

Optimal allocation of low-impact development facilities for urban runoff reduction

Fan Wen^{1, a}, Qiangqiang Rong^{2, b *}, Zhihui Gu^{1,3, c}, Jinrong Zeng^{1, d}

¹ School of Architecture and Urban Planning, Shenzhen University, Shenzhen 518060, China;

² Research Center for Eco-Environmental Engineering, Dongguan University of Technology, Dongguan 523808, China.

³ Shenzhen Key Laboratory of Building Environment Optimization Design, Shenzhen, 518060, China

^a 2210326056@email.szu.edu.cn, ^b rongqq@dgut.edu.cn,

^c gzh@szu.edu.cn, ^d 2210326054@email.szu.edu.cn

Abstract. In the context of global climate change and urbanization development, the intensity and frequency of extreme rainfall events have increased significantly, while the proportion of impermeable surfaces in cities has been increasing. These changes have led to frequent urban flooding, which seriously affects the safety of people's lives and properties and restricts the high-quality development of urbanization. Low-impact development (LID) is an important way to effectively mitigate urban flooding. How to obtain the optimal runoff control effect through the deployment of LID facilities in the construction of sponge cities is an urgent problem to be solved. This study proposed a novel implementation framework for LID optimization based on SCS-CN model and used data from Shenzhen to verify the effects. The results shows that the optimization of LID facilities proves to be effective in flooding mitigation. The results of this study can support decision-making for urban flood mitigation and sponge city construction.

Keywords: Urban rainfall runoff; Low impact development; SCS-CN model; Shenzhen.

1. Introduction

In the context of climate change and rapid urbanization, extreme rainfall shows a trend of increasing frequency and intensity, resulting in excessively fast runoff generation after rainfall and increasing rainfall drainage pressure, which further increases the risk of urban flooding disasters [1, 2]. In order to cope with the increasingly serious problem of urban flooding, the concept of sponge city is applied in the urban construction process, and the construction of low impact development (LID) facilities is carried out to alleviate urban flooding [3, 4].

In the current research to optimize LID facility configurations, most studies utilized hydrological models to simulate rainwater generation and catchment process [4, 5]. These studies aimed to establish optimal configurations for LID facilities, culminating in a set of methods for their optimal allocation [6]. However, the hydrological model has high data requirements, such as pipe network data in the study area. They are not entirely suitable for regions in large scale, especially where such data is unavailable. Thus, it is necessary to devise a LID facility allocation method tailored for larger scales [7]. This study employs the SCS-CN model and ArcGIS software to simulate urban flooding inundation under various rainfall recurrence intervals. Simultaneously, an optimization model is formulated with the primary objective of maximizing runoff storage volume. This model can provide the configuration scheme for LID facilities that maximizes runoff control benefits. Ultimately, the effectiveness of this scheme in managing rainfall runoff is verified, offering valuable insights for LID. This study provides important information for urban planners to support decision-making on flood risk management and the construction of sponge cities.

2. Materials and methods

2.1 Study area

Shenzhen City is located in the southeastern part of Guangdong Province (113°46'-114°37' E, 22°27'-22°52' N). It is on the east coast of the Pearl River Estuary, bordering the South China Sea. Shenzhen City covers an area of 1997.47km², with the terrain high in the southeast and low in the northwest, in a long and narrow east-west shape. This site has a subtropical monsoon climate and the rainy season lasting from April to September with an annual average rainfall of 1966.5mm. As Shenzhen is located in an area with frequent coastal typhoon landfalls, the frequency of extreme rainfall events has increased with the impact of climate change, exposing the city to an increasing risk of flooding.

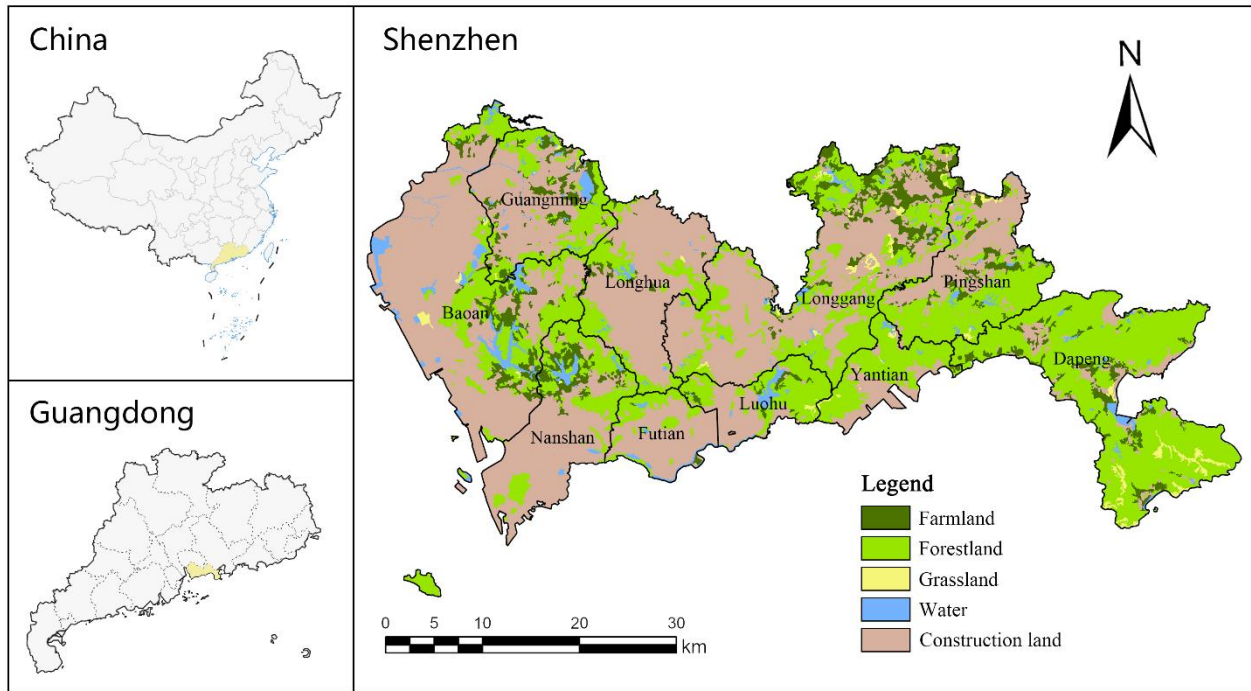


Fig. 1 Location and the land cover of Shenzhen City.

2.2 Runoff calculation

The SCS-CN model is a runoff curve model developed by the United States Department of Agriculture (USDA) in 1954. Its simple structure, high simulation accuracy, and minimal required parameters have made it a valuable tool in storm simulation and prediction, water resource management, and runoff estimation [8]. The model quantifies different soil types and land use types as parameters to calculate surface runoff, enabling the study of the interplay between subsurface and surface runoff [9,10]. In this study, the SCS-CN model and ArcGIS software are used to simulate the flood inundation in the study area under different rainfall return periods. The calculation principle of the SCS-CN model is as follows:

$$Q = \begin{cases} \frac{(p - I_a)^2}{(p - I_a + S)}, & p > I_a \\ 0, & p < I_a \end{cases} \quad (1)$$

$$S = \frac{25400}{CN} - 254 \quad (2)$$

$$I_a = \lambda \times S \quad (3)$$

where Q is the surface runoff depth (mm); p is the precipitation (mm); S is the potential maximum water storage in soil (mm); CN is the curve number ranging from 0 to 100; I_a is the

soil abstraction (mm); and λ represents the initial abstraction rate, usually set to 0.2 according to experience [11].

The important parameter factor CN value of the model is a key parameter that can reflect the characteristics of the catchment area before rainfall, which is determined by soil moisture and soil type. In this study, the calculation of runoff under average moisture conditions (AMC- II) in Shenzhen was undertaken. To accurately calculate regional surface runoff and assess water accumulation within the city, the study employed a weighted summation method to adjust the CN values of sub-catchments based on land use proportions.

Table 1. Comparison table of CN value in Shenzhen

Landuse	Soil hydrological groups			
	A	B	C	D
Farmland	67	78	85	89
Forestland	25	55	70	77
Glassland	39	61	74	80
Water	98	98	98	98
Construction land	85	90	94	96
Bare land	77	86	91	94

$$CN_n = \sum_{i=1}^n CN_i \times W_i \#(4)$$

where CN_n is the final value of the n-th sub-catchment; CN_i is the original value of each land-use type; and W_i is the weight of each land-use.

2.3 Calculation of water storage capacity per unit area of LID

Considering the constraints of the construction conditions and construction costs of each LID facility, permeable pavement (PP), sunken green space (SGS) and green roof (GR) were selected for optimization in this study. The volumetric method was used to calculate the amount of water storage of LID facilities, which is shown as follows:

$$V = 10 \times H \times \varphi \times F \#(5)$$

where V is the design water intake (m^3); H is the design rainfall depth (mm); φ is the integrated rainfall runoff coefficient; and F is the area of the target area (m^2).

The design water intake V for LID facilities with infiltration includes the effective storage and infiltration volumes, which is calculated as follows:

$$V = V_s + W_p \#(6)$$

$$W_p = K \times J \times A_s \times t_s \#(7)$$

where V_s is the effective storage volume (m^3); W_p is the infiltration volume (m^3); K is the soil permeability coefficient (m/s); J is the hydraulic gradient, usually taking the value of 1; A_s is the effective infiltration area (m^2); t_s is the infiltration time (s), usually taking 2h. The results of the unit storage capacity of PP, SGS, and GR are 0.10, 0.16, 0.2 m^3/m^2 , respectively.

2.4 Establishment of optimization model

In this paper, we take the maximization of runoff storage of LID as the objective function, and the deployment areas of LID facilities as the constraints to construct an optimal design model of LID facilities. Specifically, the main purpose of deploying LID facilities is to increase the amount of rainfall runoff storage. Thus, the optimization objective of the model is to maximize the runoff storage.

$$\max V = \sum_{i=1}^n a_i \times S_i \#(8)$$

where V is the total runoff storage volume (m^3); a_i is the storage volume per unit area of the i -th LID facility (m^3/m^2); S_i is the construction area of the i -th LID facility (m^2).

In practical engineering applications, the implementation of LID is constrained by limited space, particularly in high-density urban environments. In the context of Shenzhen, the areas allocated for installing LID facilities in this study can not exceed 20% of the municipal area. The construction of PP is restricted to roads, sidewalks, and plaza sites, while SGS is primarily located in parks and road greening areas [12]. GR is primarily constructed on buildings with 12 floors or less and a height of less than 40 m. The above limitations can be combined with the control indexes for sunken green space rate and green roof rate according to the *Shenzhen sponge city design code*.

$$0 < S_i < S_{i(max)} \quad \#(9)$$

$$S_{PP} + S_{SGS} + S_{GR} \leq S_0 \quad \#(10)$$

where $S_{i(max)}$ is the limited maximum area of the i -th LID facility (m^2); S_{PP} , S_{SGS} and S_{GR} are the construction area of PP, SGS and GR, respectively; S_0 is the area of Shenzhen municipal.

The model was solved by the *Lingo* software. According to the existing research and information, the unit costs of PP, SGS, and GR are set as 130, 50, and 300 yuan/ m^2 , respectively.

3. Results

3.1 Analysis of flood inundation areas

In this paper, three extreme rainfall return periods of 20, 50 and 100 years are simulated. The inundation extent for different rainfall return periods are shown in Fig. 2. The inundation areas of the three return periods accounted for 4.71%, 5.41%, and 5.52% of Shenzhen City, respectively. The spatial distribution of inundation areas in Shenzhen City demonstrates a tendency to cluster around river corridors and along the coastline, primarily in low-lying regions with dense river networks. The inundation areas in Shenzhen under the rainfall recurrence period of 20 years is about 92.30 km^2 , which is the key area for the construction of LID facilities. At the rainfall return periods of 50 and 100 years, the extension of the inundation areas is larger in the northwest as well as in the east.

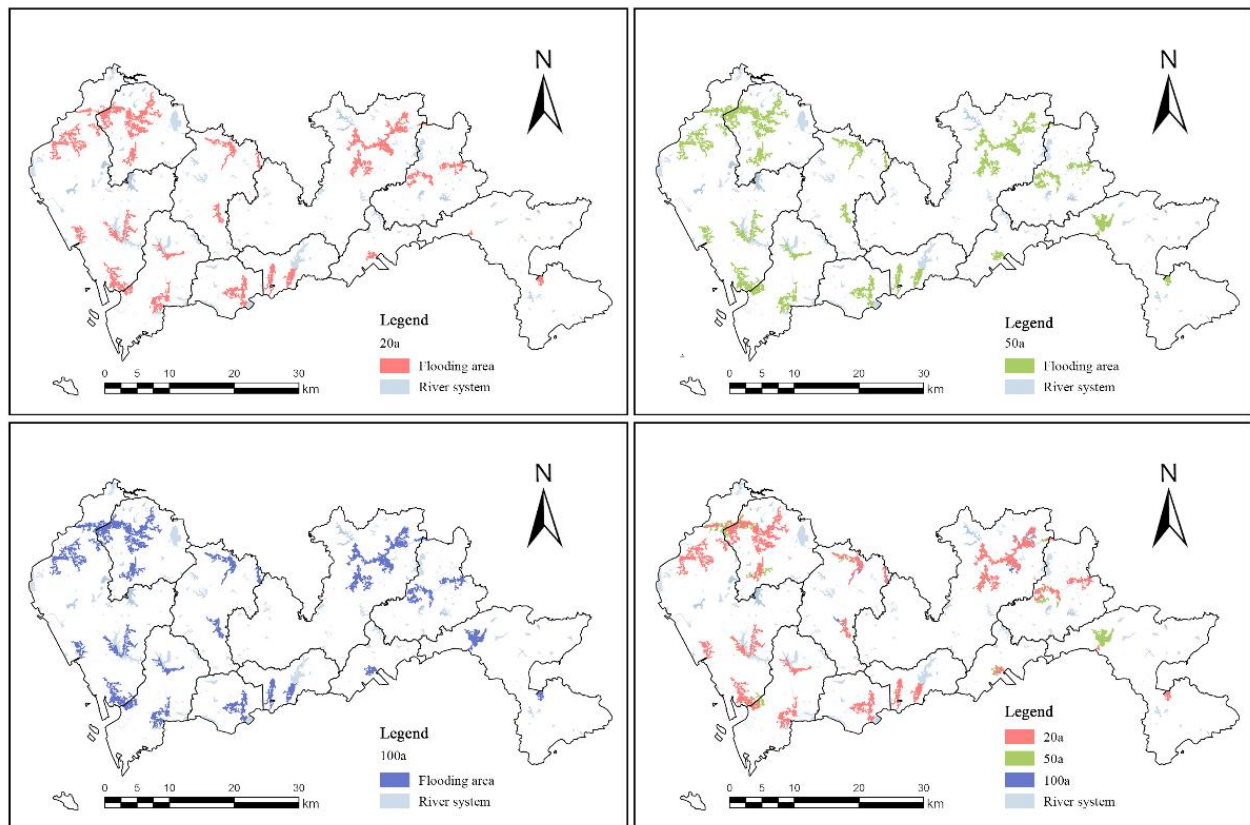


Fig. 2 Spatial distribution of inundation area during different rainfall return periods

3.2 Model solution and benefit analysis

3.2.1 Optimal configuration schemes of LID facilities

The optimization results show that PP, SGS, and GR would occupy 5.17%, 14.55%, and 1.67% of the municipal area of Shenzhen City, respectively. This optimization would lead to an increase in the runoff storage capacity by approximately 57939100 m³. The total cost of the optimized scheme would be approximately 4.0×10^9 yuan (Table 2). Notably, sunken green spaces would have the most significant impact on reducing runoff, indicating their crucial role in enhancing the city's water management capabilities. Therefore, under the requirement of maintaining a certain rate of sunken green spaces, it is advisable to increase their renovation and construction rate.

Table 2. Optimal areas of different LID facilities and the corresponding cost and runoff storage

LID Type	Area (km ²)	Runoff storage volume ($\times 10^4$ m ³)	Cost ($\times 10^4$ CNY)	Area proportion (%)
PP	10.366	1033.55	134361.5	5.17
SGS	290.605	4649.68	232484.0	14.55
GR	5.534	110.68	33204.1	1.67

3.2.2 Optimization benefit analysis

The impact of the LID optimization on runoff storage volume is compared with a designed scenario for extreme rainfall-induced flooding. The benefits of inundation volume reduction and the changes in average ponding depth for LID facilities under various rainfall return periods are calculated (Table 3). The results show that the volume of flooding water would be substantially reduced in the three rainfall recurrence periods, after optimal implementation of LID facilities. This reduction has a significant effect on mitigating inundation during extreme rainfall events. Additionally, the average depth of waterlogging would be also notably reduced, which is effective in preventing and controlling urban flooding. Specifically, the runoff reduction amplitude for the

three rainfall recurrence periods would be 82.57%, 70.50%, and 63.43%, respectively. This suggests that the LID practices are more effective in reducing medium and smaller rainfall runoffs.

Therefore, in the context of sponge city construction, the deployment of LID facilities should be integrated with urban inundation zoning. This includes increasing the rate of SGS in green areas close to main rivers and low-lying areas, enhancing surface permeability, increasing the proportion of PP, and promoting the construction of GR. These measures are expected to enhance the city's ability to manage rainfall and runoff, ultimately contributing to sustainable urban development and community resilience.

Table 3. Comparison of water-logging amount before and after Optimization

	Return period of rainfall		
	20 a	50 a	100 a
Volume of standing water before modification ($\times 10^7 \text{ m}^3$)	12.17	14.26	15.84
Depth of water before modification (m)	0.09	0.11	0.12
Volume of water after modification ($\times 10^7 \text{ m}^3$)	2.12	4.21	5.79
Depth of water after modification (m)	0.02	0.03	0.04
Volume of water reduction (%)	82.57	70.50	63.43

4. Summary

Based on the sponge city theory, this study explores the allocation method of LID facilities in response to extreme urban rainfall scenarios. The study utilizes the SCS-CN hydrological model in conjunction with ArcGIS software to calculate waterlogging volumes and simulate inundation scenarios across various rainfall recurrence periods. Additionally, by considering the current urban conditions, this study formulates an optimization model that aims to maximize runoff storage while adhering to the deployment area limitations of each LID facility. This optimization model offers a valuable reference for sponge city construction. The results of the case study in Shenzhen demonstrate that LID can enhance the ability of cities to cope with extreme rainfall events. Specifically, SGS would have the most significant runoff reduction effect, and it is recommended that the proportion of SGS should be increased. The optimal LID facility configuration scenario would reduce the amount of water by 579391100 m^3 . This option would reduce more than 60% of the water volume for the three extreme rainfall return periods, thereby mitigating regional inundation. In addition, the study simulated the inundation under different rainfall scenarios. When carrying out sponge city construction, the distribution of inundation areas can be considered for phased construction of LID facilities.

However, it is worth noting that this study primarily focuses on natural factors such as subsurface conditions and elevation for inundation simulation. Future research should incorporate the city's drainage capacity to improve the accuracy of flooded inundation zone identification. Furthermore, the spatial optimization of LID facilities needs further exploration to provide more scientific and comprehensive solutions

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