Numerical simulation and protection of the dynamic change of Jinan karst spring based on coupling of seepage and conduit flow

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ABSTRACT

The objective of this study was to predict the dynamic change in the spring water level more precisely, to provide timely solutions for karst spring protection. Using the Jinan spring region as a case study, this study established a numerical model of a karst groundwater system, and optimized the mining layout. The calculated maximum extraction volume following the optimized exploitation layout was 0.69 m³/s, in order to ensure the continuous flow of spring water in the median water year. A coupled karst groundwater numerical model with dual structure was developed using the MODFLOW-Conduit Flow Process (CFP), which simulates and then precisely predicts changes in the water level of the karst springs. Here, the plane extension direction of the karst conduit was determined by a tracer test and correlation analysis of the spring water levels and groundwater levels of the observation wells. Meanwhile, the vertical location of the karst conduit was determined by layered monitoring of the groundwater temperature and conductivity. Based on this, a coupling model of seepage and conduit flow was created to simulate the dynamic change in the spring water level, and the dual-media coupling model improved the simulation accuracy of the spring water level. The current study confirmed that, compared to the porous media seepage model, the dual-media coupling model can simulate the groundwater level dynamic change more accurately in a heterogeneous karst aquifer in northern China. The coupling model was used to analyze the effect of supplementation and optimize mining, to ensure that spring water continues to flow during the dry season while supplying the mining demand.

1. Introduction

Karst simulation models cover a wide range of application areas and can be used for “global” analysis. Hartmann et al. (2014) outlined some application scenarios and numerous distributed and lumped karst modeling approaches. Karst aquifer system is a complex aquifer system that includes various media forms, such as pores, fissures, karst conduits, and small karst caves (Chang, 2015). Groundwater flow in porous media is typically thought to follow Darcy’s law. However, under certain conditions, the rapid underground horizontal flow in the karst conduit medium should be considered as a nonlinear turbulent movement. That means the Darcy’s law cannot fully account for conduit flow in karst groundwater aquifers (Liu et al., 2017). Therefore, the use of porous media models in heterogeneous karst areas often causes significant water-level deviations (Chen and Hu, 2018).

To improve the modelling simulation precision of the groundwater level in heterogeneous aquifer systems, other simulation methods have been progressively applied. Chen and Goldscheider (2014) applied a conduit model (SWMM) to simulate highly variable flow in a folded alpine karst aquifer system. Shoemaker et al. (2007) coupled a discrete conduit flow process (CFP) conduit structure with a continuous equivalent porous media model and addressed the heterogeneity simulation problem of multiple media fields in karst areas. The CFP model enables the karst conduit to exchange water through porous media and can better characterize the non-Darcy flow characteristics of conduit media in karst areas (Qin and Jiang, 2014; Giese et al., 2018). By adjusting the relevant parameters (e.g., pipe diameter, hydraulic gradient, and exchange coefficient), the CFP model can improve the simulation of water flow in karst areas (Yang et al., 2019). Additionally, under ideal conditions, it can simulate the dynamic properties of the karst spring flow (Gallegos et al., 2021).

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2013; Chang et al., 2015). Meanwhile, the conduit simulation can provide an enhanced calibration, over the homogeneous porous-medium simulation. This reveals five important differences: (1) convergent flow to large springs, (2) equipotentials forming troughs, (3) decreases in hydraulic gradient, (4) increases in hydraulic conductivity in a down-gradient direction, and (5) substantial scaling effects (Hill et al., 2010; Worthington, 2009). The CFP model can also simulate the karst aquifer system’s response to heavy rainfall (Jiao et al., 2017). Moreover, the flow exchange between the matrix and conduits is also considered in the CFP model. Spring discharge can be better analyzed by studying the flow exchange capacity between matrix and conduits (Sivelle et al., 2019).

Therefore, the CFP model is commonly applied to karst areas in southern China. For example, Zhao et al. (2018) evaluated the feasibility of adopting a conduit flow model to simulate a karst underground river system in Zhaioli, Guanxi. Yang (2018) used the model to simulate the southern karst groundwater movement in the Xianghualing region of Hunan Province. In CFP simulations, determining the location of karst conduits is one of the challenging difficulties. Many cases of various pipeline network construction approaches have been proposed. For example, He (2015) combined geology/geophysics with 3D geological modeling technology to identify the location of a karst conduit. Fandel et al. (2020) generated multiple conduit networks constrained by geology using a stochastic karst simulator (MATLAB script). Nonetheless, geostatistical methods can yield uncertain outcomes and geophysical methods are not unique. Thus, further improvement in the method for identifying the location of a karst conduit is needed. Tracer tests and layered groundwater monitoring are trusted techniques.

Presently, numerical models of the three-dimensional karst groundwater flow in Jinan, have been established many times by different units, and are based on the porous media seepage theory (Zhou, 2012; Wang, 2016, 2017; Yu, 2017). This satisfies the model simulation precision requirements from the perspective of water resources evaluation in springs. According to historical statistics, the average annual variation in the water level of Jinan springs is approximately 1.8 m. In theory, the fitting error between the actual and modeled groundwater levels should be less than 10% of the water level change during the calculation period (Wang, 2016). In this sense, when the error of the simulated water level is less than 0.18 m, the technical requirements of relevant specifications can be satisfied. According to Jinan City’s Emergency Plan for Keeping Springs Gushing issued on April 9, 2016, a yellow warning would be issued if the groundwater level of Baotu Spring, the primary spring in the Jinan spring area, dropped to 28.15 m and the spring discharge if the groundwater level of Baotu Spring, the primary spring in the Jinan spring area, dropped to 28.00 m and the spring flow rate was less than 1.76 m³/s. If the groundwater level of Baotu Spring dropped to 28.00 m and the spring flow rate was less than 1.7 m³/s, an orange warning would be issued. Therefore, the change in the spring water level will directly affect the implementation of spring protection measures, and the standards of spring protection cannot be satisfied by using a model that merely achieves a 10% model error.

Using the Jinan area as a case study, this study uses a tracer test, long-term dynamic monitoring of the water level, layered groundwater quality monitoring, and borehole geological data to determine the locations and basic parameters of the karst conduits. A numerical simulation of the dual-media model was performed to accurately simulate the dynamic change in the water level of Jinan springs. This aim of this study was to provide a solid scientific foundation for accurately determining the timing of the implementation of spring protection measures.

2. Overview of the study area

Within the spring area of Jinan, Shandong, China, the Archean Taishan (Art) Group stratum is the base and is overlain by Cambrian and Ordovician strata. The strata exhibit a northward dip and form a monoclinic structure. The limestones of the Zhangxia Formation of the Cambrian in the south are exposed, while the limestones of the Ordovician and Fengshan Formations of the Cambrian are bare-semi bare. The northern part is the Piedmont plain and, Yanshanian magmatic rocks and Carboniferous-Permian strata buried beneath the Quaternary, which formed the northern aquifer barrier boundary. Moreover, the east boundary is the Wenzu fault as the water barrier boundary, the west boundary is the Huangshan rock vein and the Niujiaoshan fault as the water barrier boundary, and the south boundary is the groundwater divide (Figures 1 and 2). Meteoric precipitation infiltration was the main recharge source of the Jinan Spring karst water system. Spring water outflow is one of the main natural discharges of the system. The karst groundwater level is generally higher in the south and lower in the north. The groundwater flows from the recharge area in the south, to the discharge area in the north and is controlled by the topography, rock strata slope, and direction of the fault zones.

The Baotu Spring is located in the middle of the karst water system. The groundwater flows northward along the stratigraphic slope and is blocked by intrusive rocks from the Yanshan period in the north. The east plate of the Qianfoshan fault on the west side of the spring group and the west plate of the Wenuhuiqiao fault on the east side of the spring group were uplifted, forming a horst. In this area, the groundwater flows upward with pressure, discharges to the groundwater surface, and forms the well-known Jinan Karst Spring Group, including the Baotu Spring. In this discharge area, a single well from the Ordovician karst aquifer may produce a large amount of groundwater, with a flow rate of more than 0.12 m³/s. Historically, karst groundwater has been the main source of water supply in Jinan City. In the early 1960s, the amount of ground-water exploited in urban Jinan areas was less than 11.57 m³/s, the average spring water level was 30.72–31.54 m, and the spring flow rate was 3.89–4.11 m³/s. Since the early 1970s, there has been a dramatic increase in groundwater extraction owing to continued socioeconomic development and population growth. Karst systems deliver various ecosystem services and act as natural sinks for carbon dioxide thus helping mitigate climate change (Goldscheider, 2019). Mining activities affected the landscape of spring water in Jinan, and the decrease in spring discharge also altered the ecosystems of Daming Lake and the Xiaqing River (de Graaf et al., 2019). Since 2003, the self-provided mining wells in the city have been closed. Except for agricultural mining and drainage of foundation pits for urban construction, only the Eastern Suburbs Waterworks and the Western Suburbs Waterworks are allowed to mine. On September 6, 2003, the Baotu Spring water started flowing once more, and it has continued to flow since then. Thereafter, to further maintain the continuous spring water flow, the Jinan Municipal Government has also adopted artificial replenishment methods to recharge sources in the Yufu and Xingji Rivers, Liyang Lake and other sources.

The Jinan Spring Group has attracted considerable attention since it was cut off in 1972. To restore water flow, in 2003 the Jinan government implemented countermeasures to restrict or prohibit groundwater extraction. While groundwater extraction has reduced, the Jinan Spring Group may still be cut off during the dry season under the influence of anthropogenic activities. To maintain continuous spring flow during the dry season, the government needs to implement artificial recharge measures. The time of replenishment depends on the water level of the springs, therefore, an accurate prediction of the spring water levels is important.

3. Methods

3.1. Tracer test

Tracer testing is an important method for studying the hydraulic connection and law of groundwater flow. In this study, ammonium molybdate ([(NH₄)₂MoO₄·4H₂O]) was selected as the tracer, because it is nonpoisonous and stable, both physically and chemically. And ammonium molybdate is suitable for long distance tracer test. Mo has a low background value and can be determined rapidly at extremely low concentration levels. The naturally occurring chemicals in Karst water chemical components do not cause chemical interference with Mo, and experiments have shown that limestone aquifers do not adsorb Mo (Yuan, 1986).
Figure 1. Overview map of the study area. (1-Quaternary unconsolidated porous aquifer; 2-Bared Ordovician karstified carbonate aquifer; 3-Karstified carbonate aquifer overlain by Quaternary layers; 4-Fractured igneous aquifer overlain by Quaternary layers; 5-igneous rock boundary; 6-fault; 7-river; 8-sping group; 9-geological hole; 10-water level observation hole; 11-sampling hole).

Figure 2. Hydrogeological cross-section of line I–I’. (1-Quaternary; 2-Middle Ordovician; 3-Lower Ordovician; 4-Upper Cambrian; 5-Middle Cambrian; 6-Lower Cambrian; 7-Archean metamorphic rocks; 8-intrusive rock; 9-fault; 10-Spring).
In the study area, 28 kg of ammonium molybdate was injected into the S1 Well, and seven water level observation locations, and 31 sampling locations (including 28 springs) were set up. Sampling and analysis were conducted once daily. The atomic absorption spectrophotometer-graphite furnace and ICP-MS methods were used to measure the molybdenum ion concentrations. The lower detection limit of the graphite furnace method can reach 0.05 ppb. The tracer detection values were set five times higher than the naturally occurring concentration values.

3.2. Water level and water quality monitoring of springs and groundwater

The combination of natural and artificial tracers is extremely helpful in studying the flow of karst groundwater (Ravbar et al., 2012; Lauber and Goldscheider, 2014). Natural tracers are effectively used for spring hydrograph separation, discharge assessment, and to distinguish between matrix and conduit flow. For example, Mg$^{2+}$ could be an effective tracer for separating spring conduit flow from diffuse flow within a karst aquifer (De Filippi et al., 2021). Additionally, water electrical conductivity and temperature act as natural environmental tracers, which can provide valuable insight into the characteristics of groundwater flow systems and intrinsic processes (Stroj et al., 2020).

Groundwater flow is a crucial factor affecting the shallow geothermal field in spring. When a borehole passes through the dominant seepage channel of groundwater in the stratum, the horizontal flow of groundwater causes an inflection point in the temperature distribution curve (Beck and Shen, 1985).

Spring water and groundwater levels were monitored daily using wireless telemetry devices. The water level data were accurate to 0.01 m. The pH, temperature, conductivity, ammonia nitrogen, and other indicators of springs and groundwater were monitored using an Aqua TROLL 600 multi-parameter detector at a vertical interval of 2 m.

3.3. Numerical simulation

(1) Mathematical model

The numerical simulation included two parts: porous media seepage simulation and conduit flow coupling simulation. The porous medium seepage simulation was based on the finite difference method (Eq. (1)). The CFP model primarily performs conduit flow simulations by inputting NAME, CFP, CRCH, and COC files. Users can set the upper critical Reynolds number and lower critical Reynolds numbers in the CFP file to determine the motion state of the conduit flow (Eq (2)). When the conduit flow is laminar, it is calculated using the Hagen-Poiseuille equation (Eq (3)), when the conduit flow is turbulent, it is calculated using the Darcy-Weissbach equation (Eq (4)). The amount of water exchanged between the conduit and porous medium was calculated using Eq. (5) (Shoemaker et al., 2007).

\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial H}{\partial z} \right) + W = \frac{\mu}{C_1} \frac{\partial H}{\partial x} \quad (x, y, z) \in \Omega
\]

\[
H(x, y, z, t)|_{t=0} = H_0(x, y, z) \quad \text{..........................}(x, y, z) \in \Omega
\]

\[
K_{xx} \frac{\partial^2 H}{\partial x^2} + K_{yy} \frac{\partial^2 H}{\partial y^2} + K_{zz} \frac{\partial^2 H}{\partial z^2} = q(x, y, z, t) \quad \text{..........................}(x, y, z) \in \Gamma_2
\]

where $K_{xx}$, $K_{yy}$, and $K_{zz}$ (m$^{-1}$) are the values of hydraulic conductivity along the x, y, and z axes, respectively; $\mu$ (m$^{-1}$) is the specific storage; $H$ (m) is the potentiometric head; $H_0$ (m) is the potentiometric head at the initial moment; $W$ (m$^{-1}$) is the volumetric flux per unit volume representing the sources and/or sinks of water; $\Omega$ is the simulation area; and $\Gamma_2$ is the boundary.

\[
Re = \frac{\nu d \rho}{\mu}
\]

\[
Q = -\frac{\pi d^4 g \rho}{128 \mu \Delta h} \quad \text{or} \quad Q = -\frac{\pi d^4 g \rho}{32 \mu \Delta h}
\]

\[
Q = -\sqrt{\frac{d^2 g \rho \Delta h^2}{2 \mu}} \log \left[ \frac{2.51 \mu}{\sqrt{\frac{d^2 g \rho \Delta h^2}{2 \mu}}} \right] \frac{k_c}{3.71d} \frac{\Delta h}{|\Delta h|}
\]

\[
Q_{\text{ex}} = a_{ij,k} (h_n - h_{j,k})
\]

where $Q$ (m$^3$s$^{-1}$) is the flow rate in the conduit; $d$ (m) is the pipe diameter; $\Delta h$ (m) is the head loss measured along the pipe; $\mu$ (pa·s) is the absolute or dynamic viscosity of water; $r$ (unitless) is the tortuosity of the pipe; $d$ (m) is the length of the pipe; $k_c$ (m) represents the mean roughness height of the conduit micro-topography; $Q_{\text{ex}}$ (m$^3$s$^{-1}$) is the volumetric exchange flow rate; $a_{ij,k}$ (m$^{-1}$s$^{-1}$) is the pipe conductance at MODFLOW cell $j,i,k$; $h_n$ (m) is the head at pipe node $n$ located at the center of the MODFLOW cell; and $h_{j,k}$ (m) is the head in the encompassing MODFLOW cell $j,i,k$.

(2) Establishment of equivalent porous media model

The Jinan karst water system is divided into two aquifers. The first layer is a quaternary aquifer, which is a phreatic water aquifer, and the second layer is a confined karst aquifer. The boundaries (impermeable layers) were as follows: the Wenzu fault in the east; the Huangshan rock veins and the Niujiaoshan fault in the west; the groundwater divide in the south, and the Ordovician limestone roof (buried at a depth of 600 m) in the north (Figure 1). The total size of the simulation area is 2,732 km$^2$.

The discretization plane split grid size of the model is 200 × 200 m. The stress periods were set to 5, 3, and 6 days, for average, minimum, and maximum, respectively. The recharge items include precipitation recharge, river infiltration recharge, agricultural irrigation replenishment, and lateral runoff recharge. Discharge items include artificial groundwater mining, spring discharge, and lateral runoff discharge.

(3) Establishment of conduit flow model

The seepage-conduit flow simulation is mainly based on the superimposed conduit network on the porous media percolation model for the coupling simulation. After the porous media seepage model was constructed, identified and verified, the cell division data were exported as the basic input data. The conduit nodes were then set and assigned, according to the conduit plane position and vertical position (determined by the MODFLOW cell settings and parameters). In the conduit flow model, a cell has a maximum of one node, and many nodes are connected to form a conduit network.

4. Results and analysis

4.1. Identification and verification of porous media models

The simulation period of the model was from October 1, 2012, to September 30, 2013. After multiple parameter adjustments, the calculated and actual water levels compared well, meeting the requirements of model accuracy (Figures 3 and 4). The precipitation infiltration coefficient (Figure 5), hydrogeological parameters of the pore water aquifer (Figure 6), and the hydrogeological parameters of the karst water aquifer (Figure 7) were determined.

To further verify the overall accuracy of the model and parameters, the model was verified with the data acquired during an inspection period (October 1, 2013, to September 30, 2014), and the calculated
water level and actual water level of the observation had a good fit (Figure 8).

To protect the spring water and decrease the rate of the declining water level during the dry season, or prevent the spring from drying up, the Jinan City Government formulated an emergency plan for the Baotu Spring, based on its water level. When the water level drops to 27.60 m, a red warning is issued and the water source is then closed. The mining of wells is then restricted, and the river channel flow in the artificial replenishment area is released to supplement the water resource. The spring water level was set to 27.60 m at the end of the dry season, as a constraint. A numerical simulation was then used to optimize the extraction volume of each water source in the spring area, and the optimized extraction volume of each water source in each typical year was determined (Table 1).

As shown in Table 1, the models have optimal solutions for different precipitation scenarios, except for the extra-dry year. However, the result shows that even in the wet year, the total water supply might be only 1.55
m³/s. Based on 80 L per person per day for domestic use, it cannot match the domestic water demand of Jinan City’s 8 million residents. The combined supply of surface water and groundwater can achieve the goals of spring water protection and domestic water use. Therefore, to maintain a continuous flow of spring water, it is necessary to control the amount of groundwater extraction and replenish the water source in the spring system area.

Considering the inter-annual variance of precipitation, to ensure that the spring water level during the dry season is not lower than its preservation control line, it is necessary to accurately predict the spring water level during the dry season in order to implement the emergency plan for spring preservation in time.

4.2. Karst conduit

4.2.1. Determination of the plane position of karst conduit

According to the observed water levels from January 1, 2018, to January 1, 2019 (Figure 9), there is a good correlation between the S1 Well groundwater level and the Baotu Spring water level, with a correlation coefficient (R²) of 0.69. In contrast, the R² between the S2 Well groundwater level and the Baotu Spring water level was 0.10, and 0.54 at S3 Well. The tracer test lasted for 87 days. Molybdenum ions were detected in Baotu Spring approximately 47 d after tracer injection. In Figure 10, the concentration curve of molybdenum ions in Baotu Spring has a “single peak” shape, indicating that the groundwater channel
between the tracer injection location and the sampling location has a single flow channel. Therefore, it was concluded that a single karst conduit connects S1 Well with the Baotu Spring. Borehole geological data showed that the karst development near the spring group (within 200 m depth) contains vertical zones of “polar development—medium development—strong development—weak development—strong development” (Lv, 2017). The vertical depth (90 m) and extension direction in the shallow karst were generally distributed in a strip shape, along the slope direction of the stratum (Figure 11). Karst was developed along S1 Well—S4 Well—S10 Well—Baotu Spring and S1 Well—S6 Well—S9 Well—Baotu Spring. However, the depth and direction of the karst along S6 Well—S9 Well—Baotu Spring are inconsistent with regional karst development. Furthermore, the R² between the groundwater level at S10 Well and the spring water level was 0.99 (based on water level data from 2010 to 2011). Therefore, it was concluded that the karst conduit is distributed along S1 Well—S4 Well—S10 Well—Baotu Spring, which corresponds with the groundwater flow field (Figure 12).

4.2.2. Determination of the vertical position of karst conduit

The borehole geological data revealed that there are some karst caves with no filler at a depth of 34.0–38.0 m in the S1 Well. In addition, the long-term monitoring data of S1 Well (Figure 13) suggested that the inflection point of conductivity occurs at a depth of approximately 34 m (Figure 13a), and the temperature gradient abruptly changes (Figure 13b). Therefore, a karst conduit is expected in S1 Well at a depth of 34 m. Additionally, borehole data shows there is a small karst cave and no filler in S4 Well (depth of 62.5–63.5 m); some strong karst-developed section and no filler in the karst cave in S10 Well (depth of 68.2–83.0 m); some honeycomb-shaped dissolved pores and no filler in S13 Well (depth of 58–77.5 m). Combined with the inclination of the formation, the following development occurred: a single karst conduit at a depth of 34 m in S1 Well—the depth of 63 m in S4 Well—the depth of 70 m in S10 Well—and the depth of 70 m in Baotu Spring. In other words, the location of the karst conduit is the elevation of 15.93 m in S1 Well— the elevation of 25.71 m in S4 Well—the depth of 37.34 m in S10 Well— the elevation of 39.84 m below Baotu Spring (Figure 14).

4.2.3. Determination of conduit parameters

In general, the relationship between the pressure difference and flow velocity of the conduit can be expressed as (Liu et al., 2003):

$$\Delta p = \frac{\lambda L d^4}{2} \rho v^2$$

and $$\lambda = \frac{64}{Re}, \quad Re = \frac{\rho dv}{\mu}.$$ After rearrangement, the equation for calculating the conduit diameter can be written as:

| Precipitation (mm/a) | Time          | Optimal mining flowrate of water sources (m³/s) |
|---------------------|---------------|-----------------------------------------------|
|                     | Qiao zili     | Leng zhuang | Gu cheng | E meishan | Da yang | La shan | Urban area | Eastern suburbs | Total |
| 764.4 (Wet year)    | October–January | 0.93  | 0.28 | 0 | 0 | 0 | 0 | 0.35 | 1.55 |
|                     | February–May | 0.69 | 0.28 | 0 | 0 | 0 | 0 | 0.35 | 1.32 |
|                     | June–September | 0.56 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.90 |
| 622.8 (Median water year) | October–January | 0.35 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.69 |
|                     | February–May | 0.21 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.56 |
|                     | June–September | 0 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.35 |
| 522.8 (Dry year)    | October–January | 0.16 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.51 |
|                     | February–May | 0 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.35 |
|                     | June–September | 0 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.35 |
| 389.9 (Extra-dry year) | October–January | No optimal solution |
|                     | February–May | No optimal solution |
|                     | June–September | No optimal solution |
\[ d = \sqrt{\frac{32\mu Lv}{\Delta p}} \]  

(7)

where \( L \) (m) is the length of the pipe; \( d \) (m) is the pipe diameter; \( \Delta p \) (pa) is the pressure difference in pipe; \( v \) (m/s) is the mean velocity; and \( \mu \) (pa-s) is the absolute or dynamic viscosity of water.

The linear distance (L) between S1 Well and Baotu Spring was approximately 1.6 km. When the tracer was injected for 47 d, the concentration of molybdenum ions peaked. Therefore, the mean flow velocity (\( v \)) in the pipe was \( 3.94 \times 10^{-1} \) m/s. During the tracer test, the water level of Baotu Spring was between approximately 27.57 m and 27.80 m, with an average of 27.72 m; the groundwater level of S1 Well ranged between 28.93 m and 30.70 m, with an average of 29.75 m. Thus, the pressure difference (\( \Delta p \)) was \( 2.03 \times 10^4 \) pa. Assuming a water temperature of 18°C (which is the average groundwater temperature), the dynamic viscosity (\( \mu \)) is approximately \( 1.04 \times 10^{-3} \) pa-s. Based on this information, the diameter of the conduit is calculated (using Eq (7)) to be approximately 1.02 mm.

It is undeniable that the calculated value of the diameter is too small, but there are still large-diameter karst caves in the spring area. For example, less than 1 km away from the S1 borehole, there is a karst cave with a diameter of 1.5 m at a depth of 27 m. Although these underground karst caves are short in length, they can change the characteristics of groundwater movement. Therefore, it is reasonable to have conduit flow in local areas.

Following empirical studies (Hill et al., 2010), the upper critical Reynolds number was taken as 2000, the lower critical Reynolds number was taken as 4000. The tortuosity and roughness were set to 1.0 m and 0.0001 m, respectively.

**Figure 9.** Scatter plots of groundwater level and Baotu Spring water level at the study area. (a) S1 Well; (b) S2 Well; (c) S3 Well; (d) S10 Well.

**Figure 10.** The concentration variation of molybdenum ion during the tracer test period. (a) Baotu Spring Area; (b) Heihu Spring Area.
4.3. Comparative analysis of seepage simulation and seepage-conduit flow coupling simulation

4.3.1. Simulation of the seepage-conduit flow coupling model

According to the determination of the plane position, vertical position, and parameters of the conduit, edit the corresponding files required for the CFP conduit flow simulation were edited and simulation calculations were performed. The calculation results were shown in Figure 15.

The sum of the squared errors between the porous media simulation value and the observed value of the Baotu Spring water level from October 1, 2012, to September 30, 2013, was 3.07. Compared to the results of the porous media seepage simulation, the sum of the squared
error between the CFP simulation value and observed value was smaller, and the prediction accuracy of the predicted spring water level improved by 53.8%. This shows that the CFP model simulates dynamic changes in spring water more accurately.

To further investigate the attenuation of conduit flow, the seepage model and the seepage-conduit flow coupling model (from August 6, 2013, to February 1, 2014) were compared and analyzed (Figure 16). The fitting equation shows that the water level attenuation follows an exponential fitting equation. The attenuation coefficient in the porous media seepage model was 0.0122, and the attenuation coefficient in the CFP conduit model was 0.0127, indicating that the porous media seepage was relatively steady, and the water release rate was relatively slow. In the simulation of conduit flow, the karst conduit had a significant capacity for water supply. The karst conduit flow quickly gathered to reach the outlet of the basin, and the water discharge was relatively more rapid.

4.3.2. Sensitivity analysis of parameters in the CFP simulation

The perturbation analysis method was applied for the sensitivity analysis of parameters, and the corresponding objective function mean square error (RMSE) expression is given by (Li et al., 2017):

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (h_{\text{sim},i} - h_{\text{obs},i})^2}$$ (8)

where $h_{\text{sim},i}$ (m) is the simulated water level at i time; $h_{\text{obs},i}$ (m) is the observed water level at i time; and n is the total number of periods.

First, the mean square error ($\text{RMSE}_0$) of the optimal parameter was calculated to be 0.1469. Second, individual parameters were adjusted (e.g., diameter, roughness, tortuosity, and exchange coefficient) by ±10% and ±20%, and the optimized values of other parameters remained the same. Subsequently, the CFP program was re-run to obtain the corresponding spring water level simulation value, and then calculated the RMSE (after adjusting the parameter value). Subsequently, we quantified the RMSE deviation ($\Delta\text{RMSE}$) of each parameter and revealed...
the sensitivity of the model to the parameters with the absolute value of the RMSE deviation.

The results (Table 2) indicate that the CFP simulation is significantly affected by the tortuosity of the conduit and exchange coefficient. When the water head in the conduit is lower than that in the porous medium, the groundwater in the porous medium replenishes the conduit. In contrast, when the water head in the conduit was higher than that in the porous medium, the water in the conduit network recharged the groundwater in the porous medium. Notably, the amount of water exchange was predominantly controlled by the head difference and the exchange coefficient. Specifically, the karst conduit diameter in the CFP model is quite small; therefore, the adjustment range of \(-10\%\) and \(+20\%\) had little effect on the numerical value. Limited by the model accuracy, the \(\Delta\)RMSE of the diameter in this sensitivity analysis was 0. According to the Reynolds number (calculated based on the diameter and flow velocity), the water flow in the conduit was determined to be laminar flow. As roughness was excluded in the calculation of laminar flow, the \(\Delta\)RMSE of roughness in this sensitivity analysis was 0.

### 4.4. Dynamic warning of spring water during dry season

Jinan is world-famous for its springs. There are more than 800 springs in the city of Jinan and 136 well-known springs within 2.6 \(\text{km}^2\) of the urban city area (Zhang et al., 2003). Owing to the impact of human activities, the recharge of spring water has gradually decreased. In order to keep the spring water flowing continuously, the Jinan Municipal Government delineated a spring water protection warning line in 2006 (Liu, 2011). When the spring water level dropped to 28.0 m, emergency spring protection actions occurred, such as reducing the amount of groundwater source mining, increasing the surface water supply (reservoirs), and artificial replenishment in the karst water recharge area. Jinan has a monsoonal climate zone. Precipitation varies greatly throughout the year, and the spring water level shows a rapid rise in the rainy season, followed by a decline owing to long-term consumption. The Jinan spring area is a semi-closed hydrogeological unit, and the distance from the recharge areas, such as Quanlu and Yufu Rivers to the Baotu Spring is greater than 14 km. Therefore, it is of great significance to accurately predict changes in the spring water level during the dry season.

Precipitation data shows an average annual rainfall of 645 mm, which was distributed to each month in accordance with the average monthly proportion (Table 3). Maintaining the groundwater extraction volume and mining layout plan as it is, using the actual groundwater level measured on October 1, 2019 as the initial flow, the spring water level dynamics in the dry season of the following year were predicted according to the model developed in this study (Figure 17). The prediction results show that in average rainfall years, the spring water level still decreased to its lowest value of 27.49 m on June 26, which is below both the orange warning line of the spring water level (28.0 m), and also lower than the critical water level of the Wulong Spring cutoff (27.5 m). Therefore, artificial water replenishment is required to ensure that the spring water flows continuously and has good ornamental value. If the replenishment measures are taken when the spring water level is lower than 28.0 m, the start time of artificial replenishment in flat water years in the seepage-conduit coupling simulation is March 21. Additionally, the replenishment will cease after the water level rises on June 26. Under the same conditions, the initial time for the supplementary source predicted by the porous media seepage simulation was February 11, which is 40 days earlier than the coupled model. According to the daily average replenishment of 290,000 \(\text{m}^3\) in the literature (Zhou, 2016), coupled simulations can save 11.6 million \(\text{m}^3\) of water resources.
4.5. Supplementary source and optimized mining

4.5.1. Feasibility of regulating and storage of karst groundwater in spring area

Analysis of regulation and storage space: The limestone aquifer in the spring area has a wide distribution area, large thickness, and well-developed fractured karst layer, with huge storage capacity. It has a greater regulatory function and is comparable to a sizable surface reservoir. According to the calculations, the storage capacity between the peak and lowest water levels in the spring area is 362.75 million m$^3$.

Analysis of aquifer connectivity and water conductivity: Using the CuiMa tracer test in 1989, the Xikema tracer test in 1996, the Laopo-Baiyungang tracer test and the Longdong tracer test, it was proven that the groundwater of the Zhangxia Formation is closely connected to the groundwater of the Ordovician system. Tracer tests on CuiMa, Xingji River, and Liyang Lake from 2015 to 2018 confirmed that Liyang Lake and Yufu, Xingji, and Daxin Rivers are connected to springs.

Analysis of leakage capacity: According to the water recharge test of the Wohushan Reservoir and long-term flow measurement data, the leakage per unit length of the Yufu River is 0.16–0.18 m$^3$/s·km, and the Yufu River replenishment amount can be designed to be less than 2.31 m$^3$/s.

Analysis of regulating and storing water sources: Many surface reservoirs have been built in the mountainous area of the southern part of the Jinan Spring area. These reservoirs intercept a large amount of surface runoff with a storage volume of approximately 180 million m$^3$. Jinan has both local surface water resources and Yellow River water resources, particularly after the completion of the South-to-North Water Diversion Project, as well as Yangtze River water sources.

4.5.2. Optimize the supplementary source plan

Considering that Jinan has a relatively sufficient water replenishment source following the South-to-North Water Diversion Project, the Yufu River, Xingji River, Liyang Lake, and other locations were selected to recharge the source. The recharge period was the entire year. The source replenishment volumes are: 1.16 m$^3$/s (Yufu River), 2.31 m$^3$/s (Xingji River), 1.16 m$^3$/s (Liyang Lake), and 2.31 m$^3$/s (Daxin River). The optimal mining volume of water sources under the optimized supplementary source plan is presented in Table 4.

5. Conclusions

The conclusions of this study are summarized below:

(1) The combination of a tracer test and groundwater level correlation analysis can effectively identify dominant horizontal runoff channels in karst water systems. This study confirmed a karst conduit along S1 Well—S4 Well—S10 Well—Baotu Spring at the

Table 4. List of optimized mining volume of water sources in each typical years under the optimized supplementary source plan.

| Precipitation (mm/a) | Time          | Qiao zili | Leng zhuang | Go cheng | E meishan | Da yang | La shan | Urban area | Eastern suburbs | Total |
|----------------------|---------------|-----------|-------------|----------|-----------|---------|---------|------------|----------------|-------|
| 764.4 (Wet year)     | October-January | 0.93      | 0.46        | 1.16     | 0.21      | 0       | 0       | 0.46       | 3.22            |
|                      | February-May  | 0.93      | 0.46        | 0.93     | 0         | 0       | 0       | 0.46       | 2.78            |
|                      | June-September| 0.93      | 0.46        | 1.16     | 0.35      | 0       | 0       | 0.46       | 3.36            |
| 622.8 (Median water year) | October-January | 0.93  | 0.46        | 1.16     | 0.32      | 0       | 0       | 0.35       | 2.32            |
|                      | February-May  | 0.93      | 0.46        | 0.69     | 0         | 0       | 0       | 0.35       | 2.43            |
|                      | June-September| 0.93      | 0.46        | 0.42     | 0         | 0       | 0       | 0.35       | 2.15            |
| 522.8 (Dry year)     | October-January| 0.93   | 0.46        | 0.64     | 0         | 0       | 0       | 0.35       | 2.37            |
|                      | February-May  | 0.93      | 0.46        | 0.36     | 0         | 0       | 0       | 0.35       | 2.09            |
|                      | June-September| 0.83      | 0.46        | 0        | 0         | 0       | 0       | 0.35       | 1.64            |
| 389.9 (Extra-dry year)| October-January| 0.93 | 0.25        | 0        | 0         | 0       | 0       | 0.35       | 1.53            |
|                      | February-May  | 0.56      | 0           | 0        | 0         | 0       | 0       | 0.35       | 0.90            |
|                      | June-September| 0.23      | 0           | 0        | 0         | 0       | 0       | 0.35       | 0.58            |

Figure 17. Prediction simulation of the water level dynamics of Baotu Spring from January to July 2020.
plane position. Based on the tracer test data, we estimated the diameter of the pipe to be approximately 1.02 mm.

(2) The combination of borehole data and layered monitoring of groundwater can effectively identify the vertical dominant runoff channels in karst water systems. This study identified a karst conduit at the elevation of 15.93m in S1 Well—the elevation of −25.71m in S4 Well—the elevation of −37.34m in S10 Well—the elevation of −39.84m in Baotu Spring.

(3) The numerical model of karst conduit flow based on the CFP can effectively simulate the dynamic change in the spring water level. The accuracy of the groundwater level simulation was affected by parameters including the karst conduit diameter, roughness, and tortuosity. More field research should be conducted on the geometric parameters of karst pipes. The sum of the squared errors between the observed and calculated water level value obtained from the porous media seepage model of the Baodu Spring water level was 6.63. The sum of the squared errors between the observed and calculated water level value obtained from the CFP model of the Baodu Spring water level was 3.07. The MODFLOW-CFP model can simulate the dynamic process in the Jinan Spring water level more accurately. This provides a scientific basis for the protection of spring water.

(4) To maintain a continuous flow of spring water in dry years, it is necessary to implement artificial replenishment. By replenishing the water source, it increases the amount of groundwater that can be exploited, and also ensures the continuous flow of spring water, thereby protecting the spring and supplying water demands.

Declarations

Author contribution statement

Changsuo Li; Liting Xing: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Yanan Dong: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Yuming Peng; Xuerui Xing; Chunlai Li; Zhenhua Zhao: Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

Additional information

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