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Drawdown changes affected by flow rate and location of pumping wells near a river

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Abstract. Riverside groundwater exploitation is one of the main means of utilizing groundwater resources. This paper describes the impact of drawdown conditions with changes in the river flow and pumping well locations, and analyzes the interaction between the groundwater and surface water. Based on long-term hydrological gauging data, abundant hydrogeological test data, and the numerical simulation results for a typical well field of the Qinbei Power Plant, this paper presents three different cases of pumping well locations and four different cases of river flow rates. Finally, the abovementioned cases are integrated into 12 extraction groups and the drawdown conditions are calculated for each group. The results show that, for a given set of flow rate conditions, a location set in a recharge zone exhibited the maximum drawdown, while a location in a transition zone had the second-largest drawdown, and a location in a discharge zone had the minimum drawdown. In addition, assuming the same locations for the pumping wells, the drawdown change from small to large corresponded to 100%, 75%, 50%, and 25% of the original flow. This paper provides a foundation for future study of the calculation of riverside groundwater exploration with changes in the flow rate and well locations.

1. Introduction

Riverside groundwater sources offer various advantages such as good supply conditions, minimal depth, and ease of exploitation and management. Exploitation near a river is beneficial to the development and utilization of water resources. Given the purity of water from the unsaturated zone and aquifer, the quality of the riverside groundwater is generally much better than that of the surface water. Besides, due to the interaction between the aquifer and river water, riverside groundwater provides a high-capacity source of water. Therefore, great importance is currently being attached to the development of riverside groundwater resources.

Although the extraction of riverside groundwater would appear to be the exploitation of groundwater, the main supply source is actually the surface water. Groundwater and surface water always influence and restrict each other, so that there will be a wide variety of uncertainties when performing riverside groundwater exploitation. If there is any irrational exploitation of the groundwater, serious problems could result. Therefore, many researchers have been addressing the issue of riverside groundwater exploitation.

Given the special location of riverside groundwater sources, there is always a degree of interaction between the groundwater and the surface water, which results in a complex internal relationship. Many researchers have attached great importance to this interaction, and have made many valuable discoveries. For example, in 1941, Theis calculated the degree of attenuation on river flow of a

riverside groundwater source [1]. Chen and Yin [2] also used numerical models to analyze the stream flow depletion in stream-aquifer systems with a baseflow. Shu and Chen [3] used numerical models to calculate the water exchange between the river and groundwater in a river-aquifer system. Wang [4] developed a simple, inexpensive instrument that was used to measure streambed parameters under the condition of a stream being disconnected from the groundwater. Wallace [5] proposed problems of stream depletion resulting from the cyclic pumping of wells and developed equations by applying superposition principles to analytical solutions for steady, continuous pumping. Park [6] evaluated the interference and ratio of river water at riverbank filtration pumping wells and claimed that well interference is caused not only by groundwater drawdown but also by pipe headloss, which depends on the flow rate. Wang [7] set up a three-dimensional mathematical model and analyzed the effects of river width, partial penetration, and the permeability of riverbed sediments on groundwater recharges. The results showed that riverside pumping may cause groundwater to flow beneath the partially penetrating river, and that the river width, penetration, and riverbed permeability obviously influence flows from the partially penetrating river and constant-head boundaries.

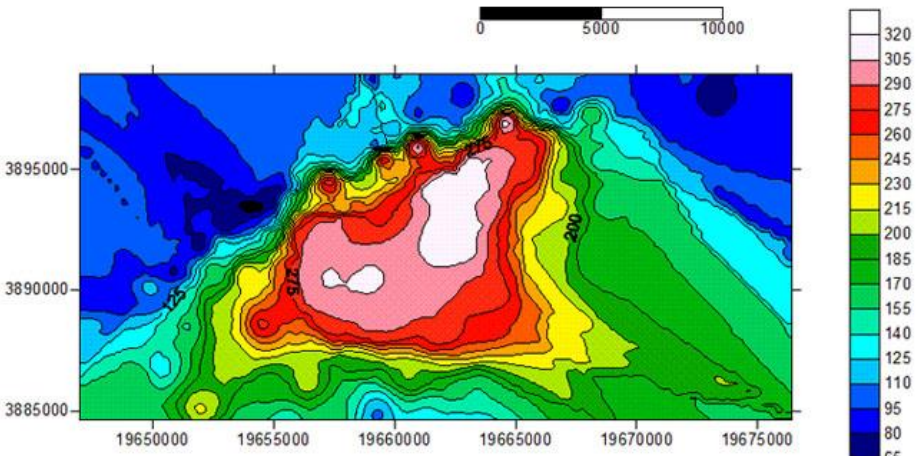
Based on the above research, this study set out to analyze the hydrogeological conditions of a typical riverside groundwater resource area, as a basis for establishing a valid numerical groundwater model. Careful analysis of the groundwater dynamics was performed under different flow conditions and a variety of well locations. The drawdown changes were calculated under different exploited cases. This paper provides the necessary theoretical basis and a specific means of calculating the scientific development of a riverside groundwater exploitation program.

2. Method

2.1. Description of study area

The study area was the Qinbei Power Plant in Jiyuan City, Henan Province, China (Figure 1). The general trend of the local terrain is from north to south, west to east. Taihang Mountain is in the north, and the alluvial sectors of the Qin River are in the south. There is abundant rainfall, and according to data gathered between 1956 and 2000, the average annual precipitation is 644.2 mm. The maximum recorded precipitation was 1027.3 mm in 1964, while the minimum recorded amount was 311.5 mm in 1997.

Location of Study area: Qinbei Power Plant, China



Contour Map of Aquifer Thickness in Qinbei Power Plant

Figure 1. Location and contour map of aquifer thicknessin study area: Qinbei Power Plant, China.

The main river in the study area, the Qin River, has its source in Shanxi Province, and flows from north to south and then though Henan Province, finally emptying into the Yellow River. In this study area, the interaction between the groundwater and surface water changes.

In the area from Wulongkou to Shagou, the groundwater flows in the same direction as the Qin River. Because the river level is higher than that of the groundwater, the groundwater starts to receive seepage from surface water. In the area after Shagou, the riverbed elevation becomes lower and the slope increases. Therefore, the groundwater overflows and drains into the river. The relationship between the groundwater and surface water thus changes. In addition, some of the groundwater will continue flow eastwards of the downstream direction.

The extracted groundwater is mainly used for seasonal irrigation. The total irrigation area is 90,950 acres, of which 50,250 acres are on the left bank. According to the results of previous surveys, the amount of industrial water consumption in the study area is 8,261,480 m3/a, the amount of water consumed as drinking water is 3,586,100 m3/a, and the amount being extracted for irrigation water is

27,058,050 m3/a (a total of 38,905,630 m3/a). Groundwater pollution is not serious. The irrigation wells and flow direction are shown in Figure 2.

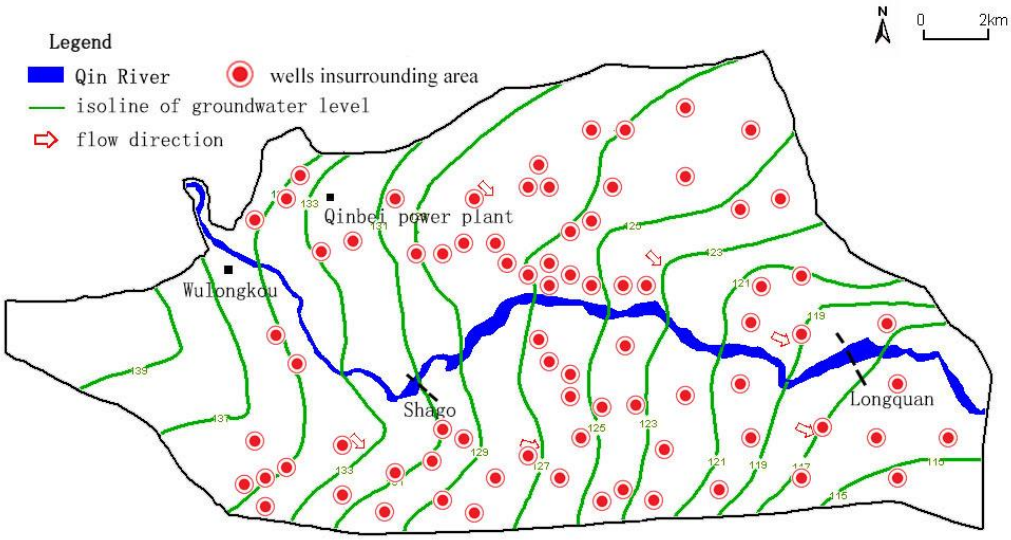


Figure 2. Distribution of surrounding wells and flow direction.

In this study, a numerical model was established by using Visual Modflow software.Modflow, a finite difference method solver developed by USGS, was selected for the groundwater flow model [8]. The solution was based on the finite difference method, and the boundaries were generalized into GHB. The main sources of recharge are lateral inflows, rainfall infiltration, and water seepage. The main discharges are exploitation, evaporation, and the recharging of rivers. As we can see from the groundwater dynamic data, the groundwater level in the area fluctuates in a non-steady state. The internal structure of the study area is non-homogeneous and isotropic, while it can be regarded as being homogeneous in a same parameter partition. The groundwater flow obeys Darcy's law.

According to the hydrogeological conceptual model mentioned above, the corresponding mathematical model can be established as follows:

$$\begin{cases} \frac{\partial}{\partial x}\left[K(H-B)\frac{\partial H}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(H-B)\frac{\partial H}{\partial y}\right]+W-Q_E-Q_V=\mu\frac{\partial H}{\partial t}, \quad (x,y)\epsilon D \\ H(x,y,t)|_{\Gamma_1}=H_1(x,y), \quad (x,y)\in\Gamma_1 \end{cases} \tag{1}$$

$$H(x,y)|_{t=0}=H_0(x,y), \quad (x,y)\in D \tag{2}$$

Where H denotes groundwater level; B denotes elevation of confining bed; K denotes hydraulic conductivity; μ denotes specific yield; W denotes the value of recharge; Q_V denotes the value of exploitation; H_0 denotes initial head; H_1 denotes boundary water level of the calculation period; D denotes the total area; Γ_1 denotes the 1st head boundary.

Based on the vertical distribution information collected in the study area, the aquifer system can be generalized into a single layer and partitioned into 146 rows and 184 columns, the length of each cell is 198 meters and its width is 144 meters. The area of this model is a total of 28,494 m^2. To accurately simulate the groundwater flow in the study area, part of the mesh was refined. Lithologic characteristics and a large number of pumping test data were taken into account. The study area was divided into 15 parameter zones, and the initial values were determined by the pumping test data and experience values. For ease of calculation and comparison, in this paper the value of the extraction was determined to be 1 m^3/s.

2.2. Cases of the flow rate

To illustrate the impact of changes in the drawdown conditions with the river flow, in this paper, four different flow rate are presented, namely, 25% of the original flow, 50% of the original flow, 75% of the original flow, and 100% of the original flow, respectively. Each case would be incorporated into the model, with 10 simulation years being examined to determine the maximum drawdown in the aquifer.

According to the data for the river stage and the runoff between 1983 and 1989 (the minimal-frequency monthly data were omitted), the relationship between the stage and discharge for the Qin River was obtained.

$$h = 6.1\times 10^{-6}Q^3 - 0.0008Q^2 + 141.63 \quad (3)$$

Where h denotes the depth of the water in the river and Q is the runoff.

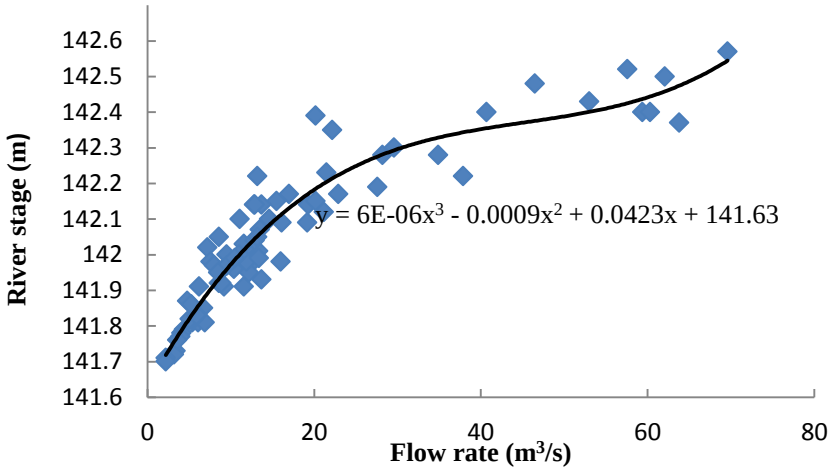


Figure 3. Stage-discharge curve for Qin River.

Given the relationship between the water depth and the discharge, the water depth in the Qin River could be determined for any flow rate provided the flow rate is known.

2.3. Pumping well locations

The locations of the existing wells around the Qinbei Power Plant is haphazard. Any further exploitation of the groundwater in the future will require the development of a scientific exploitation plan regarding the locations of the wells. To calculate the impact of the drawdown conditions with changes in the well locations, three cases were presented, with pumping wells located in the recharge zone, transition zone, and discharge zone, respectively. The extraction rate was set to 1 m^3/s. The simulation time was 10 years. Based on the above, we examined the changes in the drawdown at the end of the simulation. The wells were separated by about 8 km in each case (Figure 4). Observation wells were set up in the middle of the exploited wells. Finally, any changes in the drawdown conditions were recorded in each case.

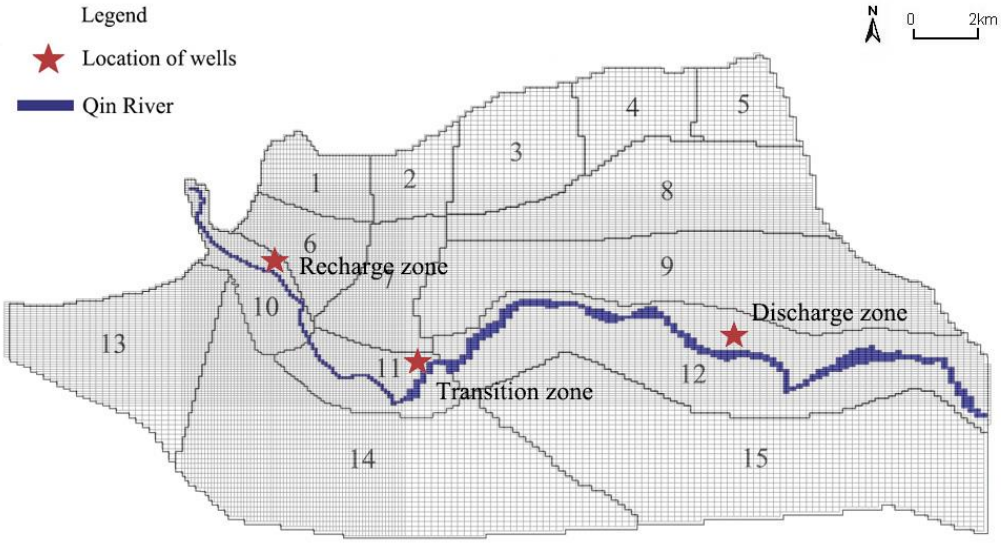


Figure 4. Locations of pumping wells and parameter partitions.

3. Results and discussion

3.1. Output of the model

In this study, a comprehensive analysis of the hydrogeological conditions around the Qinbei Power Plant was undertaken, and a numerical groundwater model was constructed. The model was calibrated and verified by using the data for 1980 to 1982. Wherein: at the end of 1980, the average error between the observed head and the calculated head was 0.868 m, the root mean square was 1.09 m, and the standardized RMS was 7.14%. At the end of 1981, the average error was 0.657 m, the root mean square was 0.812 m, and the standardized RMS was 5.68%. At the end of 1982, the average error was 0.518 m, while the root mean square and standardized RMS were 0.629 m and 4.43%, respectively. These results indicate that the model had been established correctly. Using the numerical model, we did not establish any Qinbei pumping wells, and instead only considered the exploitation of the surrounding irrigation wells. After 10 simulation years, the drawdown condition were as shown in Figure 5.

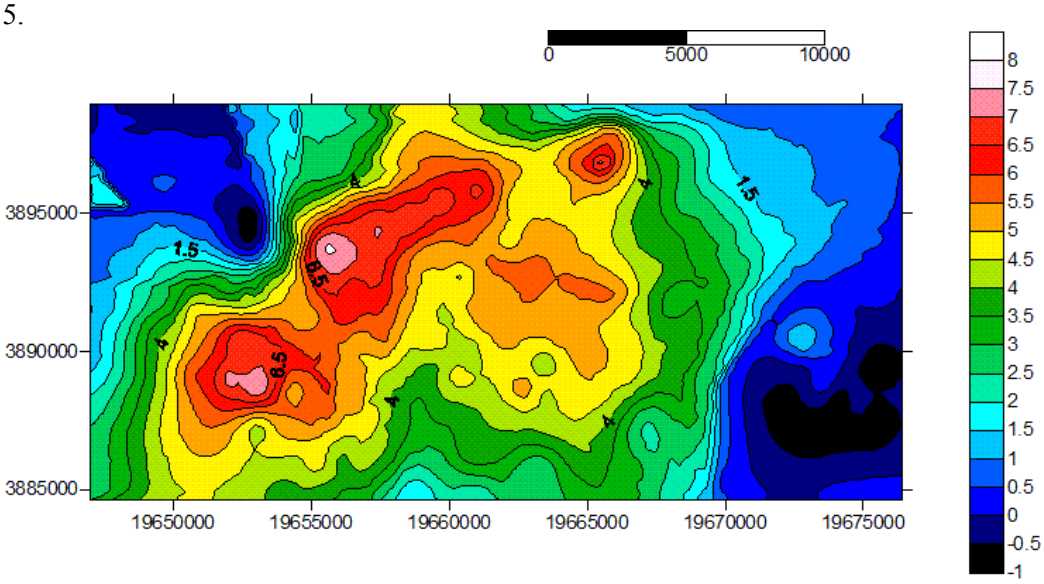


Figure 5. Drawdown conditions after 10 simulation years.

The results of the drawdown showed that the drawdowns in the recharge zone and transition zone were larger, while the drawdown in the discharge zone was smaller. However, to determine whether there is a close relationship between drawdown and the location, the pumping wells should be set in a different location and the simulation performed carefully. In addition, considering the uncertainty of the river flow in the accrual work, observation of the relationship between the river flow rate and groundwater drawdown is necessary.

3.2. Results for different cases

On several occasions, the numerical simulation gives consolidated results for different cases, as shown in Figure 6 and listed in Table 1 (both flow rate and pumping well location).

Table 1. Results of drawdown conditions for different cases.

Percentage of original flow	Pumping well locations		
	Recharge zone	Transition zone	Discharge zone
25%	31.11858	21.69895	19.96265
50%	30.36571	21.2009	19.23537
75%	29.13726	20.0006	18.501
100%	28.93994	19.5062	17.38377

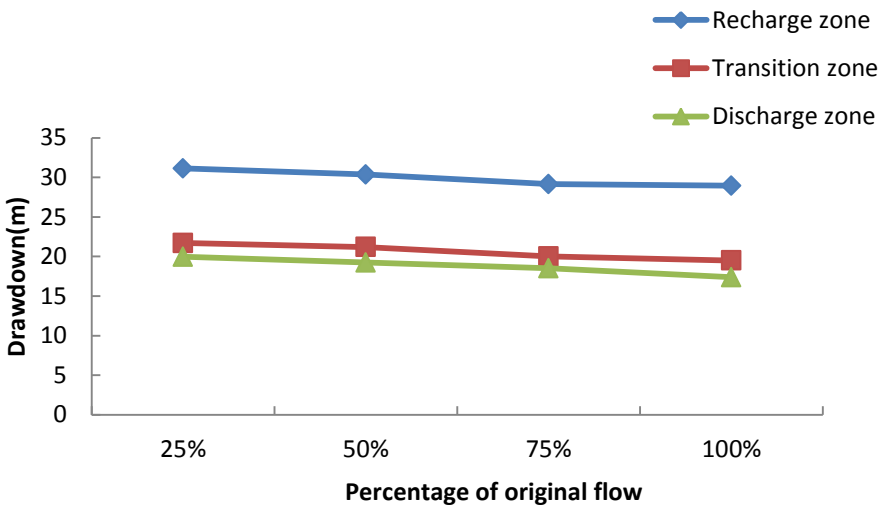


Figure 6. Results obtained for different cases.

Table 1 shows that, when the extraction volume is set to 1 m^3/s, under the same flow rate conditions, the location in the recharge zone has the maximum drawdown, with the value ranging from 28 m to 31 m. The transition zone exhibits the second-largest drawdown, ranging from 19 m to 21 m. The discharge zone is the minimum drawdown area, ranging from only 17 m to 19 m.

As can be seen from the results above, when the pumping wells are located in the recharge zone of the study area, even though the river water level is higher than the groundwater level, the groundwater itself cannot be completely recharged by the river, such that the changes in the drawdown increase. Conversely, when the pumping wells are located in the discharge zone, even though groundwater also supplies the river, the low elevation of the zone means that the groundwater in the discharge zone can be supplied with groundwater from the west, such that changes in the drawdown are minimal. These

results tell us that we cannot completely rely on the supply from the river when exploiting riverside groundwater. If the terrain is higher, and there is considerable lateral outflow, it may not be possible to supply water from the surface quickly enough, causing the drawdown to increase, possibly even causing environmental and geological problems.

In addition, when the extraction volume is set to 1 m^3/s, for pumping wells in the same locations, those corresponding to 25% of the original flow rate have the maximum drawdown, with a value ranging from 19 m to 31 m. For the case corresponding to 50% of the original flow rate, the drawdown is the second-largest, ranging from 19 m to 30 m. Then, the drawdown for the case corresponding to 75% of the original flow rate ranges from 17 m to 29 m. Finally, the drawdown for the case equal to 100% of the original flow rate is the smallest, ranging from 17 m to 28 m.

We can see that, for different flow rates, the results are in line with people's perceptions, that is: if the river flow rate is larger, the change in the drawdown becomes smaller when extracting groundwater. The reason for this is: as the river flow increases, more water is available to recharge the groundwater, thus limiting the increasing trend in the drawdown. However, it can be seen from the results that, when the river flow rate is increasing (or decreasing), changes in the drawdown are not that obvious. In the first part of the study area, the surface water recharges the groundwater; in the latter part, however, the relationship between the groundwater and surface water changed, in that the groundwater started to recharge the surface water. The complex interaction between the groundwater and surface water contributes to the fact that a change in the river flow does not result is a significant change in the drawdown.

4. Conclusions

In this study, a comprehensive assessment of the Qinbei Power Plant groundwater resources was carried out, and a numerical groundwater model was established. Careful analysis of the dynamics of the groundwater for different river flows and different well locations allowed us to determine the changes in the drawdown for each case. The following is a summary of the study and our findings:

- Based on the numerical model, without considering the establishment of any Qinbei pumping wells, and only considering the exploitation of surrounding irrigation wells, the drawdown was calculated for 10 simulation years. The results showed that the drawdown in the recharge zone and transition zone were larger, while the drawdown in the discharge zone was smaller.
- Four different cases, specifically, (1) 25% of the original flow rate, (2) 50% of the original flow rate, (3) 75% of the original flow rate, and (4) 100% of the original flow rate were considered. Each case was input into the numerical model to calculate the drawdown conditions.
- Three pumping well location cases have been presented. Pumping wells were located in the recharge zone, transition zone, and discharge zone. The extraction amount was set to 1 m^3/s. Each case was input into the numerical model to calculate the drawdown conditions.
- Based on the numerical simulations, different river flow cases, and different well locations, twelve groups of drawdown conditions were analyzed. The results show that, for the same flow rate, wells in the recharge zone exhibit the maximum drawdown, those in the transition zone have the second-largest drawdown, while the wells in the discharge zone exhibit the minimum drawdown. In addition, for pumping wells in the same locations, the drawdown changes from small to large for flow rates equal to 100%, 75%, 50%, and 25% of the original flow.

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