The influences of sponge city construction on spring discharge in Jinan city of China
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ABSTRACT
In recent years, intense human activities have threatened to dry up the well-known karst springs in Jinan, China. Sponge city construction program was one of the measures aiming to improve the recharge to groundwater and also protect sources of spring discharge. An influence study of sponge city construction on groundwater is necessary while not fully evaluated. In this paper, a three-dimensional numerical groundwater flow model was developed to address this issue. Model calibration showed that the simulated groundwater level successfully reproduced the observed results. Then, 12 scenarios were established and predicted according to different precipitation conditions and the achieved degrees of sponge city construction. The results indicated that the sponge city construction was conducive to the rise of regional groundwater level after 20 years. However, the groundwater level around the spring groups would only increase by an average of 0.22 m, and the annual spring discharge would increase by approximately 9.00 million m³ after 20 years. Results revealed that the extent of spring discharge recovery was not evident in a short time frame. The proper positioning of sponge city construction was suggested to be considered further to balance the protection of springs with the issue of waterlogging.

Key words | fractured-karst aquifer, Jinan springs, numerical simulation, sponge city

INTRODUCTION
Karst areas account for approximately 7–12% of the total land area of the Earth; however, these areas provide more than 25% of the drinking water for the world’s population (Ford & Williams 2007; Wang et al. 2018). Owing to its rich reserves, large water yield, extensive distribution, and good water quality, karst water has become an especially important groundwater resource for the world (Bakalowicz 2005). Besides, karst springs are also the sources for local rivers and lakes which are important for local ecosystems. Additionally, the unique topography of karst areas is a significant source of tourism for the development of local economies. Many karst catchment areas are present in southern and northern regions of China, including the Yunnan, Guizhou, Sichuan, Chongqing, Guangxi, Hunan, and Hubei regions, which comprise a total area of approximately $1.76 \times 10^6$ km² (Lu 2007).

Jinan, the capital city of Shandong Province in China, is famous for its numerous karst springs, including four big spring groups called Baotu, Black Tiger, Five Dragon, and Pearl springs. However, sustained and rapid economic development that occurred in the city from 1975 to 2003 caused a sharp increase in groundwater exploitation, resulting in continuous groundwater level decline and the cut off of springs. For example, the longest continuous cutoff period of Baotu spring was 926 days from 1999 to 2001 (Qian et al. 2010). The Chinese government closely monitored the spring cutoff problem and conducted research on the restoration of the groundwater level and the protection of local...
springs. Furthermore, various measures were taken to alleviate severe situations. For example, the utilization of groundwater was partially replaced by surface water (such as water from the Yellow and Yangtze Rivers), many pumping wells were shut down in spring catchment areas, artificial groundwater recharge increased, and the infiltration of surface water also increased. Since the implementation of these measures, the springs have been flowing since 2003; however, due to low water levels and flow, the springs are still at risk.

The sponge city program was announced by the Chinese government in 2013 to address the problem of urban waterlogging. This approach emphasized the use of natural systems (e.g., changing the conditions of the land surface for precipitation infiltration, control, and storage). Originally, the term ‘sponge city’ meant a city could function like a sponge, demonstrating great resilience to environmental changes and natural disasters. This approach was similar to the best management practices (Ice 2004) and low impact development system of the United States (Xu et al. 2019), the water-sensitive urban design of Australia (Ahammed 2017), and the sustainable urban drainage system of the UK (Ellis & Lundy 2016). Today, the concept of a sponge city has evolved into a modern stormwater management approach to help solve drainage issues, fully utilize land resources, and promote sustainable development. From 2015 to 2016, two pilot batches of sponge cities (30 cities in total) were supported by the Chinese Central Government, and the total investment was about 42.3 billion RMB (Jia et al. 2017). Jinan was among the first batch of pilot sponge cities in China in 2015, the purposes of which were to increase precipitation infiltration, raise the groundwater level, and to influence the springs.

Since the 1950s, many field investigations and studies regarding aquifer properties, origin of springs, groundwater quantity and quality have been carried out in Jinan using borehole logging, long-term observation of groundwater level and spring flow, tracer test and numerical simulation. The earliest two-dimensional groundwater flow model with one-year calibration was established in 1989 to explore the balance of groundwater supply and spring protection, and then over five groundwater flow models were progressively constructed (Wang et al. 2014). Two typical three-dimensional groundwater models were developed by Qian et al. (2006) and Wang et al. (2014), aiming at estimation of the causes of groundwater level decline and the drying up of springs. These investigations and studies provide good references for our further analysis. To our knowledge, the influence of sponge city construction on groundwater flow has not been fully examined, especially the short-term and long-term influences of the project on groundwater level and spring discharge. The purpose of this study was to develop a numerical model to evaluate the influence of sponge city construction on the regional groundwater level and spring discharge in consideration of the implementation of sponge city construction in Jinan. First, we established a three-dimensional (3D) numerical model of groundwater flow. Then, the model was calibrated based on the estimation of the parameters, and the factors controlling the groundwater discharge were analyzed. Finally, scenarios portraying different construction and precipitation conditions were prepared to predict changes in the groundwater level and spring discharge. This study will provide theoretical reference for further sponge city construction and the protection of springs in Jinan and similar areas.

**STUDY AREA**

**Background**

The study area (Figure 1) is located in Jinan, the capital city of Shandong Province, with an area of approximately 1,500 km² and coordinates of approximately 36°28′–36°46′N, 116°40′–117°14′E. Its eastern and western borders are the Dongwu and Mashan Faults, respectively. The southern boundary is the groundwater watershed, and the northern boundary the zone of contact metamorphism and magmatism. The elevation gradually decreases from south to north. The northern area is a piedmont alluvial plain and an intermountain plain with an elevation of approximately 20 m–50 m. The urban district is mainly distributed in this area. To the south is a continuously low and hilly area with an elevation just over 200 m. Further south is a steep lower-middle mountainous area with a maximum elevation of 800 m. The study area has a temperate continental climate. The annual average amount of precipitation...
there is 670.47 mm, while the annual average amount of evaporation is approximately 1,475.6 mm. Moreover, precipitation is mainly concentrated during the months of June to September, which accounts for 75% of the total annual precipitation. The four main rivers in the study area are the Yellow, Xiaoqing, Dashahe, and Yufu Rivers.

**Geology and hydrogeology**

As shown in Figure 1, the Archean Taishan Group (Art), consisting of metamorphic rocks, is distributed in the southern area and is the basement of the study area. The Cambrian (ε) strata is characterized by interbeds of limestone and shale, which are well exposed from south to north. The Ordovician (O) strata is composed of thick-bedded limestone and mainly distributed in the middle of the study area. Most of the Carboniferous (C) and Permian (P) strata are buried and exposed only slightly in the northwest. The Quaternary (Q) strata is well exposed in the northern area. Several large faults are distributed throughout the study area in northwest and northeast directions. The Dongwu Fault is impermeable in most areas, demonstrating weak permeability only in the northeastern part of the spring area; the Mashan Fault is impermeable in the southern mountainous area and permeable in the northern area. The Qianfoshan Fault is in the central part of the Jinan spring area and is permeable in the south and permeable in the north. The remaining small faults are all permeable.

Pore water in a Quaternary aquifer and fractured-karst groundwater in an Ordovician aquifer are the main types of groundwater in the study area, which account for more than 80% of the total groundwater discharge, especially the karst aquifer, which is the major recharge resource for

![Figure 1](image-url)
the springs. Precipitation recharges the groundwater mainly through surface fissures that have developed in the metamorphic rock and limestone in the southern and central areas, which are the main recharge sources for groundwater (Figure 2). Surface water and irrigation infiltration are also important components for groundwater recharge. Recently, artificial recharge has become another important recharge source. The karst groundwater in the study area is mainly discharged through groundwater exploitation, springs, and recharge of the Quaternary pore water, while the pore water is mainly discharged through evaporation, springs, and groundwater exploitation.

**Groundwater utilization**

Groundwater utilization can be classified into four stages (Figure 3). During the first stage (pre-1965), groundwater exploitation was limited, and precipitation was the main factor affecting the groundwater regime, and so the highest spring discharge reached $51 \times 10^4$ m$^3$/d in 1962. The second stage was the period from 1965 to 1980. Groundwater exploitation gradually increased from $10 \times 10^4$ m$^3$/d in 1965 to approximately $30 \times 10^4$ m$^3$/d in 1980 in the urban district. The total groundwater exploitation in the spring area reached $60 \times 10^4$ m$^3$/d in 1972 and then increased to $70 \times 10^4$ m$^3$/d by 1980. Due to the overexploitation of groundwater, the springs have begun to dry up during each dry season since 1972, and the number of dried-up days increased correspondingly. The third stage was the period from 1981 to 2000. For spring protection, groundwater exploitation was transferred from urban areas to suburban areas, and the exploitation decreased suddenly from $30 \times 10^4$ m$^3$/d to $12 \times 10^4$ m$^3$/d in the urban areas. However, the groundwater level and spring discharge were still reduced, and the springs continued to dry up. The last stage was the period that began post-2001, after which more effective measures were taken by the Jinan government to protect the springs. For example, water from the Yellow and Yangtze Rivers and the Wohushan and Yuqingtghu reservoirs was utilized, and the groundwater was gradually replaced by these surface waters in the water supply system. At the same time, artificial recharge of the groundwater system was conducted. The implementation of these measures has ensured continuous flowing of the springs since 2003. Furthermore, the groundwater level began to rise, and spring discharge gradually increased. However, the springs still face the risk of drying up and are in a low water level state, especially from April to June each year.

**METHODS AND DATA**

**Simulation method**

Flow in a fractured-karst aquifer is usually a non-Darcy flow. Flow simulation in a fractured-karst medium is challenging. According to the condition of whether physical processes

![Figure 2](https://iwaponline.com/hr/article-pdf/51/5/959/775462/nh0510959.pdf)
are considered, these models can roughly be classified into two categories (Hartmann et al. 2014; Meng et al. 2015). The first category is a physically based model. This type of model usually applies a finite differential method or a finite element method to discretize a fractured-karst aquifer into several small grids, where different hydrogeological parameters and boundary, recharge, and discharge conditions are given. Owing to the high heterogeneity and anisotropy of karst aquifer media, it is difficult to accurately characterize the hydrogeological parameters of an aquifer; thus, aquifers are often generalized. Many simplification methods have been proposed, such as the equivalent porous media model (Scanlon et al. 2003; Dragoni et al. 2015), double media model (Robineau et al. 2018), triple media model (Chen & Hu 2008), discrete fractured network model (Dverstorp et al. 1992), and discrete conduit network model (Ghasemizadeh et al. 2012). The second category is a lumped model; this type of model takes a karst groundwater system as a unified entity without considering spatial difference, and it only measures the structural relationship between inputs and outputs. Some examples of a lumped model are the commonly used artificial neural network model (Meng et al. 2015), linear or nonlinear reservoir model (Padilla & Pulido-Bosch 2008), wavelet analysis (Labat et al. 2001), and regression analysis (Felton & Currens 1994). Lump models cannot reflect the hydraulic parameters of an aquifer, the flow direction of groundwater, or the velocity of groundwater flow.

The geology structure in the study area is complex, and the aquifer contains karst, fissures, and porous aquifers with different pore sizes, which are difficult to generalize with one another. In this study, a convenient and efficient equivalent medium simulation method was chosen, which is widely used at present in physically based models. In particular, when the main aquifer media are dissolution pores rather than caves and channels, this kind of model can be used to simulate water balances and trends of the regional groundwater flow (Scanlon et al. 2005). Therefore, this

Figure 3 | Changes in precipitation, spring discharge, and groundwater exploitation in urban district; average groundwater level and number of dried-up days of Baotu spring from 1958 to 2010.
method could be employed in our study area. Likewise, it has been successfully applied in most of the karst aquifer systems in northern China (Kang et al. 2011).

Simulation program

This study chose a polygon grid finite difference groundwater modeling system (named PGMS) to establish a 3D groundwater flow numerical model. The PGMS was based on a polygonal grid, which was more convenient, flexible, and accessible and had more advantages than a rectangular grid. Moreover, the PGMS could deal well with problems associated with karst groundwater and karst springs, and it was applied in the Heihe River Basin (Hu et al. 2007) with good results. In addition, the authors have the source code of the PGMS, which could be further improved based on the need for other numerical simulations.

Uncertainty analysis software called Uncertainty Quantification Python Laboratory (UQ-PyL) (Wang et al. 2016) was chosen for parameter optimization. UQ-PyL coupled with the PGMS through ‘control files’ (‘template’ and ‘driver’ files). The template file was a parameter control file that wrote the parameters in a separate file, and the model file generated by the PGMS needed this file to read the parameters automatically. The driver file contained all the adjustable parameters. The model parameter settings could be changed in this file, and the results of the model operation could also be processed.

Conceptual model and data preparation

Conceptual model

The Jinan spring catchment was selected as the model area. The boundary conditions were set according to previous studies (Wang et al. 2014). The northern boundary of the model area was regarded as a no-flow boundary, but a permeable boundary was present where the Yellow River flows. The southern boundary was generalized as an impermeable boundary. The eastern boundary was represented as a no-flow boundary, except the northeastern section of the spring area, which was a weakly permeable boundary. The western boundary was represented as a no-flow boundary, except the northern plains area, which was permeable. The Qianfoshan Fault was represented as a weakly permeable boundary in the southern section and a permeable boundary in the northern part. The bottom boundary of the model was set as the bottom of the upper Quaternary overburden and the lower Cambrian, and the total thickness of the model was approximately 500–600 m. There were three vertical model layers. The first layer mainly consisted of Quaternary, Cambrian, and Ordovician strata, and the thickness of this layer was approximately 185–380 m. The second layer mainly included upper Cambrian strata with a thickness of approximately 58–100 m. The third layer mainly consisted of Middle to Lower Cambrian strata, and the thickness was approximately 170–470 m. Among them, the first and third layers were major aquifers. The model was represented as a heterogeneous anisotropy with a 3D spatial structure and transient groundwater flow.

Data preparation

The main data sources concerning groundwater level and spring discharge are listed in Table 1 and include topography, precipitation, hydrogeology, observation wells, spring discharge, and many research reports (Wang et al. 2014). Sources and sinks were processed in this study. The main recharge sources included were infiltration from precipitation, rivers, and artificial recharge, and the return flow of irrigation water. The main rivers studied were the Yufu,
Beidasha, Yellow, and Xiaoqing Rivers. Artificial groundwater recharge was primarily from two strong seepage zones (reaches of the Yufu and Xingji Rivers). The area of irrigation was determined by remote sensing images.

Groundwater evaporation was calculated from a model based on the depth of groundwater, soil types, and given limits (Hu et al. 2007). Groundwater exploitation occurred in local regions. Spring discharge was calculated based on the groundwater level and the thickness and permeability of underlying media, which included Baotu, Black Tiger, Five Dragon, and Pearl springs. The critical water level elevation of the spring groups was set according to the actual outflow elevation. The outcrops of Baotu, Black Tiger, Five Dragon, and Pearl springs were 27.01 m, 27.30 m, 26.20 m, and 26.77 m, respectively.

**Model discretization and calibration**

**Model discretization and zonation of hydrogeological parameters**

The study area was divided into three layers, and each layer was divided into 6,488 auxiliary triangles for a total of 19,464 auxiliary triangles (Figure 4). The period of model calibration was from January 2014 to December 2016. The time step was set as one month; therefore, there were a total of 36 time steps. The trial-and-error method was used to calibrate the model against observed data to achieve the smallest possible objection function, which was defined as the sum of the squares of the differences between the observed and calculated results, including both the water

![Figure 4](https://iwaponline.com/hr/article-pdf/51/5/959/775462/nh0510959.pdf)
level and spring discharge. Then, UQ-PyL software was used to optimize the parameters.

Many aquifer parameters, including horizontal ($K_{xx}$ and $K_{yy}$) and vertical ($K_{zz}$) hydraulic conductivities, specific yield ($S_y$), and specific storage ($S_s$), were involved due to the complexity of the aquifer system ($K_{zz} = \frac{1}{2} K_{xx}$, $K_{yy} = K_{xx}$). Based on the obtained borehole data, the hydrogeological parameters of the three simulation layers were subdivided into 71 zones. The hydrogeological parameters were initially assigned, and then they were adjusted and fixed after the model was calibrated. Considering the changes of the hydrogeological parameters caused by sponge city construction, the first layer of the sponge city pilot area was subdivided separately to better simulate the changes in the groundwater flow field and spring discharge (Serial Zones 16 and 31, Table 2). The zonation of the three aquifers is presented in Figure 5, and the optimized parameters are listed in Table 2.

**Comparison of observed and simulated groundwater level data**

Calibration targets were calculated as the root mean square of the difference between the observed and simulated groundwater levels ($\Delta h$). There was a total of 17 observation wells (13 in the plains area and four in the mountainous area), and the observation data were collected from 2014 to 2016. The results (Table 3) indicated that the number of absolute errors between

| Serial zone | $K_{xx}$ (m/d) | $S_s$ ($10^{-4}$ m$^{-1}$) | $S_y$ | Serial zone | $K_{xx}$ (m/d) | $S_s$ ($10^{-4}$ m$^{-1}$) | $S_y$ | Serial zone | $K_{xx}$ (m/d) | $S_s$ ($10^{-4}$ m$^{-1}$) | $S_y$ |
|-------------|----------------|-----------------|------|-------------|----------------|-----------------|------|-------------|----------------|----------------|------|
| 1           | 0.02           | 0.40            | 0.10 | 25          | 40.00          | 7.00            | 0.05 | 49          | 10.00          | 0.10            | 0.01 |
| 2           | 0.02           | 0.60            | 0.10 | 26          | 20.00          | 5.00            | 0.05 | 50          | 5.00           | 0.10            | 0.01 |
| 3           | 0.05           | 0.60            | 0.20 | 27          | 80.00          | 5.00            | 0.05 | 51          | 0.10           | 0.20            | 0.05 |
| 4           | 0.03           | 0.40            | 0.20 | 28          | 70.00          | 7.00            | 0.05 | 52          | 0.05           | 0.50            | 0.10 |
| 5           | 0.06           | 1.00            | 0.20 | 29          | 30.00          | 7.00            | 0.05 | 53          | 0.10           | 0.20            | 0.15 |
| 6           | 0.05           | 0.60            | 0.25 | 30          | 1.00           | 1.00            | 0.01 | 54          | 0.10           | 0.10            | 0.15 |
| 7           | 0.04           | 0.60            | 0.20 | 31          | 10.00          | 7.00            | 0.01 | 55          | 0.10           | 0.20            | 0.10 |
| 8           | 0.02           | 0.60            | 0.001| 32          | 50.00          | 0.50            | 0.005| 56         | 0.05           | 1.00            | 0.10 |
| 9           | 0.05           | 0.60            | 0.20 | 33          | 5.00           | 1.00            | 0.05 | 57          | 0.01           | 1.00            | 0.05 |
| 10          | 0.05           | 0.60            | 0.20 | 34          | 40.00          | 0.10            | 0.001| 58         | 0.01           | 0.50            | 0.10 |
| 11          | 0.01           | 1.00            | 0.05 | 35          | 30.00          | 0.10            | 0.005| 59         | 5.00           | 2.00            | 0.01 |
| 12          | 0.008          | 1.00            | 0.05 | 36          | 0.10           | 1.00            | 0.01 | 60         | 5.00           | 2.00            | 0.05 |
| 13          | 50.00          | 7.00            | 0.05 | 37          | 0.10           | 1.00            | 0.05 | 61         | 0.10           | 0.50            | 0.01 |
| 14          | 30.00          | 7.00            | 0.05 | 38          | 1.00           | 0.50            | 0.10 | 62         | 0.10           | 0.20            | 0.01 |
| 15          | 30.00          | 4.00            | 0.10 | 39          | 50.00          | 5.00            | 0.10 | 63         | 0.10           | 1.00            | 0.01 |
| 16          | 30.00          | 4.00            | 0.005| 40          | 1.00           | 1.00            | 0.10 | 64         | 0.10           | 2.00            | 0.05 |
| 17          | 10.00          | 4.00            | 0.20 | 41          | 10.00          | 5.00            | 0.10 | 65         | 0.10           | 2.00            | 0.05 |
| 18          | 40.00          | 7.00            | 0.05 | 42          | 10.00          | 5.00            | 0.10 | 66         | 40.00          | 1.00            | 0.01 |
| 19          | 30.00          | 7.00            | 0.04 | 43          | 3.00           | 2.00            | 0.10 | 67         | 40.00          | 1.00            | 0.01 |
| 20          | 30.00          | 7.00            | 0.10 | 44          | 10.00          | 5.00            | 0.10 | 68         | 40.00          | 1.00            | 0.10 |
| 21          | 5.00           | 1.00            | 0.20 | 45          | 3.00           | 1.00            | 0.10 | 69         | 40.00          | 1.00            | 0.05 |
| 22          | 4.00           | 1.00            | 0.10 | 46          | 1.00           | 1.00            | 0.10 | 70         | 0.10           | 0.50            | 0.01 |
| 23          | 1.00           | 1.00            | 0.10 | 47          | 10.00          | 0.50            | 0.10 | 71         | 0.10           | 0.20            | 0.10 |
| 24          | 5.00           | 7.00            | 0.05 | 48          | 10.00          | 0.50            | 0.05 |
the simulated and observed values were less than 0.5 m, 1.0 m, and 3.0 m, which accounted for 27%, 47%, and 79%, respectively. The relative errors within 5%, 10%, and 20% accounted for 70%, 85%, and 94%, respectively. The goodness-of-fit in the plains area was higher than that of the mountainous area. If the observation holes in the plains area were solely analyzed, the absolute errors were less than 0.5 m, 1.0 m, and 3.0 m, accounting for 33%, 58%, and 92%, respectively; the relative errors within 5%, 10%, and 20% accounted for 77%, 92%, and 95%, respectively. The fitting accuracy of the observation holes in the mountainous area was slightly poor, but the relative errors of the simulated value that were less than 20% also accounted for 91%, and more than half of them were less than 5%. Figure 6 shows the comparison between the simulated and observed groundwater levels (corresponding with observation wells a, b, c, d, e, and f in Figure 1). The results indicated that the prediction could adequately reflect the actual groundwater level.

**Groundwater budget analysis**

There were four springs in total, and observation data were collected from 2014 to 2016. The observed average annual spring discharge for Pearl, Five Dragon, Baotu, and Black Tiger springs was 0.06, 0.12, 0.18, and $0.16 \times 10^8$ m$^3$, respectively. The simulated average annual spring discharge for Pearl, Five Dragon, Baotu, and Black Tiger springs was 0.07, 0.14, 0.22, and $0.17 \times 10^8$ m$^3$, respectively. For the four springs, the observed and simulated annual total discharges were 0.53 and $0.60 \times 10^8$ m$^3$, respectively, and the absolute error of discharge was approximately $0.07 \times 10^8$ m$^3$ with a relative error (the ratio of the absolute difference of observed and simulated discharge to the observed results) of approximately 13%. Meanwhile, for the observation wells around the four springs (Figure 6(e)), the simulated water level was consistent with the observed results.

The simulated groundwater budget in the study area from 2014 to 2016 was obtained. The main groundwater
recharge sources included infiltration from precipitation and rivers (natural river infiltration and artificial recharge), and the average recharge values were 3.24 and 0.77 × 10^8 m^3 (accounting for 78% and 19% of the total recharge), respectively. The main groundwater discharge sources included groundwater exploitation and springs, and the average discharge was 1.41 and 0.61 × 10^8 m^3, accounting for 57% and 24% of the total recharge, respectively. From 2014 to 2016, the total annual value of groundwater recharge was 3.39, 3.93, and 5.21 × 10^8 m^3, respectively, and the total annual value of groundwater discharge was 2.43, 2.49, and 2.56 × 10^8 m^3, respectively. The changes in groundwater storage from 2014 to 2016 were 0.96, 1.44, and 2.65 × 10^8 m^3, respectively, and the groundwater system was always in a

![Figure 6](http://iwaponline.com/hr/article-pdf/51/5/959/775462/nh0510959.pdf)

**Figure 6** | Comparison of observed and simulated groundwater levels: (a), (b), (c), (d), (e), and (f) represent observation wells a, b, c, d, e, and f from Figure 1.
positive balance. The increase in groundwater storage should have a beneficial impact on the recovery of spring discharge.

MODEL APPLICATION AND RESULTS

Construction of Jinan sponge city

The sponge city pilot was located in the southeast region of the study area with mountains to the south; the pilot was approximately 1.8 km north of the springs (Figure 7). The elevation of the pilot area ranged from 23 m to 460 m. In this area, the mountains and plains were merged, and the plains area (with its low permeability) was primarily utilized for development and construction. According to the construction and implementation plans for Jinan sponge city, the planning targets were to be set by each planning area, and when combined with our own research purposes, this area was divided into two zones. Zone $a$ was the development and construction area with a sponge city construction target of runoff coefficient and annual runoff control rate of 0.7 and 75%, respectively. Zone $b$ was the mountainous area with a sponge city construction target of runoff coefficient and annual runoff control rate of 0.4 and 85%, respectively. The total area of the pilot area was 39 km², including 22 km² in Zone $a$ and 17 km² in Zone $b$.

Scenarios set

The most direct effect of sponge city construction on groundwater was an increase in the infiltration capacity of the underlying surface; namely, the degree of sponge city construction could be represented by a precipitation infiltration coefficient. Twelve scenarios (S) were set, as shown in Table 4. Scenarios S0–S3 corresponded to the infiltration

Figure 7 | Sponge city pilot area.
conditions caused by different degrees of sponge city construction. Among them, S0 was the scenario when sponge city construction had not yet begun, while S3 was the scenario when sponge city had been completed according to the initial planning target.

Precipitation conditions were simulated according to dry (D), normal (N), and wet (W) years (obtained by the P-III curve), based on the multi-year precipitation series. The amount of precipitation (P) in the wet year \( P = 25\% \), normal year \( P = 50\% \), and dry year \( P = 75\% \) was 782.45 mm, 648.73 mm, and 534.87 mm, respectively. The precipitation conditions (D, N, or W) corresponded with the benchmark scenarios (S), and were represented by D-S0, N-S0, and W-S0, respectively. The prediction time frame was 20 years, and the time step was one month.

### Results analysis

#### Regional water level distribution

Under different precipitation conditions, the groundwater level changed in scenarios S1, S2, and S3, in contrast to that of scenario S0 (Figure 8). No matter what the scenario was, it was demonstrated that the most rapid and largest increase of groundwater level was in the mountainous area, and it gradually expanded to the surrounding areas and formed a high value area of the regional groundwater level. When the infiltration conditions were the same, the groundwater level increased gradually with an increase in precipitation. When the precipitation conditions were the same, we observed that the greater the infiltration capacity of the underlying surface, the greater the increment of the groundwater level.

The increment of the groundwater level under different precipitation conditions in the pilot area was analyzed when sponge city construction was completed according to the initial target. In successive ‘dry’ years, the areas where the groundwater level rose more than 2 m, 4 m, 6 m, and 8 m accounted for approximately 58%, 25%, 9%, and 3% of the total area, respectively. In successive ‘normal’ years, the areas where the groundwater level rose more than 2 m, 4 m, 6 m, and 8 m accounted for approximately 71%, 40%, 14%, and 7% of the total area, respectively. In successive ‘wet’ years, the areas where the groundwater level rose more than 2 m, 4 m, 6 m, and 8 m accounted for approximately 86%, 50%, 22%, and 11% of the total area, respectively. No matter what the precipitation conditions, the groundwater level in most of the pilot area could rise more than 2 m after 20 years. Sponge city construction generally raised the groundwater level of the pilot area and its surroundings, and the higher the degree of sponge city construction and the more precipitation there was, the larger the increment, and the wider the range of increment.

#### Change in groundwater level around springs

We took observation well e as an example to demonstrate the influence of sponge city construction on the groundwater level near the spring groups. Under different precipitation conditions, the increment of the groundwater level from scenarios S1, S2, and S3 was compared to that of scenario S0 (Figure 9), and 240 data were collected for each scenario. Compared with scenario D-S0, where the maximum increment of the groundwater level was 0.09, 0.13, and 0.27 m, the average increment of the groundwater level...
Figure 8 | Distribution of increased groundwater level for various scenarios in pilot area surroundings after 20 years.
level was 0.03, 0.06, and 0.13 m in scenarios D-S1, D-S2, and D-S3, respectively. Compared with scenario N-S0, where the maximum increment of the groundwater level was 0.15, 0.23, and 0.40 m, the average increment of the groundwater level was 0.03, 0.08, and 0.18 m in scenarios N-S1, N-S2, and N-S3, respectively. Compared with scenario W-S0, where the maximum increment of the groundwater level was 0.16, 0.23, and 0.46 m, the average increment of the groundwater level was 0.04, 0.10, and 0.22 m in scenarios W-S1, W-S2, and W-S3, respectively. The simulation results indicated that when precipitation was sufficient, the groundwater level near the spring groups would increase by 0.46 m, and the average water level would increase by 0.22 m compared to the results that would occur in the absence of the sponge city after 20 years. The higher the construction level of the sponge city and the more precipitation there is, the more the groundwater level near the spring groups should rise.

Change in spring discharge

Figure 10 shows the increment of spring discharge in scenarios S1, S2, and S3 compared with that of scenario S0 under various precipitation conditions. It can be seen that when the infiltration conditions were the same, the spring discharge increased the most in wet years. When the precipitation remained the same, the larger the infiltration capacity was, the more the spring discharge increased; 20 years later, the sponge city construction could increase the annual spring discharge by 0.0672, 0.0766, and $0.0875 \times 10^8$ m$^3$ in a dry year, normal year, and wet year, respectively. The observed data indicated that the discharge of Pearl spring in 2014 was $0.058 \times 10^8$ m$^3$. It could be seen that under the condition of continuous wet years, sponge city construction could increase the annual spring discharge there by approximately 1.5 times the Pearl spring discharge after 20 years.

DISCUSSION

Based on our analysis, we found that sponge city construction, due to an increased precipitation infiltration capacity of the underlying surface, could affect the precipitation to recharge the local groundwater, which would be beneficial for the increment of the groundwater level in and around
the sponge city area. After 20 years, in all scenarios, the groundwater level should have increased. The higher the degree of sponge city construction, the greater the amount of precipitation and the more obvious the uplift effect would be. However, the effect of sponge city construction with regard to increasing the groundwater level and spring discharge near the spring groups was not proportional. The average increment of the groundwater level near the spring groups should rise by about 0.22 m, the maximum increment of the groundwater level near the spring groups could rise by 0.46 m, and the annual spring discharge should increase by approximately $0.09 \times 10^8$ m$^3$ in continuous wet years after 20 years. In 20 continuous wet years, the proportion of annual increment gradually changes from 0.40% to 5.00% when compared with the simulated annual spring discharge for the four springs in the scenario S0. As time goes on, the influence of sponge city construction on spring discharge is increasingly prominent. Therefore, an immediate response by the increment of spring discharge would not be observed in a short time frame.

In the Jinan spring area, the main groundwater recharge source was from the southern region where the Cambrian and Ordovician limestones were exposed over a large area (Figure 2). The pilot test area of sponge city construction was almost located in the local groundwater system of the Jinan watershed and partially belonged to the recharge area. Therefore, when the infiltration coefficient of the groundwater in the sponge city pilot area increases, it could affect the local groundwater flow within a certain range, which has a limited effect on spring restoration (the simulated maximum annual increment percentage was approximately 5%). The construction of the sponge city was a project that necessitated both huge quantities in construction and monetary funds. The construction of the Jinan sponge city cost approximately 7.831 billion yuan, and it involved the reconstruction of a building area, garden and green space, roadways, an urban water system, among other aspects. To increase groundwater recharge to the greatest extent possible, so as to protect the springs by means of sponge city construction, it would be necessary to expand the pilot area; however, this method could require further investments. It could be more effective if the pilot area were moved to the southern part of the Jinan watershed. Owing to the short distance between the recharge and discharge areas of the watershed and the large
topographic slope when rainstorms occur, the runoff would not be able to be intercepted in time, which would result in urban waterlogging; therefore, how to balance the protection of the springs with the issue of waterlogging will be a question worthy of further consideration.

CONCLUSIONS

As the first batch of pilot sponge cities in China in 2015, one of the important purposes of sponge city construction in Jinan was to increase the precipitation infiltration and protect the springs. The effect of sponge city construction on the groundwater system in Jinan was discussed in detail in this study. Groundwater types vary from the karst aquifer in the southern region to the porous media in the northern region of the study area. The groundwater mainly received infiltration recharge from precipitation in the southern area. Four well-known major springs were located in the northern part of the study area, and the sponge city pilot area in Jinan was located in the north part. A finite-difference groundwater flow model in the Jinan spring area was developed to evaluate the influences of the project on the groundwater system. The equivalent media method was used to characterize the karst and fissure aquifers. Model calibration was conducted based on the observed groundwater level and spring discharge data, using a trial-and-error method and optimized software (UQ-PyL). After model calibration, the model was applied to evaluate the changes in the groundwater level and spring discharge after sponge city construction near the pilot area.

The results from the 12 scenarios showed that the larger the infiltration capacity of the sponge city pilot area, the more the groundwater level and spring discharge rose. Additionally, the more precipitation that fell, the more the uplift of the groundwater level occurred. Sponge city construction was beneficial to the increment of the groundwater level in the pilot area. After 20 years, even under the condition of dry years, the groundwater level in most areas of the pilot could rise more than 2 m. However, the effect of the sponge city construction on the protection of the springs was not very obvious. After 20 years, under the condition of continuous wet years, the groundwater level around the spring groups would only increase by 0.22 m, on average, and the maximum annual spring discharge would increase by approximately $0.09 \times 10^8$ m$^3$. The increased maximum annual spring discharge after 20 years could account for approximately 5% of the simulated average annual spring discharge. It was not possible for water managers to observe an immediate response of the groundwater level and spring discharge in a short time frame after the implementation of the project.

To increase spring discharge after the implementation of sponge city construction in Jinan, one method would be to further expand the pilot area, which would incur further expenses; the other method, to increase spring discharge, would be to move the pilot area to the southern region, which would probably enhance the recharge sources of the groundwater system. Jinan has a waterlogging issue due to its short distance from the recharge zone to the discharge zone. The combined influence of waterlogging and sponge city construction on the groundwater level was present and not discussed in this article; however, the proper positioning of a sponge city pilot area could depend on properly balancing the protection of springs with the issue of waterlogging.

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