Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

Geological suitability of natural sponge body for the construction of sponge city—a case study of Shuanghe Lake district in Zhengzhou airport zone

Yong-jun Su, Hui Tang, Ai-min Wu, Xue-ping Dai, Shuang Liu, Hong-wei Liu, Heng Kuang

Citation:
Su YJ, Tang H, Wu AM, *et al*. 2023. Geological suitability of natural sponge body for the construction of sponge city—a case study of Shuanghe Lake district in Zhengzhou airport zone. Journal of Groundwater Science and Engineering, 11(2): 146-157.

View online: https://doi.org/10.26599/JGSE.2023.9280013

Journal of Groundwater Science and Engineering 11(2023) 146–157

Journal homepage: http://gwse.iheg.org.cn

Research Paper

Geological suitability of natural sponge body for the construction of sponge city—a case study of Shuanghe Lake district in Zhengzhou airport zone

Yong-jun Su[1,2*], Hui Tang[3*], Ai-min Wu[4], Xue-ping Dai[5], Shuang Liu[1], Hong-wei Liu[2], Heng Kuang[3]

[1] *School of Geophysics & Geomatics, China University of Geosciences, Wuhan* 430074, *China.*
[2] *Tianjin Center, China Geological Survey, Tianjin* 300170, *China.*
[3] *Henan Acdemy of Geology, Zhengzhou* 450000, *China.*
[4] *China Geological Survey, Beijing* 100037, *China.*
[5] *China University of Petroleum-Beijing at Karamay, Karamay* 834000, *XinJiang, China.*

Abstract: Natural and geological environmental conditions have an important impact on the planning and construction of sponge cities. This paper analyzes geological factors that influence the usage of natural sponge bodies, taking the Shuanghe lake district of Zhengzhou airport zone as an example. An evaluation system with seven factors has been established and the weights of these factors are determined using the analytic hierarchy process (AHP) method. Overlay analysis is then carried out on all factors using GIS to evaluate the geological suitability of the construction of the sponge city. The results show that geologically suitable area for city construction in Shuanghe lake district accounts for 12.3%, relatively suitable area accounts for 76.1%, and relatively unsuitable area accounts for 11.6%. For suitable and relatively suitable areas, we should make full use of the advantages of surface infiltration, vadose zone transportation and aquifer storage to build a sponge city infrastructure with geological engineering as the main component, supplemented by engineering measures such as surface water storage and drainage, and jointly establish a sustainable urban hydrological cycle. For less suitable areas, artificial rain and flood control works, such as roof garden, should be considered. The findings of this paper can serve as an important reference for sponge city planning and construction not only in the research area but also in other regions with similar geological conditions.

Keywords: Natural sponge bodies; Low impact development; Rain flood control; Hierarchy analysis

Received: 05 Aug 2022/ Accepted: 11 Mar 2023/ Published: 15 Jun 2023

Introduction

In recent years, as new urbanization patterns and integration accelerate, there has been intensified use of natural lands. Blind and excessive urban exploitation and urbanization have led to an increase in impermeable ground surfaces, preventing rainwater from seeping into the ground, and resulting in urban waterlogging and water scarcity. A solution is urgently needed that can address both the water shortages and urban flooding (Wang et al. 2013; Liu and Wang, 2016; Qiu, 2015; Liu and Xie, 2016; Liu, 2021).

The essence of sponge city construction is to establish a sustainable urban water circulation system, which manages and utilizes rainwater and floodwater from atmospheric precipitation to groundwater discharge (An, 2015; Li et al. 2022). Neglecting the utilization of natural sponges, such as aeration zone and aquifer with inherent regulation and purification capacity for rainwater and flood resources, would deviate from the ecological concept of " respecting and harmonizing with nature" (Zhang and Pang, 2014; Han and Zhao, 2016; Yu et al. 2019).

Since the 1970s, many countries have developed relatively integrated systems for magaging rainfall flood. In the late 1980s, Australia introduced the

*Corresponding author: Yong-jun Su, Hui Tang, *E-mail address*: syj95123@163.com tanghuiqyj@163.com

DOI: 10.26599/JGSE.2023.9280013

Su YJ, Tang H, Wu AM, et al. 2023. Geological suitability of natural sponge body for the construction of sponge city—a case study of Shuanghe Lake district in Zhengzhou airport zone. Journal of Groundwater Science and Engineering, 11(2): 146-157.

concept of Water Sensitive Urban Design (WSUD) for the first time (Sun et al. 2019; Wong et al. 2012; Morison and Rebekah, 2011). In the late 1990s, the United States came up with the concept of Low Impact Development (LID), and subsequently, the United Kingdom and New Zealand the Sustainable developed the Urban Drainage System (SUDS) and Low Impact Urban Design and Development (LIUDD) system, respectively. These systems provided theoretical foundations for the sponge city concept; however, research on suitability, especially geological suitability, is insufficient (Fletcher et al. 2014).

Since the 1980s, Chinese scholars have conducted scientific research on sponge city from various perspectives, including urban rainwater control, land use and ecological construction. In 2017, Xie et al. (2018) and Huang et al. (2018) evaluated the suitability of sponge city construction using AHP based on the analysis of regional geological and hydrogeological conditions. Ye et al. (2018) provided suggestions on suitable rainwater management facilities for sponge cities in different zones based on evaluations of geological suitability for sponge city construction in the research area. Wang et al. (2019) analyzed the characteristics of sponges, such as surface vegetation, topographic slope, vadose zone, and aquifer, and constructed a geological suitability evaluation system for sponge city construction, which was evaluated using AHP.

Although previous research has provided basic theoretical support for the sponge city, there is a lack of research on the suitability evaluation during the construction process. Cities located in the Yellow River basin have relatively flat terrain, frequent floods, and a high demand for sponge city construction. Therefore, based on the geological environment conditions of the Yellow River alluvial plain and the evaluation system established by previous researchers, this paper considers the water seepage, storage and purification performance of the surface, aeration zone and aquifer, and establishes an evaluation index system for the geological suitability of constructing an alluvial flat sponge city. Using the results of the urban geological survey in Zhengzhou, this paper takes the Shuanghe Lake district of Zhengzhou airport area as an example to carry out the suitability evaluation of sponge city construction based on geological environmental conditions.

1 Study area

The Zhengzhou Airport economic comprehensive experimental zone is the first and only pilot airport economic development zone in China. Shuanghe Lake district is one of the four major areas in the airport area and serves as the pilot area for the integrated service sub-center and the integrated development of industry and city in the south of the airport area (Wang et al. 2019; Cui et al. 2016). Fig. 1 shows the location of the study area.

1.1 Ground surface condition

The study area has a flat and open terrain with a slight slope of 2.5‰–3.6‰ towards the south-

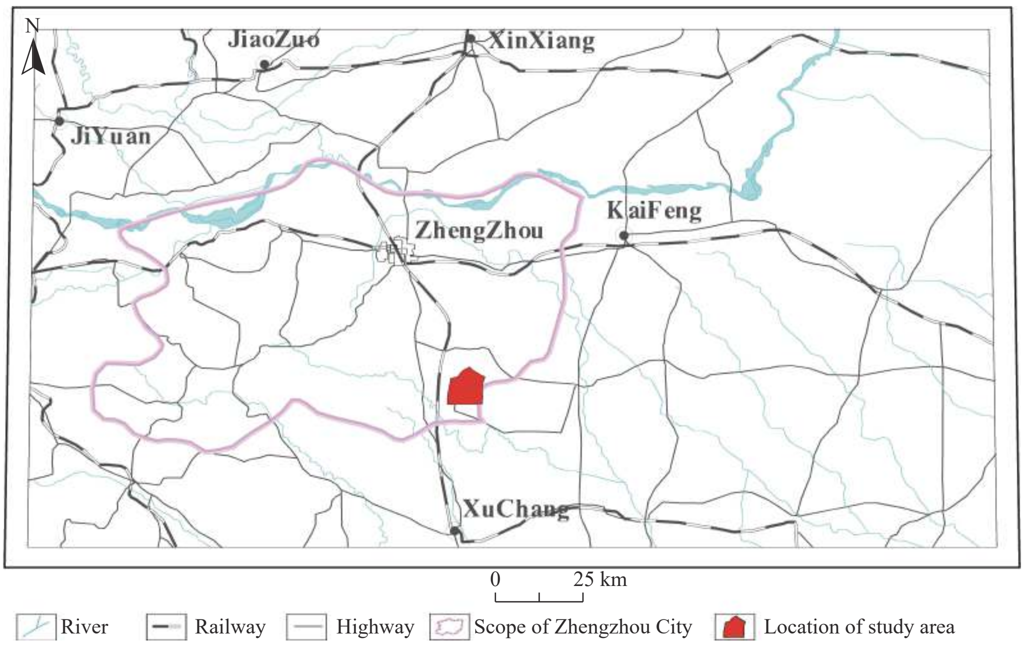

Fig. 1 Location map of the study area

east. The main geomorphological types are the Piedmont alluvial plain and the former Yellow River alluvial plain. The Piedmont alluvial plain is mainly located in the southwest of Baqianxiang with a relatively flat terrain and a slight slope to the southwest. The alluvial plain of the ancient Yellow River is distributed in other areas, with land sloping to the southeast and wind dunes scattered across the surface.

The surficial lithology of the study area mainly consists of silty sand, followed by silty soil (Fig. 2). The silty soil area is mainly distributed in the western belt areas of West Tieli Village—East Wangma Village—Dingzhuang Village, and in Zhangzhuang, Liudian Village and Henan Wang Village. The surficial lithology of the silty sand zone is mainly distributed in the east of Tieli Village—Dongwangma Village—Dingzhuang village belt, and in the north of Leizhuang Village and West Baqianxiang.

1.2 Vadose zone features

The vadose zone in the study area is primarily composed of silty soil and silty soil mixed with silty sand, with some areas containing silty clay up to several meters thick (Fig. 3). The thickness of the vadose zone in the study area ranges from 4 m to 15 m, with the thickest area located near the Baqianxiang in the southwest, and thickness decreasing towards Xianglei Zhuang—Sanshi Village (Fig. 4).

1.3 Aquifer features

The shallow groundwater in the study area is mainly stored in alluvium of the Quaternary Holocene, Upper Pleistocene and Middle Pleistocene, with a buried depth of 4–15 m. The main sources of groundwater include precipitation infiltration, irrigation infiltration, groundwater runoff in the south and southeast directions, and the main groundwater discharge includes mining drainage, evaporation drainage, etc.

The lithology of the shallow aquifer is mainly fine sand, silty sand and sandy silt, with a thickness of 5–20 m in most areas (Fig. 5). The aquifer thickness near Kuiyuanfu Village in the southeast

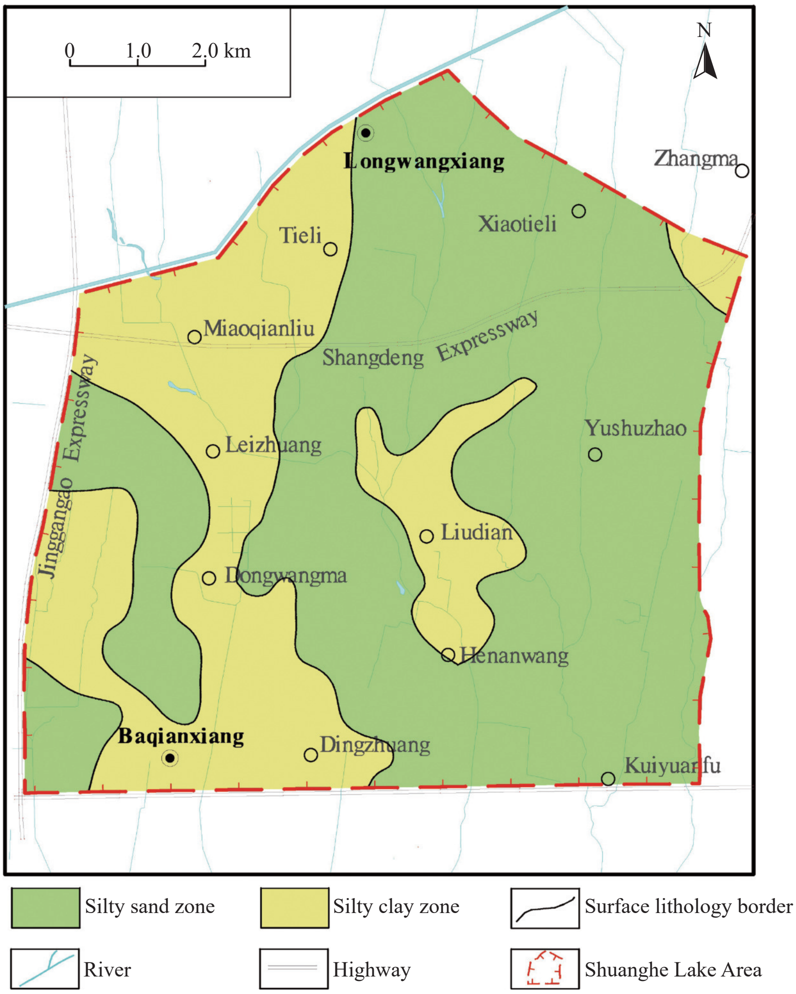

Fig. 2 Surface lithology map of the study area

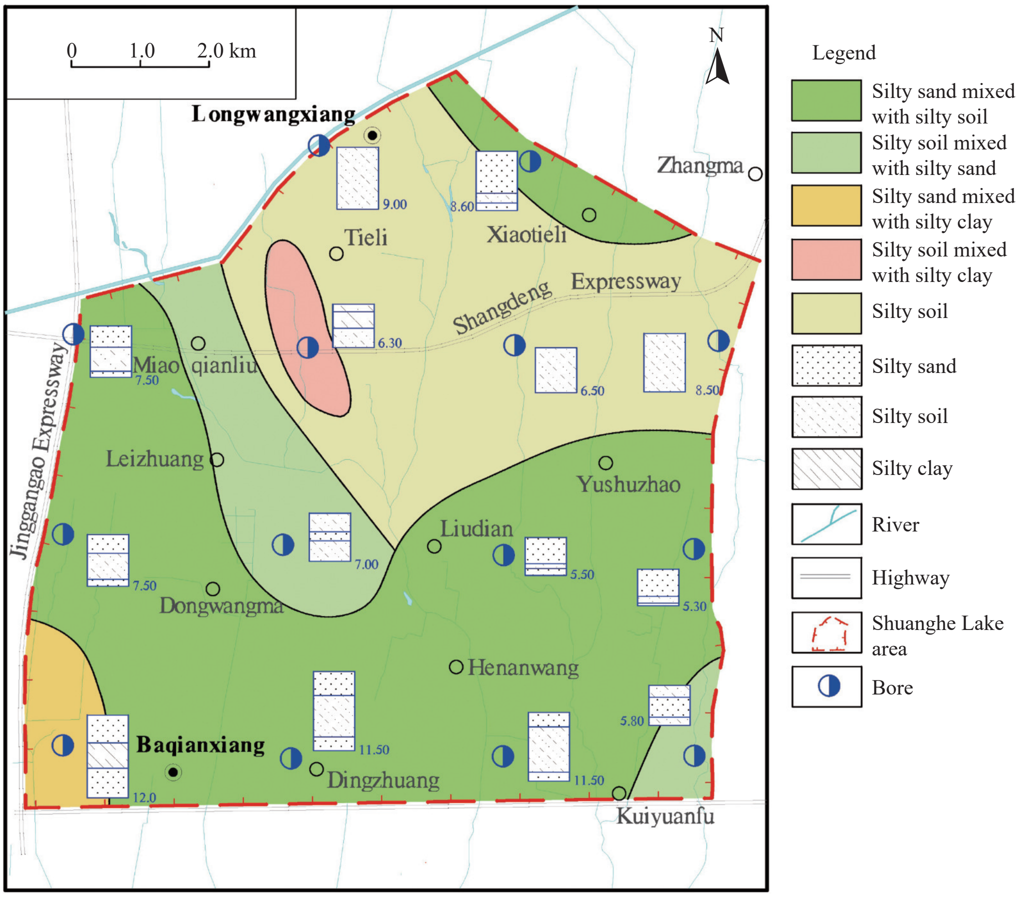

Fig. 3 Distribution of lithology in the vadose zone in the study area

is 15–20 m, with mainly fine sand and medium water abundance grade (Fig. 6 and Fig. 7). The aquifer thickness is 5–10 m in the strip area, east of Henanwang Village-Yushuzhao Village strip and west of Kuiyuanfu Village, with mainly fine sand and with medium water abundance grade. The aquifer thickness in the south of Longwang Township and north of Xiaotiezhuang Liudian Village Tieli Village is 0–5 m, with mainly silty sand and a weak water abundance grade. In other areas, the aquifer thickness is mostly 10–15 m, with mainly silty sand and low water abundance grade.

2 Geological suitability evaluation method for natural sponge bodies

2.1 Affecting factors

Sponge city are designed to absorb, seep, store, purify and utilize rainwater. The geological environment of the region plays a crucial role in achieving these goals, considering the "six principles" of the sponge city–seepage, stagnation, storage, purification, utilization and drainage. Therefore, geological factors can be classified into three categories: Surface, vadose zone and aquifer (Song, 2016; Li et al. 2022; Wang et al. 2019; Bian et al. 2021).

2.1.1 Ground surface

The ground surface is the direct where atmospheric precipitation directly interacts with the earth, influencing both "infiltration" and "retention" of water in the sponge city construction. The factors that affect the surface mainly include terrain slope and surface lithology, in which, slope affects the ability to collect and retain the precipitation. A steeper slope generates runoff more quickly, producing a greater amount of runoff, while a gentler slope generates runoff more slowly, providing more contact time for rainwater to infiltrate. Surface lithology also affects rate of precipitation entering the underground water storage space and determines the infiltration capacity of surface rain flood during rainfall. Coarser surface lithologic grain provides greater atmospheric precipitation infiltration capacity.

2.1.2 Vadose zone

The vadose zone acts as a connection between soil water, atmospheric water, surface water and groundwater. It plays a vital role in "infiltration", "retention", "storage" and "purification" in the sponge city construction. The influencing factors

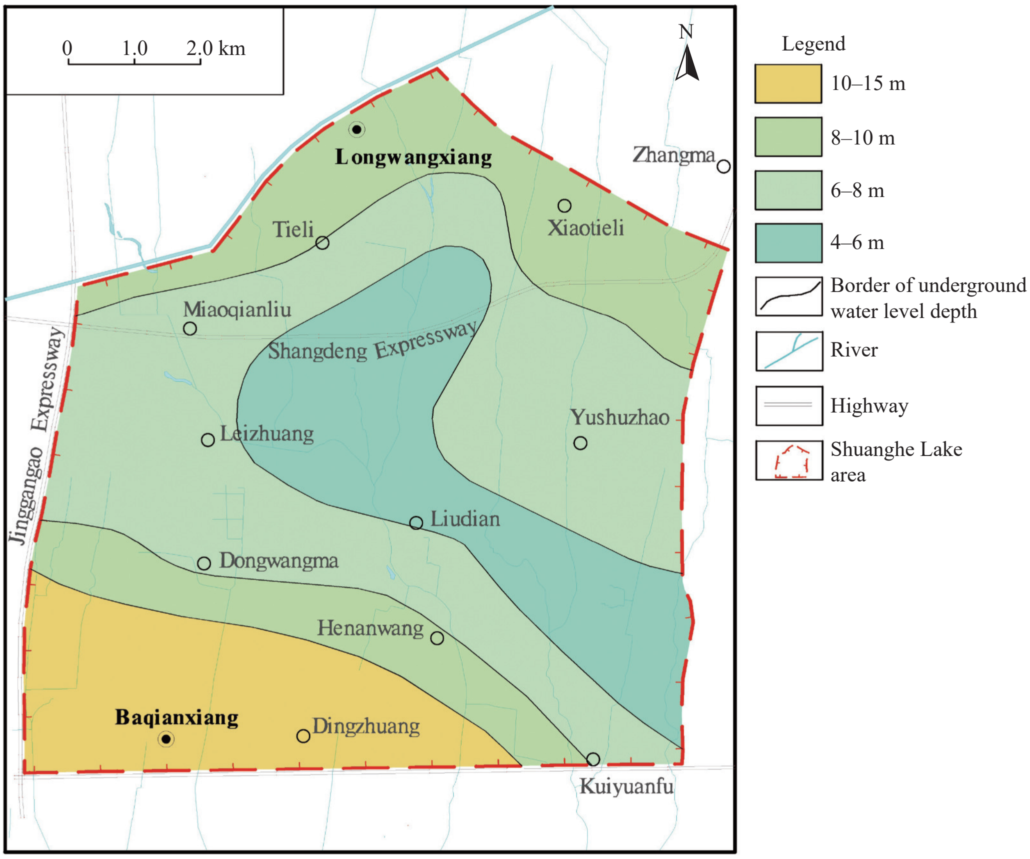

Fig. 4 Vadose thickness distribution map of the area

mainly include the lithology and thickness of vadose zone. If a vadose zone has finer lithologic particles, there are fewer gaps and rainfall infiltration channels, resulting in a smaller infiltration coefficient. Therefore, less rainwater can infiltrate from the surface, and less rainwater runoff can be replenished from groundwater. Research has shown that different strata have different permeability with medium to coarse sand being the most permeable and clay being the least permeable. The thickness of the vadose zone directly affects the storage space for infiltrated rainwater. A thicker vadose zone can store more infiltrated rainwater, giving the sponge a greater capacity to regulate and store infiltrated rainwater (Ma et al. 2022; Miao et al. 2022).

2.1.3 Aquifer

The shallow aquifer acts as a "retention", "storage", "use" and "discharge" area in the construction of the sponge city. It is the storage and migration place of precipitation after infiltration into underground. The factors affecting the aquifer's functions are mainly aquifer thickness, lithology and water abundance. The thickness determines the regulation and storage capacity of the aquifer. Thicker aquifer has more storage space. Aquifer lithology is an essential indicator of groundwater permeability. Coarser particles in the aquifer result in higher permeability, allowing groundwater to flow more quickly in the aquifer, making it more conducive to transport and store water resources. Water abundance reflects the effluent capacity of aquifer and determines the availability of groundwater.

2.2 Evaluation index

2.2.1 Evaluation index selection

After analyzing the impact of geological factors on the construction of sponge city, including the ground surface, vadose zone and aquifer, and considering the geological characteristics of the study area and following the principles of systematicness, comprehensiveness, independence and practicability, three primary factors were determined, including the features of ground surface, vadose zone and aquifer. The ground surface features were divided into two secondary factors, surface lithology and topographic slope. The vadose zone also had two secondary factors: Vadose zone thickness and vadose zone lithology. The aquifer had three secondary factors, including thickness, lithology and water abundance (Table 1).

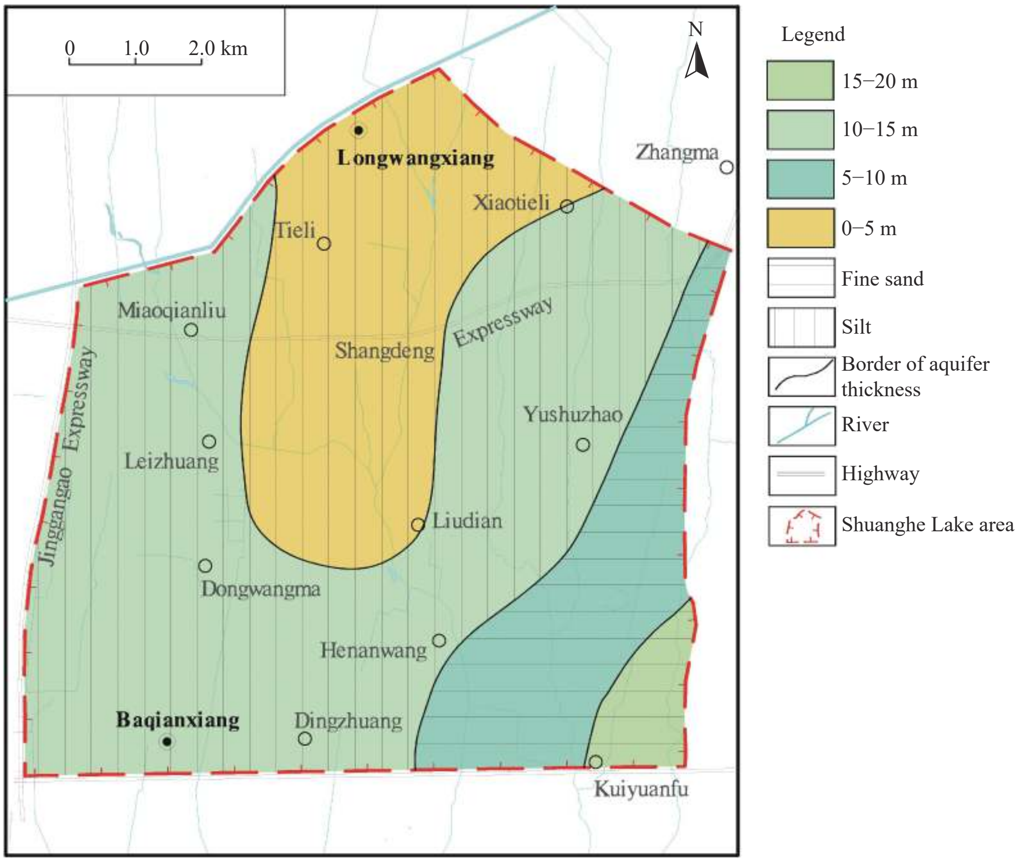

Fig. 5 Aquifer thickness and lithology distribution map of the study area

2.2.2 Weights determination

In the process of geological suitability evaluation, there are many influencing factors, and the importance of each factor is different. It is important to determine the weights of different factors. The widely used and relatively mature weight determination methods are expert scoring, sequence synthesis, entropy, AHP and formula method. In this study, AHP method is used due to its simplicity and practicality, and requirement of less quantitative data (Wang, 2008; Deng et al. 2012).

Among the three factors, topographic slope and surface lithology jointly determine the infiltration rate of rain and flood in the sponge city. However, the study area is relatively flat and the lithology is consistent, so the importance of these two is relatively low. The lithology and thickness of the vadose zone affect the absorption rate of rain and flood, while the aquifer thickness, lithology and water abundance of the aquifer determine the storage capacity of the sponge city to the rain and flood. Therefore, both vadose zone and aquifer are equally important.

2.2.2.1 Construction of judgement matrix

The judgement matrix indicates the relative weights of two elements of the next level compared with that of the upper level. If the two elements are set as i, j, relative weight is a_{ij}, number of elements is n, then the judgement matrix is $A = (a_{ij})_{n\times n}$. The value of a_{ij} can be assigned in many ways, in this research its value is assigned from 1 to 9, as shown in Table 2. With the analysis of the importance of each factor, judgement matrices B-A and C-B are obtained (Table 3-Table 6). The judgement matrices obtained in this way are shown in Table 3, Table 4, Table 5 and Table 6.

2.2.2.2 Calculation of factors' weight

According to the judgment matrix, the maximum eigenvalue and the corresponding eigenvector are calculated, and the eigenvector provides the order of importance for each evaluation factor. After obtaining the eigenvector of the matrix, it is normalized to determine the weight of each evaluation factor.

2.2.2.3 Consistency verification

Due to the complexity of the problem, the constructed judgment matrix is not necessarily the consistency matrix. If there is a significant deviation from consistency, error can occur. Therefore, after obtaining λ_{max}, consistency and randomness tests are conducted. If the order of the judgment matrix is less than 3, it has complete consistency. Otherwise, the following formula is used to

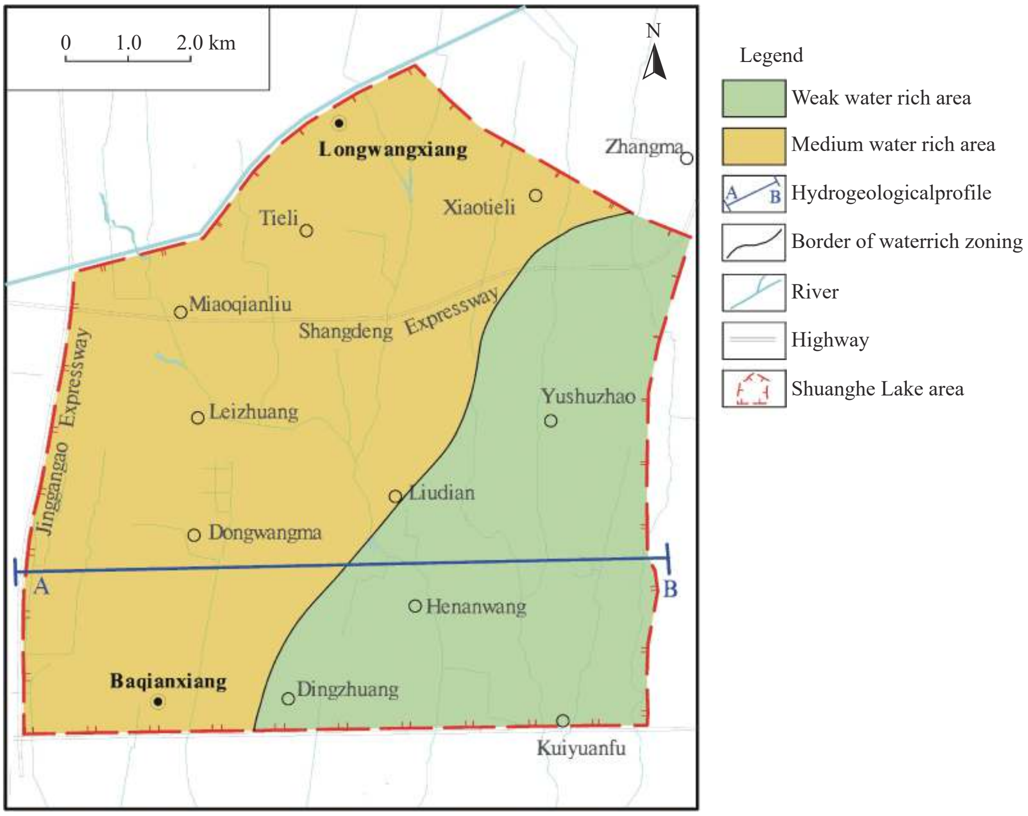

Fig. 6 Shallow aquifer abundance distribution of the study area

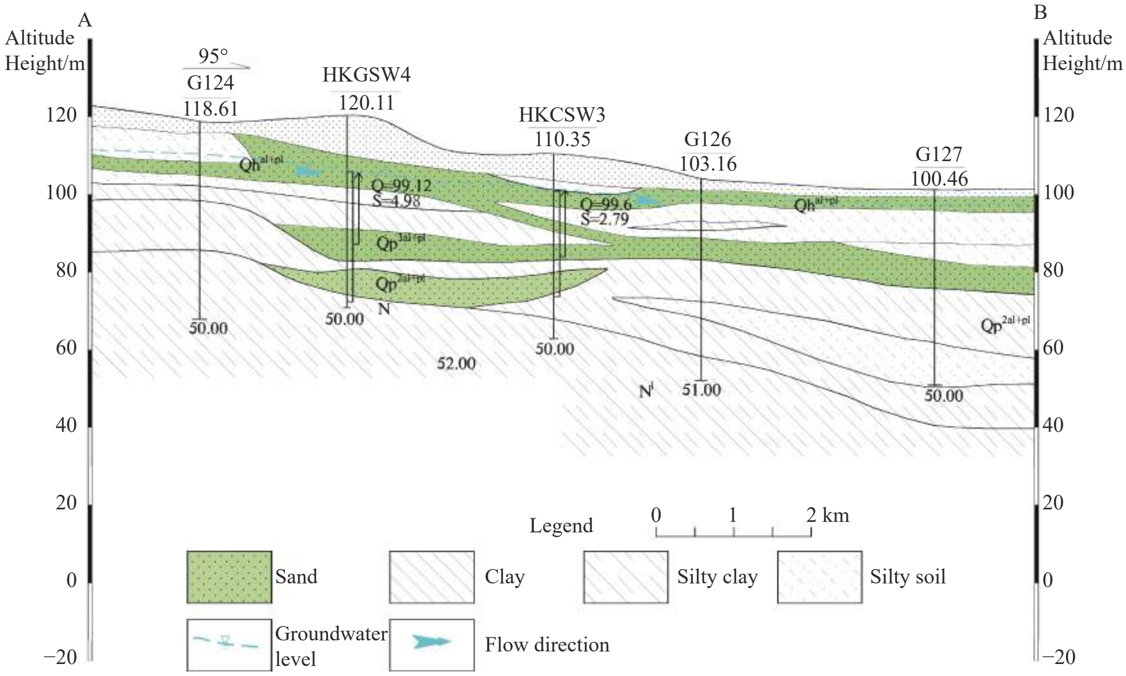

Fig. 7 Hydrogeological profile

perform consistency and randomness test:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

Where: CI represents the consistency index, λ_{max} is the maximum eigenvalue, RI is the mean random consistency index, CR is the random consistency ratio.

When n=3, RI=0.52, generally, the judgement matrix is considered consistent only when CR<

Table 1 Hierarchical structure of evaluation factors

Target layer	First-level factors	Second-level factors
Geological suitability research (*A*)	Surface (*B1*)	Surface lithology (*C1*)
		Topographic slope (*C2*)
	Vadose zone (*B2*)	Vadose zone thickness (*C3*)
		Vadose zone lithology (*C4*)
	Aquifer (*B3*)	Aquifer thickness (*C5*)
		Aquifer lithology (*C6*)
		Aquifer abundance (*C7*)

Table 2 Judgement matrix value assignment rule

a_{ij}	Description
1	*i* and *j* have the same importance
3	*i* is slightly more important than *j*
5	*i* is obviously more important than *j*
7	*i* is much more important than *j*
9	*i* is extremely more important than *j*
2, 4, 6, 8	Intermediate value of the above adjacent judgments

Table 3 *B-A* judgement matrix

Indicator	*B1*	*B2*	*B3*
B1	1	1/3	1/3
B2	3	1	1
B3	3	1	1

Table 4 *C-B1* judgement matrix

Indicator	*C1*	*C2*
C1	1	1/2
C2	2	1

Table 5 *C-B2* judgement matrix

Indicator	*C3*	*C4*
C3	1	1/2
C4	2	1

Table 6 *C-B3* judgement matrix

Indicator	*C5*	*C6*	*C7*
C5	1	2	3
C6	1/2	1	3
C7	1/3	1/3	1

0.10, and the obtained values can be considered reasonable. After that, eigenvectors are calculated corresponding to λ_{max}, and weights are obtained by normalizing these eigenvectors. If $CR \geq 0.10$, the judgement matrix needs to be reconstructed.

According to the calculation requirements, consistency calculation is required for judgment matrices B-A and C-B3, and *CR* is 0 and 0.052, respectively, to meet the consistency requirements. Weights of each evaluation factor are listed in Table 7.

3 Geological suitability evaluation for natural sponge bodies

3.1 Evaluation process

Based on the actual situation of sponge city construction in the research area, single-index evaluation indexes and grading standards were established for the seven evaluation indexes. A 5-point scoring system was used, as shown in Table 8 and Table 9.

Each evaluation index was rated and graded, and the grading of aquifer water abundance referred to the Hydrogeological Manual (Second Edition) of the Bureau of China Geological Survey. The grading of topographic slope was determined according to the General Principles for Comprehensive Control Planning of Water and Soil Conservation (GB/T 15772), in combination with the change in topographic slope in the study area. Surface lithology, vadose zone thickness, vadose zone lithology, aquifer thickness and aquifer lithology were classified according to the actual conditions in the study area as there were no corresponding standards or specifications. The grading results are shown in Table 8.

The geological suitability evaluation for natural sponge bodies was conducted using vector element method based on GIS. This involves directly superimposing multi-layer spatial data on the basis of single element vector graph, and expressing the evaluation unit as the actual spatial attribute boundary. The comprehensive evaluation index of geological suitability of natural spongy body in the study area is calculated with the following equation:

Table 7 Table of evaluation factors' weights

Evaluation index	Weight
Vadose zone lithology *C4*	0.321 4
Aquifer thickness *C5*	0.226 2
Aquifer lithology *C6*	0.142 5
Vadose zone thickness *C3*	0.107 1
Topographic slope *C2*	0.095 2
Aquifer abundance *C7*	0.059 8
Surface lithology *C1*	0.047 6

$$Z_q = \sum T_i A_i \tag{3}$$

Where: T_i is the index of the evaluation factors, A_i is the weight of the evaluation factors.

3.2 Evaluation results

MapGIS was used to implement the superposition of all factors, statistical analysis of spatial attributes, clustering and merging of the comprehensive map (Zheng et al. 2014), and then the geological suitability zoning map of natural spongy body in the construction of sponge city in Shuanghe Lake District of the airport area can be generated (Fig. 8).

The resulting geological suitability zoning map shows that the suitable area for constrction of a sponge city is located in strips in south part of Shuanghe Lake District: Dingzhuang Village—Henan Wang Village and Kuiyuanfu Village—Sanshi Village, covering an area of 11.2 km^2, or 12.3% of the total area of Shuanghe Lake District. The terrain is flat, the surface lithology is mainly silty sand, the lithology of the vadose zone is silty sand mixed with silty soil, the lithology of the aquifer is mainly fine sand and silty sand with a thickness of 10–20 m. The buried depth of the groundwater level is 8–15 m. The area has good natural conditions for rainwater and groundwater, and the underground aquifer has a high water storage capacity. It is recommended to make use of the regulation and storing function of the natural spongy body to absorb urban stormwater runoff in this area and adjacent areas.

The results also show that the relatively suitable area is distributed in most areas of the Shuanghe Lake District, covering 69.3 km^2, accounting for 76.1% of the total area. The terrain is flat and the surficial lithology is mainly silty sand, followed by silty soil. The lithology of the vadose zone is silty soil mixed with silty sand, and the lithology of the aquifer is silty sand and sandy silt mixed with silty sand. The thickness of the aquifer is 5–15 m, and the buried depth of the groundwater is 6–10 m. The area has good natural rainwater and groundwater infiltration conditions, and the underground aquifer has strong water storage capacity, all contributing to a high geological relevance of the construction of the sponge city. The creation of artificial storage, as well as the utilization and transmission of resources, should be properly considered while maximizing the use of natural sponges. The primary focus of storage should be on stormwater runoff within the region, while the stormwater runoff of the neighboring region should be given moderate consideration. The less suitable areas are primarily located in the area surrounded by Tieli Village, Wanjia Village, Zhangzhuang, Leizhuang and Miaoqian Liu Village in the southeast of Shuanghe Lake District, covering an area of 10.6 km^2, accounting for 11.6% of the total area of Shuanghe Lake District. The terrain is relatively flat, and the surficial lithology is predominantly silty soil. The lithology of the vadose zone consists of a mixture of silty

Table 8 Value assignment basis for evaluation factors

Evaluation factors	Suitability level and value assignment basis				
	Unsuitable	Relatively unsuitable	Moderately suitable	Relative suitable	Suitable
Surface lithology *C1*	Clay	Silty clay	Silt	Silty sand	Fine sand
Topographic slope *C2*	>9‰	7‰–9‰	4‰–7‰	2‰–4‰	<2‰
Aquifer thickness *C3*	4–6 m	6–8 m	8–10 m	10–15 m	>15 m
Vadose zone lithology *C4*	Silty clay	Silt+silty clay	Silt	Silty sand	Fine sand
Aquifer thickness *C5*	0–5 m	5–10 m	10–15 m	15–20 m	>20 m
Aquifer lithology *C6*			Sandy silt	Silty sand	Fine sand
Aquifer abundance *C7*	Inferior	Relatively inferior	Medium	Relatively good	Good

Table 9 Value assignment standard for evaluation factors

Suitability level	Unsuitable	Relatively unsuitable	Moderately suitable	Relative suitable	Suitable
Evaluation factor value	1	2	3	4	5

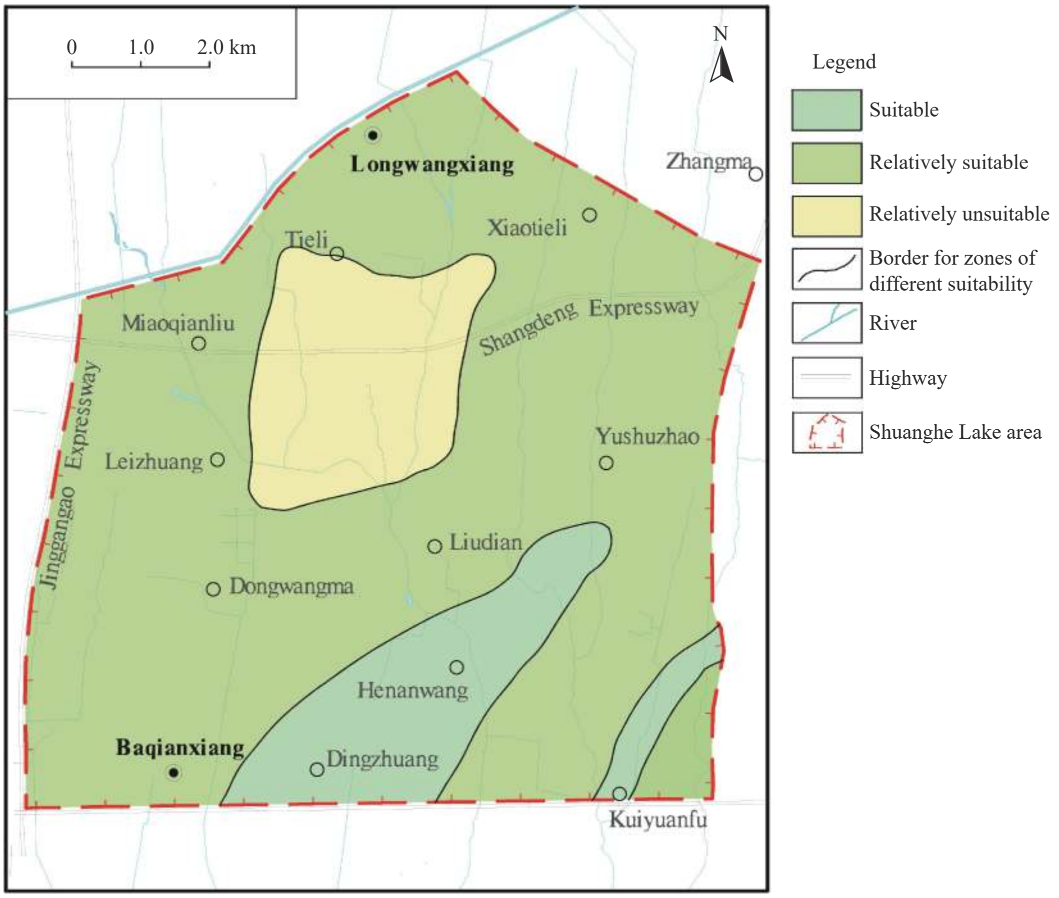

Fig. 8 Zoning map of geological influence and suitability evaluation of sponge city construction

soil and silty soil mixed with silty clay. The lithology of the aquifer is mainly sandy silty soil with a thickness of less than 10m, and the groundwater level is found at a depth of 4 m to 8 m. Natural sponges in this area are poorly developed and thus more attention should be given to artificial stormwater control infrastructures, such as roof gardens, water storage tanks and bioretention. The focus of regulation and storage should be on stormwater runoff in this region.

4 Conclusions

(1) Based on the analysis of the geological environment conditions in the study area, it is identified that the main geological factors affecting the construction of sponge cities are the lithology of the vadose zone, the lithology and thickness of the aquifer, followed by the terrain slope, surface lithology and water abundance of the aquifer. The surface characteristics, vadose zone characteristics, and aquifer characteristics are considered primary indicators, and the surface lithology, terrain slope, vadose zone thickness and lithology, aquifer thickness and lithology, and water abundance are secondary indicators. The weight of each indicator is determined using the analytic hierarchy process (AHP), and an indicator system is established to evaluate the geological suitability of sponge city construction in the study area. This system is classified into three levels: Suitable, relatively suitable, and less suitable.

(2) Different plans are proposed for the construction of geological environment sponge cities based on the assessment grades. In the suitable and relatively suitable areas, it is recommended to take advantage of surface infiltration, vadose zone transportation and aquifer storage to build a sponge city infrastructure with geological engineering as the main focus, supplemented by engineering measures such as surface water storage and drainage, and jointly build a sustainable urban hydrological cycle. For the less suitable areas, the focus should be on artificial rain flood control projects such as roof gardens, surface ponds, bioretention facilities, supported by some geological engineering measures to implement the construction of sponge cities.

Acknowledgements

This study is supported by China Geological

Survey project " Monitoring and evaluation of resources and environment bearing capacity in Beijing-Tianjin-Hebei Coordinated Development Region and xiong'an New Area" (DD20221727), "Engineering Geological and Soil & Water Quality Survey of Xiong' an New Area" (DD20189122) and a multi-factor municipal geological survey project in Zhengzhou City: Evaluation of geological conditions for sponge city construction in Zhengzhou City (Zhengzhou financial bids for procurement-2021-217).

References

An SL, Huang JJ, Zhang L, et al. 2015. The urban geological survey working direction and supporting role on sponge city construction—take Xuzhou city as an example. Urban geology, 10(4): 6−10. (in Chinese) DOI：10.3969/j.issn.1007-1903.2015.04.002.

Bian XR, Chen YC, Su D, et al. 2021. Study on geological impact and suitability in Sponge City construction—A case study of Changzhou City. Coal Geology Of China, 33(03): 35−42. (in Chinese) DOI：10.3969/j.issn.1674-1803.2021.03.08.

Cui Z, Yang P, Zhang Z. 2016. Comprehensive suitability evaluation of urban geological environment in Zhengzhou-Kaifeng area. Journal of Groundwater Science and Engineering, 4(3): 204−212. DOI：10.19637/j.cnki.2305-7068.2016.03.006.

Deng X, Li JM, Zeng HJ, et al. 2012. Analytic hierarchy process weight calculation method and its application research. Mathematics in Practice and Theory, 42(7): 93−100. (in Chinese) DOI：10.3969/j.issn.1000-0984.2012.07.012.

Fletcher TD, Shuster W, Hunt WF, et al. 2014. SUDS, LID, BMPs, WSUD and more-The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 12(7): 525−542. DOI：10.1080/1573062X.2014.916314.

Han X, Zhao YQ. 2016. "Sponge" development in sponge city construction. Journal of Earth Sciences and Environment, 38(5): 708−714. (in Chinese) DOI：10.3969/j.issn.1672-6561.2016.05.014.

Huang JJ, Wu X, Jiang S, et al. 2018. Geological impact and suitability evaluation of sponge city construction—a case study of Xuzhou. Geological review, 64(6): 1472−1480. (in Chinese) DOI：10.16509 /j.georeview.2018.06.011.

Li Y, Xu LS, Chen JL, et al. 2022. Construction of hydrogeological structure model based on sponge city construction: A case study in the starting area of Changjiang New Town in Wuhan. Resources Environment & Engineering, 36(2): 198−203. (in Chinese) DOI：10.16536/j.cnki.issn. 1671-1211.2022.02.010.

Liu M, Nie ZL, Cao L, et al. 2021. Comprehensive evaluation on the ecological function of groundwater in the Shiyang river watershed. Journal of Groundwater Science and Engineering, 9(4): 326−340. DOI：10.19637/j.cnki.2305-7068.2021.04.006.

Liu SY, Wang HQ. 2016. Dynamic assessment of pollution risk of groundwater source area in Northern China. Journal of Groundwater Science and Engineering, 4(4): 333−343. DOI：10.19637/j.cnki.2305-7068. 2016.04.009.

Ma Z, Huang QB, Lin LJ, et al. 2022. Practice and application of multi-factor urban geological survey in Xiongan New Area. North China Geology, 45(1): 58−68. (in Chinese) DOI：10.19948/j.12-1471/P.2022.01.04.

Miao JJ, Liu HW, Guo X, et al. 2022. Quantitative simulation of retardation effect of NH_4^+ and NO_3^- by aquitard layer on confined water in plain: A case study of Tongzhou district in Beijing. North China Geology, 45(3): 62−68. (in Chinese) DOI：10.19948/j.12-1471/P.2022.03.09.

Morison PJ, Rebekah R. 2011. Understanding the nature of publics and local policy commitment to water sensitive urban design. Landscape and Urban Planning, 99(2): 83−92. DOI：10.1016/j.landurbplan.2010.08.019.

Qiu BX. 2015. The connotation, way and prospect of Sponge City (LID). Construction Science and Technology, 41(3): 1−7. (in Chinese) DOI：10.16116/j.cnki.jskj.2015.01.003.

Song ZL. 2016. Sponge effect and purification function of phreatic aquifer under background of urban hardening. Journal of Hubei Polytechnic University, 32(2): 9−12. (in Chinese) DOI：10.3969 /j.issn.2095-4565.2016.02.003.

Sun XF, Qin H, Lu WT. 2019. Evolution of water sensitive urban design in Australia and its enlightenment to Sponge City. Chinese Gardens, 35(9): 67−71. (in Chinese) DOI：1000-6664(2019)09-0067-05.

Wang SW, Wang XY, Sun L, et al. 2019. A suitability evaluation system of sponge city construction based on environmental geological condition of urban sponge body and its application—a case study of Jiaozuo City. Water Resources and Hydropower Engineering, 50(2): 79−87. (in Chinese) DOI：10.13928/j.cnki.wrahe.2019.02.011.

Wang YL. 2008. Systems engineering-4th edition. China Machine Press. (in Chinese)

Wang Z, XieJ, Xie Q, et al. 2013. Advances on the research of the detention and purification of urban stormwater runoff by permeable paving. Environmental Science & Technology, (12M): 138−143. (in Chinese) DOI：10.3969/j.issn.1003-6504.2013.12M.031.

Wong THF, Allen R, Beringer J. 2012. Blueprint 2012-stormwater management in a water sensitive city. Sydney: Cooperative Research Centre for Water Sensitive Cities.

Xie JH, Peng HF, Xia DS, et al. 2018. Study on the suitability of geological conditions for sponge city construction-a case study of Wuhan urban development area. Exploration Engineering (geotechnical drilling and excavation engineering), 45(10): 6−10. (in Chinese) DOI：CNKI:SUN:TKGC.0. 2018-10-002.

Ye XY, Li MJ, Du XQ, et al. 2018. Selection of suitable facility types of sponge city based on geological conditions. Journal of Jilin University (Earth Science Edition), 48(3): 827−835. (in Chinese) DOI：10.13278/j.cnki.jjuese.2017011.

Yu KJ, Wang CL, Li DH, et al. 2019. The concept, methodology and a case study in defining the ecological redline for the hydro-ecological space. Acta Ecologica Sinica, 39(16): 5911−5921. (in Chinese) DOI：10.5846/stxb201812052663.

Zhang W, Pang JP. 2014. Construction of sponge city should be an important part of urban water management in the New Era. Water Resources Development Research, 14(9): 5−7. (in Chinese) DOI：10.13928/j.cnki.wrdr.2014.09.002.

Zheng XC, Zheng WF, Liu W, et al. 2014. Application of Comprehensive Evaluation of City Engineering Geology Based on Vector Evaluation Graphics Using GIS. China University of Geosciences Press. (in Chinese)