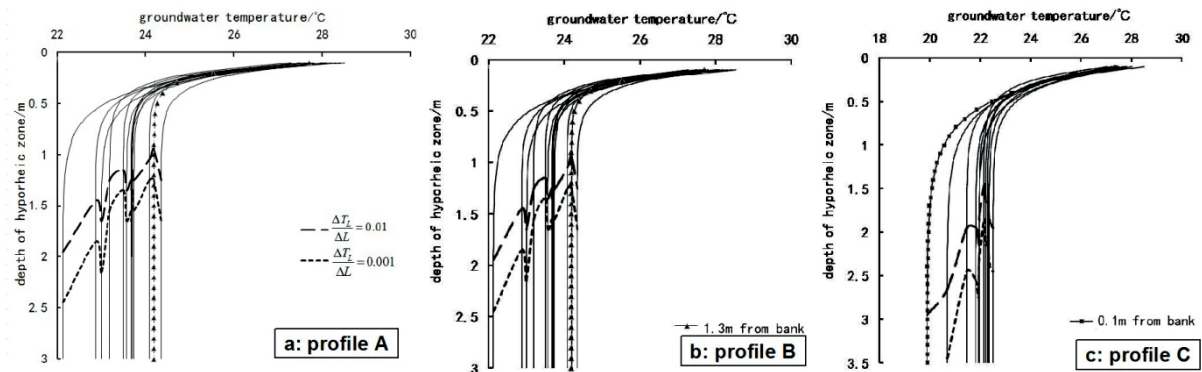


Fig. 6 Hyporheic zone depths and groundwater temperatures relation curves.

and the heterogeneity within the river was more remarkable than the riverbank, which confirmed the validity of studying heterogeneity of hyporheic flux via heat tracing method.

The high discharge zones determined by low temperature zones of the observed streambed temperature profiles were in line with big flux zones calculated from analytical solutions.

The depth of the hyporheic zone was inversely proportional to the hyporheic flux. The bigger the hyporheic flux, the smaller the depth of the hyporheic zone. The range of the hyporheic zone depth was controlled by the heterogeneity of the magnitude of hyporheic flux.

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