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Analysis and Validation of Sponge City Construction in Mountainous Cities based on SWMM - Taking Nanan District of Chongqing as an Example

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Abstract:

Sponge city construction is one of the key topics in today's research. China's sponge city construction has gradually entered the stage of optimization and effect evaluation. However, there are still some gaps in issues such as the verification of the effect of sponge cities. Therefore, in this paper, Storm Water Management Model (SWMM) is carried out by collecting data on surface runoff, waterlogging, peak flow, control rate, etc. in Nanan District of Chongqing City. At the same time, reasonable Low Impact Developments (LID) facilities such as rain gardens, permeable paving, bioretention tanks, rain barrels, rooftop rainwater harvesting and rooftop gardens are incorporated into the sponge city design and verified by using a typical rainfall process with a return period of 5a and a duration of 3 hours. The results of the study showed that the surface runoff drainage time in one catchment was 11.1% faster before and after the LID facilities were installed in contrast, the peak flow reduction rate of the main pipe was 71.55%, and the average runoff control rate in each catchment was around 40.57%. In conclusion, the LID facilities are not effective enough to reduce the rainfall runoff above the medium rainfall, while they are more effective below the medium rainfall.

Keywords: SWMM; sponge city; mountainous city; LID facility.

1. Introduction

Chongqing, as the only municipality directly under the central government in Southwest China, the construction demand and scale of sponge city are gradually increasing. According to the requirements of the construction department, the civic living area is also the key area of the sponge city design. In the sponge city design, the construction and renovation projects of urban living areas are full of complexity and diversity, with many roofs, large hardened ground areas, and scattered green arrangements [1]. On the one hand, a large amount of rainwater is easy to form a depression, resulting in serious runoff pollution, affecting the normal life of citizens. On the other hand, most urban land was built in the last century, making it difficult to arrange Low Impact Development (LID) projects effectively. Large-scale construction will also affect the lives of citizens.

An effective strategy for building a sponge city is to use LID facilities. This is a sustainable approach to urban flood management. The goal of LID is to compensate for the impact of land development on the on-site hydrological cycle and water quality by utilizing natural processes. Unlike traditional stormwater management systems, which tend to collect and discharge stormwater runoff into downstream drainage systems or outlets, LID focuses on local treatment, control and infiltration of stormwater runoff at the source.

Chongqing, an important city in southwest China, was listed as one of the first batch of pilot cities for sponge city construction in China in 2015. Chongqing is located at the confluence of the Yangtze River and Jialing River. The mountainous terrain and frequent rainfall have led to serious urban waterlogging problems. Therefore, the government has adopted many LID facilities to build sponge cities, and has also achieved important achievements in reducing waterlogging, improving water quality, and improving the ecological environment. In the study of Chen et al. [1], Storm Water Management Model (SWMM) was used to fully verify the feasibility of building a sponge city in Chongqing Industrial Park.

In a study on landslides, Kumar et al. [2] summarized the variables, Natural Based Solution (NBS) types and most commonly used models used to understand landslide hazards [2]. In particular, they mentioned the way roots strengthen soil structure and the Root Bundle Model

(RBM) used to quantify root strength, which helps to enhance slope stability. At the same time, it has a high demonstrative value in mountainous cities with high slope rates.

In the study by Hamidi et al. [3], the concept of sponge city was found to be globalized. The study showed that the concept of sponge city is spreading from developed countries to developing countries, such as China's important position. China plays an important role in the research and practice of sponge city, especially in its high-impact institutions and researchers. Chinese institutions have the highest betweenness centrality in sponge city research, indicating that they play a bridging role in the research network [3]. At the same time, a scientific quantitative analysis of the sponge city field was introduced, which used CiteSpace and SWMM software for analysis [3]. The article pointed out that emerging keywords such as "resilience" and "hard surface" indicate that the practice of sponge city is moving in a more practical direction [3]. In addition, computer science and its sub-disciplines – Geographic Information System (GIS) have also played an important role in changing the structure of sponge cities [3].

In the study by Gulshad et al. [4], a sensitivity analysis was conducted to help understand how weights and scores affect the geographical location construction of LIDs and was validated based on GIS and Multi-Criteria Decision Analysis (MCDA). In the study by Chen et al. [5], the focus was on the comparative analysis of LID site selection methods, especially the details of LID site selection methods and their characteristics in practical applications [5]. They used LID Demand Index, GIS-based MCDA and SUSTAIN LID Site Selection Tool for data attributes and analysis scale. They also used the website "https://xiangtan.crctool.org/" to study the methods of sponge city planning in China and conducted a case study of Qinhuai District, Nanjing [5]. By comparing Nanjing Sponge City Planning with Auckland Water Sensitive Urban Design (WSD), the study pointed out the key problems in Nanjing Sponge City Planning, including the lack of flood control goals, planning intervention strategies and interdisciplinary cooperation tools [5].

In this paper, SWMM software is used to model Nanshan Scenic Area in Nanan District of Chongqing, and the feasibility of sponge city construction is verified by comparison. In addition, surface runoff and water storage in catchment area after rainfall as well as peak discharge of main drainage pipes are analyzed to demonstrate the effect and significance of LID facilities and sponge city construction. The study is also supported by the Xiangtan Adaptation Support Tool.

2. Research Methods

2.1 Model Overview

SWMM software is a computer program developed by the US Environmental Protection Agency (EPA) for urban watershed hydrological simulation. This software is mainly used to simulate rainfall runoff processes, the water quality and quantity in mixed sewage systems, and can also simulate sponge city construction. SWMM can be used to help planners better understand the behavior of stormwater management and sewage treatment systems, and can be used to design new or improve existing urban drainage systems. It has the characteristics of modular parameter management, running simulation, and data output. This research project is located in Nanshan Scenic Area and Nanbin Road (part) in Nanan District, Chongqing. The total planned area is 61.8 hectares, including urban express highway, water amusement parks, villa residential areas, high-density residential areas and commercial areas, divided into 10 catchments and shown in Fig. 1. The proportion of LID facilities in each catchment ranges from 76.67% to 8.45%. This model has a total of 16 simplified pipelines, 13 nodes, and 1 external outlet to the Yangtze River. The Yangtze River is 147 meters above sea level, and from left to right are 237 meters and 323 meters (the lowest point).

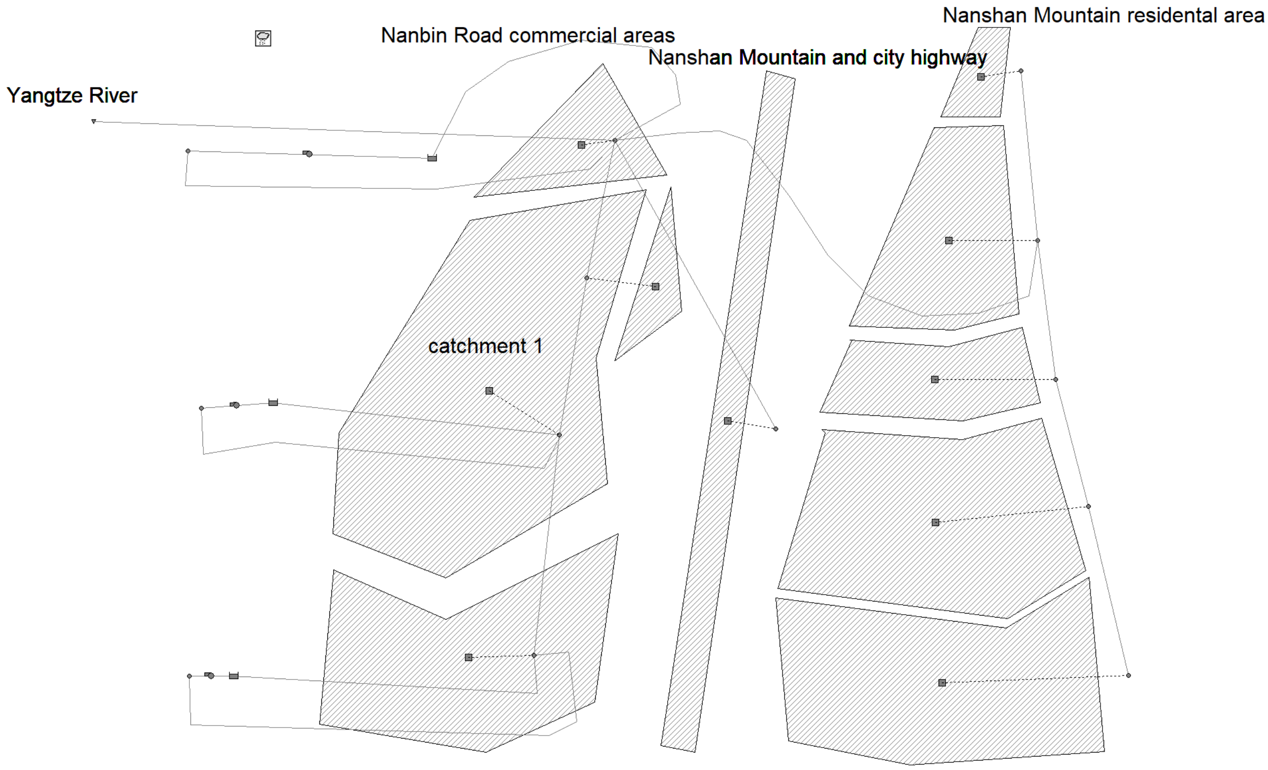

Fig. 1 SWMM modeling overview

According to DBJ 50/T-292-2018 “Low Impact Development Stormwater System Design Standard”, the rainstorm intensity formula for the study area is shown in Eq. (1) [6]. The model precipitation type selects the Chicago rainfall type generated by Eq. (1) for analysis [7].

$$q = 1898(1+0.867lgP)^{\cdot\cdot}M(t+9.480)^{0.709} \quad (1)$$

where q is the rainstorm intensity [L/(s•hm2)], P is the design return period (a), and t is the rainfall duration (min). A typical rainfall process with a return period of 5a over 3 hours is therefore derived as in Fig. 2.

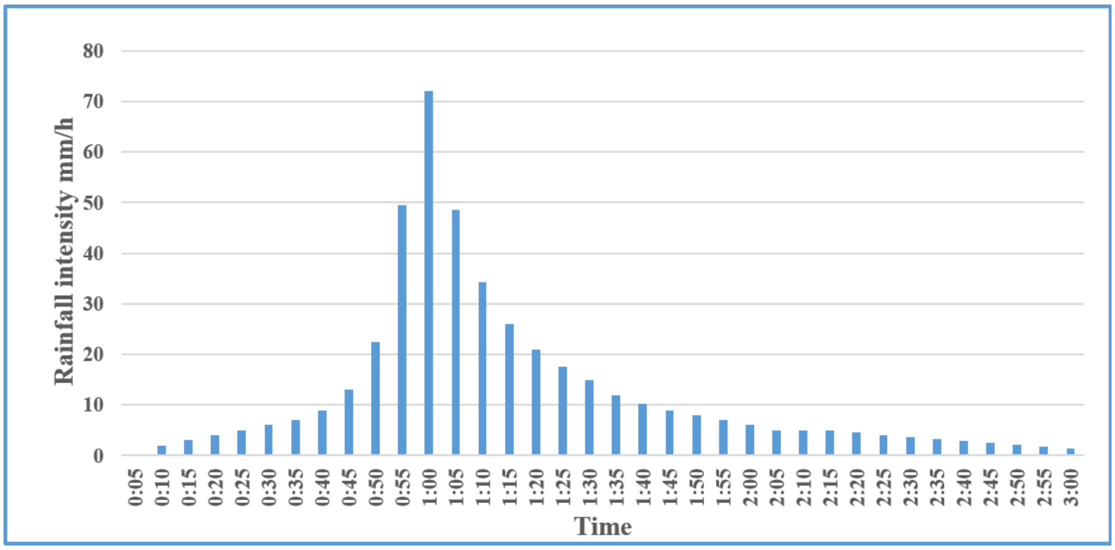

Fig. 2 Precipitation Intensity

2.2 Cost Evaluation Indicators ($C_{o\&m}$)

The cost assessment indicators include the estimated construction and maintenance costs of the sponge technology solution ($C_{o\&m}$), where the construction costs are included. Maintenance cost period is the same as the return period – 5 years [8].

$$C_{o\&m} = C_{capital} + \sum_{t=1}^{n} Pmt \quad (2)$$

$$Pmt = Fmt / (1+d)^t \quad (3)$$

$$Fmt = C_{capital} * p * (1+r)^t \quad (4)$$

In Eq. (2) to Eq. (4), $C_{capital}$ refers to the construction cost of the technical solution for sponge facility systems. Pmt refers to the present value of the maintenance cost of the sponge facility in the t years, Fmt refers to the inflation value of the maintenance cost of the facility in the t years, d is the discount rate, n is the operating years of the facility, r is the inflation rate, and p is the proportion of the annual operation and maintenance cost of the facility to the initial cost. The values are shown in Table 1.

Table 1. Cost evaluation index values [8]

Index	$C_{capital}$	Pmt / ￥/yr	Fmt	d	n	r	p	$C_{o\&m}$
Value	22447222	4405000	100000	8%	5	3%	3.7%	44472222

2.3 Modeling Ideas and Parameter Settings

The improved Horton infiltration model is used to calculate rainfall infiltration in the whole map, where the maximum infiltration rate is 86 mm/h, the minimum infiltration rate is 12 mm/h, the infiltration decay coefficient is 4 h^{-1}, and the drainage time is 7 days [1]. Other parameters are shown in Table 2.

Table 2. Regional infiltration parameters [1, 8]

Index	Impervious surface roughness	Pervious surface roughness	Impervious surfaces depression storage depth of water/ mm	Pervious surfaces depression storage depth of water/ mm	Surface Manning's coefficient for impervious areas	Surface Manning's coefficient for pervious areas
Value	0.012	0.15	1.27	6.4	0.015	0.304

This study analyzes the feasibility and effect of building sponge cities in mountainous areas. Urban land with an impermeability of 70%-80% is used for sponge city planning by using LID facilities. The specific research method is to compare the peak flow difference between the main drainage pipes of traditional cities after the construction of sponge cities.

The LID facilities used include roof gardens, bioretention tanks, rain gardens, rooftop water collection measures, permeable paving and rain barrels. Because most urban ground is impermeable paving and hard ground, the LID facilities in some areas need to work together with reservoirs and pumps to achieve the ideal sponge city construction effect.

In the plan, the right half is located on Nanshan Mountain, which is a low-density residential area, villa area and water park, which is conducive to the construction of LID facilities. The middle part is a heavy urban highway, so a small amount of permeable pavement and rain barrels can be laid to achieve the goal. The left half of the plan is a commercial area near the Yangtze River, with more hard roads and scattered green spaces. Therefore, LID facilities must be combined with reservoirs and water pumps to achieve ideal working conditions.

Considering the cost of LID facilities, this research project uses LID facilities reasonably to achieve maximum cost-effectiveness. Among them, the villa area is most suitable for arranging roof gardens, considering that the roofs are small and dense. The water park is large and surrounded by forests. Furthermore, the additional water is used, so rain gardens are most suitable. High-density residential areas are high-rise community buildings, so rainwater collection systems are set up on the roofs to reduce surface runoff. The commercial area is located on hard and paved ground, so a small amount of bioretention tank is sufficient. The highway can use permeable paving and rain barrels to reduce surface runoff.

3. Results and Discussion

It can be seen from Fig. 3 and Fig. 4 that after the sponge city designs and arranges LID facilities, the peak discharge volume is significantly reduced, the reduction is 71.55%, and the average runoff control rate in each catchment is around 40.57%. In addition, due to the intervention of LID, the surface runoff in catchment area will quickly drain into the LID facility or tank or undergo infiltration after experiencing short-term water accumulation, as shown in Table 3, which is 11.1% faster in comparison.

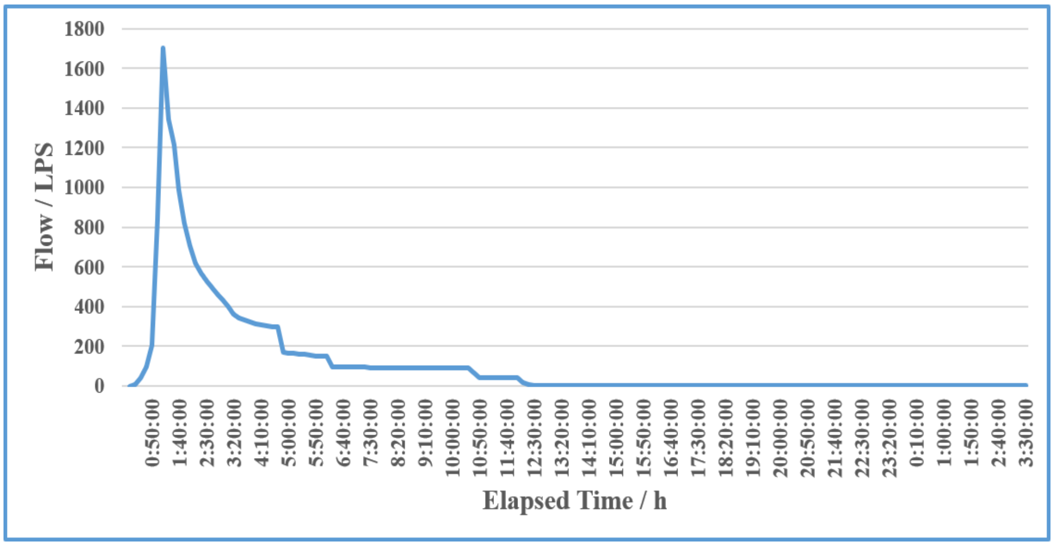

Fig. 3 Peak flow of main pipeline after construction of sponge city

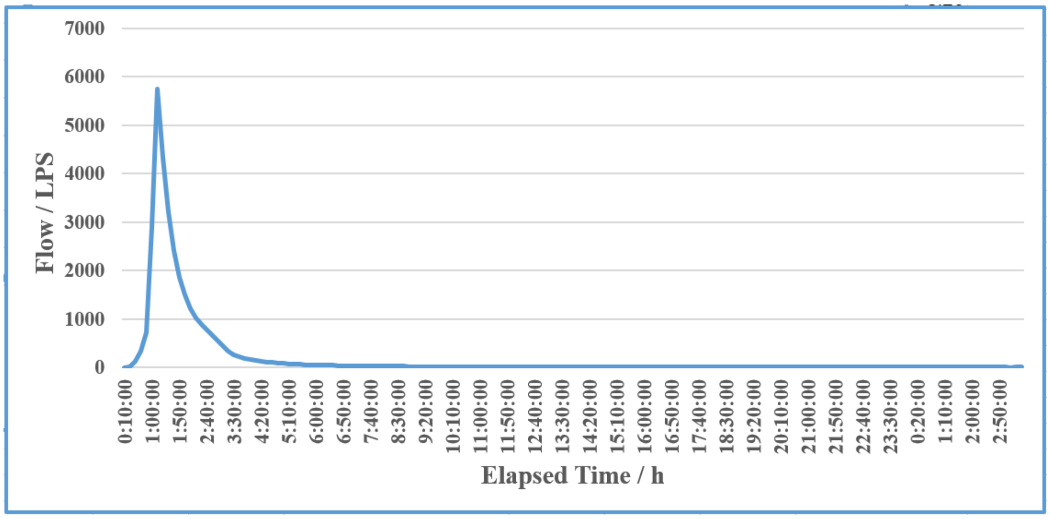

Fig. 4 Peak flow of main pipeline before building sponge city

Table 3. Time to drain accumulated water before and after the construction of sponge city in catchment area 1 (unit: hours)

Catchment 1	After building a sponge city	Before building a sponge city
Draining time	8.0	9.0

Research results show that the adoption of sponge city management strategies and the rational use of LID facilities and reservoirs can significantly improve the carrying capacity of urban drainage systems, ensure the normal operation of urban water environment functions, and help save water resources and protect the ecological environment. Therefore, this sponge facility has a good positive effect when facing rainfall within 5 years return period, and has a better peak flow control effect. The reduction is 71.55%. The positive effects include but are not limited to: drainage time, flow delay, green and carbon reduction [9]. At the same time, the runoff of the catchment area at the time of peak flow has a certain reduction, which also indirectly shows that the peak time of each catchment area has a certain delay after the construction of the LID facility [10]. In addition, the drainage time of the waterlogged area has also been reduced: it is 1 hour faster after the rain stops, which is 11.1% faster. This will help increase the safety of the city, because the accumulated water can be drained quickly, and it will be more convenient for citizens to travel after the rain. Problems such as traffic congestion caused by urban flooding and urban waterlogging will also be solved.

Research has found that for a single rainfall event, the annual runoff control rate, peak shaving effect, and local water accumulation in living areas are mainly achieved by source regulation and storage of LID facilities [1]. In short, LID facilities can reduce the peak flow in the main pipeline caused by a rainfall with a 5a return period lasting 3 hours, but it is difficult to achieve low total effluent flow and high annual runoff control rate.

Furthermore, urban rainstorm water is more likely to cause urban pollution. From 2010 to 2021, the correlation between various pollutants in rainfall runoff in the main urban area of Chongqing showed an increasing trend [11]. In the latest research on rainfall runoff from roofs and pavements, SS has a significant correlation with COD, NH3-N, TN, and TP. Therefore, technical improvements such as LID purification of rainwater and water storage play a leading role in the impact of rainfall runoff water quality [11].

Although urban planning has various sponge facilities such as LID facilities, the runoff control rate is poor (not reaching the standard 65%) for typical rainfall with a return period of more than 5 years and lasting 3 hours, which will significantly increase flood season insecurity and urban waterlogging. The reason is probably that except for the reservoir, the existing facilities are all runoff source control facilities, i.e. LIDs, and are subject to greenfield layout constraints, civic amenity land constraints, etc., and the rainfall is heavy and persistent, resulting in low overall hydrological control performance of the system [8]. Studies have shown that LID facilities are not effective in reducing rainfall runoff above moderate rain [12]. Secondly, this study found that building rain barrels on highways is a relatively effective solution. Studies have shown that rain barrels are small in size and can help reduce high runoff peaks [13]. Their construction and maintenance costs are much lower than reservoirs, and they can also improve the aesthetics of the city.

4. Conclusion

In summary, this study successfully verified the feasibility of building sponge cities and LID facilities in mountainous cities.

(1) This study adopted a variety of LID facilities, which led to cost issues such as municipal expenditures. At the same time, the city built a reservoir, indicating that the LID facilities were not used efficiently. The plan still needs to be improved to achieve the best balance between cost and efficiency.

(2) This study verified that the water storage and drainage after the construction of LID facilities in mountainous cities with high slopes can help improve the hydrological resilience of urban sponge city construction. This shows that the construction of sponge cities has better improvements in the above aspects.

(3) The impermeability of hard urban ground is generally 70% or above, which makes it difficult for the streets to penetrate or drain away in a short period of time after being saturated with water after heavy rain. The short-term peak value of each catchment area in response to continuous rainfall gradually increases and gradually approaches the runoff peak under the traditional development model, bringing serious waterlogging risks.

(4) The construction of sponge cities still has a certain effect on surface runoff and water accumulation, which can be reflected in facilitating citizens' travel, beautifying the environment, reducing the urban heat island effect and increasing cool places.

The future vision of sponge cities revolves around how to better utilize and manage urban water resources to meet the challenges of climate change. This concept focuses on improving the adaptability and resilience of cities by mimicking the natural water cycle process. The following are some key directions for the future development of sponge cities:

(1) There is a need to support the planning and management of sponge city projects, which includes the use of big data, artificial intelligence and machine learning to improve the ability to predict and respond to extreme weather. In addition, smart monitoring systems will be more widely deployed to achieve real-time monitoring of urban hydrological conditions.

(2) Policymakers will increase support for sponge cities, including providing financial subsidies, tax incentives and other incentives to encourage the private sector to participate in the construction and operation of sponge cities. At the same time, the government will also promote cross-departmental cooperation to ensure the effective implementation of sponge city projects.

(3) technological innovation will play an important role in the future development of sponge cities. This includes the development of new permeable materials and technologies, as well as the creation of facilities such as smart

rain gardens and permeable paving to improve the performance and durability of LID facilities.

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