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Original Research

Comprehensive Effectiveness Evaluation of Constructing a Multi-Objective Sponge Campus

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Abstract

A sponge campus aims to improve the overall effectiveness of the stormwater system of campus through the use of low-impact development (LID) measures to cope with climate extremes, heavy rainfall, and flooding. This study endeavors to assist companies and organizations in addressing issues such as evaluating the effectiveness of LID measures in sponge campuses to confirm the soundness of sponge solutions. To accomplish the goal, this study employs a methodology to assess the effectiveness of LID measures by constructing five objectives (total annual runoff control rate, runoff pollutant reduction rate, flood flow control, peak present time extension, and stormwater utilization system) and finally verifies the validity of this methodology through real examples. The results of the study demonstrate that the Sponge campus program is reasonable and meets the requirements for Sponge City construction in the area. After implementing LID measures, the total annual runoff control rate reaches 81.5%, the reduction rate of runoff pollutants (SS) exceeds 65%, the flood peak flow is reduced by more than 30%, and the peak moment of the flow at the outfall is extended by 4-6 minutes. The campus can effectively alleviate urban flooding problems by rationally configuring the LID measures and constructing a sustainable stormwater management system with a multi-objective orientation. This also improves the efficiency of stormwater resource utilization. The contribution of this study lies in providing valuable methods and insights for understanding and evaluating the effectiveness of LID measures. It also provides a certain reference for engineers and planners engaged in the field, which is crucial for the future construction of Sponge City.

Keywords: sponge campus, low impact development, SWMM, runoff control, effectiveness assessment

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Introduction

Extreme weather, heavy rainfall, and flooding disasters occur frequently and are becoming more severe globally, especially in China. Studies have indicated that China's rapid urbanization has intensified the frequency of floods, leading to severe urban flooding and economic losses. Examples include the extremely heavy rainfall floods in Changzhou City in 2015 and 2016 [1], the extremely heavy rainfall in Zhengzhou in 2021, and the Zhuozhou floods in Hebei Province in 2023. Urban flooding is a major societal concern because it endangers human life and property. As a result, it becomes imperative to investigate sustainable water management strategies to tackle the problem of urban flooding. [2] emphasized the complexity and high cost of retrofitting urban pipe networks, thereby making sustainable stormwater management a more feasible approach to mitigating flooding compared to overhauling urban drainage networks. In response to challenges like flooding and urban waterlogging, a variety of sustainable stormwater management strategies, including Best Management Practices (BMPs) and Low Impact Development (LID), have been suggested and put into action. BMPs focus on engineering solutions or natural pollution management, a concept that has been extensively researched in the United States and Europe. The LID concept, introduced in 1996, aimed to diminish runoff, curb pollution, and encourage rainwater recycling. Furthermore, Sustainable Urban Drainage Systems (SUDS) in the UK [3, 4] and Water Sensitive Urban Design (WSUD) in Australia [5, 6] are frequently cited. Both strategies strive to diminish stormwater runoff by implementing LID measures for urban stormwater management. The sponge cities concept was initiated by the Chinese government in 2012, with vigorous promotion of their development commencing in late 2014. The goal of sponge cities is to amalgamate natural and artificial strategies for managing natural precipitation, surface water, and groundwater. This strategy aims to establish robust urban water management systems capable of absorbing, storing, infiltrating, purifying, discharging, and reusing rainwater across diverse natural environments. The Technical Guidelines for Sponge City Construction in China (for Trial Implementation) emphasize that LID should adopt different measures at the source, midway, and end of the process to maintain the site's hydrological characteristics before development. The guidelines advocate for a runoff management approach that uses low-intervention measures to effectively control the total amount of runoff, peak runoff, and runoff pollution. Consequently, Sponge City Construction integrates and manages the LID system. The technical measures employed in sponge city construction are more scientific, and safer, and offer greater advantages for sustainable urban stormwater management compared to traditional municipal stormwater systems that discharge stormwater directly and rapidly. Currently, the primary methods for simulating urban rainfall-runoff response include the U.S. Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM), the Best Management Practices Decision Support System Model (BMPDSS), and the Urban Stormwater Treatment and Analysis Integrated Modeling System (SUSTAIN) [7]. The SWMM model has been widely applied in multiple fields and scenarios. In terms of urban stormwater runoff and urban drainage systems, the SWMM model was used to study the quantity and quality of runoff in multiple scenarios such as urban residences, businesses, and roads [8]; [9] used SWMM to estimate surface runoff and assessed the safety of urban drainage systems. In addition, SWMM was used to study LID scenario conditions under different climate changes and different rainfall recurrence periods [10, 11].

Campuses are among the areas most severely impacted by flooding. For instance, in Fuzhou city, schools have received multiple closure notices from the Education Bureau over the past two years due to urban flooding, significantly disrupting the daily lives of teachers and students. Thus, the establishment of a sponge campus has emerged as a crucial necessity. The objective of a Sponge Campus is to improve and regulate the campus's stormwater system through the adoption of LID measures. This strategy aims to handle extreme weather conditions, heavy rainfall, and flooding, thereby augmenting the comprehensive benefits of Sponge Campus construction. More research has showcased the effectiveness of implementing sponge campuses or LID measures on campuses in curbing stormwater runoff and reducing runoff pollution. The Sponge Campus strategy is an adaptive technical solution customized for the campus environment, and its promotion aligns with the development of China's Sponge City construction. In recent years, the Chinese government has strengthened regulations pertaining to sponge city construction technology. For example, the Shanghai Municipality has promulgated the Technical Standard for Sponge City Construction (DG/TJ 08-2298-2019) and the Management Measures for the Planning and Construction of Sponge Cities in Shanghai. Likewise, the Changzhou Municipality has promulgated the Guidelines for the Construction of Sponge Cities in Changzhou City (Trial) and the Measures for the Management of the Construction of Sponge City Projects in Changzhou City (Trial) (Changjian Regulation (2018) No. 3).

The present research on sponge campuses mainly focuses on three aspects: (1) retrofitting existing campuses with LID measures, the primary objective of controlling runoff, and adhering to regional sponge city construction management regulations. For example, [12] used the CRITIC method to assess the impacts of LID on an existing campus in Xi'an. Their findings showed that the combination of LID measures used in Scenario 4 resulted in a 4.7% reduction in runoff volume and pollutants when compared to other scenarios. (2) The benefits of sponge campuses also constitute a significant focus of these studies. [13] used a monetary-economic quantification method to assess the environmental, economic, and social benefits of Urban Runoff Source Control Facilities (URSCFs) in residential neighborhoods and on campuses. Their findings suggested that although residential neighborhoods produce higher environmental benefits than campuses, they are less cost-effective. Moreover, the existing concrete is expensive and has a substantial environmental impact, suggesting that alternative materials could be sought for future use. To assess the environmental and economic impacts of LID-BMP in China, [14] combined Life-Cycle Assessment (LCA) and Life-Cycle Costing (LCC). According to their findings, grass depressions and buffer strips had the least negative environmental impact, followed by artificial wetlands, bioretention ponds, and infiltration ponds. Grass depressions and buffer strips continue to be the least expensive, followed by bioretention ponds and infiltration ponds, with artificial wetlands being the most expensive. (3) The establishment of a model to examine the effects and impacts of LID facilities. [15-17] used a two-dimensional coupled model, MIKE FLOOD, to analyze the control effects on total waterlogging and runoff. The results showed that by implementing a variety of LID measures, the runoff control rate could be increased to 42.84%, the 15cm deep flooded area could be reduced by 72.87% to 100%, and the most advantageous program was a combination of 9% rain garden, 3% green roof, and 3% permeable paving. [18] used Canadian campus stormwater management as a case study to assess the environmental and economic impacts of implementing four LID measures. The study's results indicated that campus box planters and natural wetlands were the most effective LID measures, although wetlands were costly. Bioswales and rain gardens showed no change in ecological efficiency but had increased economic impacts compared to man-made wetlands. [19] constructed a SWMM-MIKE21 coupled model by integrating the results of physical experiments simulations to investigate the urban hydrological response under LID in the Beiyang Campus. The results indicated that LID measures can effectively control runoff. Permeable pavement outperformed bioretention basins and depressed green spaces in terms of runoff reduction, inundation area, and inundation depth. [20] evaluated the effectiveness of LID measures in the arid areas of Soltan Abad, Iran, using various techniques from Rainwater+. Their results demonstrated that the total annual runoff control rate can reach 60%, thereby effectively reducing water stress in the area. Rooftop rainwater is collected via rainwater harvesting tanks for daily use, and the cisterns, which store enough water for year-round use, provide the greatest social benefit by effectively alleviating water shortages in the area.

The Sponge Campus is a crucial component of Sponge City construction, necessitating systematic research to effectively enhance the campus's sustainable stormwater management. Campuses are typically guided by a lack of specifications during the planning, design, and retrofitting processes, resulting in significant cost and resource waste [2]. This is an issue that warrants the attention of both research scholars and government policymakers. Therefore, this study aims to assist companies and institutions in addressing several issues. Specifically, it seeks to assess the effects of LID measures on campuses before and after implementation using the SWMM model, and ultimately to confirm the rationality and feasibility of sponge programs. The effectiveness of LID measures will be assessed using a methodology to reach these goals. This methodology will construct five objectives: total annual runoff control rate, runoff pollutant reduction rate (SS), flood flow control, peak present time extension, and stormwater utilization system. The effectiveness of this methodology will be validated through examples. The contribution of this study lies in its provision of valuable insights for evaluating the effectiveness of LID measures, offering useful references for companies and organizations, and having significant implications for future sponge city construction.

Materials and Methods

Study Site

The study area is situated in Changzhou City, Jiangsu Province, China, characterized by a North Asian hot monsoon climate and significant monsoon influences (Fig. 1a). The average annual temperature is 16.5ºC. There are about 81 rainy days in the city each year. The rainfall season is primarily concentrated in the spring, summer, and fall months (April-September), and heavy rainfall during this season often leads to flooding [1]. The study area is rectangular, extending approximately 200 meters north to south and 700 meters east to west. The construction site spans an area of 136,899.5 m^2, equivalent to approximately 205.34 acres. The current site, a natural Greenland, is yet to be developed and utilized. It features a flat terrain with an elevation ranging from 5.500 to 5.600 (based on the National 85 Elevation Datum) (Fig. 1b). The study area implements rainwater and sewage diversion, utilizing the park's central lake for storage. Excess rainwater is collected through the rainwater pipe, flows into the front pond, and ultimately drains into the lake. Rainwater from building roofs is disconnected by rainfall pipes and then directed to the sponge facility via planted grass ditches. Some rainwater from building roofs cannot be disconnected by other pipelines and is directly discharged into the cistern via the rainwater outlet.

Rainfall Scenarios

The design storm, calculated from long-term actual measurements, represents the maximum storm that may occur with the objective of flood control. Extreme storms occurring within the same return period may influence the design storm [21]. In the absence of measured rainfall data, rain-type information can be obtained by referring to the regional hydrological manual. As per the Changzhou Urban and Rural Construction Bureau

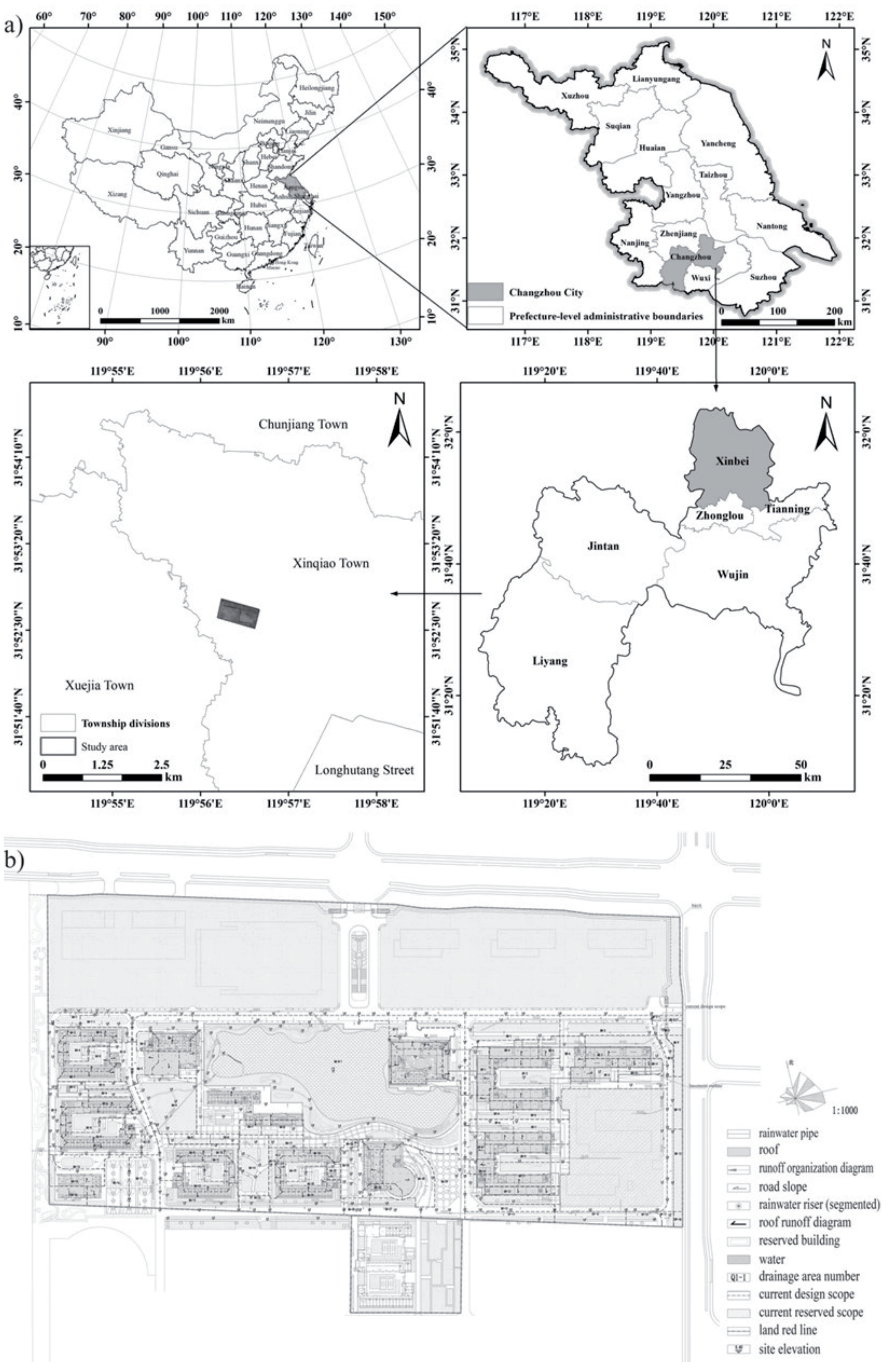

Fig. 1. a) study area; b) overview map of the study area.

Table 1. Daily design rainfall (mm) for different annual total runoff control rates.

Total annual runoff control rate	60	65	70	75	80	85
Design rainfall (mm)	14.0	16.5	19.5	23.2	28.2	35.2

document Chang Jian [2013] No. 163, shows that 28.2 mm of design rainfall equals 80% of the total annual runoff control rate (Table 1).

Its revised storm intensity formula is:

$$i = \frac{134.5106\,(1+0.4784LgTm)}{(t+32.0692)^{1.1947}} \quad (1)$$

Where i is the rainfall intensity (mm/min), t is the rainfall duration (min), and Tm is the return period (years). The Chicago rainfall model, derived from the storm intensity equation, determines the location of the rain peak based on the statistics of storm events from previous years. This model applies to the design rainfall of urban short-calendar time [22, 23]. Short calendar time generally refers to a rainstorm duration that is primarily 2 hours, and not exceeding 6 hours. The Chicago rain-type design rainfall was determined in this study, with the rain peak coefficient chosen as the mature rainfall coefficient, which takes the value of 0.381 [24]. The rainfall calendar time is set at 120 min, and rainfall of 22.8 mm is obtained using the Chicago Storm Intensity Equation (Fig. 2a). A rainfall of 22.8 mm is obtained using the Chicago storm intensity equation. Assessing flooding due to extreme rainfall events and determining the return period of the event, as well as its comparison with the return period used in the design, is critical for attributing responsibility [25]. The return period is a statistical concept that refers to the expected frequency of a storm reaching or exceeding a particular

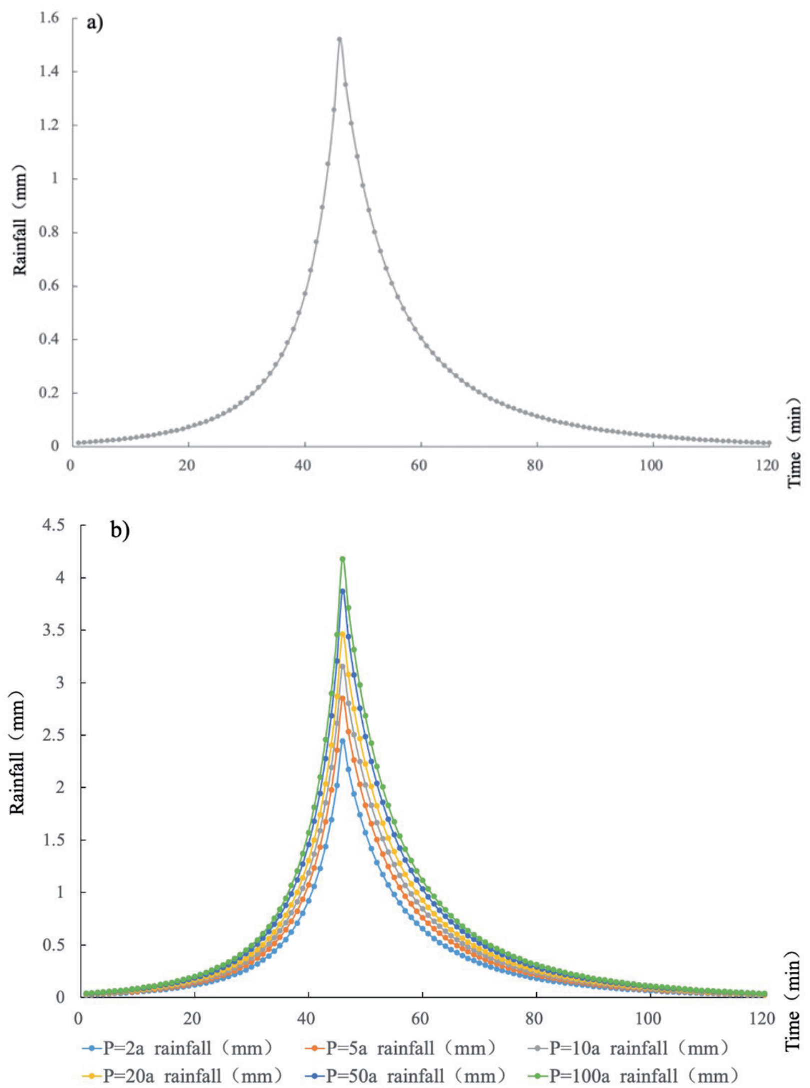

Fig. 2. a) 22.8 mm of rainfall; b) Plot of rainfall intensity of 28.2 mm for different return periods.

intensity magnitude within a certain chronological rainfall range. According to the “12th Five-Year Plan” issued by the Changzhou People’s Government, the urban area satisfies the criteria for flood protection in a 100-year interval. Therefore, rainfalls of 2a, 5a, 10a, 20a, 50a, and 100a were selected for this recurrence period. The reporting interval was set at 1 minute to obtain rainfall process lines for different return periods (Fig. 2b).

Modeling of the Study Area

The flow chart for this study is depicted in Fig. 3. The model generalization of the study area primarily involves the generalization of catchment zoning and the drainage pipe network, with the results of this generalization displayed in Fig. 4. Catchment zoning is primarily based on the original design scheme, taking into account factors such as the current status of the site, site elevation, the direction of rainwater runoff organization, rainwater pipe network, building roof diversion line, the location of building downpipes, and the distribution of green space. The study area is divided into 90 catchment areas, labeled Q1-1 through Q9-12. Each sub-district functions as a stand-alone unit. The type of underlayment is rigid roofing, hard surface, green area, water, and permeable pavement, and the area is 30148.63 m^2, 27042.3 m^2, 33702.38 m^2, 15648.48 m^2, and 30357.71 m^2.

The establishment of the model in the study area first requires the organization of basic data, which includes drainage partition, subsurface interpretation, and drainage pipe network data (check wells, pipelines, drainage outlets). Emphasis is placed on

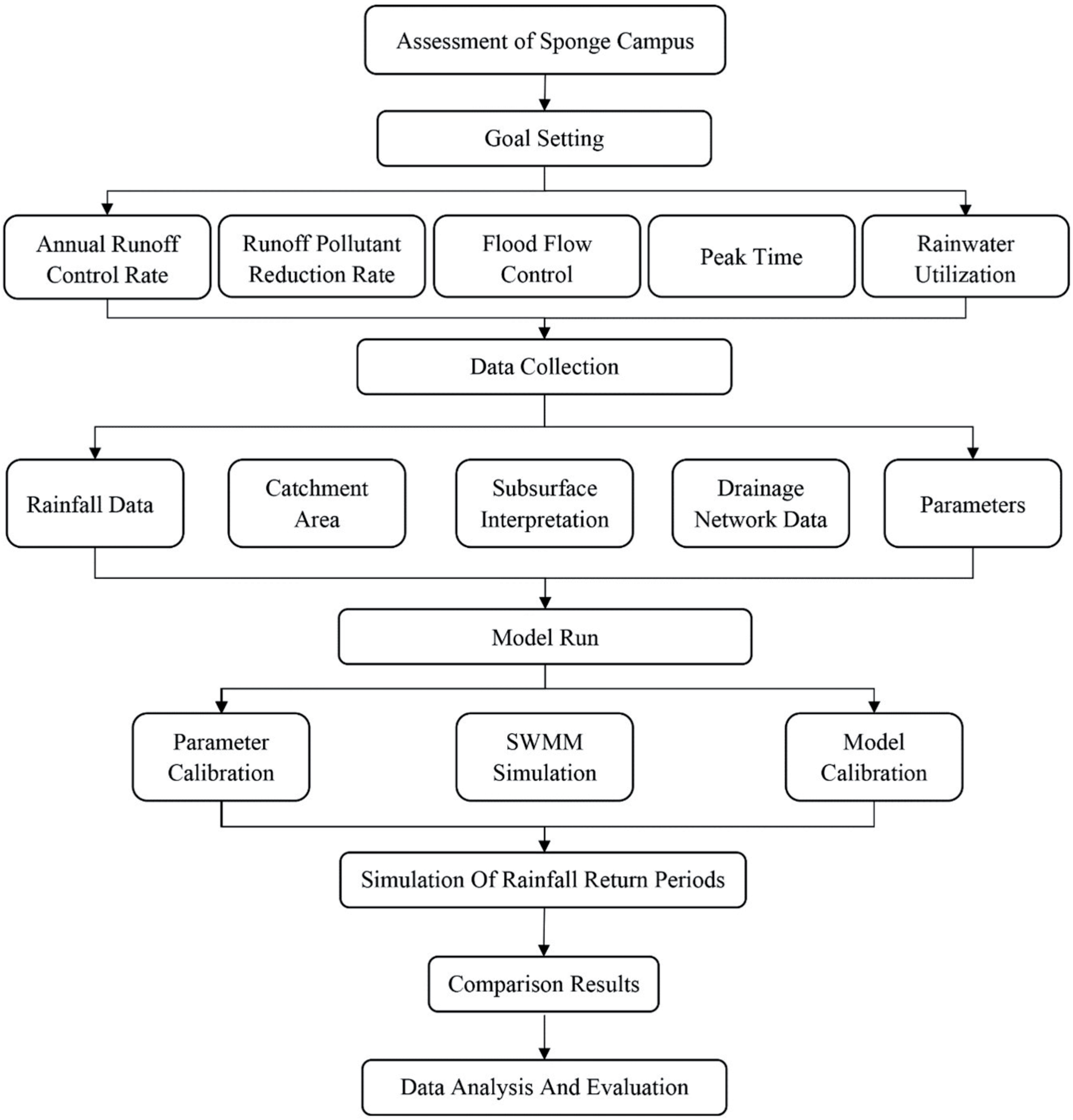

Fig. 3. Research flowchart.

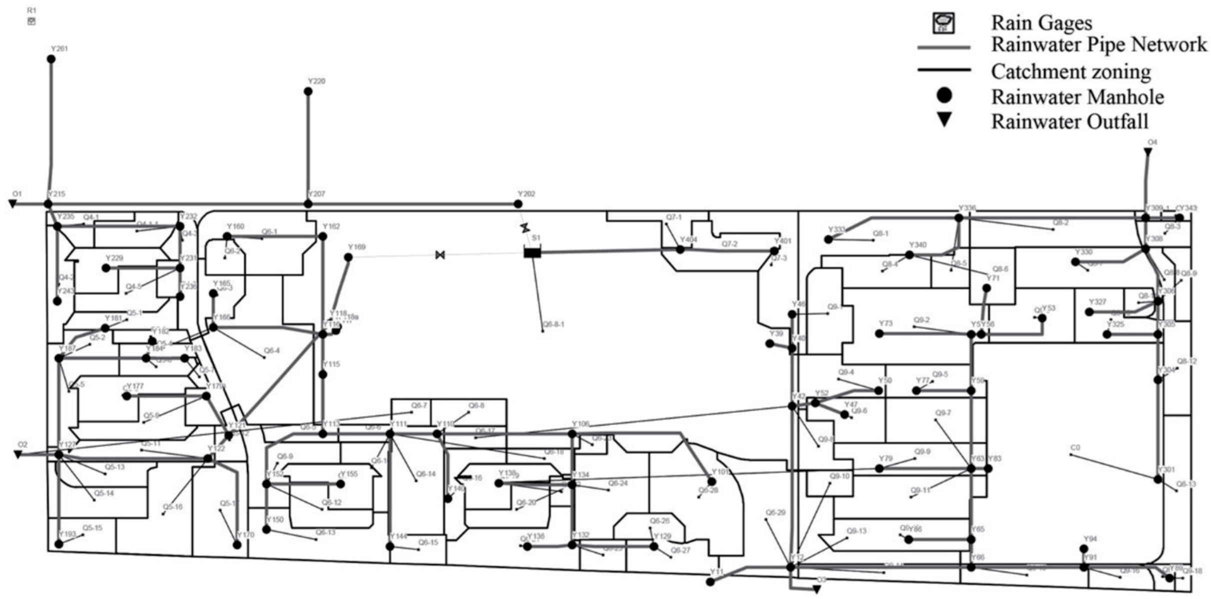

Fig. 4. LID facility allocation map.

the sub-catchment division in the drainage partition, conventional parameters of the catchment partition in the subsurface interpretation, and the generalization of the pipe network and the assignment of parameters in the drainage pipe network data, including the pipe network layout and slope. Next, the model was run and calibrated. AutoCAD2014 was used to transform the base data, which was then imported into ArcGIS. Rate parameters were substituted into the SWMM simulation, and the LID assignment was designed. The calibration model was run, and finally, simulation results were obtained for different rainfall recurrence periods.

Model Parameters and Rate Determination

The setting of model parameters primarily relies on design drawings, the SWMM model user manual, and research experience. The Horton infiltration model is selected for the surface runoff model to simulate the rainfall infiltration process. Horton mainly studies the relationship between infiltration rate and rainfall time, including the maximum infiltration rate, minimum infiltration rate, and decay constant. Horton is mainly applicable to urban areas, and in Chinese cities, we often use Horton. The study area is located in Xinbei District, Changzhou City, China, and the complex and diverse land use and soil types determine the choice of the Horton model. The parameters for the SWMM model mainly encompass hydrology, hydraulics, and water quality. The hydrologic parameters primarily consist of rain gauge and catchment zoning parameters. Hydrological parameters in the catchment area, such as slope, width, and elevation, are determined from AutoCAD drawings. Other parameters, such as surface impermeability (infiltration), Manning's coefficient, surface impermeability (infiltration) puddle storage, and the rate of impermeable area without puddle storage on the surface, are determined based on the "Outdoor Drainage Design Specification GB50014-2021" (see Table 2). Parameters for the Horton model of soil permeability include the maximum infiltration rate (mm/h), minimum infiltration rate (mm/h), and attenuation constant (1/h), among others, based on empirical determination (see Table 3). Hydraulic parameters include check wells, drainage pipelines, and drainage outlets (see Table 4). The pipeline network confluence is calculated using the dynamic wave algorithm. The pipe Manning coefficient is based on the empirical value, and the pipeline length, pipe size, and pipeline node elevation are generalized from the design

Table 2. Parameterization of sub-catchment areas.

Parameter name	Description	Ranges	Calibrated value
N-Imperv	Manning's coefficient of impervious area	0.001-0.015	0.014
N-perv	Manning's coefficient for pervious areas	0.1-0.3	0.12
Dstore-Imperv	Impervious area storage	1-4	2
Dstore-perv	Permeable Zone Puddle Storage	3-10	5
% Zero-Imperv	Percentage of impervious area without puddle storage	5-100	25

Table 3. Soil infiltration parameters.

Parameter name	Description	Ranges	Calibrated value
Max. Infil. Rate	Maximum infiltration rate (mm/h)	10-254	120
Min. Infil. Rate	Minimum infiltration rate (mm/h)	0-10	10
Decay Constant	Decay constant (1/h)	0-7	4

Table 4. Hydraulic parameters.

Parameter name	Description	Ranges	Calibrated value
Manning-N	Pipeline Manning's Coefficient	0.009-0.01	0.01
	Pipeline Attribute Parameters	--	Length generalized from design information
	Node Attribute Parameters	--	Length generalized from design information

data. Water quality parameters are determined by the design data, including the dynamic wave calculation method and the pipeline Manning factor, which is based on experience. Pipe length, pipe diameter, and pipe node elevation are generalized from the design data. Water quality parameters primarily consist of surface pollutants and solid pollutants (SS), which are selected as water quality evaluation indexes. According to the "Technical Guidelines for Sponge City Construction", the concentration of solid pollutant SS is 10 mg/L during rainfall. The surface pollutant accumulation is selected as a half-saturation function, and the scouring model is chosen as an exponential function.

Parameters of LID Measures

The study area is equipped with a total of five LID measures, including permeable paving, depressed green space, a rain garden, a grass-planted ditch, and a storage pond. Each technical parameter is determined based on the "Technical Guidelines for Construction of Sponge Cities in China (for Trial Implementation)", the "Stormwater Management Model SWMM User's Manual", and the design information, as shown in Table 5.

Storage Volume

Facility sizing methods can include the volumetric method, the flow method, or the water balance method. For LID facilities, the design storage volume is typically selected as an indicator of "control volume per unit area" to manage the total amount of runoff and runoff pollution. The design storage volume for each sub-area is computed using the volume method, as outlined in the Technical Guidelines for Sponge City Construction - Low Impact Development Stormwater System Construction (Trial).

$$V = 10H\varphi F \tag{2}$$

Where: V is the design storage volume, m³; H is the design rainfall, mm; the design rainfall of this project is 28.2 mm; φ is the integrated rainfall runoff coefficient (weighted average calculation); F is the catchment area, hm2. In this study area, the weighted average of the subdivided underlayment runoff coefficient is used. The building roof runoff coefficient is set at 0.85, the hard road runoff coefficient is also 0.85, the runoff coefficient for the pavement of large blocks and other paving and plaza areas is 0.55, the permeable pavement runoff coefficient is 0.3, and the greening runoff coefficient is 0.15. The runoff coefficient for plaza areas is 0.55, the permeable pavement runoff coefficient is 0.3, and the greening runoff coefficient is 0.15. This data, derived from the "Sponge City Construction Technical Guidelines - Low Impact Development of Stormwater System Construction (Trial)", is used to calculate the project's comprehensive runoff coefficient, which is 0.6. The design rainfall control within the site is calculated as follows: V = 28.2/1000 * 136899.5 * 0.60 = 2316.33 m. SWMM was used to conduct simulations.

Results and Discussion

Model Validation and Evaluation

In this study, we conducted simulations using SWMM to assess the effectiveness of LID measures in the region. The assessment focused on key factors in evaluating the effectiveness of LID measures, including the total annual runoff control rate, runoff pollutant reduction rate (SS), flood flow control, peak present time extension, and stormwater utilization system. These factors provide a comprehensive assessment of the results. Six distinct rainfall return periods, each lasting 120 minutes, were used to simulate the rainfall process. We compared the campus's surface runoff parameters both before and after the LID measures were implemented (Table 6), as well as the assessment diagram of the effectiveness of the surface runoff

Table 5. Parameters of LID measures.

Stratification	Parameter name	Permeable pavement	Sunken green space	Rain garden	Grass swale
Surface layer	Water storage depth	0	200	100	100
	Coefficient of vegetation cover (%)	0	0.2	0.2	0.2
	Surface Roughness Coefficient	0.014	0.1	0.1	0.25
	Surface slope	0.5	1	1	1
Layer of soil	Thickness (mm)	120	500	300	—
	Porosity (volume ratio)	0.5	0.4	0.4	—
	Water production capacity	0.2	0.2	0.2	—
	Blight	0.1	0.1	0.1	—
	Hydraulic conductivity	0.5	10	10	—
	Hydraulic conductivity slope (%)	10	10	10	—
	Suction head (mm)	3.5	90	90	—
Pavement layer	Thickness (mm)	120	—	—	—
	Porosity (pores/solids)	0.15	—	—	—
	Impermeable Surface Coefficient	0	—	—	—
	Penetration rate (mm/h)	100	—	—	—
	Clogging factor	0	—	—	—
Water storage layer	Thickness (mm)	150	—	500	—
	Porosity	0.75	—	0.6	—
	Penetration rate (mm/h)	5.5	—	10	—
	clogging factor	0	—	0	—
Culverts	Flow coefficient (mm/h)	0.2	—	—	—
	traffic flow index	0.5	—	—	—
	Offset height (mm)	6	—	—	—

process line reduction for different return periods (Fig. 5). The comparison reveals that the surface runoff, infiltration, and peak runoff of the campus increased as the rainfall return period increased, both before and after the implementation of LID measures. Following the implementation of LID measures on the campus, we noted a substantial decrease in both surface runoff and peak runoff volume, accompanied by a delay in the commencement of runoff. This implies that LID measures effectively control runoff and mitigate flood pressure. Additionally, we found a significant reduction in the runoff coefficient, further attesting to the efficacy of the LID measures. We also observed that with an increase in the rainfall return period, the infiltration volume escalated while the infiltration rate declined. This could be attributed to the soil's infiltration capacity reaching saturation during extended return periods, resulting in a decline in the infiltration rate.

Following the implementation of LID, we observed variations in the runoff volume reduction effect under different rainfall recurrence periods. Specifically, the runoff volume was reduced by 60.8% and 51.2% during the 2a and 5a rainfall recurrence periods, respectively (Fig. 6a). These periods exhibited the most significant reductions, both exceeding 50%. This could be attributed to the LID measures being more effective in controlling the runoff volume under shorter return periods when the rainfall is less intense. Conversely, the runoff volume is only reduced by 35.1% when the return period is 100a. This is likely due to the greater rainfall under longer return periods, making it challenging to fully control the runoff volume even when the LID measures are operating at high capacity; Additionally, we found that the infiltration rate increased by 47.8%, 41.8%, 37.9%, 34.7%, 31.2%, and 29.0% (Fig. 6b). However, as the rainfall return period increased, the trend of the increasing infiltration rate gradually slowed down, decreasing from 47.8% to 29.0%. This could be due to the soil's infiltration capacity gradually becoming saturated as rainfall rises, which leads to a decrease in the infiltration rate; As depicted in Fig. 6c, the simulated runoff coefficients decreased by 60.84%, 51.15%, 46.37%, 42.31%, 37.88%, and 35.12%, respectively. This suggests that the reduction in the runoff coefficient

Table 6. Surface runoff parameters before and after the placement of a LID facility for various return periods.

Recurrence period of rainfall	LID arrangement	Rainfall (mm)	Runoff volume (mm)	Infiltration (mm)	Simulated runoff coefficient	Permeability (%)	Peak runoff (m^3/s)	Runoff start time (min)	Total annual runoff control rate (%)
2a	Before setting	45.719	36.071	4.665	0.789	10.2	2.96	10	21.20%
	After setting	45.719	14.125	26.497	0.309	57.96	1.24	16	69.87%
5a	Before setting	53.327	41.581	4.351	0.78	8.16	3.67	10	22.14%
	After setting	53.327	20.298	26.653	0.381	49.98	1.81	14	62.63%
10a	Before setting	59.082	47.133	4.357	0.798	7.37	4.22	8	20.34%
	After setting	59.082	25.278	26.758	0.428	45.29	2.27	14	57.86%
20a	Before setting	64.837	52.702	4.362	0.813	6.73	4.76	8	18.83%
	After setting	64.837	30.396	26.854	0.469	41.42	2.78	12	53.72%
50a	Before setting	72.445	60.087	4.369	0.829	6.03	5.49	8	17.17%
	After setting	72.445	37.304	26.967	0.515	37.22	3.47	12	49.06%
100a	Before setting	78.201	65.686	4.373	0.84	5.59	6.05	8	16.11%
	After setting	78.201	42.601	27.046	0.545	34.59	4	12	46.05%

decreases as the rainfall return period increases. This may be attributed to the runoff coefficient decreasing as the rainfall becomes more intense at longer return periods, making it difficult to fully control the runoff even with the implementation of LID measures; Furthermore, the peak runoff was reduced by 58.1%, 50.7%, 46.2%, 41.6%, 36.8%, and 33.9%, respectively (Fig. 6d). The peak runoff reduction was most significant at P = 2a and 5a. As the rainfall return period increased, the reduction effect of peak runoff gradually weakened, decreasing from 58.1% to 33.9%. This could be due to the increase in the intensity of sustained rainfall, which makes it challenging to completely control the peak flood flow even with the implementation of LID measures, thereby weakening the peak runoff reduction effect; Fig. 6e shows that the onset of runoff is delayed following the implementation of LID measures, with the delay ranging from 4 to 6 minutes. The result indicates that LID measures are effective in controlling runoff, thereby delaying the onset of runoff; Finally, the total annual runoff control rate increased by 48.7%, 40.5%, 37.5%, 34.9%, 31.9%, and 29.9% (Fig. 6f). This also suggests that the total annual runoff control rate decreases with the increasing intensity of the rainfall return period, it decreases from 48.7% to 29.9%. Therefore, it is challenging to fully control the total annual runoff under a larger intensity of rainfall recurrence period, even with the implementation of LID measures. These findings highlight the effectiveness of LID measures in managing runoff and reducing flood pressure but also underscore the challenges posed by heavy rainfall at longer return periods. Further research could explore strategies for enhancing the performance of LID measures under these conditions.

We compared the changes in the outfall flow rate for different rainfall return periods before and after the implementation of LID facilities, with specific parameters shown in Table 7. We observed that without the implementation of LID measures, the outfall flow and flood flow increased as the rainfall return period increased. However, upon implementing LID measures on the campus, the discharge and peak flood flow rates of all four outfalls were reduced, though they still increased with the increasing rainfall return period. This could be because, although the LID measures were effective in controlling the flow rate at the outfalls, the flow rate at the outfalls still increased due to an increase in rainfall under longer return periods. This could explain why previous studies have shown nodal stormwater overloading. Following the implementation of LID measures, the peak flood flow was reduced by 47.7%, 41.8%, 37.9%, 34.7%, 31.2%, and 29.0% under different rainfall recurrence periods (P = 2a, 5a, 10a, 20a, 50a, and 100a). Upon comparison, we found that the flood flow was reduced by 47.7% when the rainfall return period was 2a, while the flood flow was reduced by only 29.0% when the rainfall return period was 100a. The reason for this could be the increase in the return period ground and higher rainfall intensity. Even

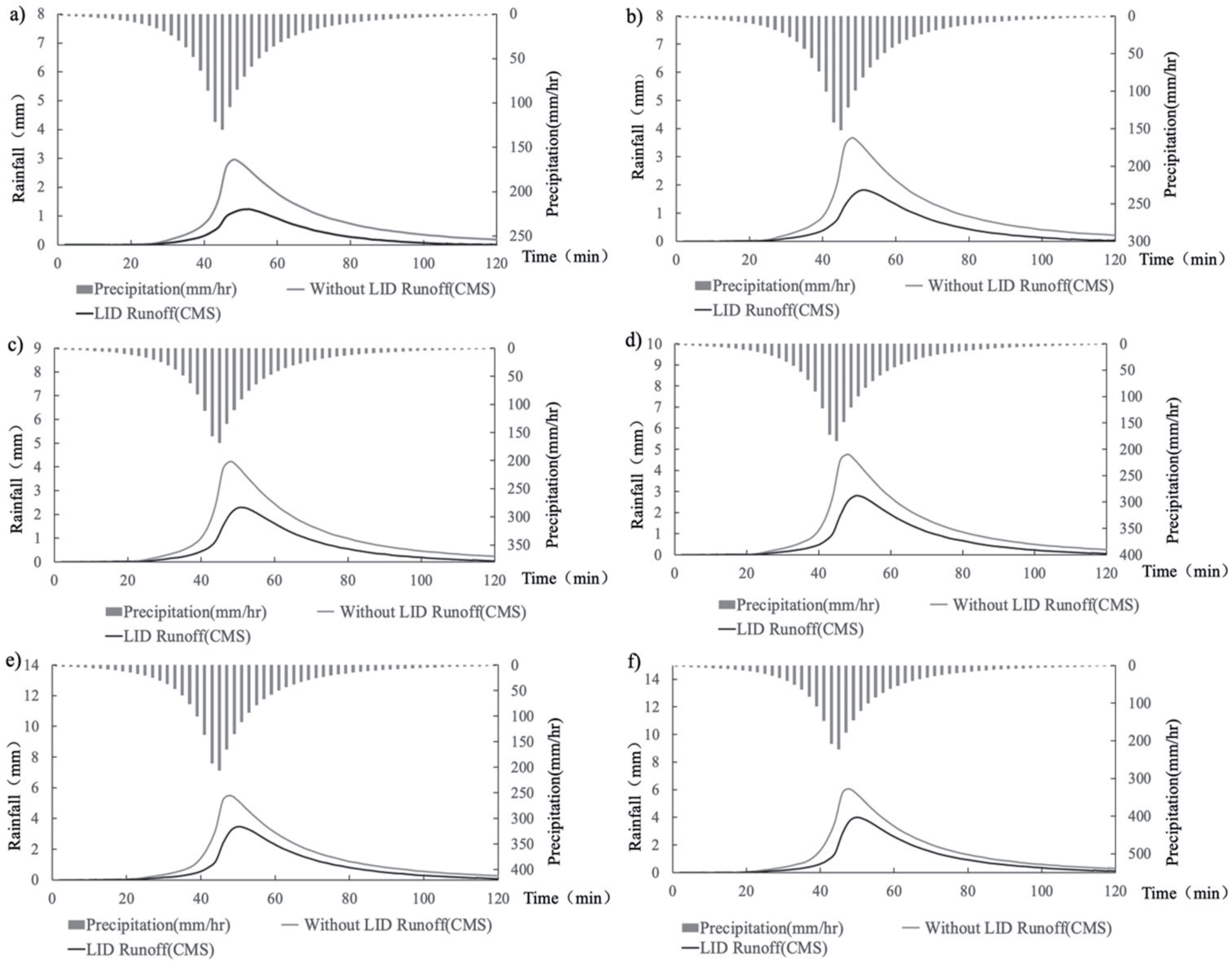

Fig. 5. Runoff control effect under different return periods.

with the implementation of LID measures, it becomes difficult to fully control the flood flow, and the capacity to reduce the flood peak weakens. The results indicate that by implementing a combination of LID measures on campus, we successfully reduced the outfall discharge and peak flood flow, and delayed the peak time by up to 6 minutes. This result underscores the effectiveness of LID measures in practical applications.

Variations in pollutant concentrations at the outfall before and after the implementation of LID measures are shown in Table 8. Fig. 7 illustrates the relationship between the SS reduction effect and rainfall before and after the implementation of LID measures. We observed that without the implementation of LID measures, the mass of solid pollutants was 148.377 KG when the rainfall return period was 2a. However, when the rainfall return period was increased to 20a, the mass of solid pollutants did not show any significant change, but it was close to saturation and stabilized at around 151.7KG. This would also suggest that with the increase in rainfall, the amount of surface runoff pollutants increased accordingly and gradually decreased after reaching the peak value. The reason for this occurrence could be that the increase in rainfall also increases its surface runoff capacity, which can wash away more solid pollutants. At larger rainfall return periods, by the time runoff reaches a certain amount, the pollutants at the surface have essentially been washed away, so the amount of solid pollutants no longer increases significantly with the increase in the rainfall return period. Following the implementation of LID measures, the total amount of solid pollutant reduction increased, from 52.674 KG at a rainfall return period of 2a to 63.574 KG at a rainfall return period of 100a. Simultaneously, the solid pollutant reduction rate also increased, reaching 64.50%, 64.10%, 63.20%, 62.00%, 59.50%, and 58.10%. Therefore, the LID measures are effective in controlling surface runoff, thereby effectively reducing solid pollutant discharges. Additionally, it's important to note that although the LID measure is effective in controlling SS discharge, it may not be able to completely eliminate SS discharge. Therefore, other management measures, such as regular cleaning and maintenance, should also be considered to ensure the long-term effectiveness of the LID facilities.

In general, the implementation of LID measures effectively controls surface runoff, runoff pollutants,

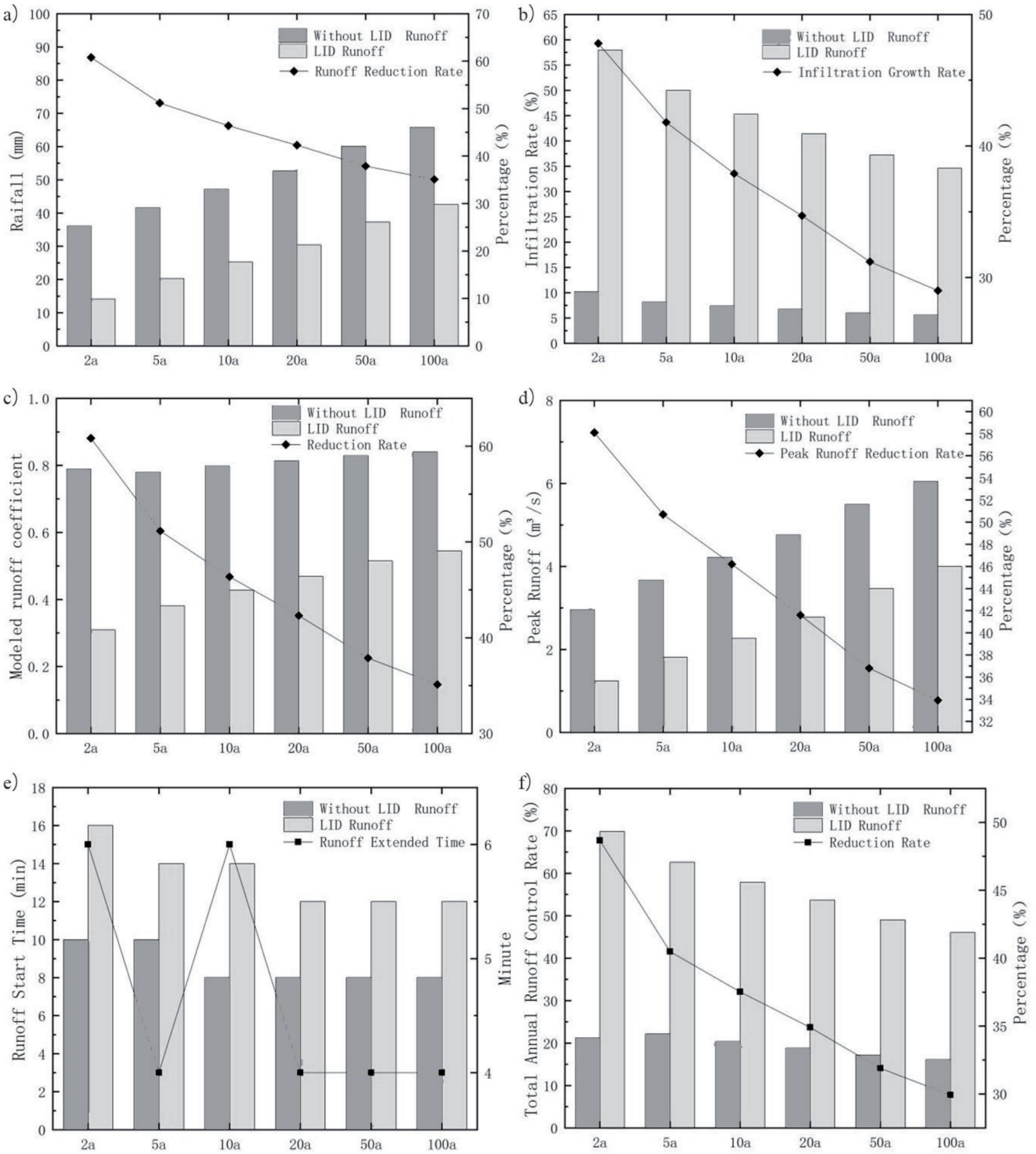

Fig. 6. a) Runoff reduction rate; b) Subsurface infiltration rate; c) Simulated runoff coefficient; d) Peak runoff rate; e) Time of commencement of runoff from outfalls; f) Total annual runoff control rate.

peak flood flows, and peak recurrence times on campus. We also found that the effectiveness of LID measures decreases as the rainfall return period increases. This could be because the rainfall is greater under longer return periods, thus making it difficult to fully control runoff, pollutant discharges, and peak flood flows even with the implementation of LID measures, which is consistent with our findings. Therefore, the effect of the rainfall return period needs to be fully taken into account when designing and implementing LID measures.

Rainwater Utilization System

The rainwater drainage in the study area employs a combination of ecological drainage and traditional pipeline drainage. Through the use of grass-planting ditches, sunken green spaces, bioretention facilities, and other ecological measures, the rainwater in the area is collected, purified, and utilized. This not only reduces surface source pollution but also decreases the runoff coefficient of the area, reduces the amount of rainwater discharged from the area, alleviates the pressure on the drainage system, and improves the urban water

Table 7. Surface runoff parameters before and after LID facility placement for different return periods.

Recurrence period of rainfall	LID arrangement	O1 emissions (m^3)	O2 emissions (m^3)	O3 emissions (m^3)	O4 emissions (m^3)	O1 Flood flow (m^3/s)	O2 flood flow (m^3/s)	O3 Flood flow (m^3/s)	O4 Flood flow (m^3/s)	Peak Moment/ Minute	Flood flow/m^3/s
2a	Before setting	845	1358	921	1012	0.253	0.558	0.426	0.568	0:52:00	2.96
	After setting	644	1049	255	562	0.144	0.343	0.142	0.314	0:58:00	1.24
5a	Before setting	878	1509	1072	1155	0.283	0.659	0.524	0.637	0:52:00	3.67
	After setting	699	1179	429	767	0.18	0.435	0.237	0.408	0:56:00	1.81
10a	Before setting	909	1624	1174	1258	0.295	0.734	0.578	0.69	0:50:00	4.22
	After setting	742	1281	574	907	0.206	0.51	0.316	0.527	0:56:00	2.27
20a	Before setting	939	1739	1269	1356	0.305	0.809	0.628	0.744	0:50:00	4.76
	After setting	786	1385	726	1020	0.243	0.578	0.405	0.596	0:54:00	2.78
50a	Before setting	977	1893	1390	1479	0.32	0.908	0.693	0.793	0:50:00	5.49
	After setting	843	1525	913	1155	0.28	0.69	0.515	0.67	0:54:00	3.47
100a	Before setting	1004	2010	1475	1567	0.33	0.981	0.733	0.819	0:54:00	6.05
	After setting	879	1663	1026	1251	0.294	0.767	0.569	0.728	6.05	4

Table 8. Total emissions of pollutants at the outfalls before and after the placement of the LID facility for different return periods.

Rainfall return period	LID arrangement	SS (kg)	SS reduction rate
2a	Before setting up	148.377	64.50%
	After setting	52.674	
5a	Before setting up	151.909	64.10%
	After setting	54.535	
10a	Before setting up	151.787	63.20%
	After setting	55.858	
20a	Before setting up	151.702	62.00%
	After setting	57.647	
50a	Before setting up	151.773	59.50%
	After setting	61.468	
100a	Before setting up	151.729	58.10%
	After setting	63.574	

ecological environment. From the perspective of the rainwater utilization system (Fig. 8), this study involves collecting roof rainwater and pavement rainwater and discharging them into the rainwater collection pipe network. Any excess rainwater is directly overflowed into the municipal rainwater pipe network. Other rainwater is decontaminated and precipitated using the interception basket, which effectively removes large particles of pollutants and other impurities. The initial rainwater is directed into the module cistern, where it is further filtered and purified through ultraviolet disinfection before being transferred into the module clear water tank. It should be noted that the initial excess rainwater and filtered purified sewage are discharged into the municipal rainwater (sewage) pipe network. The purified water from the modular pond is utilized for greening and road sprinkling. Therefore, the rainwater utilization system scheme is practical and reasonable, and it effectively improves the utilization rate of water resources.

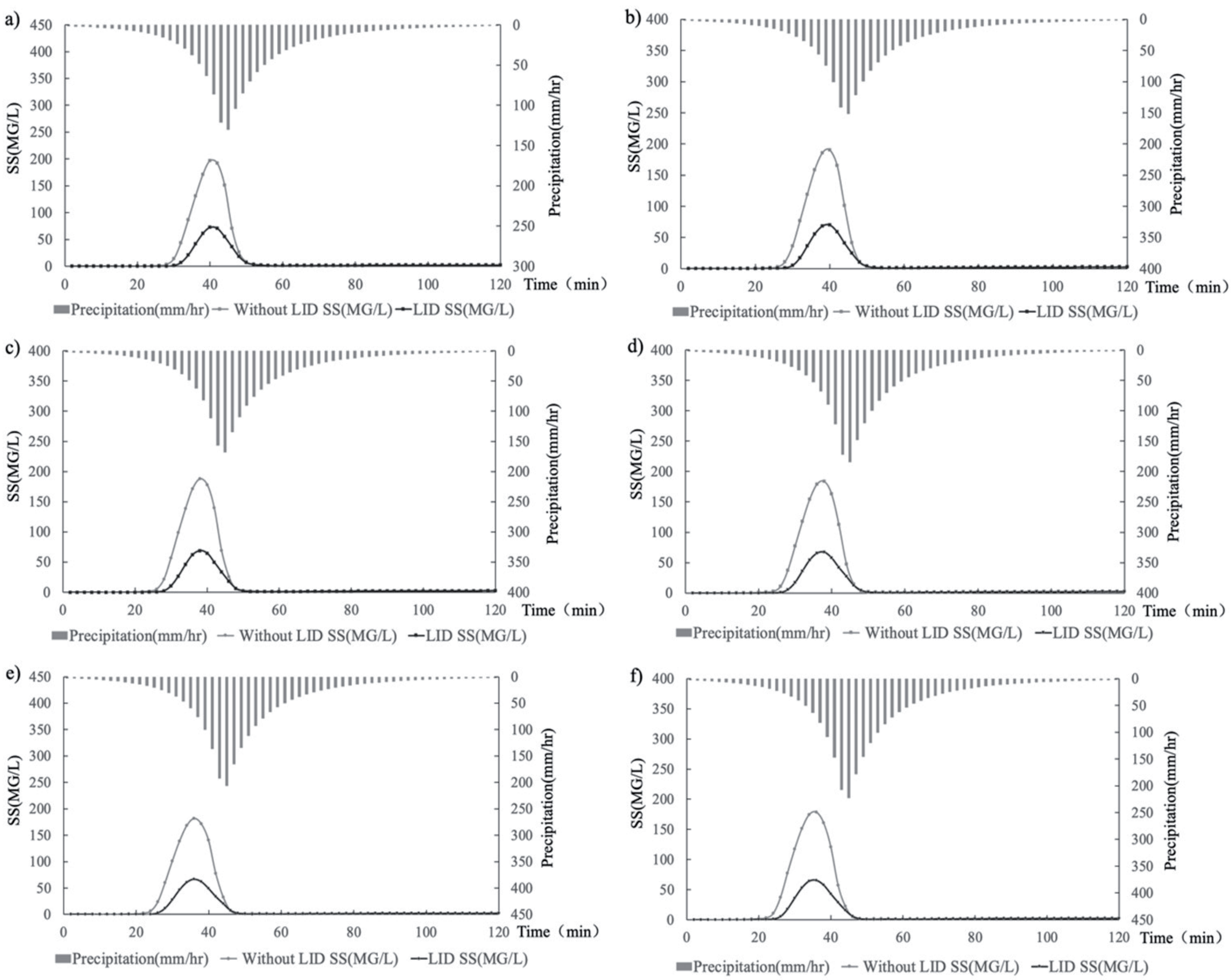

Fig. 7. Assessment of the effectiveness of pollutant reduction at emission outlets under different return periods: a) P = 2a; b) P = 5a; c) P = 10a; d) P = 20a; e) P = 50a; f) P = 100a.

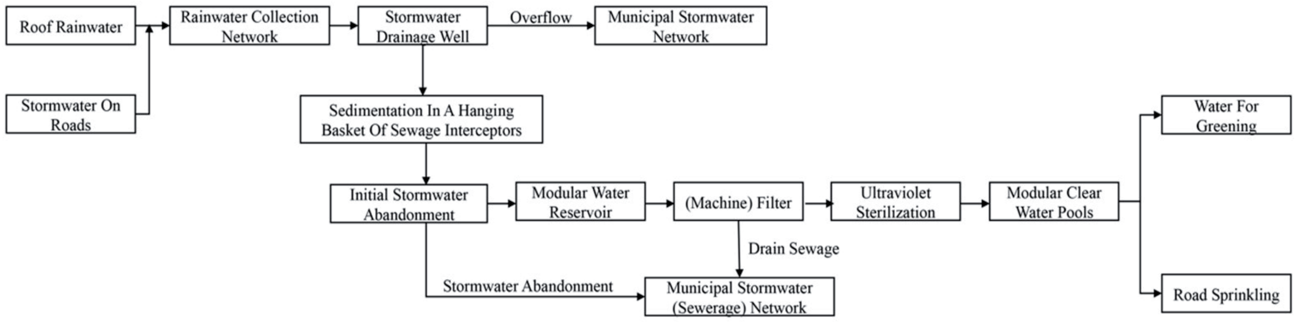

Fig. 8. Rainwater utilization systems.

Conclusions

Facing the challenges of extreme weather and frequent stormwater flooding, the development of efficient and sustainable stormwater management systems has become an urgent task for engineers and urban planners [26]. In this study, we use a methodology to evaluate the effectiveness of LID measures by constructing five objectives: total annual runoff control rate, runoff pollutant reduction rate, flood flow control, peak present time extension, and stormwater utilization system. The effectiveness of this methodology is then verified through a real-world case. In this case, the total annual runoff control rate reached 81.5%, the reduction rate of surface runoff pollutants (SS) exceeded 65%, the peak flow was reduced by more than 30%, and the peak flow moment at the outfall was extended by 4-6 minutes. Utilizing this research methodology can effectively assist companies and organizations in evaluating the effectiveness of LID measures on the Sponge campus, thereby confirming the reasonableness of Sponge programs. Our findings suggest that campuses can effectively mitigate urban flooding issues and improve the efficiency of stormwater resource utilization by rationally configuring LID measures and constructing a sustainable stormwater management system with a multi-objective orientation.

However, our study also has some limitations. Due to the unavailability of several years of actual hydrologic data, our model might not fully simulate real-world complexity. Future research should further explore the effects of these factors. Overall, existing studies that use numerous optimization formulations or cross-modeling approaches from other disciplines may be innovative. However, it is obviously more important to have research methods that can quickly validate and evaluate the results from the perspective of companies and organizations. Therefore, the contribution of this study lies in providing valuable insights for understanding and evaluating the effectiveness of LID measures. As such, this research is definitely beneficial in this field. It also provides a reference for companies and organizations, which is crucial for future sponge city construction.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. JU W.Y., WU J., CAO H.Z., KANG Q.C., SYED SALMAN ALI S., XING Z.X. Flood Risk Assessment of Subway Stations Based on Projection Pursuit Model Optimized by Whale Algorithm: A Case Study of Changzhou, China. International Journal of Disaster Risk Reduction, **98**, 104068, **2023**.
2. LUO P., YAN P., WANG X., WU Y., LYU J., HE B., DUAN W., WANG S., ZHA X. Historical and Comparative Overview of Sponge Campus Construction and Future Challenges. Science of the Total Environment, **907**, 167477, **2023**.
3. DIERKES C., LUCKE T., HELMREICH B. General Technical Approvals for Decentralised Sustainable Urban Drainage Systems (SUDS) – the Current Situation in Germany. Sustainability, **7** (3), 3031, **2015**.
4. FERRANS P., TORRES M.N., TEMPRANO J., RODRÍGUEZ SÁNCHEZ J.P. Sustainable Urban Drainage System (SUDS) Modeling Supporting Decision-Making: A Systematic Quantitative Review. Science of the Total Environment, **806**, 150447, **2022**.
5. COUTTS A.M., TAPPER N.J., BERINGER J., LOUGHNAN M., DEMUZERE M. Watering Our Cities: The Capacity for Water Sensitive Urban Design to Support Urban Cooling and Improve Human Thermal Comfort in the Australian Context. Progress in Physical Geography: Earth and Environment, **37** (1), 2, **2013**.
6. KULLER M., BACH P.M., RAMIREZ-LOVERING D., DELETIC A. Framing Water Sensitive Urban Design as Part of the Urban Form: A Critical Review of Tools for Best Planning Practice. Environmental Modelling and Software, **96**, 265, **2017**.

7. JIANG Y., QIU L., GAO T., ZHANG S.X. Systematic Application of Sponge City Facilities at Community Scale Based on SWMM. Water, **14** (4), 591, **2022**.
8. TSIHRINTZIS V.A., HAMID R. Runoff Quality Prediction from Small Urban Catchments Using SWMM. Hydrological Processes, **12** (2), 311, **1998**.
9. BABAEI S., GHAZAVI R., ERFANIAN M. Urban Flood Simulation and Prioritization of Critical Urban Sub-Catchments Using SWMM Model and PROMETHEE II Approach. Physics and Chemistry of the Earth, Parts A/B/C, **105**, 3, **2018**.
10. YANG Y., LI J., HUANG Q., XIA J., LI J., LIU D., TAN Q. Performance Assessment of Sponge City Infrastructure on Stormwater Outflows Using Isochrone and SWMM Models. Journal of Hydrology, **597**, 126151, **2021**.
11. BAEK S.-S., LIGARAY M., PYO J., PARK J.-P., KANG J.-H., PACHEPSKY Y., CHUN J.A., CHO K.H. A Novel Water Quality Module of the SWMM Model for Assessing Low Impact Development (LID) in Urban Watersheds. Journal of Hydrology, **586**, 124886, **2020**.
12. LIU K.H., LI J.K., XIA J., GAO X.J., GAO J.Y., JIANG C.B. Study on LID Facilities Comprehensive Effect Evaluation: A Case in Campus. Ecohydrology & Hydrobiology, **22** (3), 530, **2022**.
13. ZHU Y.F., XU C.Q., YIN D.K., XU J.X., WU Y.Q., JIA H.F. Environmental and Economic Cost-Benefit Comparison of Sponge City Construction in Different Urban Functional Regions. Journal of Environmental Management, **304**, 114230, **2022**.
14. XU C.Q., HONG J.L., JIA H.F., LIANG S.D., XU T. Life Cycle Environmental and Economic Assessment of a LID-BMP Treatment Train System: A Case Study in China. Journal of Cleaner Production, **149**, 227, **2017**.
15. GAO J.Y., LI J.K., JI J.W., LIU K.H., JIANG C.B. Multi-Objective Optimization of Sponge Facility Layout in Built-up Urban Areas. Ecohydrology & Hydrobiology, **24** (1), **2024**.
16. WAN S.Y., XU L.Y., QI Q., YANG H., ZHOU Y.Z. Building a Multi-Objective Optimization Model for Sponge City Projects. Urban Climate, **43**, 101171, **2022**.
17. SU J.H., LI J.K., GAO X.J., YAO Y.T., JIANG C.B. Comprehensive Analysis of Waterlogging Control and Carbon Emission Reduction for Optimal LID Layout: A Case Study in Campus. Environmental Science and Pollution Research, **29** (58), 87802, **2022**.
18. ISHAQ S., RANA A., HEWAGE K., LI J., SADIQ R. Environmental Impacts and Cost Analysis of Low Impact Developments in Arid Climate: A Case Study of Okanagan Valley (Canada). Journal of Cleaner Production, **419**, 138226, **2023**.
19. ZHAO L.D., ZHANG T., LI J.Z., ZHANG L.B., FENG P. Numerical Simulation Study of Urban Hydrological Effects under Low Impact Development with a Physical Experimental Basis. Journal of Hydrology, **618**, 129191, **2023**.
20. JOKAR D., KHAKZAND M., FAIZI M. The Application of Low Impact Development Approaches toward Achieving Circularity in the Water Sector: A Case Study from Soltan Abad, Shiraz, Iran. Journal of Cleaner Production, **320**, 128712, **2021**.
21. JIDAI J.Q., YU H., ZHANG L., LIU Y.H., HAN J.Q. The Global Importance of Increasing Design Rainstorms under Specific Return Periods in China. Water, **15** (11), 2049, **2023**.
22. KEIFER C.J., CHU H.H. Synthetic Storm Pattern for Drainage Design. Journal of the Hydraulics Division, **83** (4), 1, **1957**.
23. CHEN J., LI Y.W., ZHANG C.H. The Effect of Design Rainfall Patterns on Urban Flooding Based on the Chicago Method. International Journal of Environmental Research and Public Health, **20** (5), 4245, **2023**.
24. YUAN T.T., LI G.F., WANG Y.H. Research on the Design Rainstorm Formula and Rain Pattern in Changzhou Urban Area. Hydropower Energy Science, **37** (6), 16, **2019**.
25. HUARD D., MAILHOT A., DUCHESNE S. Bayesian Estimation of Intensity-Duration-Frequency Curves and of the Return Period Associated to a given Rainfall Event. Stochastic Environmental Research and Risk Assessment, **24** (3), 337, **2010**.
26. BISHT D.S., CHATTERJEE C., KALAKOTI S., UPADHYAY P., SAHOO M., PANDA A. Modeling Urban Floods and Drainage Using SWMM and MIKE URBAN: A Case Study. Natural Hazards, **84** (2), 749, **2016**.