Groundwater discharge downstream of an arid inland river in Northwestern China
Bo Kang, Weihong Dong, Wei Xu and Fengtian Yang

ABSTRACT
Nalenggele River is an inland river located in the arid, fragile ecological environment area in Northwestern China. Groundwater discharge to the river can significantly impact the ecological environment in the Nalenggele River basin, but few hydrogeological studies have been conducted in the inland arid basin. In this paper, two sections were chosen to analyze the groundwater discharge in the downstream of Nalenggele River. Section I–I’ is located in the west of the downstream of this river, while section II–II’ is in the east. Two methods were used to calculate the discharge in section I–I’: Darcy’s law and Modflow simulation. In these two methods, the vertical hydraulic conductivity of the stream sediment is a key parameter, which was determined by a falling-head permeameter test in the river. The results show that the groundwater discharges by the above two methods are very close to the results of a previous study by the 222Rn mass balance method. This is the first attempt to use a field test method to obtain the vertical hydraulic conductivity and the hydraulic gradient, and to illustrate the groundwater discharge in the downstream of Nalenggele River in Northwestern China by classic methods.

Key words | Darcy’s law, falling-head permeameter test, groundwater discharge, Modflow simulation, Nalenggele River

INTRODUCTION
As an important part of water resources in arid regions, groundwater has acted not only as the water supplier that promotes economic development, but also as an active factor that affects the ecological environment. In the fragile ecological environment in Northwestern China, groundwater has an intimate connection with the vegetation ecology, soil salinization and desertification. Under dry climatic conditions in arid inland river basins in Northwestern China, surface water comes mainly from melted snow in mountain areas, discharging into groundwater in desert plains. During the flow, transformation between surface water and groundwater occurs frequently (Wu et al. 2004). Because of the rare precipitation, the discharge of groundwater to surface water is the main factor in maintaining the ecological balance in Northwestern China. Therefore, it is necessary to calculate the discharge from groundwater to river. Several methods, including hydraulic methods (McDonald & Harbaugh 1988; Mitchell-Bruker 1993), field monitoring methods (Sophocleous 1991), numerical simulation methods, and hydrochemical methods (McCarthy et al. 1992; Otz et al. 2003), can be used to estimate the discharge of groundwater to surface water. However, the applications of these methods are limited under specific conditions.

Darcy’s law and Modflow simulation are two classic methods to calculate the vertical discharge of groundwater to surface water. In both of these methods, the riverbed hydraulic conductivity and the values of the hydraulic gradient are necessary parameters. Calver (2001) summarized the characteristics of the riverbed hydraulic conductivities (K)
from various reports and showed a variation of over four orders of magnitude, with a common range of 0.0086 to 86.4 m/d. Therefore, for a given study site, a field test (such as the standpipe test) conducted directly in the section of a river channel is a necessary method to determine the hydraulic conductivity of the riverbed sediment and the values of the hydraulic gradient.

In Nalenggele River basin, the groundwater discharge to surface water is the main freshwater resource and the main factor in maintaining the vegetation’s ecological balance. Because of the poor traffic conditions, few hydrogeological investigations have been conducted and the applications of many of the methods mentioned above are limited to evaluating the discharge of groundwater to surface water. Therefore, in this study, the falling-head permeameter test was used to get $K_v$ and the hydraulic gradient. Darcy's law and Modflow simulation were used to calculate the groundwater discharge. This study offered a solution to quantitative calculation of groundwater discharge in an area with a poor traffic condition.

**STUDY AREA**

The Nalenggele River basin is located in the southwestern part of the Qaidam basin in Qinghai Province, Northwestern China (Figure 1). The largest perennial river in the Qaidam basin, the river originates in the Kunlun Mountains, flows from south to northeast, and disappears into the West Taijinaier Lake and East Taijinaier Lake. The study area lies in the east Kunlun Mountain tectonic zone to the southwest of the Qaidam basin.

Since the Quaternary Period, the plain in front of Kunlun Mountain has been involved in a continuous process of subsidence, leading to the formation of a very thick and loose sediment sequence in the piedmont plain that hosts a porous aquifer system with great water yield. From the sub-mountain region to the foreland of the alluvial–pluvial fan, the lithology of the aquifer changes from coarse-grained pebbly gravel to fine sediment consisting of fine sand, silt, and clay, and the aquifer system changes from a unique phreatic aquifer to multiple confined aquifers (Figure 2). The thickness of the phreatic aquifer in the sub-mountain region is tens of metres, whereas in the groundwater overflow zone at the front of the alluvial–pluvial fan, the total thickness of the phreatic aquifer and multiple confined aquifers extends for hundreds of metres.

Under the control of the geologic structure and geomorphological characteristics, the groundwater depth decreases from more than 100 m in the sub-mountain region to near the surface at the front of the alluvial–pluvial fan where groundwater overflow occurs. When the groundwater flows upwards to the surface of the riverbed, gas bubbles and sand rings can appear in the seepage zone (Dong et al. 2012). During our field work in summer, many sand rings of different diameters were observed at the front of the alluvial–pluvial fan (Figure 3).

The surface water and groundwater are closely related, and water transfers frequently from the sub-mountain region to the front of the alluvial–fluvial fan, which is a typical characteristic of the inland river basins of Northwestern China (Figures 1 and 2). Rivers in the mountainous upper reaches are perennial with recharge from precipitation,
melted ice-snow and groundwater, but rivers in the middle and lower reaches are ephemeral. Most of the river water infiltrates into the aquifer when it flows through the Gobi Desert in the intermountain basin; however, near the uplift zone at the front of the mountain, groundwater discharges into the river and then infiltrates into the aquifer again at the upper zone of the alluvial fan. At the front of the alluvial fan, groundwater overflows to the surface in the form of springs owing to the obstruction of fine sediment, and then after a period of runoff the river disappears into the salt lake or dissipates because of evaporation (Figure 2). Section I–I’ and Section II–II’ are two classic sections of groundwater. In Figure 1, Section I–I’, located on the west side of the alluvial fan, and Section II–II’, located on the east side, are two classic sections of groundwater discharge to surface water.

In this study, an in-situ vertical pipe falling-head experiment was used to obtain the vertical hydraulic conductivity of the stream bed sediment and the hydraulic gradient, and then Darcy’s law and numerical modeling were used to calculate the groundwater discharge to surface water.

When applying Darcy’s law and numerical modeling, the basis is to obtain the permeability coefficient and hydraulic gradient through the vertical pipe waterfall experiment in the field work. Then, using the parameters acquired in the field work based on the abundance of hydrogeological materials, the discharge from groundwater to surface water can be calculated by the Modflow module.

**In-situ vertical pipe waterfall experiment**

In this experiment, a transparent plastic tube, 150 cm in length, 5.0 cm in inner diameter and 0.1 cm in pipe thickness, was pressed vertically into the riverbed sediment to a design depth of around 50–70 cm, and a column of unconsolidated riverbed sediments with a length of \( L_1 \) was formed in the tube. To reduce the disturbance to the riverbed, the tube was knocked down at a constant velocity. River water was added to the tube from the top opening, and the hydraulic head began to fall; hydraulic head readings were recorded over a given time period and used for calculating \( K_v \) for this sediment column. The test stopped when the hydraulic head reached a near equilibrium inside the tube. The riverbed \( K_v \) values for
the tested locations were calculated using Equation (1) (Hvorslev 1951).

\[ K_v = \frac{\pi D/11m + L_v}{t_2 - t_1} \ln(h_1/h_2) \]  

(1)

where \( L_v \) is the length of sediment core in the tube; \( h_1 \) and \( h_2 \) are the hydraulic head inside the tube measured at times \( t_1 \) and \( t_2 \), respectively, \( \pi \) is the circumference ratio, \( D \) is the interior diameter of the tube, and \( m = \sqrt{K_h/K_v} \). \( K_h \) is the horizontal hydraulic conductivity of the riverbed sediment around the base of the sediment core. In this calculation, \( K_h \) was unknown. The research of Chen (2000) showed that \( h \) was a slight effect of \( K_h \). When \( L_v/D > 10 \), for the isotropy \( m \) is equal to 1 and for the anisotropy \( m \) is equal to 10 (Chen 2009). The error value of the two different \( m \) is less than 5%.

These two sections, where groundwater discharges to the surface water, were chosen to do the in-situ vertical pipe waterfall experiment (Figures 2 and 4). The width of section I-I’ was 51 m. The width of section II-II’ was 32.4 m. There were 15 test points in section I-I’, and eight in II-II’. The radius of influence in each section could be calculated by empirical formula \( R = 2S\sqrt{HK}(S \text{ is the drawdown of the groundwater, } H \text{ is the aquifer depth, } K \text{ is the hydraulic conductivity of the aquifer). The radius of influence was about 3 m in section I-I’ and 2.7–7.3 m in section II-II’}. The horizontal space between every test point was 3 m in section I-I’ and 2.7–7.3 m in section II-II’.

**Estimation of groundwater specific discharge using Darcy’s law**

**Darcy’s law**

Given the values of hydraulic gradient \( i \) and vertical hydraulic conductivity \( K_v \) at each test location, the specific discharge is calculated using Darcy’s law:

\[ Q = -i \times K_v \]  

(2)

Multiplication of \( Q \) by the surface area of the riverbed gives the volumetric rate of subsurface flow discharge or the volumetric rate of river water infiltration. The hydraulic gradient \( i \) could be calculated by \( i = \Delta h/Lv \). For calculating the groundwater discharge in one section of the river, the space between two test points was chosen as the radius of influence. Then the calculated result \( Q \) of every test point could represent the section within the radius of influence. The groundwater discharge in the complete section could be calculated by all the test point results added together.

**Modflow simulation**

A three-layer hydrogeology conceptual model was established. The first layer was an unconfined aquifer, the second layer was an aquitard aquifer, and the third layer was a confined aquifer. The parameter which was mentioned in Equation (3) of this model was from the research of Han (2013). A river module was added to the first layer, and the hydraulic conductivity was given by the field test results, which were used in the Darcy’s law. A zone budget module was added to the first layer.

According to the hydrogeological condition, a 2D stable flow model of the groundwater was established. The equations are shown below:

\[
\begin{align*}
K \left( \frac{\partial}{\partial x} (H - B) \right) + K \left( \frac{\partial}{\partial z} (H - B) \right) + \varepsilon &= 0 \quad (x, z) \in D \\
h(x, z, t)|_{\Gamma_1} &= h_1(x, z, t) \quad (x, z) \in \Gamma_1 \\
T_n \frac{\partial h}{\partial n} |_{\Gamma_2} &= q(x, z, t) \quad (x, y, z) \in \Gamma_2
\end{align*}
\]  

(3)
where $D$ is the infiltration area, $H$ is the groundwater level, $B$ is the level of the top of the aquitard (m), $K$ is the hydraulic conductivity (m/d), $T_n$ is the transmissivity in the direction of the normal vector of the boundary, $\Gamma_1$, $\Gamma_2$ is the first and the second boundary condition of the infiltration, $q(x,z,t)$ is defined as the unit flow rate of the second boundary condition (m$^2$/d), and $\varepsilon$ is the recharge and discharge of the infiltration area.

**RESULTS**

$K_v$ values of riverbed sediment

The results of the in-situ vertical pipe waterfall experiment are shown in Tables 1 and 2.

The $K_v$ values of riverbed sediment in section I–I’ vary from 0.3 to 3.2 m/d, with an average value of 1.95 m/d.

The values of $K_v$ in section II–II’ vary from 0.9 to 35.7 m/d, with an average value of 13.6 m/d.

Groundwater discharge

The calculated results $K_v$ and hydraulic gradient $i$ were taken into Equation (2). Then the flow discharge of section I–I’ was 5.34 m$^3$/d (d m) by using Darcy’s law. $K_v$ was taken into the Modflow simulation. A zone budget module was added to the first layer. The result of the zone budget shows that the discharge of groundwater to the Nalenggele River was 7.36 m$^3$/d (d m).

Only Darcy’s law method was used in section II–II’. The result showed that the total discharge of section II–II’ was 58.68 m$^3$/d (d m) and the discharge had great differences at every test point, varying from 0.19 to 25.08 m$^3$/d (d m).

**DISCUSSION**

$K_v$ values of riverbed sediment

In order to test the creditability of $K_v$ by the in-situ vertical pipe waterfall experiment, after the tests, the sediments of the river were collected to do a grain size analysis.

The result of the grain size analysis was compared with the calculated permeability coefficient in Section I–I’, where the riverbed deposits are mostly comprised of silver sand, silt and clay with a particle radius of less than 0.5 mm, with a percentage from 91.01% to 98.36% (Figure 5). In the test point with the lowest water level, the percentage is the minimum with a smaller permeability coefficient, and vice versa.

Particle size analysis for the sediment columns of each test site in section II–II’ shows the riverbed deposit of this section is badly-sorted, in which test points 1 and 4 have the maximum percentage of silt at 41.49% and 56.17%, respectively (Figure 6). However, in the remaining test points, sand is the maximum percentage, with test point 4 having the minimum value at 39.5% and the maximum percentage test point is point 8, with 57.69.

### Table 1 | The $K_v$ values of riverbed sediment in section I–I’

<table>
<thead>
<tr>
<th>ID</th>
<th>The distance of the river band (m)</th>
<th>$K_v$ (m/d)</th>
<th>$L_v$ (cm)</th>
<th>Hydraulic gradient $i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>1.9</td>
<td>2.6</td>
<td>40</td>
<td>0.27</td>
</tr>
<tr>
<td>1-2</td>
<td>4.9</td>
<td>2.2</td>
<td>47.5</td>
<td>0.22</td>
</tr>
<tr>
<td>1-3</td>
<td>7.9</td>
<td>2</td>
<td>46.5</td>
<td>0.20</td>
</tr>
<tr>
<td>1-4</td>
<td>10.9</td>
<td>2.1</td>
<td>39.9</td>
<td>0.23</td>
</tr>
<tr>
<td>1-5</td>
<td>13.9</td>
<td>0.9</td>
<td>46.4</td>
<td>0.23</td>
</tr>
<tr>
<td>1-6</td>
<td>16.9</td>
<td>1.5</td>
<td>54.9</td>
<td>0.23</td>
</tr>
<tr>
<td>1-7</td>
<td>19.9</td>
<td>0.5</td>
<td>38</td>
<td>0.26</td>
</tr>
<tr>
<td>1-8</td>
<td>23.9</td>
<td>2.6</td>
<td>41.2</td>
<td>0.06</td>
</tr>
<tr>
<td>1-9</td>
<td>27.9</td>
<td>0.3</td>
<td>44.1</td>
<td>0.11</td>
</tr>
<tr>
<td>1-10</td>
<td>31.4</td>
<td>1.8</td>
<td>62.3</td>
<td>0.15</td>
</tr>
<tr>
<td>1-11</td>
<td>34.9</td>
<td>2.3</td>
<td>43.7</td>
<td>0.14</td>
</tr>
<tr>
<td>1-12</td>
<td>38.4</td>
<td>2.9</td>
<td>43.2</td>
<td>0.11</td>
</tr>
<tr>
<td>1-13</td>
<td>41.9</td>
<td>2.5</td>
<td>38.6</td>
<td>0.18</td>
</tr>
<tr>
<td>1-14</td>
<td>46</td>
<td>3.2</td>
<td>41</td>
<td>0.20</td>
</tr>
<tr>
<td>1-15</td>
<td>50.8</td>
<td>1.6</td>
<td>50</td>
<td>0.24</td>
</tr>
</tbody>
</table>

### Table 2 | The vertical permeability test result of riverbed sediment in section II–II’

<table>
<thead>
<tr>
<th>ID</th>
<th>The distance of the river band (m)</th>
<th>$K_v$ (m/d)</th>
<th>$L_v$ (cm)</th>
<th>Hydraulic gradient $i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>1</td>
<td>4</td>
<td>46.1</td>
<td>0.10</td>
</tr>
<tr>
<td>2-2</td>
<td>4</td>
<td>0.9</td>
<td>33.9</td>
<td>0.21</td>
</tr>
<tr>
<td>2-3</td>
<td>11.3</td>
<td>16</td>
<td>15.5</td>
<td>0.35</td>
</tr>
<tr>
<td>2-4</td>
<td>14</td>
<td>3.8</td>
<td>27.7</td>
<td>0.26</td>
</tr>
<tr>
<td>2-5</td>
<td>18</td>
<td>16.9</td>
<td>29.3</td>
<td>0.41</td>
</tr>
<tr>
<td>2-6</td>
<td>23.8</td>
<td>1</td>
<td>28</td>
<td>0.47</td>
</tr>
<tr>
<td>2-7</td>
<td>27.8</td>
<td>30.5</td>
<td>33.2</td>
<td>0.62</td>
</tr>
<tr>
<td>2-8</td>
<td>31.8</td>
<td>35.7</td>
<td>24.2</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Through the comparison, the compositions in the test points, test point 2 and 6 have a similar particle composition, with a relatively high percentage of gravel and 40% silt. Test points 1 and 4 have a similar particle composition with both having a higher percentage of silt. The permeability coefficients of test points 3, 5, 7, 8 increase as the percentage of gravel increases. The results of the pipe experiment and the grain size analysis were basically consistent.

**Comparison of groundwater discharges by different methods**

The discharge of section I–I′ was 5.34 m³/(d·m) by using Darcy’s law and 7.36 m³/(d·m) by using the Modflow simulation method. In section I–I′, naturally radioactive ²²²Rn was used to estimate the discharge of groundwater (Su et al. 2013). The result was 7.95 m³/(d·m).

Comprehensively comparing the results from these three methods, we found that the result from Darcy’s law was a little lower than the other two, and the results of the other two methods were close to each other. This was because of the different definition of the hydraulic gradient. For a given time and a given site, the hydraulic gradient should be a constant data. The hydraulic gradient was the test result that was the difference between the surface water and the groundwater level of the riverbed sediment while using Darcy’s law, while in Darcy’s law, the hydraulic gradient was the difference between the river level and the groundwater level of the riverbed sediment. There are some differences between groundwater level of the riverbed sediment and the nearest well. The groundwater level of the riverbed sediment was higher than the nearest well. And when the Modflow simulation was established, the area from the nearest well to the river was also included in the model. The Modflow simulation was calculated by cell and cell. The size of cell and the data for every cell could affect the result directly. According to the radius of influence, the size of the cell was 3 × 3 m in this study. The data of every cell was the result of the field test. This could avoid the effect of \( K_v \). The result of Darcy’s law was a little lower than Modflow simulation. In the ²²²Rn mass balance method, the samples were the river water and the groundwater of the nearest well. These differences could explain why the discharge of Darcy’s law was lower than the Modflow simulation and the ²²²Rn mass balance. Because of the same groundwater resource, the results calculated by using the Modflow simulation and the ²²²Rn mass balance were close. Su et al. (2013) has demonstrated the feasibility and credibility of the ²²²Rn mass balance method. By comparing the results of the three methods, we believed that the results of Darcy’s law and the Modflow simulation methods were credible in the downstream of Nalenggele River basin.

The values of the riverbed sediments’ \( K_v \) in section II–II′ vary from 0.9 to 35.7 m/d, with an average value of 13.6 m/d. These relatively large values of vertical hydraulic conductivity in section II–II′ indicate that the discharge from groundwater to surface water can occur quickly if a vertical hydraulic gradient exists across the riverbed. Because there was no well in section II–II′, a hydraulic coefficient was not observed, such as the groundwater level, and the level
of the top of aquitard. Only Darcy’s law was used to calculate the discharge using the field test results. The result showed that the total discharge of section II–I was 58.68 m³/(d·m) and the discharge had great differences at every test point, varying from 0.19 to 25.08 m³/(d·m). The flow rate of the river, the hydraulic gradient and the depositional condition were all different in the two sections. Thus the different results were reasonable.

In the process of the discharge calculation, a field test of the riverbed sediment was taken before the discharge calculation by the Darcy’s law method. All the calculation parameters could be obtained from the field test. The hydrogeological condition, including aquifer distribution, lithology, groundwater level and surface water level, had to be collected before the conceptual model was established. In order to make the results more accurate, the field test results could be taken into the Modflow simulation. The 222Rn mass balance method is highly sensitive for studying such interactions, even in areas for which conventional hydrologic data are sparse. But at least one well must be near the river. Above all, the Darcy’s law method could be widely applied to areas that lack data. The Modflow simulation method could be applied to data abundant areas.

CONCLUSION

In the downstream of the Nalenggele River, the discharge of section I–I’ was 5.54 m³/(d·m) using Darcy’s law and 7.36 m³/(d·m) using the Modflow simulation method. In section I–I’, naturally radioactive 222Rn was used to estimate the discharge of groundwater (Su et al. 2015). The result was 7.95 m³/(d·m). The results of the three methods were close. The groundwater discharged to the river by volume of 58.68 m³/(d·m) in section II–II’ by Darcy’s law. Darcy’s law was suitable for sites that have little data, like section II–II’ in this study. The Modflow method and radioactive 222Rn were appropriate for fields that have a lot of boreholes and groundwater level observations. As the seepage zone of Nalenggele River, the particle size distribution of the two selected sections differed. The discharge of the left section was lower than the right section. The particle size of the left section was smaller than the right section. The anisotropy and the heterogeneity should be considered when the river seepage zone is analyzed.

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