



## RESEARCH ARTICLE

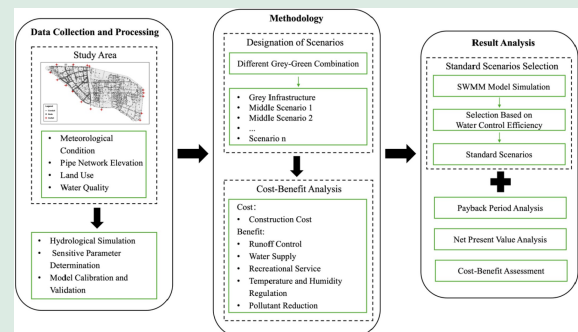
# Stormwater management model based cost-benefit analysis of integrated grey-green infrastructure scenarios

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## HIGHLIGHTS

- SWMM was used to evaluate 15 scenarios and to compare their various benefits.
- Temperature and humidity regulation accounted for over 88% of the total benefits.
- All gray-green scenarios had positive net benefits in a 30-year operational period.
- Scenario 9 had the highest net benefit of 1957.7 million yuan.



**ABSTRACT:** This study promotes the integration of ecological green infrastructure with traditional gray infrastructure to tackle urban water management challenges and safety issues. Using the Storm Water Management Model (SWMM), we simulated runoff control in Beijing Tongzhou District Sponge City Pilot Area across 15 gray-green infrastructure scenarios and identified the optimal strategy through a cost-benefit analysis focusing on scenarios that meet runoff control standards. A cost-benefit evaluation framework was developed for gray-green infrastructure projects, employing payback period and net present value methods to assess cost-effectiveness. Findings revealed notable operational benefits, particularly in temperature and humidity regulation, which accounted for 88% of the total benefits. A standout scenario with a rapid payback period of 7.16 years and a net benefit of 1957.7 million yuan was highlighted. The research provides a holistic assessment, integrating environmental, ecological, and economic aspects of gray-green infrastructure, offering insights for effective green infrastructure deployment and evaluation in sponge city construction.

**KEYWORDS:** Green infrastructure, Life cycle assessment, Stormwater management model, Cost-benefit analysis, Sponge city

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## 1 Introduction

To address the pressing environmental challenges posed by urban expansion, including urban flooding and deteriorating water quality, China has proposed the innovative Sponge City (SC) initiative, emphasizing enhanced stormwater management strategies within urban landscapes (Xia et al., 2017). The cornerstone of this project is the utilization of green infrastructure (GI) (encompassing bio-retention cells, green roofs, and more) as a primary means of managing urban runoff at its source. This approach aims to alleviate the burden on conventional “grey” infrastructure, fostering a more resilient and eco-friendly urban water system. However, during extreme storm events, GI alone may not suffice in fully mitigating runoff. As such, a harmonious integration of gray and green infrastructure is crucial. By combining the strengths of both systems, we can more effectively control urban runoff, enhance the overall quality of the urban water environment, and foster a sustainable urban water cycle that benefits both the environment and society. This integrated approach ensures that cities are better prepared to adapt to climate change and manage water resources responsibly and sustainably.

Early research on the value of ecosystems primarily involved qualitative descriptions of their crucial role in conserving biodiversity and sustaining planetary development yet lacked quantitative assessments of ecosystem value. This changed following a seminal study (Costanza et al., 1997), which quantitatively evaluated the value of 17 types of ecological services in monetary terms. In 2001, international organizations such as the World Health Organization initiated the Millennium Ecosystem Assessment project. Ecosystem services were categorized into four types, which laid a significant foundation for the classification and value assessment of ecosystem services.

Current research endeavors predominantly concentrate on elucidating the myriad benefit of GIs, encompassing pollution mitigation (Flynn and Traver, 2013), runoff reduction (Abdeljaber et al., 2022), and overall environmental enhancement (Li and Wang, 2021). While a substantial portion of these studies compare GIs with their gray counterparts in isolation, they often underscore the superior performance of GI in areas like water quality improvement (Wang et al., 2013) and broader environmental benefits (Casal-Campos et al., 2015). However, it is acknowledged that GI cannot solely assume the comprehensive rainwater management responsibilities traditionally held by gray infrastructures. Notably, the synergetic effects of integrating gray and green infrastructures have received

limited in-depth exploration, despite their potential to offer a holistic solution. Xu et al. (2019) underscored the urgency for future research to delve into this integration, advocating for a multi-faceted evaluation framework encompassing environmental, economic, and safety considerations. Accurate and balanced assessments of the combined benefits of gray and green infrastructures are imperative to inform sustainable urban planning and infrastructure development strategies.

In China, as artificial ecosystems continue to evolve and be established across various fields, the corresponding frameworks for evaluating their costs and benefits are undergoing a process of continual refinement. However, the analysis of benefits can not be separated from cost evaluation. Achieving high returns with low investment in the overall benefits of GI is a key issue in constructing of sponge cities.

As an important component of the new ecological stormwater management system, GI has been extensively studied using urban stormwater and pollutant models. Representative models include the Storm Water Management Model (SWMM), the System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN), and the Model for Urban Stormwater Improvement Conceptualization (MUSIC). Elliott and Trowsdale (2005) evaluated dozens of models and found that the SWMM model has broad applicability, can achieve very small simulation time steps, and offers high accuracy in results. These include the simulation of stormwater control effects and water quality regulation in GI, sensitivity analysis and identification in urban stormwater flood simulation, and the analysis and estimation of non-point source pollution characteristics and loads in urban stormwater runoff. Among these, SWMM is the most frequently used in related studies. Therefore, this research employs the SWMM model for modeling analysis.

Accordingly, this study selects the Tongzhou District, the urban sub-center of Beijing, and a pilot area for national sponge city construction, as its research subject. Recognizing the current lack of research focused on the cost-benefit analysis of gray-green infrastructure integration, our work seeks to bridge this gap by offering actionable insights into optimizing the balance between ecological and economic factors within urban water management systems. The primary objective is to develop a comprehensive regional model utilizing the SWMM, which will be employed to assess the cost-effectiveness of various scenarios through detailed simulation outcomes. Besides, the final objective is to determine the best construction scenario for implementing GI, using multiple evaluating methods, making sure that the benefits to the economy

and environment are maximized. The findings of this study aim to provide guidance for the precise layout and construction of GI. They are expected to play a proactive role in technological verification and planning leadership for the next phase of large-scale SC construction.

## 2 Methodology

The technical route of this study, as depicted in Fig. 1, encompasses two main stages: creating standard scenarios and analyzing their cost-effectiveness. Initially, standard scenarios are developed using the SWMM, customized to the local weather, rainfall patterns, and the layout of both gray and green infrastructure. The model uses a year's rainfall data to simulate runoff control, which is then compared to standards to select the best scenarios. The second stage involves a detailed cost-benefit analysis of the most suitable scenarios, considering their long-term performance. It includes calculating costs and benefits over the operational lifespan of the GI. Economic viability is assessed using payback period and net present value (NPV) methods, offering a solid basis for evaluating the financial sustainability of the proposed solutions.

### 2.1 Study area description and hydrological simulation

This study is based on Beijing's national pilot area for sustainable city initiatives, situated in Tongzhou District, the burgeoning sub-center of the capital city of China. Encompassing a total construction area of 19.36 km<sup>2</sup>, including an administrative zone, built-up zone, and new development zone, whose area is 6.75 km<sup>2</sup> (approximately 5.88 km<sup>2</sup>, with an additional 0.87 km<sup>2</sup> of water area), 7.41 km<sup>2</sup> (approximately 4.08 km<sup>2</sup>, with an additional 3.33 km<sup>2</sup> of water area) and 5.20 km<sup>2</sup>, respectively. The annual average rainfall is 544 mm, and the annual average evaporation exceeds 1300 mm. Furthermore, the region's relatively flat terrain contributes to frequent water accumulation issues, underscoring the need for targeted interventions to mitigate flooding and enhance overall water resilience. Based on meteorological conditions, the drainage pipe network system and land use, the SWMM model for the study area was constructed (Fig. 2).

To check the simulation results of the mechanism model, we employed the Nash-Sutcliffe efficiency (NSE) as the evaluation index of the simulation results of the mechanism model (Zhang et al., 2020).  $NSE \geq$

0.5 is the minimum requirement for model calibration and verification (Bal et al., 2021). NSE is calculated by Eq. (1):

$$NSE = 1 - \frac{\sum_{t=1}^N (Q_{ss,t} - Q_{ms,t})^2}{\sum_{t=1}^N (Q_{ms,t} - \bar{Q})^2}, \quad (1)$$

where  $N$  denotes the total number of monitoring points;  $Q_{ms,t}$  denotes the monitored sequence at time  $t$ ; and  $Q_{ss,t}$  denotes the simulation sequence at time  $t$ .

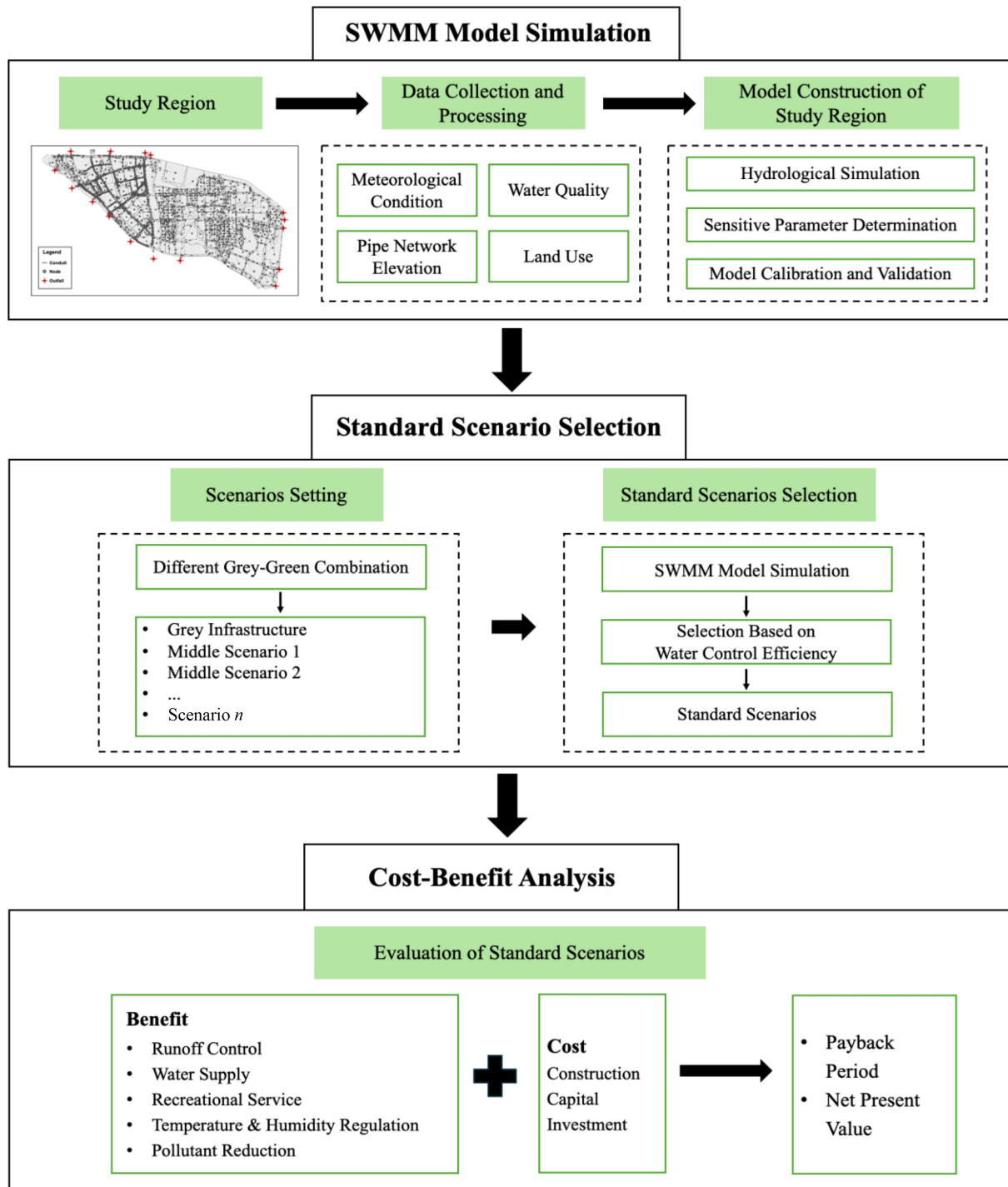
Zhu et al. (2023) calibrated and validated the SWMM model for Tongzhou District, adjusting it with observational data. The calibration yielded NSE scores of 0.66 and 0.92, while validation produced scores of 0.62 and 0.71, both of which met the required standards and affirmed the model's optimal parameters. Additionally, the model's accuracy was thoroughly verified, enhancing its credibility for application in the target area. Detailed results of the calibration and validation processes can be found in Appendix A.

### 2.2 Designation of green infrastructure scenarios

In this study, according to actual geographical and 'Sponge City Construction Technical Guidelines (Trial)', bio-retention cell (BRC) and wet pond (WP) are chosen as the optimal GI.

Given the land use distribution within the study area, approximately 30% of the total area comprises green spaces. Assuming an 80% conversion rate from green fields to BRCs, the scenarios for deploying BRCs in the study area encompass high, medium, and low deployment ratios, corresponding to converting 24%, 16%, and 8% of the total area, respectively. With a total of 1516 ha of the study area, under the high deployment scenario, 364 ha would be converted, while 244 and 121 ha would be converted under the medium and low scenarios, respectively. These conversion scenarios enable a flexible approach to implementing GI for stormwater management, water quality improvement, and enhanced ecological resilience, adapting effectively to different levels of land use change. The detailed parameters employed for modeling the BRCs within the SWMM are presented in Table 1.

WPs are typically designed to offer ecosystem services such as water filtration, flood control, and biodiversity support, which require significant land to achieve. As for the WP designation, given the substantial area required for a single WP and the constraints posed by limited construction space, the high, medium, and low deployment ratio scenarios for WP have been devised to cover 10%, 6.7%, and 3.3% of the total study area, respectively. This translates to total construction areas of 152, 102, and 50.3 ha, each



**Fig. 1** Technical route.

with a depth of 3 m.

By combining the three WP scenarios with the three BRC scenarios, as well as incorporating three scenarios featuring WP and three scenarios solely featuring BRC, a comprehensive set of 15 distinct gray-green integrated infrastructure construction scenarios has been

formulated (Table 1). This approach facilitates a thorough evaluation of the various options for enhancing stormwater management and promoting sustainable urban drainage. A more detailed explanation of the scenario’s designation is presented in Appendix B.



**Fig. 2** SWMM model for the study area.

**Table 1** 15 Grey-green integrated infrastructure construction scenarios

Construction scenarios	Construction area of WP (ha)	Construction area of BRC (ha)
S1 Grey infrastructure + WP H	152	0
S2 Grey infrastructure + WP M	102	0
S3 Grey infrastructure + WP L	50.3	0
S4 Grey infrastructure + WP H + BRC H	152	363.8
S5 Grey infrastructure + WP M + BRC H	102	363.8
S6 Grey infrastructure + WP L + BRC H	50.3	363.8
S7 Grey infrastructure + WP H + BRC L	152	121.3
S8 Grey infrastructure + WP M + BRC L	102	121.3
S9 Grey infrastructure + WP L + BRC L	50.3	121.3
S10 Grey infrastructure + WP H + BRC M	152	243.6
S11 Grey infrastructure + WP M + BRC M	102	243.6
S12 Grey infrastructure + WP L + BRC M	50.3	243.6
S13 Grey infrastructure + BRC L	0	121.3
S14 Grey infrastructure + BRC M	0	243.6
S15 Grey infrastructure + BRC H	0	363.8

Notes: S stands for scenario, H stands for high, M stands for medium, and L stands for low. The same below.

### 2.3 Cost-benefit analysis

Given that all GI projects in China are either in the construction phase or operational, our assessment encompasses both the construction and operational costs and benefits. For the cost evaluation of GI, we focus primarily on the construction-phase expenses,

which include production, consumption, transportation, and on-site construction costs. These encompass both capital investment and associated environmental impacts.

Prokešová et al. (2022) emphasize that the primary goal of sponge city construction is to mitigate flood disasters, with its effectiveness often evaluated by

runoff control capabilities. Drawing on the existing research (Demuzere et al., 2014) and the situation of the study area, our assessment of the benefits of GI focuses on the operational phase and includes stormwater runoff management, pollutant reduction, rainwater storage, and resource utilization, as well as landscape, recreational, and climate regulation benefits. The assessment of benefits further delves into the mitigation of negative environmental impacts during the operational phase of GI, as well as the quantification of the ecological services provided.

### 2.3.1 Runoff control benefits

The benefits derived from GI through the control of stormwater runoff are manifested in two aspects: First, the reduction of the volume of wastewater treated at sewage plants, leading to savings in sewage treatment costs ( $L_1$ ). According to the research by Long et al. (2021), the average cost of wastewater treatment in 36 major and medium-sized cities in China in 2019 was 1.37 yuan/t. Based on the construction targets in the study area, the stormwater and sewage drainage system covers 520 ha (Tongzhou Water Bureau, 2018), approximately 30% of the total study area. Therefore, 30% of stormwater runoff in the study area is directly discharged into environmental water bodies, while 70% is diverted to sewage treatment plants. In analyzing the costs, benefits are calculated for the 70% reduction in stormwater runoff. Second, the reduction of runoff also lowers the operational pressure on the sewage network, resulting in savings in network operation costs. The above-mentioned economic benefit can be calculated with Eqs. (2) and (3).

$$L_1 = \alpha_1 \times \beta_1 \times V, \quad (2)$$

$$L_2 = \alpha_2 \times V, \quad (3)$$

where  $L_1$ : the benefit of reduced sewage treatment cost;  $\alpha_1 = 1.37$  yuan/t, the average cost of wastewater treatment;  $\beta_1 = 70\%$ , the runoff rate of which diverted to sewage treatment plants;  $V$ : controlled stormwater volume;  $L_2$ : the benefit of reduced pipe network maintenance cost;  $\alpha_2 = 0.13$  yuan/m<sup>3</sup>, the average pipe network maintenance cost (Zhu et al., 2023).

### 2.3.2 Water supply benefits

Utilizing GI for rainwater harvesting has multiple environmental and economic benefits that go beyond simple stormwater management. By capturing and reusing rainwater, cities can reduce pressure on their municipal water systems, lower utility costs, and

conserve water resources. These efforts contribute to long-term sustainability and help urban areas adapt to variable climate conditions by ensuring a steady water supply during dry periods. Additionally, the use of harvested rainwater contributes to the health and resilience of urban green spaces, enhancing ecological benefits and overall environmental quality. However, not all stored rainwater can be utilized, with some loss due to infiltration and evaporation. Refer to Zhu et al. (2022), the rainwater reuse rate is 3% ( $\beta_2$ ). Besides, the first-tier price of tap water in Beijing is 5 yuan/m<sup>3</sup>. This economic benefit can be calculated with Eq. (4).

$$L_3 = \alpha_3 \times \beta_2 \times V, \quad (4)$$

where  $L_3$ : the water supply benefits;  $\alpha_3 = 5$  yuan/m<sup>3</sup>, the first-tier price of tap water in Beijing;  $\beta_2 = 3\%$ , the rainwater reuse rate;  $V$ : controlled stormwater volume.

### 2.3.3 Recreational service benefits

As multifunctional landscape water bodies, BRC and WP contribute significantly to improving urban living environments and enhancing residents' quality of life. These water features not only help manage stormwater by filtering pollutants and reducing runoff but also provide aesthetic and recreational spaces that support mental and physical well-being. By integrating natural elements into urban landscapes, BRC and WP foster biodiversity, improve air quality, and create cooler microclimates, which is particularly valuable for mitigating urban heat island effects. Since BRC are transformed from existing grasslands, their additional recreational and cultural value is limited, so the recreational service benefit of BRC is not considered. This social benefit can be calculated with Eq. (5).

$$L_4 = \alpha_4 \times S_{GS}, \quad (5)$$

where  $L_4$ : the recreational service benefits;  $\alpha_4 = 14862$  yuan/hectare, the recreational and cultural value per hectare (Shang, 2020);  $S_{GS}$ : the area of green space.

### 2.3.4 Temperature and humidity regulation benefits

The benefits of temperature and humidity regulation include reduced air conditioning and humidifier use, saving electricity. Besides the 60% reuse component, runoff volume is controlled by evaporation, plant transpiration, and infiltration. Only evaporated and transpired rainwater contributes to temperature and humidity regulation; infiltration is excluded. Therefore, only the additional infiltration from GI construction needs consideration, as it is part of the GI-controlled runoff. According to Liu (2020), the GI increases the

infiltration volume in the study area by 7.0–12.7 mm compared to before its construction, approximately 16% of each rainfall event. Thus, in the ‘WP M + BRC M’ gray-green integrated scenario, 16% of the total rainfall is considered infiltration volume. This scenario, chosen for its moderate construction proportion, results in 19% of the controlled runoff being attributed to infiltration. The remaining 21% of the controlled runoff is used for the calculation of temperature and humidity regulation benefits.

The calculation method for electricity savings and benefits are shown in Eqs. (6)–(8).

$$E = \frac{Q \times \gamma}{3600 \times \omega} + \beta \times Q, \tag{6}$$

$$L_5 = \theta_1 \times E, \tag{7}$$

$$Q = \theta_2 \times \theta_3 \times V, \tag{8}$$

where  $E$ : the electricity savings;  $Q$ : the rainfall evaporation volume;  $\gamma = 2.26 \times 10^6$  J/kg, the latent heat of vaporization at standard atmospheric pressure;  $\omega = 3$ , the coefficient of performance (COP) of air conditioning, which is the ratio of the cooling capacity to the power consumed;  $\beta = 125$  kWh/m<sup>3</sup>, the electricity consumption to vaporize 1 m<sup>3</sup> of water;  $\theta_1 = 0.5$  yuan/kWh, the Beijing’s latest residential electricity price;  $\theta_2 = 40\%$ , the proportion of rainwater involved in the water cycle;  $\theta_3 = 21\%$ , the evaporation and transpiration ratio of rainwater.

### 2.3.5 Pollutant reduction benefits

Pollutants in stormwater runoff can be effectively managed through GI, which offers the benefit of reducing the volume of water requiring treatment at wastewater facilities. By intercepting and treating runoff on-site, GI lowers the burden on wastewater treatment plants, resulting in cost savings and increased efficiency in pollutant management. The pollutants considered in this study are chemical oxygen demand (COD), ammonia nitrogen (NH<sub>3</sub>-N), total nitrogen (TN), and total phosphorus (TP). According to [Zhu et al. \(2022\)](#), the pollutant treatment fees for COD, NH<sub>3</sub>-N, TN, and TP are  $3.27 \times 10^3$ ,  $2.39 \times 10^4$ ,  $2.30 \times 10^4$ , and  $5.24 \times 10^4$  yuan/t, respectively. The calculation methods for pollutant reduction benefits are shown in Eqs. (9)–(12).

$$L_6 = \sum A_{cn} \times \alpha_{5n}, \tag{9}$$

$$A_{cn} = \sum A_{pn} \times \eta_n, \tag{10}$$

$$A_{pn} = U_n \times V, \tag{11}$$

$$\eta_n = \sum \eta_{nm} \times P_m, \tag{12}$$

where  $L_6$ : the pollutant reduction benefits;  $\alpha_{5n}$ ,  $A_{cn}$  and  $A_{pn}$ : the treatment cost, control amount and produced amount of the  $n$ -th pollutant respectively;  $\eta_n$ : the average removal rate of the  $n$ -th pollutant;  $U_n$ : the concentration of pollutants on the underlying surface (Appendix C);  $\eta_{nm}$ : the removal rate of the  $n$ -th pollutant by the  $m$ -th GIs (Appendix C);  $P_m$ : the ratio of the area of the  $m$ -th GI to the total area of GI.

## 3 Results

### 3.1 Standard scenarios selection

According to the ‘Sponge City Construction Technical Guidelines (Trial)’, promulgated by the [Ministry of Housing and Urban-Rural Development of the People’s Republic of China \(2015\)](#), along with other relevant index systems, this study adopts an annual runoff control rate of 84% or higher as the benchmark criterion for assessing whether a given scenario conforms to the established standards. The formula for calculating the annual runoff control rate is outlined in Eq. (13):

Annual Runoff Control Rate

$$= \left( 1 - \frac{\text{Total Annual Discharged Rainwater}}{\text{Total Annual Rainfall} \times \text{Catchment Area}} \right) \times 100\%. \tag{13}$$

Employing the SWMM to simulate the aggregate drainage outflow from the various outlets, the simulation results pertaining to the annual runoff control rate of 15 different scenarios were shown in Appendix B. Based on these results, a final selection of 10 scenarios (S4, S5, S6, S7, S8, S9, S10, S11, S12, and S15) that met the prescribed standards was made. This study will use these 10 composite standard setting scenarios for subsequent cost and operational benefit analysis.

### 3.2 Cost analysis results

The construction costs refer to the financial investment required for purchasing raw materials, labor, and transportation during the construction phase. This study calculates the total capital expenditure required for the construction of GI based on market quotation methods. According to the ‘Sponge City Construction Technical

Guidelines (Trial)’ and its cost statistics for some GI projects implemented in the Beijing area in recent years, the construction cost of BRC ranges from 150 to 800 yuan/m<sup>2</sup>, and WP cost between 400 and 600 yuan/m<sup>2</sup>. We calculated the construction cost range by using both the maximum and minimum values. The capital investment costs for each scenario are shown in Table 2.

### 3.3 Benefit analysis results

Based on the analyzation about five types of benefits mentioned in Section 2.3, the total annual benefits of each scenario and the proportion of each benefit are calculated, as shown in Table 3.

### 3.4 Cost-benefit assessment results

To make the cost-benefit comparison of these scenarios more equitable, the analysis calculates the number of years it takes for the benefits generated to completely offset the initial costs, which is the payback period. To ensure the accuracy of the results, we calculated the payback period using the average construction cost under each scenario setting.

Besides, to evaluate cost-benefit more objectively, the NPV method is introduced, calculating the total net benefits generated by different scenarios over a defined operational period. Based on previous literature on the lifespan of GI (Xu et al., 2017; Sagrelius et al., 2023), this study set the calculation for 30 years. The method for calculating the NPV is demonstrated in Eqs. (14) and (15).

$$NPV = \sum_t^{T=30} \frac{B_t}{(1+r)^t} - C_0, \tag{14}$$

**Table 2** Capital investment for 10 selected standard scenarios

Scenarios	WP area (ha)	BRC area (ha)	Capital investment (× 10 <sup>6</sup> yuan)
S4	152	363.8	1153.7–3826.0
S5	102	363.8	953.7–3526.0
S6	50.3	363.8	746.9–3215.8
S7	152	121.3	790.0–1883.6
S8	102	121.3	590.0–1583.6
S9	50.3	121.3	383.2–1273.4
S10	152	243.6	973.4–2863.2
S11	102	243.6	773.4–2563.2
S12	50.3	243.6	566.6–2253.0
S15	0	363.8	545.7–2914.0

$$B_t = B_0(1 + \alpha)^t, \tag{15}$$

where  $B_t$ : the benefits produced in the t-th year of operation;  $r = 3.73\%$ , the discount rate;  $C_0$ , the total initial construction costs;  $B_0$ : the initial year’s revenue;  $\alpha = 2.22\%$ , the inflation rate.

Based on the “Monetary Policy Execution Report of the First Quarter of 2024” published by the People’s Bank of China, the weighted average lending rate is 3.73%, and the average annual consumer price inflation rate in China over the past decade is 2.22%. Therefore, this study uses these two figures to calculate the NPV. The total benefits generated over a 30-year operational period, payback period, and net profit for each scenario are presented in Table 4.

## 4 Discussion

Ecosystem services are typically divided into four main categories: provisioning, regulating, supporting, and

**Table 3** Percentage of different benefits in 10 selected standard scenarios

Scenarios	Total benefit (× 10 <sup>6</sup> yuan)	Runoff control benefits (%)	Water supply benefit (%)	Recreational service benefits (%)	Temperature and humidity regulation benefits (%)	Pollutant reduction benefits (%)
S4	123.4	6.7	1.0	1.8	88.9	1.7
S5	121.1	6.7	1.0	1.3	89.3	1.8
S6	118.5	6.7	1.0	0.6	89.8	1.9
S7	121.3	6.7	1.0	1.9	88.9	1.6
S8	118.6	6.7	1.0	1.3	89.4	1.7
S9	115.6	6.7	1.0	0.7	89.9	1.8
S10	122.3	6.7	1.0	1.9	88.9	1.7
S11	119.8	6.7	1.0	1.3	89.3	1.8
S12	117.1	6.7	1.0	0.6	89.8	1.9
S15	113.4	6.8	1.0	0.0	90.3	2.0

cultural services. In the context of these scenarios, the dominant benefits are aligned primarily with regulating and cultural ecosystem services, underscoring the role of GI in enhancing urban sustainability and resilience.

As the results shown in Table 3, the data reveal that temperature and humidity regulation comprise over 88% of the total benefits across all scenarios, highlighting the significance of regulating ecosystem services. Through processes such as evapotranspiration, GI systems—especially vegetated components—can lower ambient temperatures and regulate humidity levels, thereby mitigating the urban heat island effect. This regulatory function is essential for improving urban climate resilience, illustrating the critical role of GI in sustainable urban development strategies.

Although less prominent than climate regulation, the benefits of runoff control and pollutant reduction (constituting around 6.65% to 6.75% and 1.64% to 1.98% of total benefits, respectively) also fall under regulating ecosystem services. GI manages stormwater and filter pollutants, enhancing water quality and reducing flood risks—crucial functions for alleviating urban environmental stresses and supporting healthier ecosystems.

As for water supply benefits, though relatively minor (constituting less than 1% of total benefits across scenarios), they represent provisioning ecosystem services. Although a smaller component, this provisioning service supports resource efficiency and sustainability in urban water management. Besides, recreational benefits, representing cultural ecosystem services, contribute between 0.63% and 1.86% across scenarios. These services encompass the non-material benefits that enhance human well-being, such as aesthetic enjoyment, recreation, and opportunities for outdoor activities provided by GI spaces.

As demonstrated in Table 4, the payback period for

each scenario ranges from 7 to 20 years, exhibiting significant variability. When considering the specific scenario settings, it becomes apparent that the payback period for larger GI is generally extended. However, it is insufficient to make benefit judgments based solely on the payback period; it is also necessary to consider the time value of money and other financial indicators.

Based on the net profits calculated using the NPV over a 30-year operational period, it is observed not all scenarios meet the standards for positive net benefits. The net profit values range from 482.4 to 1957.7 million yuan, indicating varying levels of financial viability across scenarios. This suggests that a larger construction scale does not necessarily yield higher net benefits. For instance, in scenario S4, the high initial construction cost results in the lowest net profit, with a return of 482.4 million yuan. On the other hand, scenario S9, with a smaller construction scale, achieves the highest net profit of 1957.7 million yuan by balancing cost efficiency and benefits, highlighting the importance of optimal project sizing for maximum economic return.

This underscores the critical necessity of meticulously balancing costs and benefits in the development of GI for sponge cities. It is imperative to implement strategic approaches to prevent the inefficient use of valuable resources such as labor, land, and capital. Consequently, there is a pressing need for a comprehensive benefit evaluation system tailored specifically to green facilities. When opting to construct GI, it is imperative not only to consider the initial construction costs but also to conduct a thorough analysis incorporating various benefits, payback periods, and other relevant financial indicators. This multifaceted approach ensures a more holistic understanding of the long-term value and sustainability of GI investments, thereby fostering more informed and

**Table 4** Payback periods and net profit for selected 10 standard scenarios over 30-years’ operation

Scenarios	Total cost (× 10 <sup>6</sup> yuan)	Total benefits (× 10 <sup>6</sup> yuan/year)	Total profit in 30 years (× 10 <sup>6</sup> yuan)	Payback period (year)	Net profit (× 10 <sup>6</sup> yuan)
S4	2489.9	123.4	2972.3	20.2	482.4
S5	2239.9	121.1	2916.9	18.5	677.1
S6	1981.4	118.5	2854.8	16.7	873.4
S7	1336.8	121.3	2921.6	11.0	1584.8
S8	1086.8	118.6	2856.9	9.2	1770.2
S9	828.3	115.6	2786.0	7.2	1957.7
S10	1918.3	122.3	2945.8	15.7	1027.5
S11	1668.3	119.8	2887.4	13.9	1219.1
S12	1409.8	117.1	2822.4	12.0	1412.6
S15	1729.9	113.4	2732.9	15.2	1003.0

judicious decision-making processes. By ensuring the judicious allocation and optimal utilization of these resources, we can foster sustainable urban development and enhance the overall efficacy and longevity of sponge city initiatives.

We further recognize several limitations in our study. While the SWMM model used was carefully calibrated and validated, yielding a satisfactory NSE score, a sensitivity analysis was not included, which might have provided additional insights into how parameter variations could affect the outcomes. Additionally, our cost analysis does not currently incorporate dynamic elements, such as regional cost differences and fluctuations over various construction periods. As a result, our baseline estimates may not fully reflect the economic variability across different contexts. Future studies, with more data available, could incorporate these factors to produce more tailored cost projections, including accounting for labor and other maintenance costs during the operational phase.

One more drawback is the scope of benefit indicators. While our analysis includes key indicators, a broader evaluation encompassing additional social, environmental, and economic benefits would provide a more comprehensive picture. Expanding the range of benefit indicators in future research would allow for a more nuanced understanding of infrastructure impacts, capturing a wider array of potential benefits relevant to diverse urban contexts. Addressing these areas in future work could enhance the robustness of our assessment of sponge city infrastructure benefits.

## 5 Conclusions

This study addresses the current research gaps in the cost-benefit analysis of GI by developing a SWMM model for the study area. Through SWMM simulation, the runoff control effectiveness of different GI scenarios was evaluated and selected those achieving a minimum 84% runoff control rate. Subsequently, we devised a rigorous and quantitative index system to assess the cost-benefit of these GI scenarios, facilitating a holistic evaluation that encapsulates environmental, ecological, and economic dimensions at the regional level. The main conclusions are as follows:

1) Among the evaluated scenarios, the thermal and humidity regulation benefits emerged as the most significant, contributing over 88% of the total benefits. All scenarios generated substantial net benefits ranging from 482.4 to 1957.7 million yuan over a 30-years' operational period, emphasizing the value proposition of investing in GI.

2) Out of the 10 qualifying scenarios, the “Grey + WP L + BRC L” (Scenario 9) configuration stood out for its exceptional performance in terms of payback period and net benefits. With a payback period of just 7.16 years and a staggering net benefit of 1957.7 million yuan over 30 years. This is mainly attributed to the smaller construction area and lower investment in GI. In contrast, while the “Grey + WP H + BRC H” (Scenario 4) generated higher annual benefits, its steeper upfront costs translated into lower net benefits and a longer payback period.

**Conflicts of Interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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