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Monitoring, Analysis, and Evaluation of Sponge City under the Background of Urban Space Governance

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The rapid urbanization in China has led to an increasing conflict between urban construction and ecological preservation, making the implementation of sponge city concepts essential. In this paper, we explore the monitoring, analysis, and evaluation techniques for sponge city construction within the framework of urban space governance. By leveraging urban territorial space monitoring, we established a comprehensive monitoring system for the underlying surfaces of sponge cities. The urban spatial information obtained through sensors serves as the data foundation for sponge city governance, enabling the precise tracking and management of critical urban factors. The methodology involves developing a multi-factor analysis model for assessing the status of sponge cities, surface runoff estimation, and the spatial layout optimization of impervious surfaces using an improved ant colony algorithm. The research highlights innovations such as integrating national spatial information technology with sponge city construction and establishing a correlation model between rainfall runoff coefficients and underlying surface variations. The findings demonstrate the effectiveness of the proposed methods through a case study in Beijing's urban subcenter, which showed significant improvements in urban water management, green infrastructure, and ecological resilience. This study provides a replicable and scalable framework for sponge city construction that can be adapted for other regions.

1. Introduction

Under the background of urban spatial management, a large number of ecological environmental problems such as flood disaster, river pollution, and urban waterlogging have appeared in the process of rapid urbanization in China.(1) The "2012 Low Carbon City and

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Regional Development Science and Technology Forum" first put forward the concept of "sponge city".[2] It is based on the concept of harmonious coexistence between humankind and nature, advocating for the integration of natural ecosystems and man-made systems. It aims to optimize rainwater management and urban ecology by enhancing the infiltration, purification, and storage of rainwater, while ensuring the safety of urban drainage and flood control.[3] In the context of spatial governance, sponge city is a new thinking and new concept of high-quality urban development and a systematic development concept and method to solve the shortage of urban water resources.[4] It can promote the coordination between urban development and natural resources. This includes soil, water resources, and other ecological components. By enhancing water conservation and environmental carrying capacities, sponge city construction significantly improves urban resilience.

Since the 1980s, with the gradual development of landscape ecology, western developed countries such as the United States, Britain, Germany, and Japan have successively formulated corresponding measures for top-down stormwater management. The United States promulgated the "Best Stormwater Management Program," and Maryland introduced the concept of environmentally sensitive development. Building on this concept, the UK developed a sustainable hydrological system.[5] Germany proposed the "infiltration pipe network system," Japan implemented the "rainwater storage plan," and Singapore launched the water-sensitive urban design and more.

At present, sponge city construction in China is a relatively new research direction, although there are many cases and experiences in foreign countries worth learning. However, because of the differences in regional characteristics, we still need to explore the application of technology and target control and other issues. To this end, research on technologies related to "sponge cities" is urgently needed.

2. Materials and Methods

To accelerate the establishment of a unified survey, evaluation, and monitoring system for natural resources, the nation has adjusted geographical monitoring to urban land space monitoring. The Beijing Municipal Government has taken into account the huge social value of the original geographical conditions in light of the actual situation and through inheritance, enrichment, and innovative development. The land cover monitoring of the original geographical conditions will be retained and incorporated into the new urban land space monitoring, and other relevant natural resource information will be integrated, the information connotation will be continuously mined, the application level will be expanded, and the typical application demonstration of multi-point flowering will be formed to effectively promote the construction of national ecological civilization.[6] To maximize the role and impact of urban land space monitoring, efforts will focus on enhancing its applications in natural resource management, ecological environment protection, urban governance, and other related fields.

This study is centered on the information and technology of urban territorial space monitoring, which serves as the foundation for establishing a monitoring system for the underlying surface of a sponge city. On this basis, the comprehensive factors of sponge city status are obtained and analyzed comprehensively. Surface runoff analysis technology and a spatial layout optimization model were used to evaluate sponge city construction, and a comprehensive technology system for integrated sponge city monitoring was formed. The specific technical process is shown in Fig. 1.

2.1 Construction of sponge city monitoring index system integrating national information technology

The success of sponge city construction hinges on the characteristics of the urban underlying surface, particularly its permeability and capacity to manage stormwater effectively. This includes elements such as pavement systems, buildings, traffic areas, soil, water bodies, and vegetation. At present, one of the most prominent problems encountered in urbanization construction is the high-speed and high-frequency changes of the underlying surface.

The most prominent feature of the land coverage data of the geographical conditions is "what you see is what you get". Under the new situation, urban land space monitoring results based on Beijing's geographical coverage data provide objective and accurate insights. From 2013 to 2022, Beijing began to carry out urban land space monitoring for nearly ten years, and Beijing has well inherited and optimized the relevant contents of the monitoring of original geographical national conditions, improving the quality and deepening the monitoring around the surface cover of the urban underlying surface. According to the requirements of sponge city construction, this study adopts a problem-oriented approach and emphasizes scientific planning in terms of content and indicators to effectively support government decision-making.

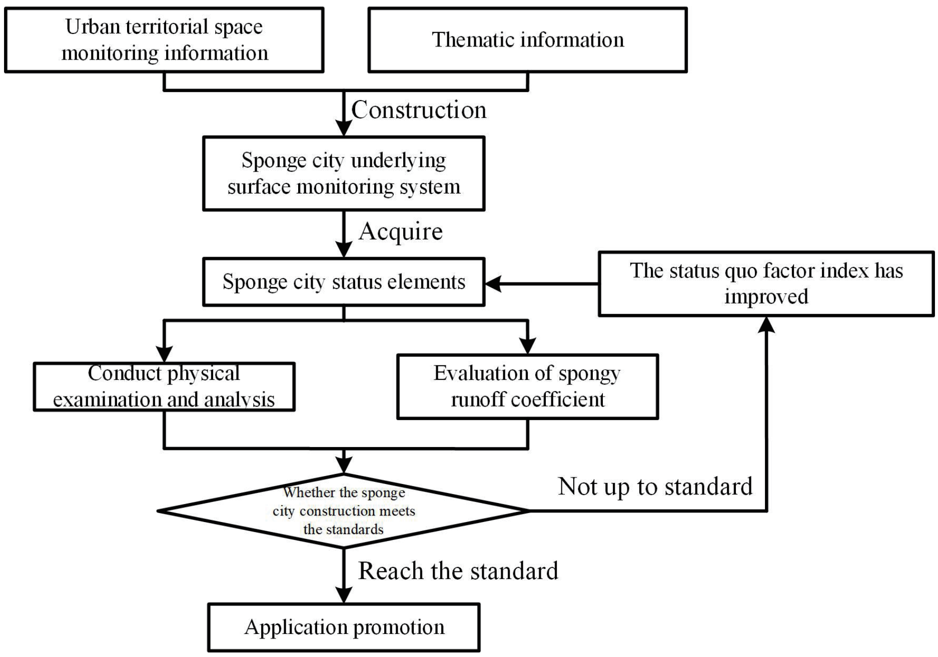

Fig. 1. Flowchart of overall structure of sponge city construction.

We established the classification contents and indexes of the underlying surfaces of sponge cities from the perspective of national geographic conditions.[7] The related indexes of sponge cities were mainly classified according to seven categories of factors (namely, water body, vegetation, architecture, geology, landform, special facilities, and climate conditions) that significantly affect water balance and hydrological processes.

To fully adapt to the characteristics of sponge city construction under the new situation,[8] the missing items in the original index were expanded, summarized, and integrated, and the relevant requirements of sponge city construction were maximized. Finally, 13 categories of contents and indicators were formed (Table 1). By using geographic information technology and referring to the classification index system of the underlying surface of a sponge city, sponge city monitoring data can be easily obtained through urban territorial space monitoring.

2.2 Comprehensive analysis model of sponge city monitoring results

According to administrative, regional, and grid layers, the data of the underlying surface of a sponge city in different years are obtained by long-time series monitoring, and the spatial superposition analysis is carried out by using the relevant algorithm model. The formulas are as follows:

$$Rs = \Delta S_{ijk} \,/\, S_{ij}, \tag{1}$$

$$Ur = \Delta S_{ijk} \,/\, T_{jk}. \tag{2}$$

In these formulas, Rs represents the area change rate, ΔS_{ijk} denotes the difference in the area of class i between stage k and stage j, and S_{ij} is the area of stage j. The variable i = 1, 2, 3, ..., 13 represents the 13 monitoring classification categories of the sponge city's underlying surface, while Ur stands for the rate of area change. T_{jk} represents the time difference between the periods j and k. The year is the smallest unit.

Table 1
Correspondence between the classification of sponge city's underlying surface and the monitoring classification data of urban territorial space (original geographical conditions).

<table>
<tr><th>Classification type</th><th colspan="13">Correspondence</th></tr>
<tr><td rowspan="2">Sponge city underlying surface classification</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td></tr>
<tr><td>Plowland</td><td>Plantation plot</td><td>Forest land</td><td>Meadow</td><td>Multi-floor building</td><td>One storey house</td><td>Urban road</td><td>Internal road</td><td>Rural road</td><td>Hard paving area</td><td>Bare land</td><td>Water body</td><td>Others</td></tr>
<tr><td>Urban territorial space coverage data classification</td><td colspan="2">Cultivated land</td><td colspan="2">Forest and grass cover</td><td>Housing construction (district)</td><td>Railways and roads</td><td colspan="2">Structure</td><td>Bare land</td><td colspan="2">Waters</td><td colspan="2">Nothing</td></tr>
</table>

Through calculation, the change rate and rate of different land classes are obtained, and the change characteristics and trends of various land classes are mastered, so as to better carry out statistical analysis and evaluation, and provide a scientific basis for sponge city construction.

2.3 Surface runoff coefficient analysis and runoff estimation model

On the basis of long-term monitoring results and relevant regional thematic data, the underlying surface variation and its coupling relationship with the regional rainfall surface runoff coefficient (abbreviated as runoff coefficient) were analyzed. The runoff coefficient is a dimensionless value representing the proportion of rainfall that becomes surface runoff instead of being absorbed by the soil. It provides an indication of how well an area manages rainwater and reflects the relationship between precipitation and resulting runoff.

$$\alpha = R/P \tag{3}$$

Here, α represents the runoff coefficient, P represents the precipitation depth, and R represents the runoff depth. α ranges from 0 to 1, where a higher runoff coefficient indicates that a greater proportion of rainfall cannot infiltrate the soil, leading to an increased load on drainage systems and related infrastructure.

On the basis of the runoff coefficient, applied research on the correlation between the rainfall runoff coefficient and the impervious area can be carried out, and we can establish a correlation model between the virtual runoff coefficient and the impervious water surface, which can deduce the response of the runoff coefficient to the changes in the underlying surface during river rainfall and flood.(9) The discharge before the stormwater process is taken as the base flow. On the basis of the stormwater process line, the flat-cut method is introduced to divide the total runoff and the area calculus method is used to calculate the total stormwater. The formula used is as follows:

$$W = \int_0^T Q(t)\,dt = \bar{Q}T, \tag{4}$$

where W is the total runoff, $Q(t)$ is the instantaneous flow at time t (m^3/s), T is the calculation duration (s), and $\bar{Q}$ is the average flow rate. The above mathematical model takes time as the horizontal axis and the flow rate as the vertical axis, and draws the flow process curve to express its full cycle change with time. The area surrounded by the flow process line and horizontal coordinate is the runoff. The hydrological and flow process data observed in a station of Tonghui River in the city's subcenter in 2012 were selected to carry out relevant research and verification, and the flood process line was drawn through the relevant hydrological and water data.

S is the area surrounded by the two adjacent moments t_1 and t_2 in the process and base flow process lines in Fig. 2. Q_1 and Q_2 are the flood flow rates at times t_1 and t_2, respectively, and Q_b is the base traffic. The overall flood process of Beijing on 21 July 2012 is shown in Fig. 2.

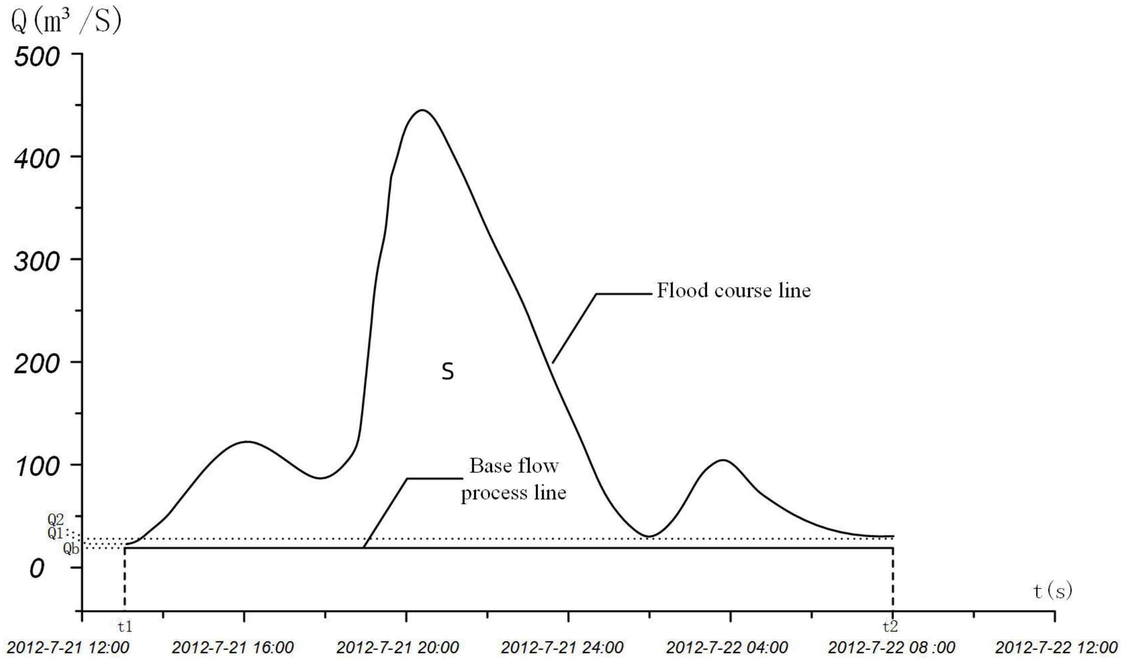

Fig. 2. Drawing of the flood process line observed at a station in Tonghui River during the 7.21 rainstorm.

2.4 Spatial layout optimization model of impervious surface in sponge city

The ant colony optimization algorithm is a probabilistic algorithm used to find an optimal path, which was first proposed by Marco Dorigo in 1992, inspired by ant foraging. The optimal allocation model of an impervious surface proposed in this paper is based on the extensible multi-objective ant colony algorithm, aiming at the characteristics of multi-objective decision-making technology and impervious surface spatial layout optimization.(10) Impervious surfaces (hard surfaces that do not allow water to penetrate, such as concrete, asphalt, and rooftops), permeable surfaces (surface vegetation and soil characteristics), and the slope and topography of the surface water catchment area will all affect the runoff coefficient.(11) The superior optimization ability of the ant colony algorithm and the SCS-CN hydrological model are used to optimize the spatial layout of the impervious surface, and finally to optimize the spatial layout of the underlying surface in sponge city construction.

On the basis of high-resolution remote sensing image data, the classification of an urban impervious surface was obtained as the benchmark spatial layout data, and the density of the impervious surface was kept constant.(12) A new spatial distribution map of the impervious surface was obtained by applying this algorithm, and the CN parameters of the SCS-CN hydrological model were optimized to obtain the runoff coefficient. On the basis of the updating rules of ant colony information in the preset ant colony algorithm, the optimal impervious surface spatial layout is obtained through continuous iteration.

The core selection probability function of the ant colony algorithm is

$$P_{ij}^{K} = \frac{\alpha \times \tau_{ij} + \beta \times \eta_{ij}}{\sum_{s \in Allowed_s} \alpha \times \tau_{sj} + (1-\alpha) \times \eta_{sj}}, \tag{5}$$

where P_{ij}^K refers to the selection probability of the group algorithm, α refers to the heuristic factor, β refers to the expected heuristic factor, $\beta = 1 - \alpha$, η_{ij} is the heuristic function, τ_{ij} refers to the pheromone concentration between the types i and j of the impervious surface, and $Allowed_s$ refers to the various impervious surface types that can be converted by the permeable surface unit. The SCS-CN hydrological model developed by the United States Department of Agriculture is a highly extracted and simplified hydrological system, and has been widely used in the calculation of surface runoff and precipitation events. It has the characteristics of a simple algorithm, few variables, and easy simulation. On the basis of this model, it is possible to construct sequence units and complete objects for each link of basin hydrology. The mathematical expression of the model is

$$\begin{cases} Q = \dfrac{(P - 0.2S)^2}{P + 0.8S}, & P > 0.2S \\ Q = 0, & P \le 0.2S \end{cases} \tag{6}$$

where Q represents the direct runoff per second, P represents the rainfall per second, and S represents the potential maximum water retention. S can be calculated using the runoff curve coefficient CN value, and the formula used is

$$S = \frac{25400}{CN} - 254. \tag{7}$$

Finally, Q can be calculated. Owing to the impact of impervious areas and slope on urban runoff, accurately calculating the CN value requires a comprehensive CN correction calculation.

The advantage of this model is that the underlying surface information of the basin is used, and the model parameters are connected with the remote sensing data. The model can be used for the basin without data to accurately and reliably calculate the actual runoff of the basin, and then to calculate the runoff coefficient and other related parameters.[13,14] At the same time, the runoff index calculated in Eq. (3) can also be used as an evaluation index to carry out the optimal design and construction of an impervious water surface spatial pattern, and the subsequent quantitative assessment of the mitigation degree of rainstorm waterlogging after the optimization of the impervious water surface spatial pattern.

3. Application Practice - Sponge City Monitoring, Implementation Evaluation, and Layout Optimization of Beijing City Subcenter

In 2016, Beijing successfully joined the second batch of national sponge city construction pilot cities. The pilot area was selected in Tongzhou, especially to build the 155 km^2 area of the Tongzhou urban subcenter into a sponge city demonstration area, and the construction goal is to achieve the overall 80% annual runoff total control rate.

The construction concept of the Beijing subcentral sponge city is to protect and restore the original ecosystem of the subcentral city according to the topographic and hydrological characteristics and development status. This involves the construction of sponge parks and green spaces, sponge roads and squares, water system regulation, ecological restoration, and measures for flood control, drainage, and waterlogging prevention, achieved through methods such as infiltration, storage, excavation, and drainage.

Since the selection of the pilot area, the subcenter has completed a total of 178 projects such as sponge building communities, park green spaces, roads and drainage pipes, and flood control and drainage, and 123 projects in the pilot area. Through a six-year pilot construction, the spatial distribution information of pervious and impervious surfaces in a typical sponge city's underlying area within the subcenter was extracted using geographic information technology. The effectiveness of sponge city construction was comprehensively analyzed and evaluated by integrating thematic data on territorial spatial planning, transportation, water management, municipal affairs, ecology, and digital elevation models.

According to the relevant requirements of sponge city monitoring, the monitoring results of urban territorial space (geographical conditions and land coverage) are extracted and analyzed. The physical examination conditions of sponge cities from 2017 to 2022 within the scope of urban subcenters are shown in Table 2.

The analysis found that the area of impervious surfaces, including housing construction and other structures, in the subcenter of the city showed a yearly decreasing trend. In contrast, the permeable areas, such as green spaces, squares, urban roads, and water bodies, exhibited a yearly increasing trend. The remarkable progress of the subcenter sponge city construction has been continuously monitored.

This study relies on the classification of underlying surfaces in sponge cities and their corresponding surface runoff coefficients, combined with the sponge city effectiveness evaluation model, to conduct quantitative analysis. This approach enables the accurate calculation of the integrated surface runoff coefficient for each evaluation unit.(15) The model algorithm is

$$\varphi_i = \frac{1}{S_i} \times \Big[\left(S_{Building\ area} + S_{Industrial\ facility} \right) \times 0.9 + S_{Hardened\ surface} \times 0.85 \\ + S_{Trackless\ pavement} \times 0.8 + S_{Rail\ pavement} \times 0.5 + \cdots \Big]. \tag{8}$$

Table 2
Monitoring statistics of spongy urban subcenters over the years.

Feature type	2017		2019		2020		2021		2022		2017–2022
	Area	Ratio (%)	Area	Ratio (%)	Area	Ratio (%)	Area	Ratio (%)	Area	Ratio (%)	Area change
Permeable surface	81.75	52.55	83.25	53.51	84.88	54.56	90.69	58.30	95.9	61.70	14.23
Impervious surface	73.82	47.45	72.11	46.35	70.48	45.30	64.88	41.70	59.5	38.30	−14.23

The surface runoff coefficient of evaluation region i is calculated as the ratio of the weighted sum of the areas of various underlying surface types multiplied by their respective surface runoff coefficients to the total area of the region. Specifically, φ_i represents the surface runoff coefficient, S_i denotes the total area, $S_{Building\ area}$ refers to the total area of "building construction zones," and $S_{Hardened\ surface}$ represents the total area of "hardened surfaces." All parameters pertain to evaluation region *i*.

The ratio of the total runoff caused by rainfall in evaluation region i to the total rainfall is the comprehensive surface runoff coefficient, that is, the sum of the product of the surface runoff coefficient of block n and the area of block n in the interior of the region divided by the total area of the evaluation region, as shown in Eq. (9).

$$\varphi = \frac{s_1 \times \varphi_1 + s_2 \times \varphi_2 + \cdots s_n \times \varphi_n}{s} \quad (9)$$

1–*n* is the serial number of plots in the monitoring area and the total number is *n*. *S* represents the total area of the monitoring area and φ represents the comprehensive surface runoff coefficient of the pilot area. By comparing the calculated results with the surface runoff coefficient in the regional planning data, the implementation effect of sponge city construction can be effectively evaluated.

We found that the comprehensive coefficient of surface runoff of the Tongzhou subcenter in 2022 is 0.52 and that the spatial distribution of the surface runoff coefficient of each township is distinct: it shows a trend of gradual decline outward from the central area. Among them, the surface runoff coefficient of Yongledian Town is the smallest and that of Zhongcang Street is the largest, followed by Beiyuan Street and Yuqiao Street. The smaller the runoff coefficient, the better the ecological condition, and its spatial distribution pattern is shown in Fig. 3. In addition, combined with the sponge city classification monitoring content data, the water permeability of the urban subcenter also showed a yearly increasing trend, indicating that the ecological environment of the urban subcenter continued to develop well, and the side also coincides with the successful construction of the sponge city.

After the efforts during the pilot period, a new green city with breathing, elasticity, and a high aesthetic standard has emerged. Through the monitoring and implementation evaluation of the underlying surfaces in the subcenter sponge city, several issues have been identified. For instance, surface runoff needs to be reduced, the proportion of green spaces and water retention facilities requires further improvement, and impervious surfaces still need to be renovated and upgraded. We should use the spatial layout optimization model to improve the spatial distribution and proportion under the sponge city and minimize the surface runoff. In the future development process, it is still necessary to maximize the protection of the original green space, rivers, lakes, wetlands, and other "spongy bodies" from destruction.

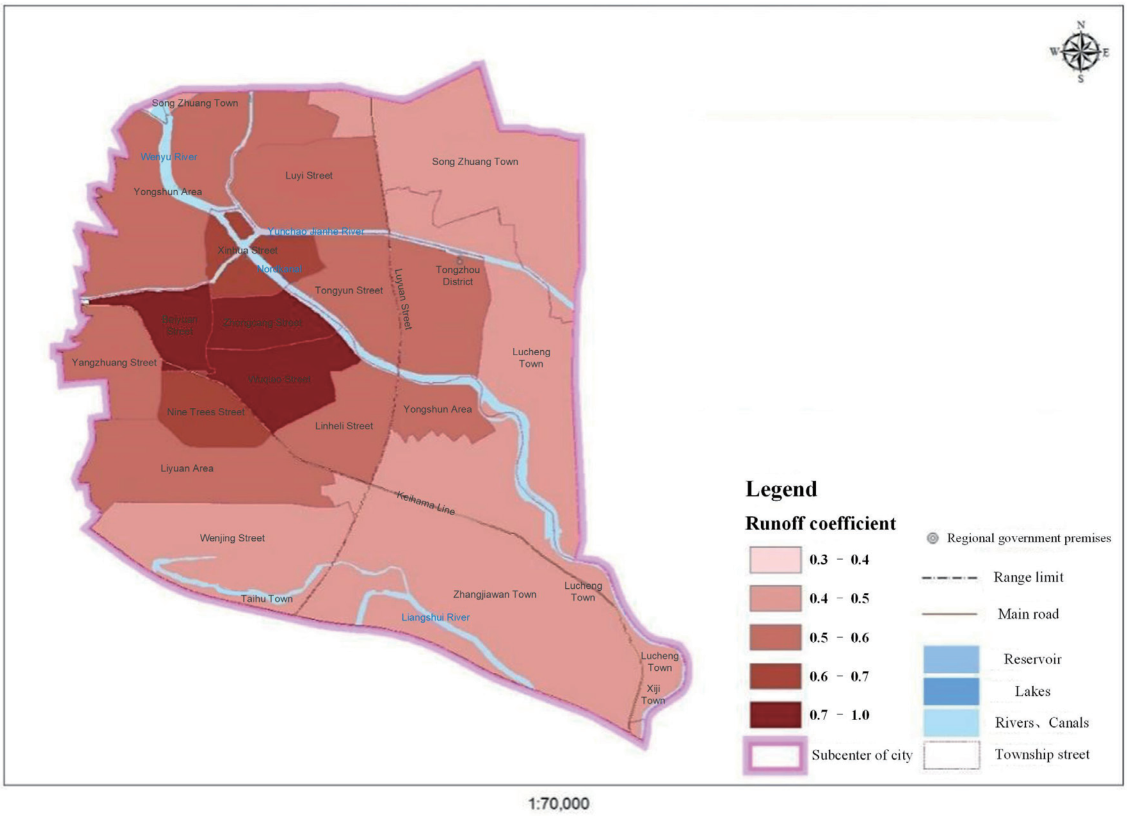

Fig. 3. (Color online) Spatial distribution of surface runoff coefficient of urban subcenter in 2022.

4. Conclusions

In the context of urban space governance, sponge city construction has become a major national strategy. Sponge city is a realistic demand for the implementation of high-quality urban development, an inevitable requirement for the realization of green civilization, and an important starting point for urban space governance. Sponge city construction should focus on solving urban water security, water resources, water environment, and other system problems, and create a flexible ecological space. Through analysis and evaluation, on the whole, the Beijing Municipal Subcenter has achieved good results based on local conditions and innovative technologies, which can provide reference and demonstration for the construction of sponge cities in other regions, and has formed a set of replicable, scalable, and Beijing characteristics of sponge city construction experience, which has strongly supported the sponge city construction work in the pilot area.

According to their own conditions, all localities should do a good job in the preliminary planning according to local conditions and comprehensively consider the transformation and construction of infrastructure such as urban water systems and permeable pavements, and on the basis of the continuous monitoring of natural resources such as geographical conditions, it is recommended to incorporate the monitoring of sponge city's underlying surface into the urban territorial space monitoring system and establish a long-term monitoring mechanism.[16]

Through technological innovation and standardized processes, the multi-dimensional dynamic monitoring and comprehensive evaluation of the construction effect of the sponge city are carried out, which not only provides an institutional guarantee for government departments to realize the supervision of the whole process of regions, plots, and projects, but also provides more timely and effective professional technical support for construction units.

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