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Numerical simulation and environmental impact prediction of karst groundwater in Sangu Spring Basin, China

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Abstract: The changes of development and utilization of karst groundwater in Sangu Spring Basin have made the original groundwater resource evaluation unable to meet the needs of future economic development. Based on analysis of existing data, combined with the characteristics of supplement, runoff and draining of regional karst groundwater, the Visual Modelflow software was used to build a numerical simulation model of Sangu spring Basin. The amount of karst groundwater resource and groundwater environment of the Basin were evaluated under different exploitation schemes, and the changes of karst groundwater environment in the future ten years were also predicted. The fitting error which is less than 0.5 m between the calculated value and measured value of the water level in the fitted borehole accounts for 93%. For the lithologically and structurally complex Sangu Spring Basin, the fitting effect of numerical simulation model was ideal. On the basis of the current mining amount of 111.80 million m^3/a, the total redistributed exploited amount in the spring region was 61.79 million m^3/a. Under the condition that the quantity of recoverable resources reached 173.59 million m^3/a and under different precipitation schemes, all constraint conditions were satisfied, such as regional water level drawdown, maximum allowable water level drawdown in every simulated water source area and the flow rate of Guobi Spring. The results will provide a scientific basis for the rational development and utilization of karst groundwater in Sangu Spring Basin.

Keywords: Sangu Spring Basin; Karst groundwater; Numerical simulation; Constraints

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Introduction

Jincheng City is an energy and heavy-chemical base in Shanxi Province. Affected by factors such as climate, coal mining as well as groundwater exploitation and utilization, a large number of shallow and intermediate wells were abandoned, resulting in the competition for exploiting deep karst groundwater among industry, agriculture and urban life. Significant changes have occurred in recent years in terms of the quantity, quality as well as the temporal and spatial distribution of karst groundwater in the Sangu Spring Basin of Jincheng City due to excessive exploitation of groundwater: The flow rate of the Sangu Spring decreased; small springs within the spring Basin even dried up; and the karst groundwater level dropped (WU Qiang *et al*. 2010). There are two hidden excessively exploited karst groundwater areas-Gaoping City and Jincheng City (XU Zhi-feng, 2012; LIU Xiao-

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hong, 2009). The demands for karst groundwater will grow further as economy develops in the Spring Basin, which requires us to examine the recoverable amount of karst groundwater within the Spring Basin (FANG Xiang-qing and FU Yao-jun, 2011; YANG Sheng-qi *et al*. 2017). Abundant studies were done on karst groundwater in Sangu Spring Basin (LI Xue-liang, 2003; LIU Xiao-hong, 2009; LI Hui-qing, 2018) and brought about fruitful results, which has played an important role in instructing the development of karst groundwater within the Spring Basin. Now that the water resource situation in the Spring Basin has changed, the existing evaluations of the amount of karst groundwater resources are no longer able to meet the needs of future economic development. It is of significant practical meaning to conduct updated evaluation of the amount of karst groundwater resources within the Spring Basin in order to ensure both the sustainable exploitation of karst groundwater resources in the Spring Basin and the sustainable economic and social development of Jincheng City.

1 Study area

The Sangu Spring Basin is located in the 583 kilometers southwest of Beijing and also at the southern end of the Taihang Mountains (Fig. 1), extending between longitudes of 112°35′-113°25′E and latitudes of 35°16′-36°00′N Regarding its general terrain, it has a low and undulated center that is surrounded by high mountains on all sides, shaping a broad intermountain Basin and hills. By administrative division, the studied area covers the urban area of Jincheng City, the majority of Zezhou County, Gaoping City, and the part of Lingchuan County, Zhangzi County and Changzhi City (WANG Zhen-xing *et al*. 2019a).

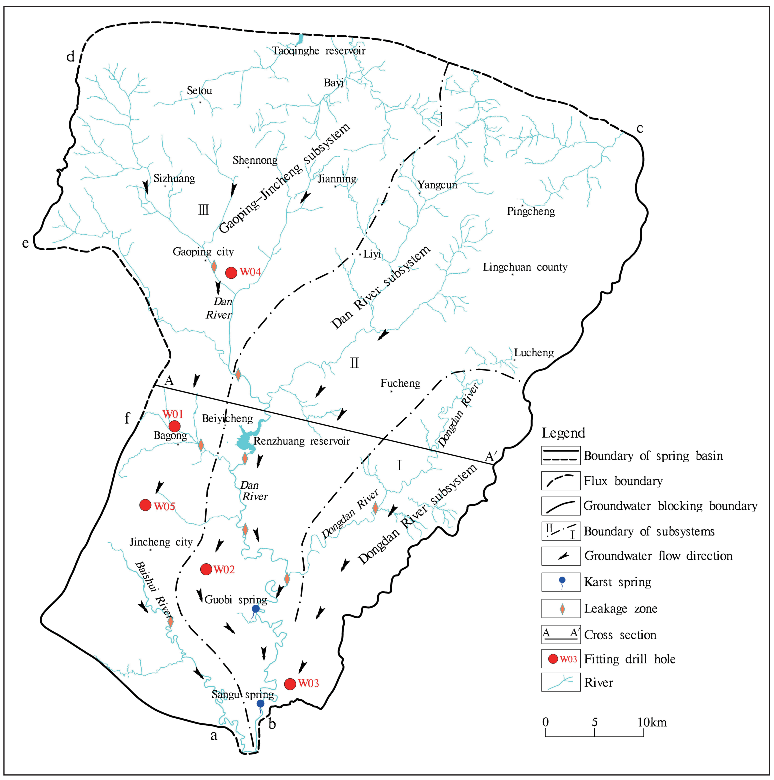


Fig. 1 Location and boundary conditions of the study area

The study area belongs to the continental half-humid monsoon climate of the warm temperate zone. Its average annual minimum temperature was 9.0°C, which occurred in 1956; and the maximum was 12.8°C, which occurred in 1988 and in 1989. The temperature of Jincheng has been trending generally upwards over the past 50 years. In the 1990’s, its temperature grew by about 2.1°C compared with that in the 1950’s. The increase in temperature has become even more obvious since 1986 (HOU Xin-wei *et al*. 2016; WANG Zhen-xing *et al*. 2019b). Over the recent five decades, the precipitation of Jincheng City has been trending downwards, with its maximum annual precipitation of 1 010.4 mm (in 1956) and minimum of 265.7 mm (in 1997). From 1965 to 2000, its average annual precipitation was 628.48 mm; from 1981 to 2000, the number was 541.08 mm; and from 2001 to 2015, the number was 587.02 mm. The multiyear average precipitation from 1965 to 2015 was 593.66 mm. The river systems within this area belong to the Yellow River Basin and the Haihe River Basin. They are divided by the Danzhuling Mountain and Jinquan Mountain into two parts-the Haihe River Basin in the north and the Yellow River Basin in the south. The Dan River water system within the Yellow River Basin is its main part, while the Zhanghe River water system within the Haihe River Basin spreads only in the northern periphery of the working area.

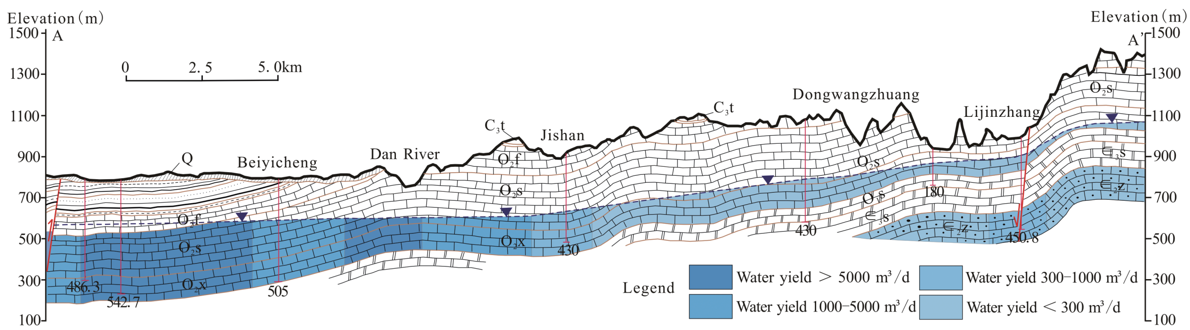


Fig. 2 Hydrogeological cross-section (A-A' in Fig. 1) of the study area

2 Storage patterns of karst groundwater

2.1 Characteristics of karst aquifer distribution

Karst water in Carbonate aquifer makes up the majority of groundwater resources in study area (Fig. 2). It includes two aquifers-the Middle Ordovician Majiagou Group and the Middle Cambrian Zhangxia Group (WANG Wen-ke, 2001a; WANG Yan-xin, 2006b). The Lower Ordovician and the Upper Cambrian are relative aquicludes. Controlled by their structures and lithological characters, Cambrian and Ordovician karst base levels generally incline from the southeastern mountain area towards the Basin, undulating along the north-south folds (LU Yao-ru *et al*. 1966; HOU Xin-wei *et al*. 2016).

The Middle Ordovician is 360~500 m thick. Its main aquifers consist of the Upper and Lower Majiagou Group. Karstic fissures are relatively developed and well connected in the pure limestone levels of both groups. At the bottom of either group, there are gypsum horizons that are karstified into seemingly laminar gypsum karst belts (XIE Zhong-an, 2007) where solution cracks and solution pores are developed and with strong water yield property. Seemingly laminar and net-like aquifers with unified water level are formed. The limestone of Middle Cambrian Zhangxia Group is 200~300 m thick. The water yield property of both the surface and the section of this stratum is uneven. The karst develops only along the ruptures or joints of cut-layers, forming into karst vein water distributed like threads.

2.2 Characteristics of the supplement, runoff and draining of karst groundwater

The supplement, runoff and draining of karst groundwater in Sangu Spring Basin are controlled by geological structures, distribution of modern hydrological networks and the karst development characters. The areas with exposed or semi-exposed limestone in northern and eastern spring Basin receive direct infiltration supplement from atmospheric precipitation; the river valley of limestone areas and reservoir areas receive seepage supplement from surface water; the covered and buried areas receive leakage supplement from overlying strata. Groundwater flows from the north and east to the south and west, ending up drained in the forms of springs and undercurrents or being artificially exploited.

There are three zones with strong runoff within Sangu Spring Basin based on the spread of its geological structure, the hydraulic power characteristics of karst water and the patterns of water yield property distribution: One along the river valley of the middle and lower Dan River; one along Gaoping-Bagong-Beishidian-Jincheng City; and another along the Dongdan River valley (HOU Xin-wei *et al*. 2016).

3 Model building

3.1 Determining the scope of the model

The southern part of the eastern boundary of Sangu Spring Basin spreads along the surface watershed. The northern part of its northeastern boundary extends to the Liuquan-Zheshui area where magmatic rocks crop out. The southern part of its western boundary spreads along the Jinhuo fault zone, while the northern part spreads basically along the surface watershed. To the north, because of excessively exploitation of karst groundwater in the spring Basin, the boundary moves northwards across the surface watershed. The northernmost end is where the grand Jinhuo rupture intersects with the Zhuangtou fault. Controlled by the epsilon-type structure of Dan River, the southern boundary spreads along the Nanhedi-Chengqun belt, with the total spring Basin area registering 3 214 km^2.

3.2 Hydrogeological structure model building

By making full use of materials about boreholes within the area, the karst aquifers exposed by every borehole were generalized, and the roof and bottom elevations of karst aquifers within the area by taking into account the geological structure and stratum undulation were concluded in the studied area (Fig. 3). Typical borehole sections were laid out to form intersecting nets, so as to genuinely reflected upon the regional geological conditions of the studied area to the greatest extent.

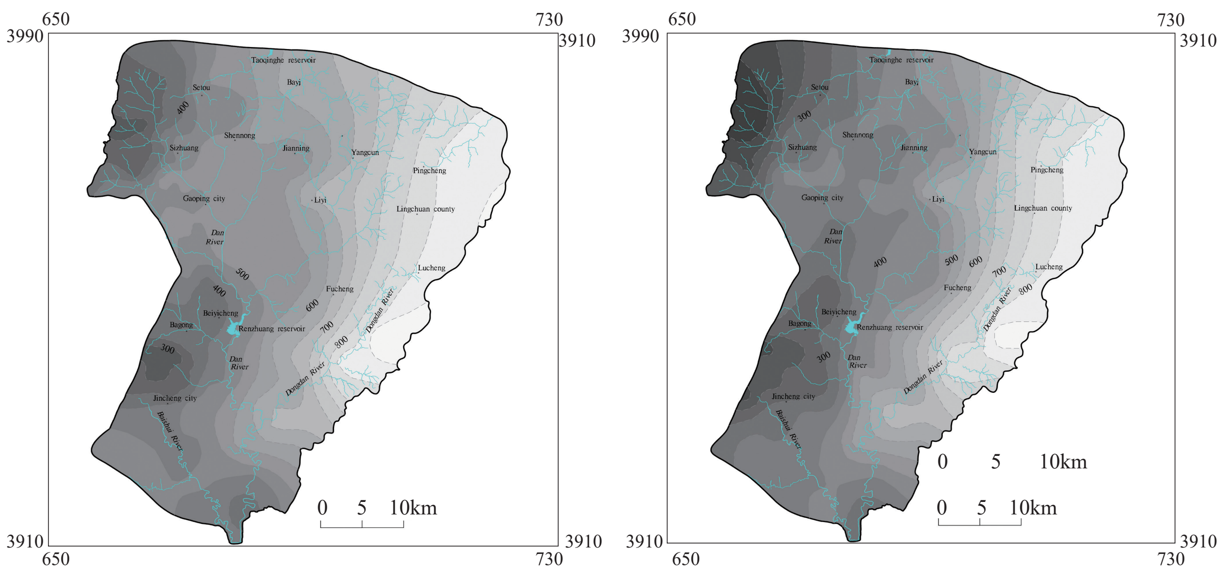


Fig. 3 Top and bottom elevation contour map of karst aquifer

3.3 Hydrogeological conceptual model building

3.3.1 Determination and generalization of boundary conditions

Whether the conditions are determined correctly or not directly influences the calculation of the elements of balance within the studied area, which can be divided into two categories-lateral boundaries and vertical boundaries.

The lateral boundaries in the studied area are categorized into flow rate boundaries of different properties based on analysis of the groundwater field characters and stratigraphic structure within this area (Fig. 1). The southern part of the western boundary and the eastern boundary are surface watersheds (segments b-c and d-e), the groundwatershed coincides with the surface watershed, and are generalized to be the confining boundary. While at the northwestern boundary from Gaoping to Yechuan Town, that fault turns into gentle folds and fractures. As the two sides of the boundary are connected by hydraulic power, this part of boundary is generalized to be the flow rate boundary (segment e-f). The southwestern boundary is influenced by the Jinhuo fault belt and the southern boundary is influenced by its formation and the elevation of $O_1 \sim \in_3$ dolomite stratum, thus they are the confining boundary (segment f-a). As most of karst groundwater is drained as springs in downstream spring Basin, and a small part of it passes through the water blocking belt and flows southward into Jiaozuo area, this part is generalized to be the flow drainage boundary (segment a-b). The northern boundary is generalized to be the flow rate boundary (segment c-d) as the underground watershed has moved northward to the intersection of Jinhuo rupture and Zhuangtou fault.

Within the spring Basin, the karst water in the deep mainly receives supplement from atmospheric precipitation infiltration in exposed and semi-exposed areas. Having been supplemented by rainfall, it supplements to the deep along fractures or structural solution cracks. The groundwater level is buried relatively deep, thus little karst water is drained through evaporation from the deep.

3.3.2 Determination and generalization of vertical structures

Based on hydrogeologic conditions within the spring Basin, the karst aquifer of Middle Ordovician is chosen to be the main target layer for numerical simulation of groundwater. There are two aquifers in the Middle Ordovician-one in the lower position and the other in part of the middle to upper position. They are hereby considered one aquifer. There are some Cambrian aquifers in the southern spring Basin. The Ordovician transitions to the Cambrian through fractures in faults. The transitional belt basically combines into one target aquifer along the Ordovician and Cambrian fault fracture belt, which becomes the phreatic water-confined water aquifer with unified groundwater level. The fractures and karstic fissures in the lower Ordovician are not developed. They have composed a stable water-proof lower confining bed in the Middle Ordovician. The top of the aquifer is mostly covered by Permian and Carboniferous sandstones and shales, becoming a slightly water-proof supplement boundary. Part of it can supplement the deeper layers through fractures. In addition, the top of the aquifer in the river valley area is mostly covered by the Quaternary sediments. Generally, karst pores and fissures are well developed in river valleys. This also provides channels for the downward seepage supplement of rivers and reservoirs. Aquifers become increasingly thicker from east of the spring Basin to its west and thinner to its drainage area in the south.

3.3.3 Determination and generalization of balance elements

The balance elements of groundwater system refer to balance among source / sink term, supplement and drainage term, which mainly include rainfall infiltration, seepage of rivers, channels and reservoirs, artificial exploitation, *etc*.

(1) Supplement amount of rainfall infiltration

Rainfall infiltration is the primary source of supplement for groundwater in Sangu Spring Basin. When calculating the supplement amount of rainfall infiltration, the following factors were considered: ① Area controlled by meteorological stations. This calculation was mainly based on data of three meteorological stations within the spring Basin-Jincheng, Gaoping and Lingchuan. With regard to Jincheng, Gaoping Basin and hills data from Jincheng and Gaoping stations was adopted; while regarding Lingchuan and the middle to lower mountain areas in the southeastern part, data from Lingchuan station was adopted; ② Determination of valid rainfall. When calculating the supplement amount of precipitation infiltration, valid rainfall amount was adopted this time, meaning that the numbers that were adopted when a single rainfall exceeded 10 mm or the continuous rainfalls exceeded 10 mm; ③ Determination of infiltration coefficients. The rainfall infiltration coefficients of the studied area was calculated with empirical formula. The rainfall infiltration coefficient was about 0.25 in the Quaternary loose layer of the river valley and 0.15~0.20 in hill areas. The rainfall infiltration coefficient was about 0.07~0.10 where fragmented rocks propped out. Among which, the coefficient was about 0.07 in the exposed Permian area, about 0.10 in the exposed Carboniferous area. In the carbonate rock areas was about 0.23. In terms of areas lacking data, the atmospheric precipitation infiltration coefficient of the studied area was selected according to the empirical value on the hydrogeology manual. Rainfall amounts in all stations within the spring area and precipitation amounts under different guarantee rates are shown in Fig. 1.

(2) Leakage amount of reservoirs

There are two relatively large reservoirs within the study area-RenZhuang reservoir and Taoqinghe reservoir. Both are leakage reservoirs. Their bottoms directly overlie Ordovician limestones. With years' karstification, the karstic features are relatively developed. But both reservoirs are still seeping despite treatments for multiple times. The relation between the water level of Renzhuang reservoir and its leakage amount is shown in Fig. 2. The leakage amount of Taoqinghe River reservoir is determined based on data from the report on detailed exploration of water supply.

(3) Leakage amount of river water

A large amount of river water leakage is found in Dan River and its tributaries when they pass through areas with exposed or semi-exposed limestones. Leakage occurred mostly in the segment of Dan River that passes through Gaoping City (Jiantou Village-Hexi Village of Daji Town), the segment from downstream Renzhuang reservoir to Hedong Village, Bagong River segment (Shuimotou Village-Guanyuan Village) and Baishui River segment (Sidi Village-Hexi Village of Daji Town). The leakage amount was calculated based on field measurement of flow rates on river sections.

The rest of balance elements are determined through calculation as follows: The spring drainage amount was gained through field measurement of flow rates; the exploitation amount of karst groundwater was gained from The bulletin of Jincheng City on water resources; the lateral runoff amount was determined by means of the cross section method combined with water pumping tests as well as water levels including that of groundwater.

Table 1 Mean rainfall and rainfall in different guaranteed rates

Series	Mean			50%			75%			95%		
	Jin-cheng	Ling-chuan	Gao-ping	Jin-cheng	Ling-chuan	Gao-ping	Jin-cheng	Ling-chuan	Gao-ping	Jin-cheng	Ling-chuan	Gao-ping
Multi-year mean	605.16	604.28	595.32	613.3	588.9	584.2	497.1	512.0	502.4	388.4	428.7	382.9
Recent year mean	563.94	569.84	537.47	558.6	560.3	487.6	525.5	543.0	435.6	414.0	471.90	378.6

Table 2 Renzhuang reservoir leakage in different water level

Elevation of reservoir's water level (m)	758~760	760~761	761~762	762~763	763~764	764~765	765~766	766~767	767~768
Leakage amount (m^3/s)	0.027 6	0.087 1	0.322	0.404	0.479	0.912	0.988	1.245	2.282

3.4 Numerical simulation of karst groundwater

3.4.1 Mathematical model

The groundwater flows are generalized into heterogeneous, aeolotropic and unstable two-dimensional groundwater flow systems by studying the supplement, runoff and draining characters of the simulated area as well as its dynamic characteristics based on the hydrogeologic conditions of the simulated area. This is expressed through following mathematical model.

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}+T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}+T_{yy}\frac{\partial h}{\partial y}\right)+W=S_s\frac{\partial h}{\partial t}$$

$(x,y\in D,\ t>0)$

$$\frac{\partial h}{\partial n}\Big|bc,de,fa=0 \qquad t>0,\ \text{Confining boundary}$$

$$-T_n\frac{\partial h}{\partial n}\Big|ef,ab,cd=q(x,y,t) \qquad (x,y\in D,t>0),\ \text{Flow boundary}$$

$$\frac{Kr}{Mr}(H_r - h) = q_r \qquad t>0,\ River\ boundary$$

$$C_D\ (H_D\text{-}h)=q_D \qquad t>0,\ Drain\ boundary$$

In this formula: h is elevation of groundwater level (m); T is water transmissivity coefficient (m^2/d); S_s is storage coefficient; x and y are coordinate variables; W is source/sink term intensity (m^3/(d·m^2)); D is range of simulated area; K_r is riverbed permeability coefficient (m/d); M_r is riverbed thickness (m); H_r is elevation of river water level (m); q_r is leakage amount per unit area (m/d); C_D is hydraulic conductivity of the spring vent (m^2/d); H_D is spring vent elevation (m); q_D is spring drainage amount (m^3/d).

3.4.2 Model identification and validation

Based on the practical conditions in the simultaneous observation of groundwater level of the studied area, the period from October 1st, 2013 to September 30th, 2014 was selected for model identification. This lasted a complete hydrologic year that was divided into 12 segments. The timestep of them each was one month. The source/sink term amounts were determined based on balance elements of the hydrogeologic conceptual model. Among which, the Recharge module of the software was adopted for rainfall infiltration supplement; the River module was adopted for river leakage and drainage of groundwater; the Lake module for reservoir leakage; the water sources within the spring Basin, concentrated water-supply wells and lateral runoff amount were determined by the Well module of the model; the Drain module was used for spring drainage.

When conducting calculation, the model divided the karst groundwater aquifer into 25 parameter zones (Fig. 4) according to the differences in hydrogeological conditions of the spring Basin. Groundwater level fitting was performed for the representative long-term observation data of three drill holes positions selected from the supplement area, runoff area and drainage area. In the identification process, the hydrogeological parameters of the model were determined based on the fact that the absolute error between the dynamic water level data of the long observation hole and the simulated calculation water level was less than 0.5 m.

Up to 93% was the case that the fitting error between the calculated value and the measured value of the water level of the long observation holes in each period was less than 0.5 m, which was ideal in this lithologically and structurally complex area. The fitting result is shown in Fig. 5. The identified parameter partitions and the parameter values of each partition is shown in Table 3.

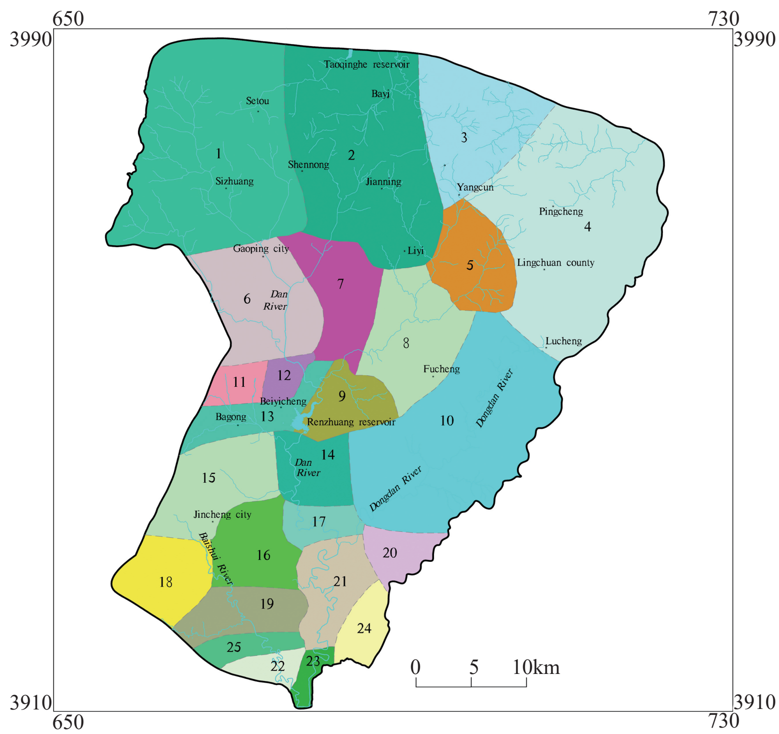


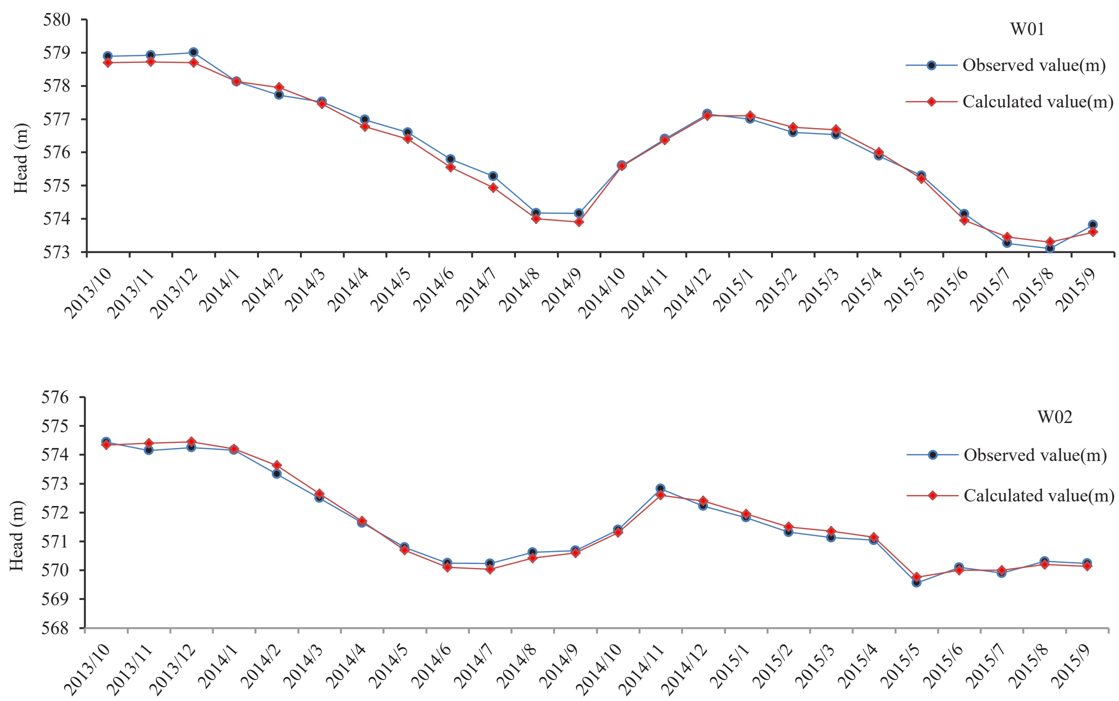
Fig. 4 Partition of hydrogeological parameters

Table 3 Hydrogeological parameters identification of model

Partition No.	T_{xx}(m^2/d)	T_{yy}(m^2/d)	S_s	Partition No.	T_{xx}(m^2/d)	T_{yy}(m^2/d)	S_s
1	50	50	0.054	14	2 100	6 500	0.030
2	40	40	0.052	15	2 000	2 500	0.030
3	70	55	0.005	16	900	1 350	0.005
4	110	25	0.020	17	4 210	6 000	0.010
5	90	65	0.015	18	35	35	0.002
6	120	150	0.003	19	550	1 700	0.008
7	30	50	0.040	20	170	750	0.018
8	2 520	1 800	0.008	21	400	740	0.064
9	5 050	5 210	0.017	22	800	4 500	0.006
10	20	40	0.013	23	2 450	25 000	0.008
11	580	580	0.005	24	750	1500	0.019
12	40	130	0.026	25	70	810	0.074
13	420	80	0.045				

Based on the practical conditions in the observation of groundwater level of the calculated area, the period from October 1st, 2014 to September 30th, 2015 was selected for simulated validation. This lasted a complete hydrologic year that was divided into 12 segments. The timestep of them each was one month. Water level fitting was performed for long-time observation positions of three karst wells. The fitting error was generally less than 0.5 m. The fitting result is shown in Fig. 5. The results of the model test indicated that the established mathematical model and generalization of its boundary conditions, the selection of hydrogeological parameters as well as the processing of source/sink terms were all correct, and that can be used for prediction of groundwater level dynamics (SUN Cong-wen *et al*. 2013; SHU Long-cang *et al*. 2007; ZHAI Yuan-zheng *et al*. 2010; Abdulrahman *et al*. 2020).

The groundwater balance analysis indicated that the karst groundwater within the spring Basin generally presented a negative balance, and the balance difference was -2 789.33×10^4 m^3/a. The karst groundwater level declined generally.



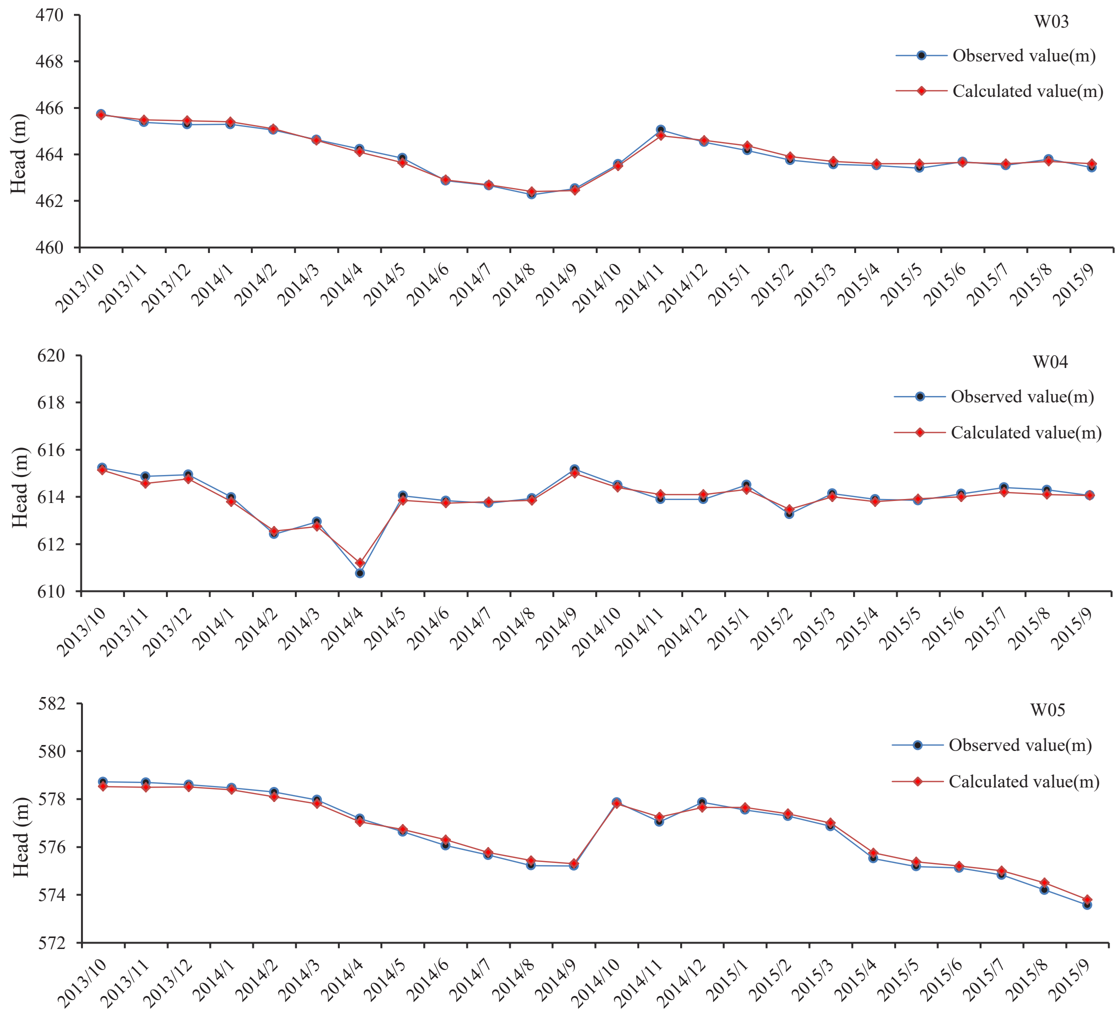


Fig. 5 Fitting curve of model recognition period and validation period

Table 4 Groundwater balance in simulation period

Supplement items ($\times10^4$ m³/a)		Drainage items ($\times10^4$ m³/a)	
Rainfall infiltration supplement	16 784.79	Karst spring drainage	14 921.87
Upper layer leakage supplement	9 125.87	Drainage of karst groundwater to watercourses	5 009.28
Watercourse seepage supplement	3 469.66	Undercurrent amount of karst groundwater	1 221.16
Reservoir seepage supplement	162.66	Exploitation amount of karst groundwater	11 180
Total	29 542.98	Total	32 332.31
Balance difference		-2 789.33	

4 Prediction and evaluation of environmental impact under different exploitation schemes

4.1 Determination of exploitation schemes

The basic idea of calculating the amount of recoverable groundwater resources is to select an exploitation schemes and calculate the groundwater level drawdown. If groundwater level drawdown is uneven or exceeds the allowable drawdown of groundwater, adjust the exploitation amount and then recalculate the water level drawdown repeatedly till the water discharge capacity of each well has been fully exerted and the water level at each position does not exceed the allowable drawdown value at the same time. The best groundwater exploitation scheme is selected after adjusting calculation repeatedly to render the allowable exploitation amount of groundwater resources (WANG Gui-ling *et al*. 2007; WANG Wen-ke *et al*. 2011).

(1) Forecast the calculation time

Based on the practical conditions in the observation of groundwater level of the calculated area, the lowest groundwater level during the dry season on April 1st, 2014 was selected to be the initial condition for mathematical model resolving. The stress period was set to be a year (365d). Changes of the karst groundwater level in Sangu Spring Basin in the future 10 years will be forecast in primarily April 2020 and April 2024.

(2) Selection of rainfall scheme

According to hydrogeological conditions in this area and the characteristics of water demand in Sangu Spring area, the precipitation amounts of Jincheng, Gaoping and Lingchuan stations in the coming decade will be forecast by using their rainfall data from 1965 to 2014 and adopting the method of periodic analysis and prediction. These precipitation amounts will be put into the mathematical model for calculation as the first set of mathematical model solution. Taking into account a more complete and comprehensive reflection of the impact that atmospheric precipitation has on model solving, the mean rainfall amounts of Jincheng, Gaoping, Lingchuan stations in the next 10 years will be put into the model as the second set of precipitation plan.

(3) Constraints for groundwater exploitation

The exploitation amount of karst groundwater should not exceed the maximum allowable exploitation value of the entire karst groundwater system in any exploitation period. Based on the water resources evaluation results, the average value of the maximum allowable exploitation amount calculated by the mining coefficient method and river base flow method is 19 399.38×10^4 m^3/a.

The karst water of Guobi Spring is an important supply source for residents' daily life, industry and agriculture in Jincheng. 30% of the original flow rate of Guobi Spring is needed for maintaining downstream ecology (ZHANG Chun-chao *et al*. 2017; SHEN Nan *et al*. 2010). By this standard, the minimum flow rate of Guobi Spring must be ensured 0.12 m^3/s. Under the condition of guaranteeing the minimum flow, the optimal exploitation amounts of water sources will be determined by simulation, and the recoverable amount of resources in the spring area will be calculated.

It is crucial to control the water level drawdown within the range of simulated karst groundwater source exploitation and to reasonably develop and utilize the karst groundwater in Sangu Spring Basin. After repeated analysis and comparison, the maximum lower limit of re-drawdown is given for groundwater within the range of simulated water sources mining in every karst groundwater on the basis of the hydrodynamic field in April 2014. Water source in Gaoping: The maximum drawdown value should be less than 15 m for Gaoping water source, 12 m for Bagong water source, 12 m for Beishidian water source, 20 m for urban area water source and 3 m for south of Guobi.

4.2 Forecast results

When performing model simulation calculations, the first is to make initial allocation of the exploitation amount of each water source according to the proposed exploitation schemes, to predict the dropdown of the groundwater level, and then to determine whether the Guobi Spring is below the minimum flow rate and whether the groundwater level drawdown exceeds the maximum allowable drawdown according to the above constraints. After these, gradually adjust the exploitation amount of each water source. Lastly, select the exploitation schemes with the largest exploitation amount, according to which the spring flow rate and drawdown both meet the requirements to be the best mining plan. The total exploitation amount is namely the recoverable resource amount of karst groundwater in the spring area.

Table 5 Redistribution of water resources exploitation in simulated water sources

Water sources	Exploitation schemes	
	Recoverable amount (m^3/s)	Recoverable amount (ten thousand m^3/a)
Gaoping	0.10	304.68

Table 5 (Continued)

Water sources	Exploitation schemes	
	Recoverable amount (m^3/s)	Recoverable amount (ten thousand m^3/a)
Bagong	0.16	499.68
Beishidian	0.19	584.99
Urban area	0.39	1 243.11
Mianshang	0.41	1 304.05
Guobinan	0.71	2 242.48
Total	1.96	6 179.00

Table 6 The depth of water level in funnel center of water source under different precipitation schemes

Forecast time	Multiyear average precipitation plan					Forecast precipitation plan				
	Gaoping	Urban area	Beishidian	Bagong	Guobi	Gaoping	Urban area	Beishidian	Bagong	Guobi
April 2020	-8.20	-7.73	-7.20	-7.93	-1.30	-8.33	-7.40	-6.87	-8.13	-1.40
April 2024	-12.13	-11.87	-10.87	-11.60	-2.13	-12.47	-11.53	-11.27	-11.80	-2.21

Table 7 Forecast results of Karst spring flow

Forecast time	Spring flow rate (m^3/s)			
	Multiyear average precipitation schemes		Forecast precipitation schemes	
	Guobi Spring	Sangu Spring	Guobi Spring	Sangu Spring
April 2014	0.40	3.50	0.40	3.50
April 2020	0.18	3.09	0.173	3.04
April 2024	0.133	2.978	0.126	2.945

Based on current exploitation of groundwater, the redistribution exploitation amounts of Gaoping, Bagong, Beishidian, the urban area and south of Guobi water source are 0.10 m^3/s, 0.16 m^3/s, 0.19 m^3/s, 0.39 m^3/s and 0.71 m^3/s. The exploitation amount is 0.41 m^3/s for scattered wells inside the area. The total redistribution amount is 1.96 m^3/s, namely 61.79 million m^3/a. Under the two precipitation plans, this exploitation amount meets the requirements of regional water level drawdown, the maximum allowable drawdown of every simulated water source and the flow rate of Guobi Spring, indicating that the mining amount is relatively reliable. According to the bulletin on water resources of Jincheng City, the current mining amount of karst water is 111.80 million m^3/a. Thus, the amount of recoverable resources of karst groundwater in the spring Basin is 173.59 million m^3/a.

5 Conclusions

Based on the comprehensive analysis of meteorological, hydrological, geological and hydrogeological data in the working area, a numerical model of karst groundwater in the Sangu Spring Basin was build, identified and verified. The results show that:

(1) From the perspective of stratigraphic lithology and its effect on karst features and karst groundwater, the Sangu Spring Basin can be divided into three groups, of which the limestones of the Middle Ordovician Majiagou group and the Middle Cambrian Zhangxia group are aquifer, and the dolomites of the Lower Ordovician-Upper Cambrian Sanshanzi group are aquitards.

(2) A numerical model of the Sangu Spring domain was built. On the basis of identification and verification, 25 hydrogeological parameter zones of karst groundwater aquifers were determined

and refined. 93% was the case that the fitting error between the calculated value of the water level at long observation holes and the measured value in each period was less than 0.5 m. For the lithologically and structurally complex Sangu Spring area, the fitting effect has been ideal.

(3) Using the method of periodic analysis and prediction, forecast on the precipitation in the next ten years was made as the first set of precipitation scheme for the mathematical model solving based on the rainfall data of each station in the spring Basin from 1965 to 2014. Taking into account a more complete and comprehensive reflection of the impact that atmospheric precipitation has on model solving, the mean rainfall amount of the entire Spring Basin was put into the model, and forecast on the precipitation in the next ten years was made as the second set of precipitation scheme for simulation.

(4) According to exploitation constraints, based on the current exploitation amount of 111.8 million m^3/a, the total redistribution exploitation amount in the Spring Basin is 1.96 m^3/s, or 61.79 million m^3/a. Under the two precipitation schemes, this exploitation amount meets the requirements of regional groundwater level drawdown, the maximum allowable drawdown of every simulated water source and the flow rate of Guobi Spring, indicating that the exploitation amount is relatively reliable. Therefore, the amount of recoverable resources of karst groundwater in the spring Basin is 173.59 million m^3/a.

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