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ORIGINAL RESEARCH ARTICLE

Decision-making study on sewer overflow pollution in mountainous cities based on the Stormwater Management Model

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Abstract The urban area of Wanzhou District in Chongqing frequently experiences flooding and sewage overflow pollution due to its steep topography, frequent and intense short-duration rainstorms, and inadequate drainage capacity. To address these issues, this study integrated sponge city concepts with low-impact development (LID) measures to establish a stormwater management framework for the Guoben Road catchment area. Hydrometeorological and drainage data were obtained from local monitoring stations. Utilizing high-resolution remote sensing imagery and a 30 m-resolution digital elevation model, 50 sub-catchments were delineated in ArcGIS. Based on regional soil information and national sponge city design guidelines, a Stormwater Management Model employing the Horton infiltration method was constructed. This model simulated runoff and sewer network performance under Chicago design storm conditions with return periods of 1, 3, 5, and 10 years. Results indicate that LID facilities (permeable pavements and rain gardens) substantially reduced runoff generation and enhanced drainage system efficiency. Across the four rainfall scenarios, the total decrease in runoff volume ranged from 69.3% to 79.3%, with runoff coefficients falling from 0.51–0.61 to 0.10–0.19. The decrease in outfall discharge ranged from 11.0% to 76.1%, with peak flow reduced by up to 70.4%, most notably during the 1-year return-period event. Mitigation effects diminished during higher-return-period storms, attributed to limited LID storage capacity and rapid soil saturation, which reduced infiltration and detention capabilities during intense rainfall events. Overall, this integrated LID scheme effectively enhanced infiltration capacity within the mountainous urban catchment, reduced peak flows, and alleviated sewer network overloading. This study provides technical support for stormwater risk management, sewage overflow pollution control, and sponge city planning in Wanzhou District, Chongqing, and other cities with similar topographic and hydrological characteristics.

Keywords: Stormwater Management Modeling; Low-impact development techniques; Sponge city construction

1. Introduction

With the acceleration of China's urbanization process, problems in the urban water environment are becoming increasingly severe, and the deterioration of urban water quality has become the core challenge.[1] The increase in impervious surfaces prevents most of the rainwater from infiltrating into the soil during rainfall, and excess rainfall transports accumulated surface contaminants across urban areas and conveys them into receiving waters via the drainage network, thereby deteriorating the quality of the receiving water bodies.[2] During dry weather intervals, various contaminants accumulate on urban surfaces. Precipitation that occurs after such a period quickly mobilizes these deposited pollutants and transports them into adjacent aquatic environments, often causing a significant deterioration in water quality. Urban black-odorous water bodies are an extreme manifestation of water pollution. Consequently, the continuous improvement of urban water environments and the remediation of black-odorous water bodies have become global focal points of public and scientific concern.[3] To mitigate the challenges associated with urban inundation and the formation of odorous, polluted water bodies since 2015, China has designated 30 cities as pilot sites for the implementation of sponge city construction projects.[4]

Research has consistently indicated that urban runoff represents a significant contributor to environmental pollution. About 46% of surface water pollution is attributed to urban runoff.[5] Increased urban surface runoff is a major cause of urban flooding.[6] Meanwhile, urban surface runoff often transports substantial amounts of contaminants into surrounding rivers, lakes, and other aquatic systems. This process accelerates the deterioration of water quality and poses significant ecological and environmental risks.[7] The increase in large paved areas and impermeable surfaces greatly reduces rainwater infiltration and increases surface runoff.[8] Previous studies have reported that urban sprawl, especially the dense expansion of impervious surfaces around the urban core, is closely associated with a significant increase in urban waterlogging during storms.[9] For example, in Guangzhou, China, studies have shown that human activities contribute up to 94% to runoff, while reduced precipitation concentration contributes only 6%.[10] This increased runoff not only causes property damage but also affects a city's ability to respond to emergencies. These challenges to the urban water environment, particularly water quality pollution, water scarcity, and flooding, point to a central and growing problem: Rainy-day surface runoff.[1]

The formation of urban surface runoff is mainly affected by changes in surface cover during urbanization, as well as rainfall characteristics and topography, with rainfall intensity, duration, frequency, and total amount as the key meteorological factors.[11] Extreme rainfall events have a multifaceted impact on urban drainage systems, notably by increasing flood risk, stressing existing infrastructure, and leading to the development of drainage system design and management methodologies.[12] Even when all drainage components operate optimally, the inherent limitations in the capacity of urban stormwater systems prevent the complete eradication of the flooding threat. This is primarily because extreme rainfall events or unexpected hydrological conditions may exceed the system's threshold, resulting in temporary surface inundation or localized waterlogging.[13]

Globally, researchers primarily use the Stormwater Management Model (SWMM) to simulate combined sewer overflow processes.[14] Validation studies using SWMM show that model outputs are not sensitive to the surface Manning's roughness coefficient, whereas they are highly sensitive to the impervious depression storage volume. Zakizadeh *et al.*[15] confirmed that SWMM has a very strong predictive ability. Kim *et al.*[16] employed the SWMM to evaluate stormwater management performance under different low-impact development (LID) scenarios. The findings indicated that LID measures effectively reduced runoff volumes, thereby alleviating the risk of urban waterlogging. Vleeschauwer *et al.*[17] demonstrated that integrating urban green open spaces with stormwater detention facilities markedly decreases the occurrence of overflow events. Autixier *et al.*[18] evaluated LID techniques for rain gardens to reduce the occurrence of overflow events and provide specific recommendations for mitigating overflow contamination of drinking water. Xu *et al.*[19] validated the practicality of the modern sponge city concept by analyzing the stormwater management mechanisms of the ancient drainage system in Ganzhou, which encompassed rainwater guidance, storage, infiltration, purification, utilization, and discharge. Drawing insights from the traditional system, Xu *et al.*[19] proposed design principles for sponge cities, emphasizing that such planning should precede new urban development. Yang *et al.*[20] proposed numerous solutions to address challenges for urban stormwater management in China through a hydrological perspective. Fu[21] explores how LID methods can be combined with rainwater harvesting systems to maximize the effectiveness of stormwater management.

To address these challenges, the development of LID and sponge city concepts has gained global attention. Existing research has demonstrated the effectiveness of green infrastructure—such as permeable pavements, rain gardens, and bioretention cells—in reducing runoff peaks, enhancing infiltration, and mitigating pollution loads. Hydrological models, such as SWMM, have been widely applied to evaluate LID performance under varying rainfall scenarios. However, most previous studies have focused on flat or gently sloped cities, where hydrological responses differ significantly from those in mountainous urban environments.

Research gaps remain particularly evident in regions with steep terrain, limited land area for green facilities, and short-duration, high-intensity storms. Mountainous cities exhibit rapid surface convergence, greater pressure on drainage systems, and a higher likelihood of overflow events, yet studies assessing how integrated LID facilities perform under these conditions are scarce. The Three Gorges Reservoir Area, characterized by complex topography and highly variable rainfall patterns, represents a typical example of such understudied regions.

To address these gaps, this study developed a SWMM-based rainfall–runoff simulation framework for the Guoben Road area of Wanzhou District, a representative mountainous urban catchment. The objectives are to: (i) Quantify the effects of combined permeable pavements and bioretention cells on runoff generation, infiltration, and peak flow attenuation; (ii) evaluate discharge reduction at multiple outfalls under different rainfall return periods; and (iii) provide practical guidance for stormwater management and sponge city construction in mountainous regions. The study aims to advance the understanding of LID performance in complex terrain and support decision-making for sustainable urban drainage design.

2. Materials and methods

2.1. Study area description

With ongoing advances in social, economic, and technological domains, China's wastewater treatment technologies have undergone significant innovation. As point-source pollution has been largely controlled in previous decades, non-point source pollution from urban surfaces has become an increasingly dominant contributor to the degradation of the aquatic environment.[22] Following the initial success in controlling point-source pollution, urban surface runoff has emerged as a major contributor to the decline in water quality and the impairment of aquatic ecosystem functions.[23,24] Wanzhou District lies in a subtropical monsoon humid zone, with a four-season climate and rolling hills and low mountains; hills account for about a quarter of the area. Numerous rivers, complex water systems, poor urban drainage, and flash floods triggered by heavy rainfall lead to frequent urban flooding. The annual rainfall is 1,100 to 1,300 mm and unevenly distributed throughout the year, with a maximum recorded rainfall intensity of 197.1 mm/h. Summer has the highest rainfall, contributing 34–46% of the annual total; spring and autumn follow, accounting for 2.5–3.0% of annual precipitation, while winter has the lowest rainfall, accounting for only 4–5% of the yearly total.

2.2. Introduction to SWMM

The SWMM, developed by the United States Environmental Protection Agency, is a dynamic precipitation-runoff simulation tool widely employed for evaluating urban drainage systems and simulating stormwater runoff in urban environments.[14,25] It is the first and most commonly used model for studying stormwater runoff in cities. It can be used to simulate and evaluate how stormwater flows in urban areas during a single rainfall or over an extended period of rainfall.[26] It has gained widespread acceptance in hydrological and urban drainage research worldwide. Wanzhou District is representative of mountainous cities that experience urban flooding caused by heavy rainfall. Therefore, we investigated the Guoben Road area of Taibai Street in Wanzhou District. The study area includes essential information regarding the city's layout, underground drainage system, rainfall patterns, and other relevant datasets, all of which serve as input for building an SWMM to simulate urban flood dynamics and the performance of the drainage pipeline network under different heavy rainfall conditions, thereby providing examples for planning urban flood prevention measures and underground drainage rehabilitation schemes.

2.3. Modeling

The study area is situated along Guoben Road in Wanzhou District. The dominant land-use types include buildings, transportation infrastructure, and grass-covered areas, while open green spaces are relatively limited. The analysis integrated high-resolution remote sensing imagery, meteorological data, and detailed information on the local drainage network. Data on urban layout and hydrological systems were collected, and fine-scale elevation data were extracted from high-quality satellite imagery obtained through a geospatial data cloud platform.

The meteorological and drainage monitoring data used for model inputs were based on field observations, covering rainfall, climate, and rainfall distribution patterns. Precipitation and water level data obtained from a local automatic weather station were maintained by the Wanzhou District Water Resources Bureau. This station is equipped with a tipping-bucket rain gauge (RG-13M, Vaisala, Finland; resolution 0.2 mm/tipping) and a pressure-based water-level sensor (PT-500, Automation Products Group, USA; accuracy ± 0.1% of full scale). The SWMM software simulates runoff generation, infiltration, outlet discharge, and pollutant migration processes. No synthetic hydrological datasets were employed beyond the Chicago design storm series required for rainfall scenarios. This ensures the model is constructed entirely upon local observational conditions and fixed rainfall formulas.

2.4. Piping and parameters

In this study, hydrological analysis tools in ArcGIS software were employed to delineate sub-catchments within the selected study area. This process also enabled the determination of the geographic coordinates, the spatial extent of each sub-catchment, and their corresponding average slope values.

The study area was divided into 50 sub-catchments based on a combination of 30 m-resolution digital elevation model (DEM), drainage pipe network layout, building footprints, and road alignments. The watershed delineation was performed using the ArcGIS Hydrology toolbox, which generated flow direction and flow accumulation layers from the DEM and extracted preliminary catchment boundaries. These boundaries were then manually adjusted to ensure consistency with the actual drainage network, ensuring that each sub-catchment drained to a single inlet point or manhole. Land-use boundaries and surface slope characteristics were also considered to avoid creating hydrologically unrealistic subzones.

2.5. Delineation of sub-catchments

The study area was divided into 50 smaller sections. Using a topographic map and pipe data, the pipeline information was simplified in ArcGIS. This data was then converted into a compatible format for the inp.PINS plug-in of SWMM for each part. Finally, based on the slope-flow map, the exit points for each section were identified. The runoff process was modeled based on the water and land features of each sub-catchment. Surface runoff comprised three parts: runoff from areas that can absorb water, runoff from areas that can hold water, and runoff from areas that cannot hold any water. In this context, runoff from previous areas equals the rainfall depth minus depression storage and infiltration into the soil. Runoff from impervious and depression-storage areas equals the rainfall depth minus the volume retained in surface depressions. Where surfaces are fully impervious, and no depression storage is present, the runoff depth is equal to the rainfall depth. The Horton infiltration model is well-suited for urban catchments with mixed land surfaces and limited soil information. Unlike the Green–Ampt method, which requires detailed soil suction head and moisture content parameters that are unavailable in the study area, the Horton model provides a flexible empirical representation of infiltration decay suitable for short-duration, high-intensity rainfall common in mountainous cities. Previous studies in similar regions demonstrated that the Horton algorithm performed reliably in SWMM simulations when soil data were incomplete,[27] thus infiltration was estimated in this study using Horton's model. This empirical model relies on a small number of calibrated parameters and is suitable for simulating rainfall–runoff processes in relatively small urban catchments.[28,29] Each hydrological and hydraulic parameter in the study area is presented in Table S1.

2.6. Analysis by simulation

To develop a generalized SWMM using ArcGIS, the research team implemented a four-stage methodology. Initially, drainage infrastructure components were translated into a geographic framework, with junctions depicted as point features and conduits represented as linear features. Following this, we leveraged ArcGIS's Thiessen polygon generator to delineate catchment areas surrounding each drainage node, which were then fine-tuned through careful manual editing and localized refinements.[30] Third, we fine-tuned the Thiessen polygons to align with the study area's specific boundary constraints, building patterns, terrain gradients, and slope orientations. These modified polygons subsequently served as our sub-catchments, with corresponding drainage points clearly identified for each. Using ArcGIS technology, we then extracted critical metrics, including pivot elevation, channel length, surface area, width, impervious coverage percentage, and overall slope, across the entire study region.[31,32] Finally, the comprehensive model was seamlessly integrated into SWMM through the inp. PINS platform, leveraging ArcGIS data to craft the appropriate SWMM input file. This approach led to the delineation of 50 sub-catchments, 50 nodes, 50 conduits, and 4 discharge points. The final model configuration is presented in Figure 1.

2.6.1. Simulation condition setting

The determination of average storm intensity (Equation [1]) followed the Chicago design storm, a representative model of precipitation distribution developed according to the storm intensity equation.

Pre-peak and post-peak rainfall were determined by introducing a rain crest factor.[33] Parameters relating to the associated calculations are shown in Table 1.

$$q = \frac{1504\left(1 + 0.945\log_{10} T\right)}{\left(t + 7.213\right)^{0.704}} \quad (1)$$

2.6.2. Computational model setup

The SWMM hydraulic module conceptualizes the drainage system as interconnected pipes and nodes, enabling the simulation of steady-state, dynamic, and kinematic wave flows in urban drainage networks.[34] This study analyzed the configuration and temporal

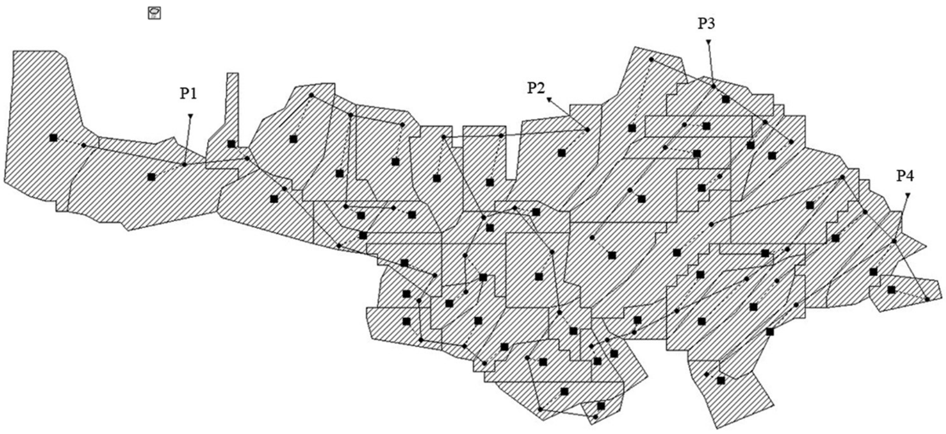

Figure 1. Stormwater Management Model generalization for the study area

Table 1. Parameters used in the Chicago design storm formulation and SWMM rainfall–runoff simulations

Variable	Definition	Unit	Value/source
q	Average rainfall intensity	mm/min	Chicago design storm
T	Rainfall return period	year	1, 3, 5, 10
t	Rainfall duration	min	120
r	Rainfall peak coefficient	-	0.4
f_0	Initial infiltration rate	mm/h	Horton model parameter
f_r	Minimum infiltration rate	mm/h	Horton model parameter
k	Infiltration decay constant	-	Horton model
S	Surface slope	%	GIS extraction
n	Manning's roughness coefficient	-	0.013 (surface)
d	Surface water depth	mm	Computed dynamically
A	Sub-catchment area	m^2	ArcGIS extraction
W	Sub-catchment width	m	ArcGIS extraction
Q	Runoff flow rate	m^3/s	Model output
V	Depression storage	mm	SWMM parameter
i	Net rainfall intensity	mm/h	Calculated
K_s	Saturated hydraulic conductivity	mm/h	LID parameter
θ	Soil porosity	-	LID parameter
H	Layer thickness	mm	LID parameter
C	Clogging factor	-	LID parameter
T	Total rainfall depth	mm	Chicago model output

Abbreviations: GIS: Geographic information system; LID: Low-impact development; SWMM: Stormwater Management Model.

variability of the local drainage pipe network to better understand its operational characteristics. The kinematic wave method simulates flow in each pipe segment based on the continuity and momentum equations. In the momentum equation, it is assumed that the water-surface gradient follows the inclination of the conduit, ensuring consistency between hydraulic forces and channel geometry. The maximum discharge capacity of a pipe under full-flow conditions was evaluated using Manning's equation. In addition, this approach enabled simulation of nodal storage, representing the excess water volume that accumulated at the downstream storage node when the pipe capacity was exceeded. The SWMM framework consists of several interrelated sub-models, including the runoff generation model, loss (or sink) model, and infiltration (underseepage) model. The structure of the runoff generation module is illustrated in Figure S1.

To assess the robustness and parameter sensitivity of the SWMM simulation, a local sensitivity analysis was conducted for key hydrological and hydraulic parameters. Each parameter was varied by ± 20% from its baseline value while keeping others constant, and the resulting changes in total runoff volume were quantified. The results, summarized in Table 2, reveal that the model is most sensitive to a decrease in the Horton initial infiltration rate (f_0), with a 20% reduction causing a 5.05% increase in total runoff. In contrast, the model exhibited lower sensitivity to the Horton decay constant (k) and was insensitive to Manning's roughness coefficient (n), as a ± 20% change in n resulted in less than a 0.05% variation in runoff. This pattern underscores that infiltration capacity, rather than surface roughness, is the dominant control on runoff generation in this steep, urbanized catchment. The findings align with prior studies and enhance the credibility of the model setup by confirming that its behavior is consistent with hydrological theory.[34]

(i) Output module: The surface runoff convergence process is the convergence of net rainfall from each watershed to the outflow segment. The rainfall process within a watershed was transformed into an outflow process by simultaneously solving the continuity equation and Manning's equation. Calculations were performed using Equation (2):

$$Q = w\frac{1.49}{n}\left(d - d_p\right)^{\frac{5}{3}} S^{\frac{1}{2}} \tag{2}$$

(ii) Surface confluence: Surface catchment is the process by which stormwater runoff from each sub-catchment unit passes through different paths and eventually converges at the same outlet or directly into the receiving water body. The calculation of non-linear reservoirs was generally solved in SWMM by establishing the continuity equation associated the Manning's equation, as shown in Equation (3):

$$\frac{dV}{dt} = \frac{Add}{dt} = Ai' - Q \tag{3}$$

(iii) Underseepage module: Infiltration within SWMM can be simulated using three algorithms: The Horton formula, the Green–Ampt curve, or the Soil Conservation Service runoff curve method. For the purposes of this study, the Horton model was applied (Equation [4]):

$$f_p = f_c + \left(f_0 - f_c\right)e^{-kt} \tag{4}$$

2.6.3. Calculation program

The precipitation plan delineates the temporal distribution of cumulative rainfall during the design phase. It serves as a modeling condition for hydraulic simulations and is instrumental in determining the design discharge of the drainage system.[35]

To investigate the effect of rainfall intensity on urban runoff, four scenarios with different rainfall return periods of T = 1, 3, 5 and 10 years were designed to simulate and analyze the systematic surface runoff generated in

Table 2. Parameters used in the Chicago design storm formulation and SWMM rainfall–runoff simulations

Parameter	Variation (%)	Change in total runoff (%)	Key finding
Manning's n	+20	−0.039	Insensitive
	−20	+0.040	
Horton decay constant (k)	+20	+2.770	Moderately sensitive
	−20	−0.550	Asymmetric response
Horton's initial infiltration rate (f_0)	+20	−0.550	Highly sensitive
	−20	+5.050	Asymmetric response Most sensitive to capacity reduction

the study area and the corresponding flow rates at the four outfalls, with the rainfall crest coefficient was set to $r = 0.4$, the rainfall duration t was set to 120 min, and the other parameters were kept unchanged. The four different return periods were entered into SWMM as a sequence of rainfalls. The model simulation and its procedural flow are illustrated in Figures 2 and 3. The 120-min rainfall accumulation and peak intensity for different design rainfall recurrence intervals are presented in Tables S2 and S3.

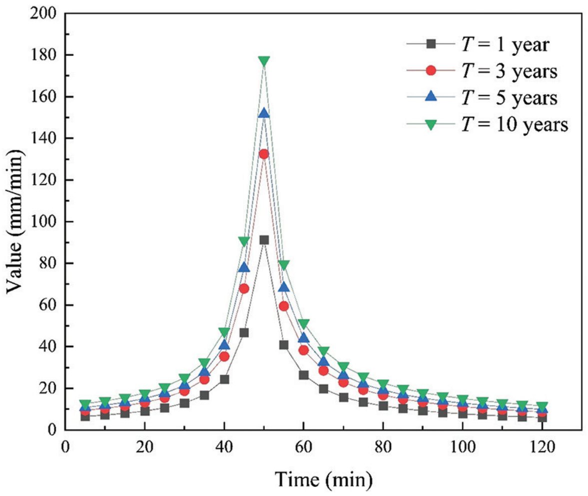

Figure 2. The 120-min rainfall process line with different return periods in Wanzhou District, Chongqing, China

2.6.4. LID control

The natural features of the urban water cycle are preserved through LID, which also mitigates flooding and reduces water pollution.[36] The core concept of LID is to minimize anthropogenic disturbance while maximizing interception of surface runoff and pollutant removal.[37] To achieve the objectives of a sponge city by enhancing the water storage capacity of each catchment and reducing surface runoff from surrounding areas, various LID facilities were modeled, including sunken green spaces, permeable pavements, bioretention areas, and vegetated depressions.[38,39] The layout principles involve directing runoff from impervious surfaces to storage facilities or ponds using surface slopes or conveyance pipes. This design ensures that excess stormwater is safely diverted into municipal drainage systems while providing the necessary infrastructure to manage heavy rainfall events. The implementation of LID facilities enhances the capacity of developed areas to manage stormwater effectively, thereby contributing to the overall sustainability and resilience of the surrounding urban environment.

Permeable pavements, a key element of source-control strategies in sponge cities, operate through

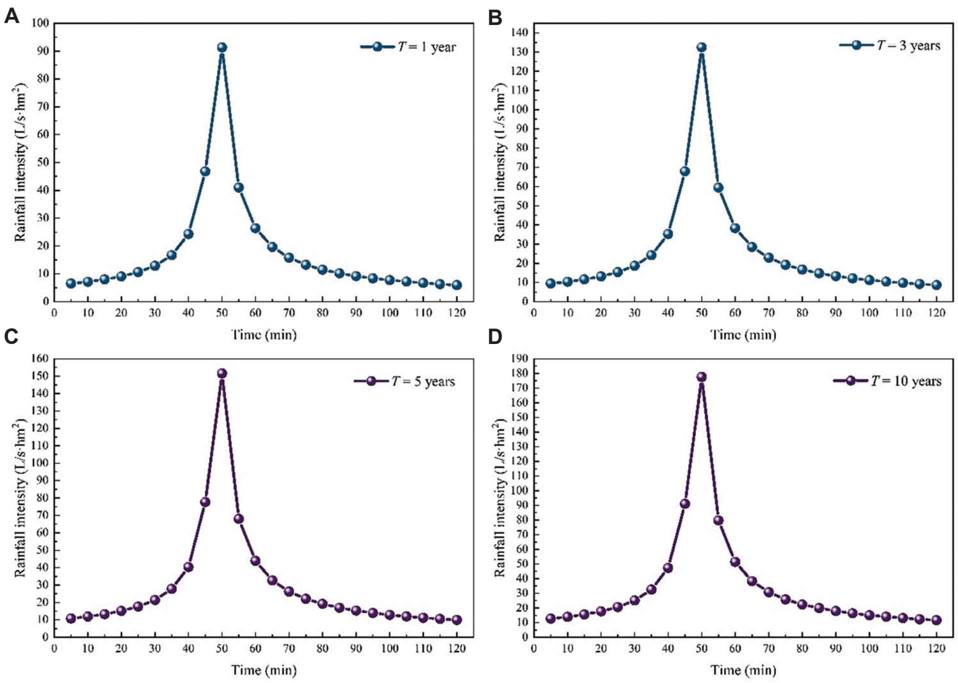

Figure 3. Chicago design storm under different rainfall return periods in Wanzhou District, Chongqing. (A) *T* = 1 year. (B) *T* = 3 years. (C) *T* = 5 years. (D) *T* = 10 years.

the combined effects of a permeable surface layer and underlying water storage. The surface layer allows infiltration into the soil beneath, while the sublayer temporarily stores runoff. Typical permeable pavement types include permeable bricks, asphalt, and cement concrete variants, bonded permeable stones, grass-covered pavers, gravel surfaces, and ceramic tiles, all designed to enhance surface infiltration.[40] Parameters relating to permeable paving facilities are shown in Table 3.

A rain garden, also known as a bioretention pond, is a shallow, recessed green space used to collect and absorb rainwater from rooftops or the ground, usually consisting of a layer of plants, soil, and gravel. After rainwater enters the rain garden through surface runoff, it is initially intercepted by plants to slow down the flow rate, then filtered and adsorbed by the soil to remove pollutants. At the final stage, stormwater either percolates into the subsurface, contributing to groundwater recharge, or is temporarily held in the gravel layer, where it can support plant growth and utilization. Rain gardens can effectively reduce surface runoff and the pressure of rainwater on the urban drainage system. They can also purify rainwater to improve the urban ecological environment and provide urban residents with a beautiful leisure space.[41,42] Parameters relating to rainwater garden facilities are shown in Table 4.

To assess the performance of LID measures in regulating runoff across different storm events, we investigated the influence of rainfall intensity and duration on LID performance in mitigating urban flooding in a mountainous city across four different storm return periods. Schematic diagrams of permeable pavements and rain gardens are presented in Figures S2 and S3.

The selection of parameter values for the LID facilities was based on a combination of national technical guidelines, local engineering standards, field investigations, and documented case studies. The bioretention cell parameters—including soil media depth, hydraulic conductivity, porosity, and storage layer thickness—were selected according to the *Technical Guidelines for Sponge City Construction (Trial)* issued by the Ministry of Housing and Urban-Rural Development, which provides recommended ranges for typical urban soil structures in Southwest China. These ranges were further constrained using information from local sponge-city demonstration projects in Chongqing, ensuring that the adopted values reflect regional construction practices and material availability.

For permeable pavements, pavement porosity, storage layer height, and subbase hydraulic properties were derived from the *Code for Design of Outdoor Wastewater Engineering* (GB 50014-2021). These

Table 3. Parameter values for each structural layer of permeable paving facilities

Structural layer	Parameter name	Parameter value
Surface layer	Berm height (mm)	10
	Vegetation volume ratio	0
	Surface roughness	0.013
	Slope of the ground (%)	0.3
Pavement layer	Thicknesses (mm)	100
	Porosity ratio	0.15
	Permeability (mm/h)	100
	Clogging factor	0
Aquifer	Thickness (mm)	100
	Porosity ratio	0.3
	Seepage rate (mm/h)	12.7
	Clogging factor	0
Drainage layer	Flow coefficient	0
	Flow rate index	0.5
	Offset height (mm)	6

Table 4. Parameter values for each structural layer of the bioretention cell facility

Structural layer	Parameter name	Parameter value
Surface layer	Berm height (mm)	150
	Vegetation volume ratio	0
	Surface roughness	0.1
	Surface slope (%)	1
Layer of soil	Thickness (mm)	500
	Porosity ratio	0.5
	Water yield	0.2
	Hydraulic conductivity (mm/h)	200
	Hydraulic conductivity slope	10
	Suction head (mm)	88.9
Aquifer	Thickness (mm)	100
	Porosity ratio	0.3
	Seepage rate (mm/h)	12
	Clogging factor	0
Drainage layer	Flow coefficient	0
	Flow rate index	0.5
	Offset height (mm)	6

engineering documents indicate that storage layers of 100–300 mm and porosity values of 0.15–0.45 are commonly applied in mountainous urban areas to achieve rapid drainage and enhanced structural stability.

The selected parameters also align with previous SWMM-based LID studies in Chongqing, Chengdu, and other subtropical mountainous cities. Therefore, the parameter set used in this study is consistent with both normative design requirements and empirical practices and is representative of locally feasible LID configurations.

3. Results and discussion

3.1. Comparative analysis of runoff before and after modification

After the retrofit, the infiltration volume, runoff volume, and runoff coefficient were analyzed based on rainfall data corresponding to different recurrence periods, as shown in Figure 4. It can be observed that for $T = 1$, 3, 5, and 10 years, the retrofit significantly reduced both the total runoff volume and peak runoff compared with the conventional model, while substantially increasing infiltration. For instance, for $T = 1$ year, the infiltration volume increased from 16.74 mm before the retrofit to 19.81 mm after the retrofit. Similarly, for $T = 10$ years, infiltration increased from 26.47 mm to 32.6 mm. These results indicate that LID facilities can effectively enhance rainfall infiltration, retention, and storage capacities, contributing to groundwater recharge and promoting a sustainable urban hydrological cycle.[43,44] In Figure 4, the runoff volume is significantly reduced after retrofitting; e.g., at $T = 1$ year, the runoff volume is 18.02 mm before retrofitting, and only 3.73 mm after retrofitting; at $T = 10$ years, the runoff volume is 41.73 mm before retrofitting, and 12.8 mm after retrofitting. When viewed together with the runoff process curve, it is evident that after installation of the LID facilities, the rate of runoff increase during sustained rainfall events is only marginally higher per unit time. Consequently, the overall runoff peak is markedly suppressed, resulting in substantially lower runoff volumes compared with pre-retrofit conditions. This indicates that LID facilities can reduce surface runoff, the risk of urban flooding, and the pressure on the urban drainage system. The runoff coefficient decreases significantly after the retrofit. At $T = 1$ year, the runoff coefficient is 0.51 before the retrofit, and 0.1 after the retrofit; For $T = 10$ years, the runoff coefficient is 0.61 before the retrofit, and 0.19 after the retrofit. The runoff coefficient reflects the percentage of rainfall that is converted into runoff, and a decrease in the coefficient indicates that more rainfall is intercepted and infiltrated rather than becoming runoff, further demonstrating the regulation effect of runoff by LID facilities.

In summary, the newly implemented permeable pavement facilities effectively enhance rainwater

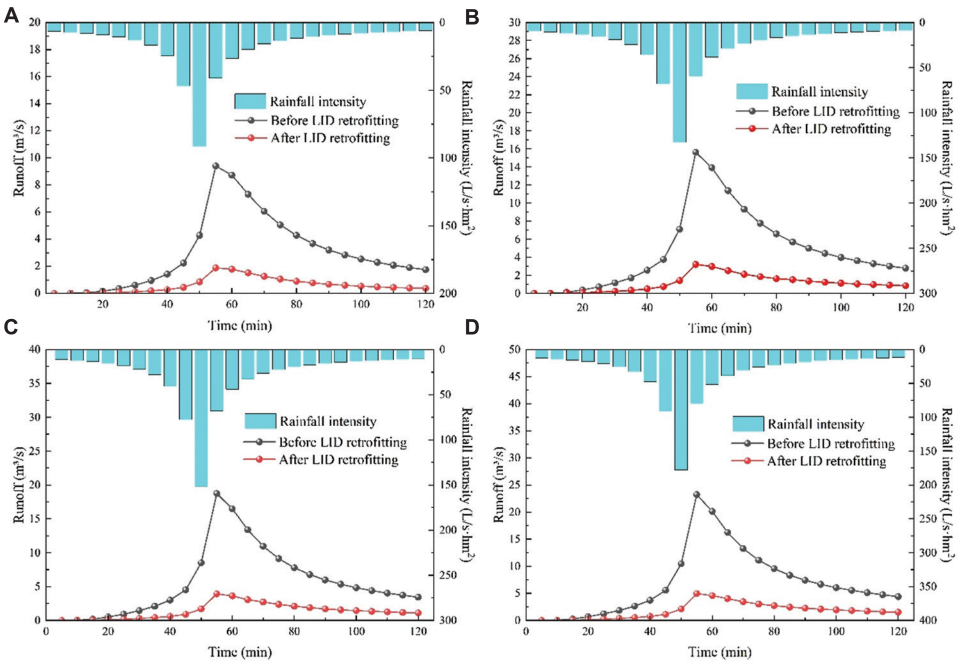

Figure 4. Surface runoff hydrographs before and after implementation of low-impact development (LID) under different rainfall return periods. (A) *T* = 1 year. (B) *T* = 3 years. (C) *T* = 5 years. (D) *T* = 10 years.

diversion, while the bioretention cells primarily improve runoff retention and infiltration. As a result, the simulated runoff coefficients in the study area were significantly reduced, markedly lowering the risk of urban flooding under extreme rainfall events. These findings demonstrate that LID facilities can substantially mitigate surface water accumulation and improve urban hydrological resilience, in line with the results of Nazarpour *et al.*[45]

3.2. Comparative analysis of discharges at outfalls before and after modification

To evaluate the impact of the combined LID facilities on outfall discharge, SWMM was used to simulate flows from four outfalls (P1, P2, P3, and P4) in the study area before and after the installation of LID facilities at four rainfall return periods (T = 1, 3, 5, and 10 years). The simulation results are presented in Figure 5, which shows a significant reduction in outfall discharge across all return periods following the deployment of LID facilities. Specifically, reductions at outfalls P1, P2, P3, and P4 ranged from 16.2% to 53.7%, 19.8% to 69.6%, 40.1% to 74.2%, and 10.96% to 76.1%, respectively, under the four rainfall scenarios. These results indicate that the LID facilities effectively mitigate stormwater runoff. However, the mitigation effect decreases with increasing rainfall return period, suggesting that LID facilities are most effective under low to moderate rainfall conditions.

Overall, the outfall discharges from all four locations were significantly reduced following the installation of LID facilities, demonstrating the effectiveness of these measures in mitigating stormwater runoff. However, the reduction effect decreases as the rainfall return period increases. Under high return periods, the intensity and total volume of individual rainfall events often exceed the infiltration, storage, and retention capacities of LID facilities. Consequently, a greater portion of runoff cannot be effectively retained or infiltrated, leading to increased surface flow into the outfalls, weakening the mitigation effect. These results indicate that LID facilities achieve the most pronounced reductions in stormwater runoff at low rainfall return periods (e.g., T = 1 year), when their regulatory functions are fully utilized.[46]

3.3. Comparative analysis of flood flows at outfalls

The objective of this analysis was to investigate how a combination of LID facilities influences the reduction of peak flows at urban drainage outfalls. The SWMM was used to simulate the peak flows from four outfalls before and after LID implementation under four return periods (T = 1, 3, 5, and 10 years). The simulation results are presented in Figure 6. As shown, peak flows at all outfalls increased with higher rainfall return periods. After implementing LID facilities, the peak flow reductions compared to the traditional model were as follows: P1, 62.5%–70.4%; P2, 35.9%–61.2%; P3,

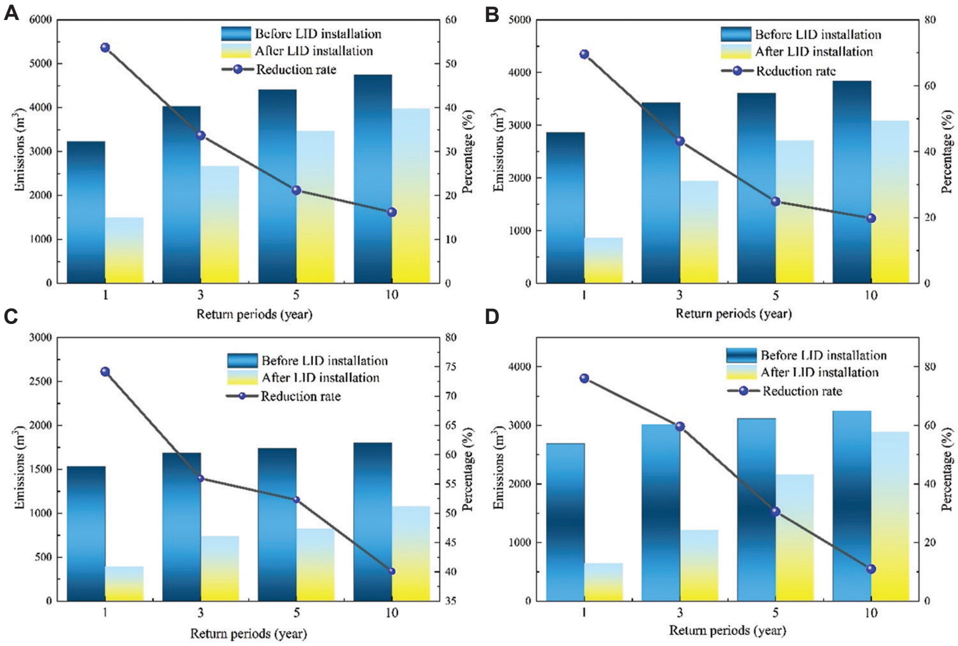

Figure 5. Pollutant emissions at the outfall before and after low-impact development (LID) installation under different rainfall return periods. (A) Outfall P1. (B) Outfall P2. (C) Outfall P3. (D) Outfall P4.

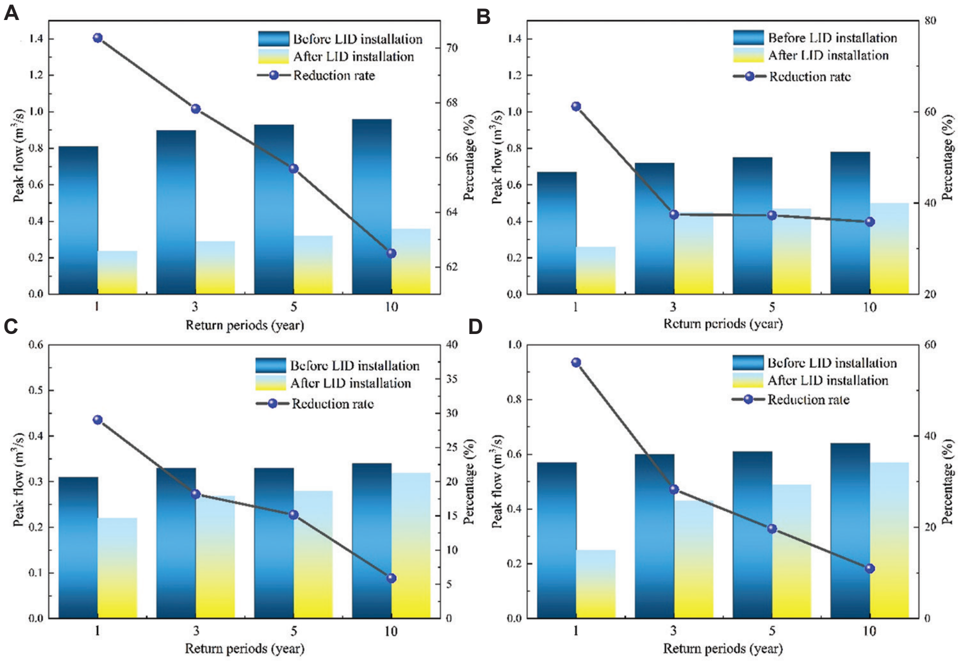

Figure 6. Flood peak flows at the outfall before and after the low-impact development (LID) facility placement for different rainfall return periods. (A) Outfall P1. (B) Outfall P2. (C) Outfall P3. (D) Outfall P4.

5.9%–29.0%; and P4, 10.9%–56.1%. Analysis indicates that while combined LID facilities significantly attenuate peak flows, the magnitude of flow reduction is not uniform and varies among outfall points.

A further comparison of simulation results between the conventional development model and the combined LID facilities indicates that the reduction in peak flow is significant and dependent on the rainfall scenario. For a 1-year return period ($T = 1$ year), peak flow reductions at outfalls P1, P2, P3, and P4 achieved 70.37%, 61.19%, 29.03%, and 56.14%, respectively. When the rainfall return period was extended to $T = 3$ years, the reductions decreased to 67.78% for P1, 37.5% for P2, 18.18% for P3, and 28.33% for P4. At $T = 5$ years, further decreases were observed: P1 at 65.59%, P2 at 37.33%, P3 at 15.15%, and P4 at 19.67%. For the extreme rainfall scenario with $T = 10$ years, the peak flow reduction was the lowest, with P1 at 62.5%, P2 at 35.9%, P3 at 5.88%, and P4 at 10.94%. These results demonstrate that the effectiveness of LID facilities in reducing peak flows diminishes as rainfall intensity and return period increase, highlighting their strong performance under low to moderate rainfall conditions.

It is observed that the ability of LID facilities to control flood flows decreased with increasing rainfall return period. When the return period changed, the capacity of the LID device to regulate stormwater through infiltration, retention, and storage became progressively limited. High-intensity, high-volume rainfall exceeds the infiltration and storage capacities of the facilities, resulting in a portion of the runoff being converted directly to surface flow that rapidly reaches the outfalls. In addition, concentrated rainfall over a short duration compresses the purification and storage cycle of the LID facilities, further weakening their runoff regulation.

The difference in the reduction effect between different outfalls also reflects the influence of the scale of LID facilities on the regulation effect: the sub-catchment corresponding to outfall P1 has a larger area of LID facilities in the planning stage, and its total storage and infiltration capacity is significantly better than that of the other sub-catchments; whereas the density of the LID facilities and the coverage area of the outfall P4 is relatively small, resulting in an overall lower peak-flow reduction rate than at P1 (e.g., 70.37% for P1 and 56.14% for P4 at $T = 1$ year; 62.5% for P1 and 10.94% for P4 at $T = 10$ years). These results suggest that the layout area, types of facilities, and their proximity to each other are important in mitigating floods. These findings can inform the optimal spatial arrangement of LID facilities in future planning and design studies. However, during longer return period storms, the hydraulic response of the catchment is dominated by rapid surface flow convergence. High-intensity rainfall shortens the concentration time and generates runoff faster than the handling capacity of LID facilities. Consequently, the peak discharge at outfalls is driven by direct runoff rather than by processes controlled by LID performance. As rainfall intensity increases, the proportion of delayed or attenuated flow decreases, resulting in a reduced peak-flow mitigation rate. Therefore, the relative hydraulic effectiveness of LID facilities declines with increasing storm magnitude, even if the absolute volume captured by the system remains significant.[47]

3.4. Comparative analysis of load reduction

As illustrated in Figure 7, a comparative evaluation of overflow loads in the study area before and after the deployment of LID measures reveals that these facilities significantly control surface-derived pollutants and decrease contaminant loads in stormwater runoff. Specifically, under four different rainfall return periods (T = 1, 3, 5, and 10 years), the overflow loads of the four major pollutants, suspended solids (SSs), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP), were significantly reduced after the LID installation. For example, under the common rainfall condition of T = 1 year, the SS load was drastically reduced from 212.16 kg to 33.74 kg, with the removal rate achieving 84.1%; even for the heavy rainfall event of T = 10 years, the load was reduced from 500.2 kg to 142.26 kg, with the high removal rate maintained at 71.6%. The pollutants, such as COD, TN, and TP, were also removed at varying degrees, with removal rates ranging from 47.57% to 82.45%.

Figure 7 illustrates that the effectiveness of the LID facilities in controlling pollution is sensitive to rainfall intensity: As rainfall return periods increase (i.e., higher rainfall intensity), the efficiency of pollutant removal varies accordingly.[48]

There is also variability in the removal efficiency of LID facilities for different pollutants. Overall, the removal of physically attached pollutants, such as SS and COD, is the most effective and stable. The removal of dissolved nutrients, such as TN and TP, in the study area is relatively low. This is primarily due to LID technologies (e.g., rain gardens and permeable pavements), which mainly operate through physical processes, such as filtration, adsorption, and deposition, whereas the conversion and removal of dissolved nitrogen and phosphorus require complex biochemical processes that are time-consuming and costly.[49]

In summary, LID facilities are an indispensable part of the urban surface pollution management system, and are particularly effective in controlling particulate matter and organic matter during regular rainfall events. To cope with stricter water quality requirements and extreme rainfall challenges in the future, LID facilities can be combined with end-of-pipe treatment processes

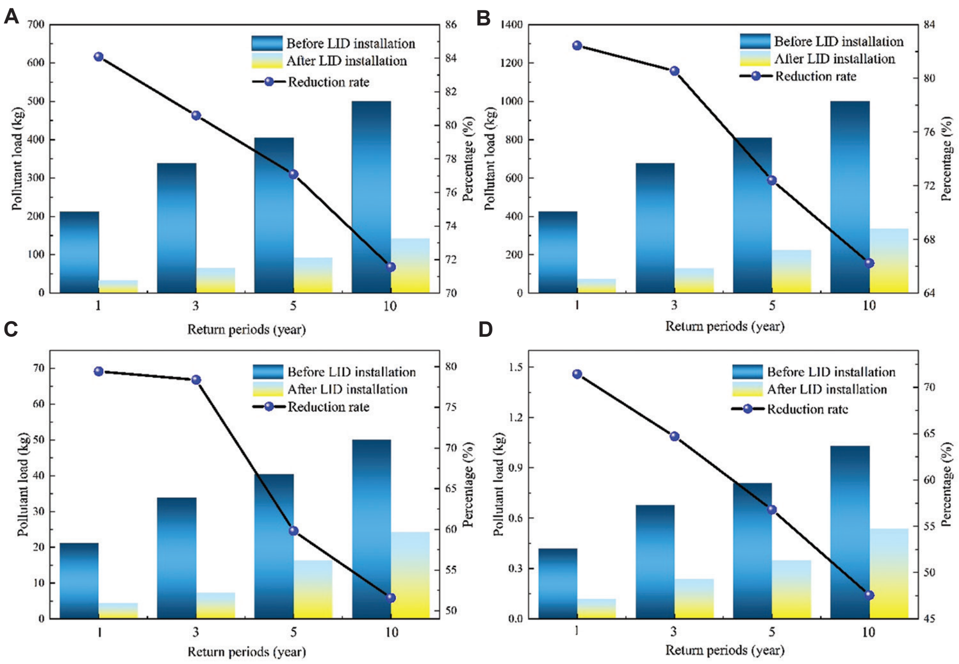

Figure 7. Changes in pollution loadings before and after low-impact development (LID) facility placement under different rainfall return periods. (A) Suspended solids. (B) Chemical oxygen demand. (C) Total nitrogen. (D) Total phosphorus.

(e.g., rainwater wetlands, eco-filters) to build a multi-level barrier system of "source reduction–process control–end-of-pipe treatment," thus achieving synergistic control of various pollutants, particularly TN and TP.

3.5. Comparison with previous studies

The findings of this study align with previous studies demonstrating that LID facilities significantly reduce surface runoff and peak flow. For example, Sui and van de Ven[50] reported that runoff decreased significantly following the implementation of LID measures, while de Vleeschauwer *et al.*[17] reported that source-control LID strategies reduced peak flows by 30–50%. In comparison, the runoff reduction rates in this study (69.3–79.3%) are slightly higher, which may be attributed to the steep terrain and favorable infiltration conditions in the mountainous catchments in Wanzhou District. Similarly, the pollutant removal efficiencies reported in this study for SS and COD (71–84%) align with the ranges reported by Zhang *et al.*[9] and Hou *et al.*[51] Overall, this study expands the existing knowledge by providing evidence from a mountainous urban environment, where terrain-induced hydrodynamics significantly influence the effectiveness of LID practices.

4. Conclusion

In this study, a SWMM-based system was developed to simulate urban rainwater runoff in the Guoben Road area of Wanzhou District, Chongqing Municipality. The effectiveness of LID facilities—specifically, a combination of permeable pavements and bioretention ponds—was systematically evaluated under four rainfall return periods (T = 1, 3, 5, and 10 years). The results indicate that the LID facilities significantly enhance rainwater infiltration and effectively reduce surface runoff volume, runoff coefficients, outfall discharge, and peak flows, particularly under low-return-period conditions (T = 1 year). By mitigating runoff at both the source and process levels, these facilities alleviate operational pressure on the combined sewer network and provide substantial benefits for controlling overflow pollution and preventing urban flooding.

The SWMM demonstrated its ability to accurately simulate rainfall-runoff processes in mountainous urban areas, offering a reliable tool for evaluating management strategies. The combination of permeable pavements and bioretention ponds effectively increases infiltration, detention, and storage capacities, thereby reducing stress on the sewer system and providing dual benefits in flood mitigation and overflow pollution control.

This study provides practical guidance for sponge city construction in mountainous urban regions, where steep terrain and concentrated rainfall intensify flooding risks. The modeling framework can support local governments in designing cost-effective LID layouts and in optimizing drainage rehabilitation projects. Future work may include long-term monitoring data for model calibration, integration of climate change scenarios, and economic assessments to develop multi-objective decision-support tools for regional stormwater management.

Future work may consider integrating clustering-based water demand analysis, as demonstrated by Barreira and Jacinto,[52] into SWMM simulations. Water consumption clusters could provide realistic, time-varying background-oriented inputs, enabling accurate prediction of sewer network stress and improved optimization of LID operation strategies. In addition, machine-learning clustering methods could be employed to classify rainfall conditions or sewer operational states, enhancing the adaptability and accuracy of rainfall–runoff modeling in smart water management systems.[53]

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Conflict of interest

The authors declare that they have no competing interests.

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Availability of data

Data are available from the corresponding author on reasonable request.

References

1. McGrane SJ. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: A review. *Hydrol Sci J*. 2016;61(13):2295-2311. doi: 10.1080/02626667.2015.1128084
2. Wang Z, Qi F, Liu L, Chen M, Sun D, Nan J. How do urban rainfall-runoff pollution control technologies develop in China? A systematic review based on bibliometric analysis and literature summary. *Sci Total Environ*. 2021;789:148045. doi: 10.1016/j.scitotenv.2021.148045
3. Cao J, Sun Q, Zhao D, *et al*. A critical review of the appearance of black-odorous waterbodies in China and treatment methods. *J Hazard Mater*. 2019;385:121511. doi: 10.1016/j.jhazmat.2019.121511
4. Yin D, Chen Y, Jia H, *et al*. Sponge city practice in China: A review of construction, assessment, operational and maintenance. *J Clean Prod*. 2021;280:124963. doi: 10.1016/j.jclepro.2020.124963
5. Kamali M, Delkash M, Tajrishy M. Evaluation of permeable pavement responses to urban surface runoff. *J Environ Manag*. 2017;187:43-53. doi: 10.1016/j.jenvman.2016.11.027
6. Zhu L, Ma J, Wang C, Defilla S, Yan Z. Sensitivity analysis of coastal cities to effects of rainstorm and flood disasters. *Environ Monit Assess*. 2024;196(4):386. doi: 10.1007/s10661-024-12516-2
7. Cojoc L, De Castro-Català N, De Guzmán I, *et al*. Pollutants in urban runoff: Scientific evidence on toxicity and impacts on freshwater ecosystems. *Chemosphere*. 2024;369:143806. doi: 10.1016/j.chemosphere.2024.143806
8. Ferreira CSS, Kalantari Z, Seifollahi-Aghmiuni S, *et al*. Rainfall-runoff-erosion processes in Urban areas. In: Rodrigo-Comino J, editor. Precipitation. Ch. 21. Netherlands: Elsevier; 2021. p. 481-498.
9. Zhang D, Mei C, Ding X, *et al*. Impacts of rainstorm characteristics on runoff quantity and quality control performance considering integrated green infrastructures. *Sustainability*. 2022;14(18):11284. doi: 10.3390/su141811284
10. Lv C, Wang X, Ling M, Xu W, Yan D. Effects of precipitation concentration and human activities on city runoff changes. *Water Resour Manage*. 2023;37(13):5023-5036. doi: 10.1007/s11269-023-03593-y
11. Rezaei AR, Ismail ZB, Niksokhan MH, *et al*. Investigating the effective factors influencing surface runoff generation in urban catchments - a review. *Desalination Water Treat*. 2019;164:276-292. doi: 10.5004/dwt.2019.24359
12. Ma T, Kim JS, Jun C, Moon YI, Moon H. Optimizing urban flood management: Enhancing Urban drainage system efficiency under extreme rainfall events. *J Hydroinform*. 2024;26(11):2704-2719. doi: 10.2166/hydro.2024.067
13. Zhou H, Chi Y. Optimized Scheduling of Fixed and Mobile Pumps for Urban Drainage Under Extreme Rainfall. In: *2025 8th International Conference on Advanced Algorithms and Control Engineering (ICAACE)*; 2025. p. 1751-1755.
14. Barco J, Wong Kenneth M, Stenstrom Michael K. Automatic calibration of the U.S. EPA SWMM model for a large Urban catchment. *J Hydraulic Eng*. 2008;134(4):466-474. doi: 10.1061/(ASCE)0733-9429(2008)134:4(466)
15. Zakizadeh F, Moghaddam Nia A, Salajegheh A, Sañudo-Fontaneda LA, Alamdari N. Efficient Urban runoff quantity and quality modelling using SWMM model and field data in an Urban watershed of tehran metropolis. *Sustainability*. 2022;14(3):1086. doi: 10.3390/su14031086
16. Kim J, Lee J, Song Y, Han H, Joo J. Modeling the runoff reduction effect of low impact development installations in an industrial area, South Korea. *Water*. 2018;10(8):987. doi: 10.3390/w10080967
17. De Vleeschauwer K, Weustenraad J, Nolf C, *et al*. Green-blue water in the city: Quantification of impact of source control versus end-of-pipe solutions on sewer and river floods. *Water Sci Technol*. 2014;70(11):1825-1837. doi: 10.2166/wst.2014.306
18. Autixier L, Mailhot A, Bolduc S, *et al*. Evaluating rain gardens as a method to reduce the impact of sewer overflows in sources of drinking water. *Sci Total Environ*. 2014;499:238-247. doi: 10.1016/j.scitotenv.2014.08.030
19. Xu YS, Shen SL, Lai Y, Zhou AN. Design of sponge city: Lessons learnt from an ancient drainage system in Ganzhou, China. *J Hydrol*. 2018;563:900-908. doi: 10.1016/j.jhydrol.2018.06.075
20. Yang M, Sang YF, Sivakumar B, Ka Shun Chan F, Pan X. Challenges in urban stormwater management in Chinese cities: A hydrologic perspective. *J Hydrol*. 2020;591:125314. doi: 10.1016/j.jhydrol.2020.125314
21. Fu L. *Advancing Rainwater Harvesting Systems to Help Mitigate the Urban Flooding Problems in China*. United States: University of Georgia; 2018.
22. Fengyun S. Urban non-point source pollution: Research progress. *Chin J Ecol*. 2013;32:492-500.

23. Wang Y, Qiao J, Hu Y, Zhang Q, Han X, Li C. Risk assessment of non-point source pollution based on the minimum cumulative resistance model: A case study of shenyang, China. *Land*. 2025;14(1):88. doi: 10.3390/land14010088
24. Wang Z, Fu RZ, Wang D, Zhang X, Lai X. Coupling Simulation of Non-Point Source Pollution and 2-D Water Quality in Nanhe River. In: *IOP Conference Series: Earth and Environmental Science*; 2021. p. 787.
25. Niazi M, Nietch C, Maghrebi M, *et al*. Storm water management model: Performance review and gap analysis. *J Sustain Water Built Environ*. 2017;3(2):10.1061/JSWBAY.0000817. doi: 10.1061/JSWBAY.0000817
26. Zhang X, Qiao W, Huang J, Li H, Wang X. Impact and analysis of urban water system connectivity project on regional water environment based on storm water management model (SWMM). *J Clean Prod*. 2023;423:138840. doi: 10.1016/j.jclepro.2023.138840
27. Yang M, Zhang Y, Pan X. Improving the Horton infiltration equation by considering soil moisture variation. *J Hydrol*. 2020;586:124864. doi: 10.1016/j.jhydrol.2020.124864
28. Annisa B. Penerapan model horton untuk kuantifikasi laju infiltrasi: Application of the horton model for quantification of infiltration rate. *J SAINTIS*. 2018;18(1):95-102. doi: 10.25299/saintis.2018.vol18(1).3198
29. Yue M, Gao X. A comparative study of infiltration methods based on the SWMM model: Application of horton and green-ampt models in drainage system design in Northeast China. *Int J Eng Adv*. 2025;2(1):25-31. doi: 10.71222/rry5ks79
30. Ni T, Zhang X, Leng P, Pelling M, Xu J. Comprehensive benefits evaluation of low impact development using scenario analysis and fuzzy decision approach. *Sci Rep.* 2025;15(1):2227. doi: 10.1038/s41598-025-85763-z
31. Chowdhury MS. Modelling hydrological factors from DEM using GIS. *MethodsX*. 2023;10:102062. doi: 10.1016/j.mex.2023.102062
32. Bajjali W. Watershed Delineation. In: *ArcGIS Pro and ArcGIS Online. Springer Textbooks in Earth Sciences, Geography and Environment*. Switzerland: Springer, Cham; 2023.
33. Su X, Shao W, Liu J, Jiang Y, Wang K. Dynamic assessment of the impact of flood disaster on economy and population under extreme rainstorm events. *Remote Sens*. 2021;13(19):3924. doi: 10.3390/rs13193924
34. Farina A, Di Nardo A, Gargano R, Van Der Werf JA, Greco R. A simplified approach for the hydrological simulation of urban drainage systems with SWMM. *J Hydrol*. 2023;623:129757. doi: 10.1016/j.jhydrol.2023.129757
35. Fortunato A, Oliveri E, Mazzola MR. Selection of the optimal design rainfall return period of Urban drainage systems. *Procedia Eng*. 2014;89:742-749. doi: 10.1016/j.proeng.2014.11.502
36. Ahiablame LM, Engel BA, Chaubey I. Effectiveness of low impact development practices: Literature review and suggestions for future research. *Water Air Soil Pollut*. 2012;223(7):4253-4273. doi: 10.1007/s11270-012-1189-2
37. Liu T, Lawluvy Y, Shi Y, Yap PS. Low impact development (LID) practices: A review on recent developments, challenges and prospects. *Water Air Soil Pollut*. 2021;232(9):344. doi: 10.1007/s11270-021-05262-5
38. Jia H, Wang Z, Zhen X, Clar M, Yu SL. China's sponge city construction: A discussion on technical approaches. *Front Environ Sci Eng*. 2017;11(4):18. doi: 10.1007/s11783-017-0984-9
39. Hu M, Zhang X, Siu YL, *et al*. Flood mitigation by permeable pavements in Chinese sponge city construction. *Water*. 2018;10(2):172. doi: 10.3390/w10020172
40. Guan X, Wang J, Xiao F. Sponge city strategy and application of pavement materials in sponge city. *J Clean Prod*. 2021;303:127022. doi: 10.1016/j.jclepro.2021.127022
41. Sharma R, Malaviya P. Management of stormwater pollution using green infrastructure: The role of rain gardens. *Wires Water*. 2021;8(2):e1507. doi: 10.1002/wat2.1507
42. Wang M, Zhuang JA, Sun C, *et al*. The application of rain gardens in Urban environments: A bibliometric review. *Land*. 2024;13(10):1702. doi: 10.3390/land13101702
43. Mooers EW, Jamieson RC, Hayward JL, Drage J, Lake CB. Low-impact development effects on aquifer recharge using coupled surface and groundwater models. *J Hydrol Eng*. 2018;23(9):04018040. doi: 10.1061/(ASCE)HE.1943-5584.0001682
44. Job C. A review of low-impact development factors affecting managed aquifer recharge. *Groundwater*. 2022;60(5):619-627. doi: 10.1111/gwat.13207
45. Nazarpour S, Gnecco I, Palla A. Evaluating the effectiveness of bioretention cells for Urban stormwater management: A systematic review. *Water*. 2023;15(5):913. doi: 10.3390/w15050913
46. Zhu Z, Chen X. Evaluating the effects of low impact development practices on Urban flooding under different rainfall intensities. *Water*. 2017;9(7):548. doi: 10.3390/w9070548
47. Garbanzos S, Maniquiz-Redillas M. Modeling the hydrologic performance and cost-effectiveness of LID

in a residential park area using a decentralized design approach. *Hydrology*. 2022;9(4):62.
doi: 10.3390/hydrology9040062

48. Fan G, Lin R, Wei Z, Xiao Y, Shangguan H, Song Y. Effects of low impact development on the stormwater runoff and pollution control. *Sci Total Environ*. 2022;805:150404.
doi: 10.1016/j.scitotenv.2021.150404
49. Liu BK, Armitage NP. The link between permeable interlocking concrete pavement (PICP) design and nutrient removal. *Water*. 2020;12(6):1714.
doi: 10.3390/w12061714
50. Sui X, Van De Ven FHM. The influence of low impact development (LID) on basin runoff in a half-urbanized catchment: A case study in San Antonio, Texas. *J Hydrol*. 2023;616:128793.
doi: 10.1016/j.jhydrol.2022.128793
51. Hou X, Qin L, Xue X, *et al*. A city-scale fully controlled system for stormwater management: Consideration of flooding, non-point source pollution and sewer overflow pollution. *J Hydrol*. 2021;603:127155.
doi: 10.1016/j.jhydrol.2021.127155
52. Barreira AP, Jacinto G. Clustered patterns of household water consumption in Portuguese municipalities: Do regional location and population trajectory matter? *Utilities Policy*. 2025;93:101887.
doi: 10.1016/j.jup.2025.101887
53. Kapanski AA, Klyuev RV, Brigida VS, Hruntovich NV. Temporal segmentation of urban water consumption patterns based on non-parametric density clustering. *Technologies*. 2025;13(10):449.
doi: 10.3390/technologies13100449