Optimization of recharged water quantity of Yufuhe River in Jinan City based on Hydrus-2D Software, China

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Abstract. Jinan, Shandong Province, China frequently faces challenges related to spring protection and water supply security, and managed aquifer recharge (MAR) presents an effective solution to these challenges. Three MAR projects with multiple sources in Yufuhe River in Western Jinan City are conductive to increasing groundwater supply and maintaining groundwater levels. In order to determine the reasonable recharge flows and time, the hydrogeological conditions of the study area were described, the river infiltration recharge processes were simulated by Hydrus-2D software, and the recharge schemes for different groundwater depths were put forward. The results show that the model can achieve the better fitting effect. When the releasing flow is small, the optimal scheme is to continuously discharge water by 286800, 282500 and 282000 m³/d for 19.5, 12.7 and 10.5 days when the groundwater depth is 42, 30, 23 m at Cuima Village respectively. This study has certain significance for the efficient water lease of the Yufuhe River recharge project in Jinan City.

1. Introduction
Managed aquifer recharge (MAR) refers to the purposeful recharging of water in aquifers to facilitate recovery or to generate environmental benefits. As the first study to examine the recharging of groundwater through streams, Boussinesq examined the interaction of streams with a contiguous alluvial aquifer[1]. Recently, MAR has been applied in agriculture, industry and other aspects. In addition, isotope is widely used in the study of groundwater recharge, which plays an important role in accurately analysing the flow direction of recharge water and the relationship between surface water and groundwater[2]. Many scholars in China have made contributions in the development of MAR schemes. For example, Li Hongliang studied the changes of river infiltration volumes of lower Yellow River in 1991-2005 by experiments and mathematical models[3]. According to Zhang Jianyou, wasted water can be recharged to underground using abandoned boreholes and surface water infiltration projects, which can restore overused aquifers[4].

Jinan City frequently faces challenges related to spring protection and water supply security with the urban development. Yufuhe River in the west of Jinan City has good seepage conditions and is an ideal place to implement MAR schemes. Liu Jiang and Li Baoxue carried out quantitative researches on MAR of Yufuhe River, but they mainly used monitoring methods, nobody using numerical simulation methods[5-6]. Thus, in this paper, the maximum water volumes of surface water recharging into karst aquifer were calculated by Hydrus-2D software. Efficient and economical recharge schemes
were put forward and the reasonable recharge flows and times were determined. All those can improve the utilization rate of water resources in the whole basin.

2. Site description
The study area is located in the strong permeable upstream of the Yufuhe River, which extends from Zhaiiertou Village to the North-South Bridge (11.14 km). The river valley is shallow U-shaped, and the floodplain is mainly composed of Quaternary alluvial layer with a thickness of 7-30m. The basin is mainly dominated by soil and medium coarse sand, directly contacting with the underlying limestone. The karst fissures in the underlying limestone are well developed and have good seepage conditions.

3. Hydrogeological model of Yufuhe River

3.1. Hydrogeological conceptual model
A hydrogeological conceptual model was established to provide a basis for numerical simulation. According to the different lithological properties of different reaches in the study area, the reach was divided into four sub-reaches. The flows in different sub-reaches were simulated as two-dimensional flows of vertical sections. The outline of the transverse section at Cuima Village and divisions of sub-reach are shown on figure 1.

![Figure 1. The sub-reaches on study area and generalization graph of cross section in Cuima Village.](image)

3.2. Generalization of boundary conditions
This paper studied the maximum infiltration volume under the premise that there was no open channel flow in the downstream of the strong seepage zone, so the influence of river water level was not considered. Since the running time of the model was short, the influences of rainfall infiltration and evaporation were not considered. The upper boundary where the river is located was constant flow boundary, the other boundaries were the zero flux boundary. In addition, the boundaries of the left and right unsaturated areas were free drainage boundary. What’s more, the lower boundary was always under the groundwater table, which was a variable head boundary.

4. Hydrological mathematical model

4.1. Model discretization
Based on the water release situation of Wohushan Reservoir, March 27–28, July 24–25, and December 7–8 were selected as the simulation periods for the model. These periods represented maximum (scenario 1), minimum (scenario 2), and medium groundwater depths (scenario 3) respectively. As shown in Table 1, each sub-reach was assumed to have the same groundwater depth which was the average depth.
Table 1. Initial groundwater depth of the four sub-reaches in three scenarios.

| Date       | Scenario | A (m) | B (m) | C (m) | D (m) |
|------------|----------|-------|-------|-------|-------|
| 2015.3.27  | Scenario 1 | 22    | 42    | 30    | 35    |
| 2015.7.24  | Scenario 2 | 14    | 23    | 24    | 30    |
| 2015.12.7  | Scenario 3 | 17    | 30    | 26    | 32    |

The simulated area is a vertical 2D area with a size of 800 m × 50 m or 800 m × 100 m. It was divided into several triangular grids by non-uniform triangular meshes at 20 m intervals. According to the actual observation well position, an observation point was installed in the simulation area. The water level changes were used as the basis for the model verification.

4.2. Initial conditions

Based on the measured water level data, pressure head was included as the initial condition in the model. The pressure head on the groundwater surface was zero, below the groundwater surface was positive, and in the unsaturated zone was negative respectively. The pressure head was linearly distributed along the vertical direction of the simulation area. Then the model automatically calculated the initial moisture content at different depths by Van Genuchten’s equation.

4.3. Selection of model parameters

In the three simulations, each period was divided into 10 steps with an interval of 0.2 days. As is shown in figure 2, I, II, and III are parameter zones, which represent different lithological properties. Zone I is sandy gravel layers; zone II represents limestone of Zhangxia Formation, shale of Gushan Changshan Formation and limestone of Fengshan Formation; zone III represents regional loam. According to the measured permeability coefficient, hydrogeological data and related literature, the parameter settings of different sub-reaches can be obtained as shown in Table 2.

![Figure 2. Schematic diagram of parameter zoning.](image)

Table 2. Model parameters of the four sub-reaches.

| Sub-reach | Thickness of quaternary (m) | 0\(\theta_r\) | 0\(\theta_s\) | \(\alpha\) | \(n\) | Ks (m/d) | \(l\) |
|-----------|-----------------------------|---------------|---------------|----------|-------|----------|------|
| A         | 7.5                         | 0.065         | 0.36          | 7.50     | 1.89  | 4.7500   | 0.5  |
|           |                             | 0.068         | 0.19          | 1.20     | 1.09  | 0.4536   | 0.5  |
|           |                             | 0.078         | 0.43          | 3.60     | 1.56  | 0.2469   | 0.5  |
| B         | 12                          | 0.065         | 0.36          | 7.50     | 1.89  | 20.3000  | 0.5  |
|           |                             | 0.089         | 0.25          | 0.98     | 1.23  | 7.2930   | 0.5  |
|           |                             | 0.078         | 0.43          | 3.60     | 1.56  | 0.2469   | 0.5  |
|           |                             | 0.065         | 0.36          | 7.50     | 1.89  | 3.3600   | 0.5  |
| C         | 25                          | 0.070         | 0.09          | 0.50     | 1.09  | 0.0005   | 0.5  |
|           |                             | 0.078         | 0.43          | 3.60     | 1.56  | 0.2469   | 0.5  |
|           |                             | 0.065         | 0.36          | 7.50     | 1.89  | 1.4500   | 0.5  |
| D         | 30                          | 0.086         | 0.12          | 1.00     | 1.13  | 0.4653   | 0.5  |
|           |                             | 0.078         | 0.43          | 3.60     | 1.56  | 0.2469   | 0.5  |
In the model, the input value of the constant flow of the boundary condition was equal to the infiltration volume divided by the area of sub-river. The infiltration volumes of different sub-reaches at different periods are shown in table 3.

| Sub-reach | Area (km²) | Infiltration volume (m³/d) |
|-----------|------------|----------------------------|
|           | March 27   | July 24                   | December 7       |
| A         | 0.1075     | 56430                     | 50320            | 53600            |
| B         | 0.2780     | 225400                    | 221300           | 214300           |
| C         | 0.1235     | 31240                     | 30100            | 32200            |
| D         | 0.0960     | 15200                     | 14380            | 13270            |

4.4. Model verification

According to the measured groundwater levels at three simulation periods, the rising values of the water levels between adjacent time steps were calculated and compared with the measured rising values. Due to the limitation of water release time and water volumes, the simulated and measured water levels did not increase significantly at the sections from Cuima Village to Jinpu Railway Bridge and from Jinpu Railway Bridge to Nanbei Bridge during the three simulation periods, except for Zhaiertou Village to Cuima Village. The karst well in Cuima Village can be automatically observed and the data is continuous. The observation wells are manually monitored from Zhaiertou Village to Dongkema Village, so three monitoring periods were carried out between 9:00 a.m and 20:00 p.m. In Figure 3, a and b denote the sections from Zhaiertou Village to Dongkema Village and from Dongkema Village to Cuima Village respectively. What’s more, 1, 2, and 3 denote the periods of March 27-28, July 24-25, and December 7-8 respectively. This figure highlights excellent fitting effects between the simulated and measured values, showing that all correlation coefficients exceed 0.95. Therefore, the Hydrus-2D model can reliably optimize the recharge quantity of Yufuhe River, which can provide a solid foundation for the next step of the Yufuhe River groundwater recharge project.

5. Simulation of recharge water quantity based on HYDRUS-2D

5.1. Model settings

The three conditions of the maximum, minimum and medium groundwater depths were taken as the input values of initial water levels in different scenarios. Other parameters in the model are shown in table 2. The operation periods of the models were adjusted based on the variation of water levels. When the groundwater levels rose to the bottom of the river, the simulation stopped. At this time, the infiltration volume of the river reached the maximum, and the corresponding time was the reasonable release duration.
5.2. Simulation results under different scenarios

The maximum infiltration volumes and corresponding time were simulated and analysed. The process of river infiltration recharge can be divided into three phase, namely, unsteady freedom phase, stable free phase and leakage phase under groundwater resistance. The maximum infiltration volume of river was calculated in this study, so only the first two stages were considered. Since the duration of unsteady freedom phase was very short and the infiltration volume was relatively small, the steady infiltration rate was used to calculate the river seepage. The simulation results of the three scenarios are shown in Table 4.

| Scenario | Sub-reaches | Total |
|----------|-------------|-------|
|          | A | B  | C  | D  | Total |
| Scenario 1 | 349.4 | 4336.8 | 1350.0 | 842.0 | 6878.2 |
| Scenario 2 | 137.0 | 2335.2 | 933.0 | 720.0 | 4125.2 |
| Scenario 3 | 172.0 | 2824.5 | 1270.0 | 757.0 | 5023.5 |

The largest water infiltration volume was observed in sub-reach B (from Dongkema Village to Cuima Village), which is also identified as the strong leakage section of Yufuhe River. In addition, given that the bottom of sub-reach C (from Cuima Village to Jinpu Railway Bridge) was impermeable, the water recharge was stored in the upper karst aquifer. Therefore, the main objective was to meet the infiltration of sub-reach B while ensuring most of water recharging into the karst aquifer. In other words, the water discharge was terminated when the infiltration volume of sub-reach B reached its maximum.

The simulation results in Table 4 reveal that the infiltration volumes of sub-reach B reaches the maximum when water releasing for 19.5, 10.5, and 12.7 days respectively. Therefore, the water release durations of all sub-reaches are equal to those of sub-reach B in the optimal schemes. Given that the water release durations of sub-reach A are all shorter than those of sub-reach B, the infiltration volumes of sub-reach A can reach its maximum and be equal to the results presented in Table 4. Similarly, the infiltration volumes of sub-reach B are equal to the results presented in Table 4. As for sub-reaches C and D, given that their water release times are all greater than those of sub-reach B, the infiltration volumes of these two sub-reaches cannot reach their maximum. Instead, they can be calculated by multiplying the steady infiltration rates by the durations of water release. The steady infiltration rate can be obtained by dividing the highest infiltration volume by the corresponding time.

6. Conclusions

From the study, we can mainly conclude the following conclusions. The infiltration volume of sub-reach B (from Dongkema Village to Chuma Village) is the largest. The simulated values of the model can fit the measured value well. When the releasing flow is small, the optimal scheme is to continuously discharge water by 286,800, 282,500, and 282,000 m³/d for 19.5, 12.7, and 10.5 days when the groundwater depth is 42, 30, 23 m at Cuima Village respectively.
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