Research on the Technical Model of Sponge City Construction: Taihu Road Park Demonstration Zone

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Abstract. Sponge City refers to a type of urban development that fully utilizes the absorption, storage, infiltration, and attenuation functions of ecosystems such as buildings, roads, green spaces, and water bodies to effectively control runoff, achieve natural storage, infiltration, and purification of rainwater through strengthened urban planning, construction, and management. This paper studies the technical model of Taihu Road Park Demonstration Zone in Hexi District, Tianjin City. Based on Low Impact Development (LID) and Best Management Practices (BMPs), two technical models for the demonstration zone are designed: Model One focuses on increasing retention and uses infiltration as a supplement, mainly utilizing LID facilities such as depressed green spaces and permeable pavements; Model Two focuses on increasing infiltration with retention as a supplement, mainly utilizing LID facilities such as bio-retention facilities and permeable pavements. Then, using Storm Water Management Model (SWMM) software, the runoff volume and pollutant concentrations in the central lake of the final drainage area under different rainfall recurrence intervals (2-year, 3-year, and 5-year) for the two technical models are simulated and compared with the scenario without LID facilities. The results show that under 3-year rainfall conditions (similar to 2-year and 5-year results), the runoff control rate before LID facilities were installed is around 51%. When using Model One (depressed green spaces) where retention is the main strategy and infiltration is supplementary, the runoff control rate increases to 75%, while for Model Two (bio-retention facilities) where infiltration is the main strategy and retention is supplementary, the runoff control rate is 69%. Regarding Total Suspended Solids (TSS), the control rate before LID facilities were installed is 51%, whereas with Model One, the control rate increases to 87%, and with Model Two, it is 55%. Therefore, considering the high groundwater level in the northern region and the current situation of Taihu Road Park, Model One: retention as the main strategy and infiltration as supplementary, is more suitable for the study area of Taihu Road Park.

Keywords: Sponge City; Low Impact Development; Stormwater Management Model

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1 INTRODUCTION

Sponge cities, mimicking the characteristics of sponges, store and manage rainwater, effectively preventing flood disasters, improving aquatic ecosystems, and promoting the healthy development of cities. (As shown in Figure 1.)

Fig. 1. Sponge City.

In the construction, operation, and management technical system of sponge cities in the central urban area of Tianjin, especially in recent years, the characteristics of high land use intensity, high proportion of hardened areas, high groundwater levels, low soil permeability coefficients, and difficulties in renovating old urban areas have been addressed. Based on low-impact development and optimal management measures, this paper analyzes and evaluates the spatial layout characteristics of the pilot demonstration area, such as Taihu Road Park, and predicts the construction of infrastructure. Two technical modes are proposed for the demonstration area: Mode One focuses on increasing infiltration, while Mode Two emphasizes increasing retention. The runoff and pollutant levels are simulated using SWMM software for both modes and compared with the demonstration area without LID facilities. Finally, the best technical mode suitable for the demonstration area is selected.

Regarding the strategic planning for the construction and management of sponge cities in Tianjin urban areas, two technical modes (Mode One: primarily retention with infiltration as a supplement; Mode Two: primarily infiltration with retention as a supplement) are proposed for comparison based on the current situation of the Taihu Road Park demonstration area in Hexi District. Considering the high groundwater level characteristics of northern regions and the current situation of Taihu Road Park, the optimal technical mode (Mode One: primarily retention with infiltration as a supplement) is identified to ensure the rational operation of its facilities, thereby achieving the best sponge effect for the demonstration area. This mode not only operates sustainably but also purifies water bodies, collects rainwater effectively, beautifies landscapes, promotes green water usage, and improves the utilization efficiency of rainwater resources.

Additionally, this mode enables the demonstration area's water quality indicators to meet the requirements of Grade IV surface water standards for sponge city assessments, fully realizing the effectiveness of sponge features and effectively addressing issues such as local waterlogging and groundwater imbalances, thereby ensuring that each facility can fully fulfill its ecological service functions.

In terms of scientific research, Yu Kongjian metaphorically refers to the flood regulation ability of natural systems as a "sponge", likening the natural wetlands on both sides of rivers to sponges, which can regulate the abundance of river water and alleviate drought and flood disasters[1].

Zhai Xiaojie studied the sponge city construction demonstration zones in Baisha and High-tech districts of Zhengzhou. Using the Analytic Hierarchy Process, she evaluated the suitability of natural geological sponge bodies in these two demonstration zones and proposed corresponding LID facility suggestions[2]. Huang Ruolin simulated the overflow distribution and impact in Haining city under different recurrence intervals and deployment ratios of LID combined measures[3]. Chen Yongfan researched approaches to mitigate waterlogging risks in sub-catchment areas of sponge city design. Using SWMM modeling, he analyzed the peak control characteristics of LID facilities under different recurrence intervals[4]. Chen Long proposed an optimization method for the spatial layout of low-impact development facilities based on rainfall-flood management models and NSGA-II. Using construction cost, runoff control rate, and pollutant removal rate as multi-objective functions, optimization schemes were suggested[5].

Nguyen T T carefully scrutinizes the concept of sponge cities and their adoption to comprehensively assess their limitations and opportunities[6]. Mark Randall, with the assistance of parameterization in the Storm Water Management Model (SWMM), utilizes detailed land cover classification based on satellite imagery to provide decision-making support for future planning in the research area[7]. Craig Lashford critically evaluates existing sustainable urban flood management methods through a comparative analysis of practices in the UK and China, questioning whether lessons can be drawn from sponge city initiatives[8]. Meicheng Ji, focusing on sponge city construction, proposes a control indicator system to address key issues at the control level, employing the Analytic Hierarchy Process to clarify indicators and control categories across different levels, thereby establishing a quantifiable and actionable indicator system to guide the planning and construction of sponge cities[9]. Chen Wang develops a sponge city flood simulation and forecasting system that integrates hydrological data, terrain data, GIS data, and hydraulic models for real-time interactive visualization in a three-dimensional environment, simulating actual and designed flood events in sponge cities[10]. Stephan Köster suggests that supplementary water services generated from sponge cities can make significant contributions to compensating for high capital investment and covering operation and maintenance (O&M) costs[11].

2 RESEARCH METHODS

This paper analyzes the current status of Taihu Road Park and concurrently conducts monitoring of relevant data. The required information for constructing the SWMM model is obtained from references and the SWMM manual. The SWMM model is then built. Through simulation using SWMM for three scenarios, the runoff and Total Suspended Solids (TSS) content under different rainfall return periods can be obtained. By employing a comparative method, the most suitable technical mode for the construction of a sponge city in Tianjin's demonstration area, specifically Taihu Road Park, is selected.

Taihu Road Park in Hexi District, Tianjin, is situated within the North China Plain, where most areas lie below an elevation of 50 meters. Marshes and low-lying areas, particularly located between the Huanghe River's alluvial fan and the northern part of Baoding and Tianjin Dagukou, constitute a significant proportion. Additionally, drainage blockages occur in the eastern part of the alluvial fan, where it connects with the hills of Shandong Province. The loose layers in the plain are divided into five aquifers from top to bottom. (as shown in Table 1)

Table 1. Classification of Tianjin's Aquifers.

Aquifer Group Categories	Aquifer Properties
1	Shallow Groundwater System
2	Shallow Groundwater System
3	Deep Groundwater System
4	Deep Groundwater System
5	Deep Groundwater System

According to monitoring conducted by the Tianjin Hydrological and Water Resources Survey and Management Center, the shallow groundwater quality in Tianjin is poor. Class V water, representing the lowest quality, covers more than 70% of the total area in the plain regions. During heavy rainfall, low-lying areas are prone to flooding due to inadequate drainage measures. Additionally, improper drainage can lead to widespread water accumulation, exacerbating soil salinization. Please refer to Figure 2 for the groundwater level situation in Tianjin.

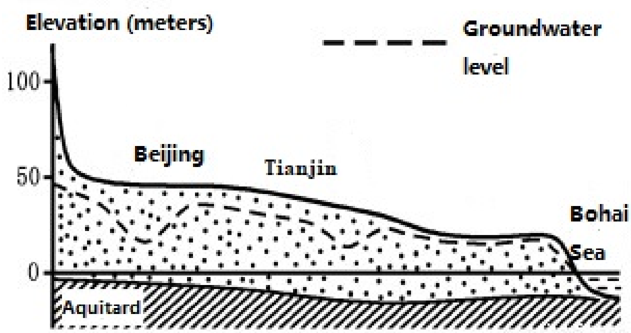

Fig. 2. Tianjin Groundwater Levels.

2.1 Technical Mode 1 (Primary Focus on Retention, with Infiltration as Secondary)

Schematic Diagram of Mode 1.

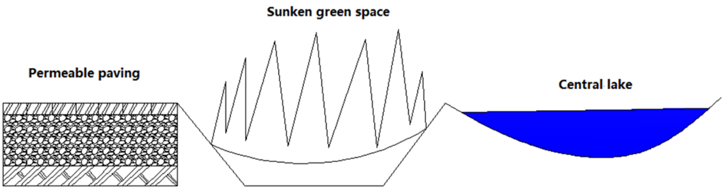

Fig. 3. Maintenance Model 1 Schematic Diagram.

Operation and Maintenance Mechanism for Mode 1.
When rainfall occurs in the demonstration area (as shown in Figure 3 and 4, Mode 1 Global Layout), the first point of contact is the permeable pavement facilities. Once rainwater reaches the LID facilities in the Taihu Lake Park, it enhances the infiltration process. The rainwater then flows through the depressed green spaces (which are LID facilities with lower centers and higher edges), preventing excess water from flowing out of the facility and causing surrounding areas to flood. Finally, when rainfall is excessive and all storage facilities in the park are full, the surplus water can enter the central lake via overflow channels. The central lake serves the purpose of attenuating and stabilizing urban rainfall, allowing for the proper disposal of precipitation in the park.

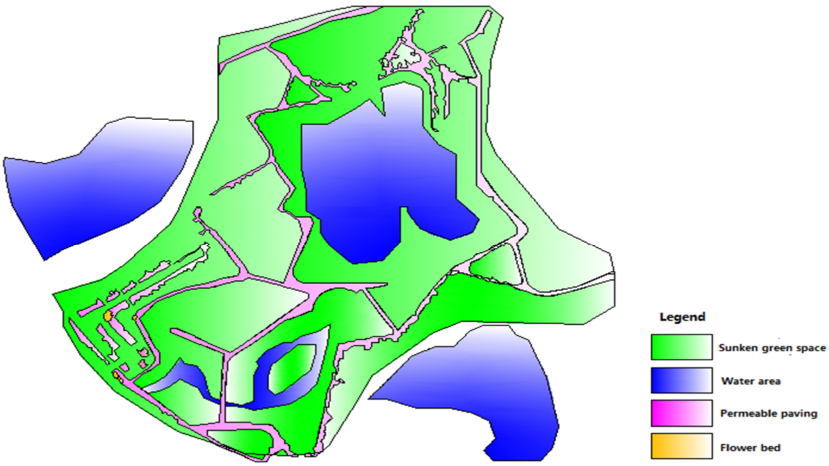

Fig. 4. Pattern One Overall Layout Diagram.

2.2 Technical Mode 2 (Primary Focus on Infiltration, with Retention as Secondary)

Mode 2 Schematic Diagram.

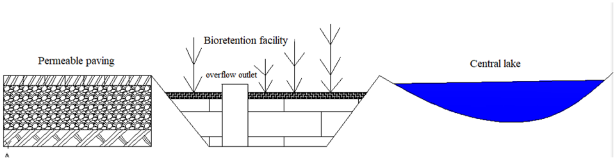

Fig. 5. Maintenance Model 2 Schematic Diagram.

Operation and Maintenance Mechanism for Mode 2.
Firstly, when rainfall occurs in the demonstration area (as shown in Figure 5 and 6, Mode 2 Global Layout), the precipitation infiltrates into the permeable pavement facilities on the pedestrian paths within the park. In areas with lower elevation, these facilities, under the comprehensive action, can remove large particulate pollutants and also slow down the flow velocity to some extent. The retained rainfall can be stored for purposes such as irrigation and flood prevention. When the rainfall reaches a certain threshold and all storage facilities are full, the excess water is discharged into the central lake within the park. Through the integrated action of microorganisms in the lake, the water quality is improved to a certain extent. This helps in climate regulation, enabling the water body to meet the requirements of Grade IV surface water, as per the Sponge City assessment criteria.

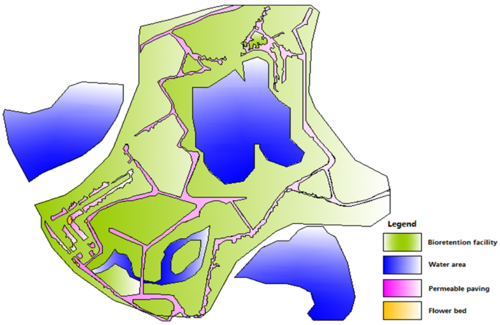

Fig. 6. Pattern Two Overall Layout Diagram.

3 COMPARATIVE ANALYSIS OF SCENARIO SIMULATION AND EFFECTS

3.1 Introduction to Storm Water Management Model (SWMM)

The Storm Water Management Model (SWMM) is a dynamic precipitation-runoff simulation model. It captures spatial variations in processes such as precipitation runoff, time-varying rainfall, and surface runoff nonlinearity by dividing the study area into smaller, uniform sub-catchment areas, building upon various types of Low Impact Development (LID) techniques. SWMM is primarily used to simulate either a single precipitation event or long-term water quantity and quality in urban areas, but it also finds wide application in non-urban regions[12].

3.2 Data Design Basis

Division of Watershed Areas in the Study Region.
The study area, covering approximately 7.6 hectares, has been divided into eight sub-watershed areas, taking into account the flow of water within the study area during rainfall events. Additionally, a drainage outlet has been set up at the location of the artificial lake (refer to Figure 7 for the division of sub-watershed areas in the study area). Furthermore, considering the topography of the study area, which is lower in the middle and higher on both sides, corresponding flow direction lines have been established for water discharge. Due to the comprehensive consideration of the drainage system depicted in the Sponge City planning map of Hexi District, Tianjin, as well as the actual conditions of Taihu Road Park, pipeline design has not been incorporated into the delineation of sub-watershed areas.

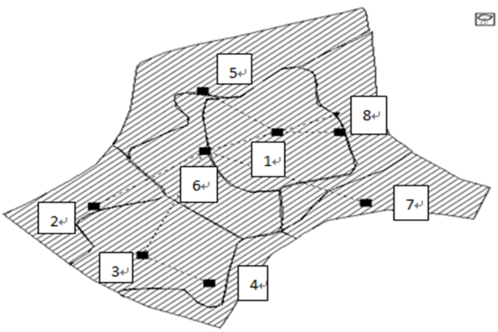

Fig. 7. Division of Sub-watershed Areas in the Study Region.

Storm Design.
When analyzing surface runoff and suspended pollutant content in Taihu Road Park in the study area using SWMM, the storm intensity in Tianjin is classified into four zones according to the 'Technical Guidelines for Design and Construction of Sponge Cities in Tianjin.' Taihu Road Park in our study area falls under Zone I. Following the guidelines, the stormwater volume for different return periods (i.e., two-year, three-year, and five-year) is calculated based on the total stormwater volume and the rainfall distribution table over 180 minutes provided in the design rainfall type.(As shown in Table 2.) These calculations yield rainfall values recorded every five minutes over a duration of two hours, as depicted in Figure 8.

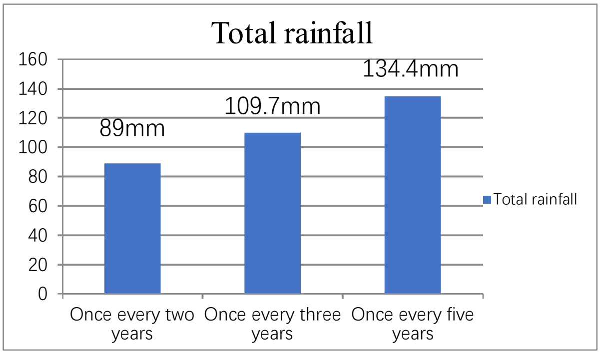

Fig. 8. Summary of Total Rainfall for Different Return Periods.

Table 2. Rainfall Distribution Table for 180-Minute Design Storm.

t (5min)	1	2	3	4	5	6
Proportion	1.38	2.01	2.82	3.40	2.80	4.34
t (5min)	7	8	9	10	11	12
Proportion	4.42	4.27	4.12	3.69	3.75	3.25
t (5min)	13	14	15	16	17	18
Proportion	3.74	2.87	2.50	4.43	4.49	3.00
t (5min)	19	20	21	22	23	24
Proportion	2.44	1.91	2.10	2.48	2.54	2.42
t (5min)	25	26	27	28	29	30
Proportion	3.11	2.56	2.95	2.07	2.65	2.34
t (5min)	31	32	33	34	35	36
Proportion	2.27	1.56	1.82	1.57	1.10	0.86

Multiplying the total rainfall for each return period by the percentages in the 180-minute design storm rainfall distribution table, we obtain the rainfall for each 5-minute interval for different return periods, as illustrated in Figures 9, 10, and 11.

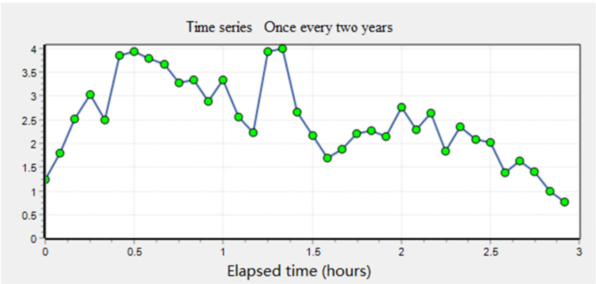

Fig. 9. Rainfall Data for a Two-Year Return Period.

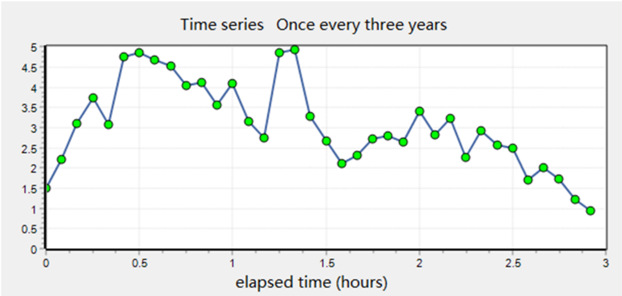

Fig. 10. Rainfall Data for a Three-Year Return Period.

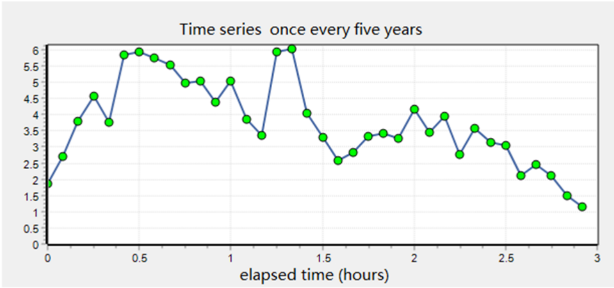

Fig. 11. Rainfall Data for a Five-Year Return Period.

Based on the collected rainfall data, it can be observed that the maximum rainfall occurs between 1 to 1.5 hours during a two-year return period, with approximately 4.00mm. Similarly, for a three-year return period, the maximum rainfall also occurs between 1 to 1.5 hours, measuring around 4.93mm. In the case of a five-year return period, the maximum rainfall again falls between 1 to 1.5 hours, approximately 6.03mm.

The rainfall amounts for two-year, three-year, and five-year return periods are 89mm, 109.7mm, and 134.4mm respectively. It is evident that with a larger return period, there is a higher amount of rainfall. In the initial planning of Taihu Road Park, no Low Impact Development (LID) facilities were incorporated. Without considering the installation of LID facilities, heavy rainfall would lead to ponding on park roads, posing serious risks to visitors and residents. Additionally, the water level in the central lake would rise, potentially overflowing and causing damage to surrounding flora, such as flowers, grass, and trees, due to excessive moisture. This would not only affect the aesthetics of the park but also its ecological benefits. Therefore, this study proposes three scenarios and simulates the runoff and pollutant content in each scenario to compare and select the most suitable technical model for Taihu Road Park.

Setting parameters for SWMM.

This study simulates three scenarios in the research area: 1. Blank scenario: LID facilities not set; 2. Scenario One: LID facilities set (depressed green space, permeable pavement); 3. Scenario Two: LID facilities set (bioretention facilities, permeable pavement).

Parameters related to LID in SWMM are set based on relevant indicators in the "Technical Specifications for Sponge City Construction in Tianjin" and relevant literature.

According to the relevant provisions of permeable pavement facilities, the surface vegetation volume is 0.4; surface roughness is 0.012; surface slope is 1.0; pavement thickness is 120mm; void ratio is 0.18; non-permeable surface area is 0.35; permeability is 100mm/hr; storage depth is set to 360mm; void ratio is 0.65; infiltration rate is 250mm/h; flow index under the channel is set to 0.5.

According to the relevant provisions of sponge city construction, parameters of depressed green space are designed accordingly. For surface embankment height is 30.4mm; vegetation volume is 0.4; surface roughness is 0.24; soil thickness is 600mm; porosity is 0.5; runoff coefficient is 0.2; wilting point is 0.1; hydraulic conductivity is 0.5mm/h; hydraulic conductivity slope is 10.0; absorption head is 3.5mm; storage depth is 300mm; void ratio is 0.6; infiltration rate is 0.5mm/h; flow index under the channel is 0.5; offset height is 6mm.

According to the relevant settings of bioretention facilities, the surface embankment height is 100mm; vegetation volume is 0.75; surface roughness is 0.24; surface slope is 1.0; soil thickness is 600mm; porosity is 0.5; runoff coefficient is 0.2; wilting point is 0.1; hydraulic conductivity is 0.5mm/h; hydraulic conductivity slope is 10.0; absorption head is 3.5mm.

The SWMM parameters in the paper are based on the standard user manual and simulated reference values in the paper. The Horton model is used for infiltration, with a maximum infiltration rate of 20mm/hr, minimum infiltration rate of 10mm/hr, decay constant of 4, and drainage time of 7. Major parameters required for runoff calculations include slope of 0.5%, non-permeable percentage of 20%, non-permeable N value of 0.012, permeable N value of 0.05, non-permeable depression storage of 3.5, and permeable depression storage of 6.5[13].

3.3 Data Processing

Simulation of the Blank Scenario (without LID Facilities).
By setting relevant parameters and performing calculations for each watershed, simulations were conducted for runoff and pollutant concentrations at different recurrence intervals for the eight watersheds. The simulations were successful. Due to the topography where the sides are higher and the middle is lower, all water eventually flows into watershed 1 (central lake). However, since SWMM software does not have a lake module, watershed 1 is treated as a regular land block in the software, resulting in a runoff coefficient. Typically, lakes have a certain storage capacity, so they do not discharge much water. This study only focuses on the total runoff volume, so only data for watershed 1 (central lake) is considered. The statistical data is presented in Table 3.

Table 3. Data Statistics for Watershed 1 (Central Lake) at Recurrence Intervals of p=2, p=3, and p=5.

Recurrence Interval (p)	Total Precipitation Amount(mm)	Total Runoff Inflow (L/s)	TSS(kg)
2	89.0	215.5	565.1

3	109.7	297.6	813.8
5	134.4	398.1	1122.1

Simulation of Scenario One (Setting LID Facilities: Depressed Green Space, Permeable Pavement) as shown in Table 4.

Table 4. Data Statistics for Watershed 1 (Central Lake) at Recurrence Intervals of p=2, p=3, and p=5.

Recurrence Interval (p)	Total Precipitation Amount(mm)	Total Runoff Inflow(L/s)	TSS(kg)
2	89.0	85.7	118.0
3	109.7	146.1	180.5
5	134.4	223.3	252.5

Simulation of Scenario Two (Setting LID Facilities: Bioretention Facilities, Permeable Pavement) as shown in Table 5.

Table 5. Data Statistics for Watershed 1 (Central Lake) at Recurrence Intervals of p=2, p=3, and p=5.

Recurrence Interval (p)	Total Precipitation Amount(mm)	Total Runoff Inflow(L/s)	TSS(kg)
2	89.0	113.1	156.2
3	109.7	182.1	229.6
5	134.4	267.5	313.3

Based on the three scenarios mentioned above, the SWMM software calculates the total runoff inflow according to the following formula[14]:

$$W = 10\Psi_{ZC} h_y F \tag{1}$$

In the equation:
W: Total runoff volume (m^3)
Ψ_{ZC}: Comprehensive runoff coefficient
h_y: Design rainfall amount (mm)
F: Watershed area (hm^2)

3.4 Model Comparison

Comparison of Runoff Volume.

By using SWMM to simulate the runoff volume for the three scenarios at different recurrence intervals, the instantaneous runoff data for Watershed 1 (Central Lake) is summarized in Figure 12, Figure 13, and Figure 14. Figure 15 displays the total inflow of runoff from other watersheds into Watershed 1 (Central Lake) under the three scenarios.

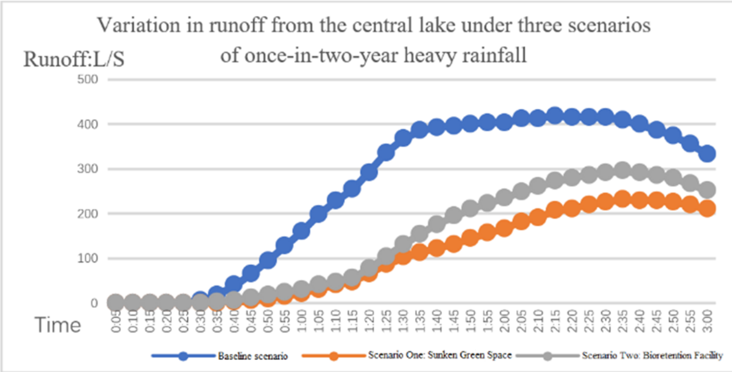

Fig. 12. Once every two years.

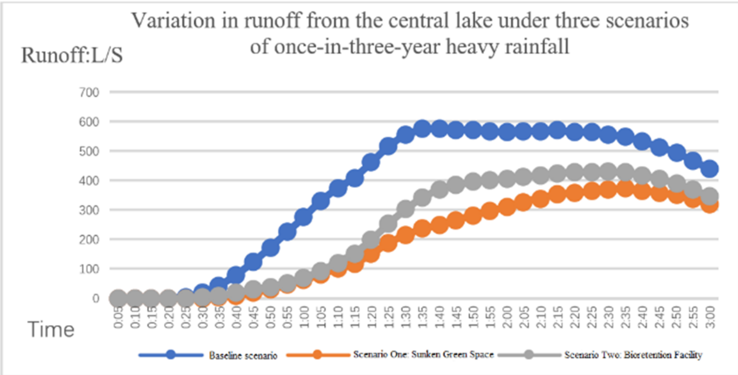

Fig. 13. Once every three years.

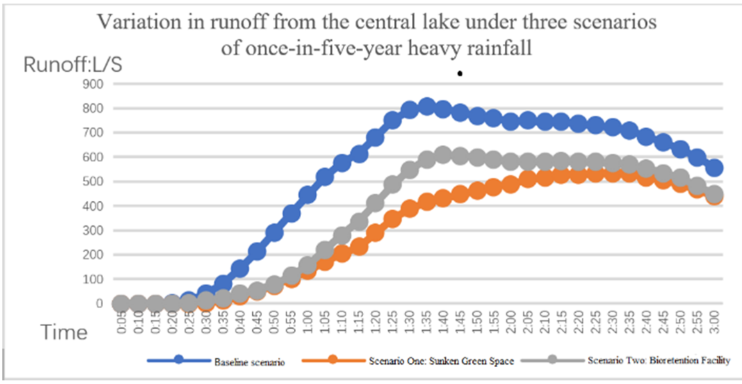

Fig. 14. Once every five years.

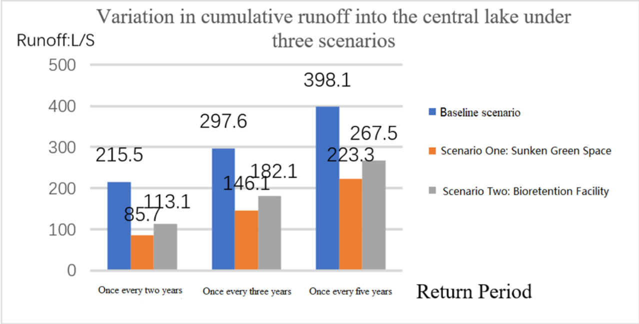

Fig. 15. Statistics of Runoff Inflow Values for the Three Scenarios.

From the four figures above, it is evident that the runoff volume into Watershed 1 (Central Lake) significantly improved after implementing LID facilities, resulting in effective reduction. It can be observed that LID facilities such as bioretention facilities, depressed green spaces, and permeable pavement are designed to effectively intercept, store, and infiltrate rainwater, ultimately reducing the amount of rainwater flowing into the central lake. Comparing the two modes of adding LID facilities, it is clear from Figure 4-12 that Scenario One is much more effective than Scenario Two.

The less runoff volume flowing into the central lake indicates better performance of LID facilities in interception, infiltration, and retention. Comparing the three scenarios under different recurrence intervals, Scenario One (depressed green space) performs better than Scenario Two (bioretention facilities). Therefore, for the Taihu Road Park research area, a retention-dominant mode with infiltration as a supplement is more suitable for retaining and storing rainwater.

Comparison of Pollutant Levels.
Using SWMM to simulate the surface pollutant concentrations for the three scenarios, the instantaneous variations in TSS concentration for Watershed 1 (Central Lake) are shown in Figure 16, Figure 17, and Figure 18. Additionally, the mass variations of TSS from Watershed 1 (Central Lake) under the three scenarios are depicted in Figure 19.

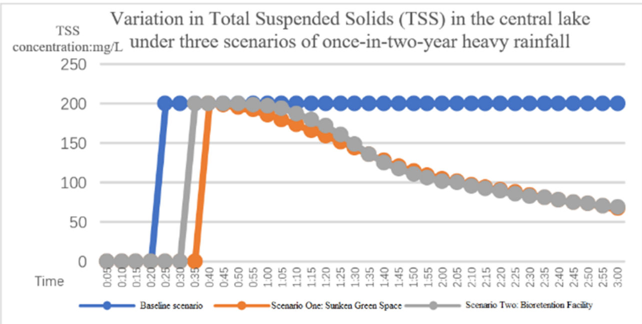

Fig. 16. Once every two years.

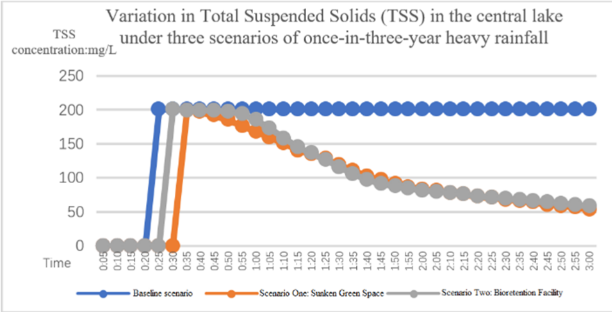

Fig. 17. Once every three years.

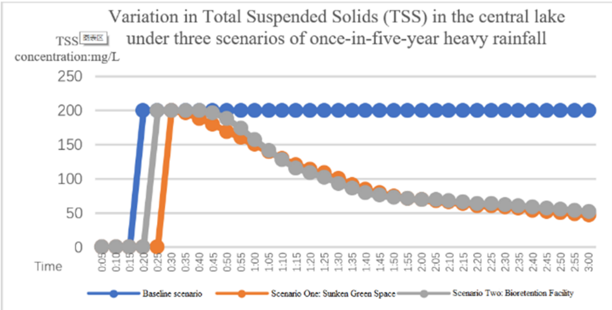

Fig. 18. Once every five years.

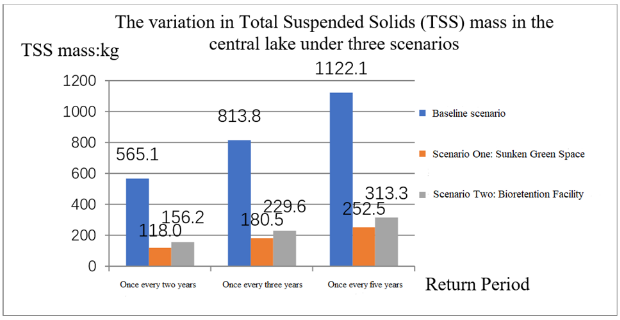

Fig. 19. The variations in Total Suspended Solids (TSS) mass for the three scenarios.

From the four graphs above, it can be inferred that the concentration of Total Suspended Solids (TSS) decreases over time after the implementation of LID facilities. This indicates that LID facilities play a role in the degradation and removal of pollutants from stormwater, leading to a significant reduction in TSS concentration in the central lake. Therefore, the implementation of LID facilities can effectively improve TSS levels in the central lake. However, when comparing the two scenarios with LID facilities, Scenario One, which utilizes Mode One (depressed green space), shows a faster decline in TSS concentration compared to Scenario Two, which employs Mode Two (bioretention facilities). Additionally, as the recurrence interval increases, TSS concentrations also tend to be higher. Mode One (depressed green space) exhibits better removal and retention of TSS compared to Mode Two (bioretention facilities), making it more suitable for the research area as it can remove TSS at a faster rate.

4 CONCLUSION

This passage discusses the construction of a SWMM model for the Taihu Road Park study area based on field investigations and relevant references, aiming to analyze the comparison between surface runoff and pollutant content under three different scenarios for various recurrence intervals.

(1) Through analysis, it was found that Model 1, focusing on detention with infiltration as a supplement, is more suitable for Taihu Road Park. Calculations show that under a two-year return period rainfall, without LID facilities, the control rate for stormwater is 58%, while Model 1 (depressed green space) controls 83% of stormwater, and Model 2 (bio-retention facilities) controls 77%. Under a three-year return period rainfall, without LID facilities, the control rate for stormwater is 51%, while Model 1 controls 75% of stormwater, and Model 2 controls 69%. Under a five-year return period rainfall, without LID facilities, the control rate for stormwater is 45%, while Model 1 controls 68% of stormwater, and Model 2 controls 61%. Therefore, Model 1 (detention as the main focus with infiltration as a supplement) is more suitable for stormwater control in Taihu Road Park.

(2) Regarding total suspended solids (TSS) pollutants, under a two-year return period rainfall, without LID facilities, the control rate for TSS is 58%, while Model 1 (depressed green space) controls 90% of pollutants, and Model 2 (bio-retention facilities) only controls 62%. Under a three-year return period rainfall, without LID facilities, the control rate for TSS is 51%, while Model 1 controls 87% of pollutants, and Model 2 only controls 55%. Under a five-year return period rainfall, without LID facilities, the control rate for TSS is 45%, while Model 1 controls 85% of pollutants, and Model 2 only controls 50%. Model 1 (detention as the main focus with infiltration as a supplement) is more suitable for TSS control in Taihu Road Park.

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