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SWMM-Based Assessment of Urban Mountain Stormwater Management Effects under Different LID Scenarios

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Abstract: The types of urban mountains are diverse, and the surrounding environment is complex. The conditions of runoff generation and convergence in different regions of the same mountain vary. Using the Lijia Mountain in China's Nanjing City as a case study, this study investigates the effects of such mountain-region-based LID (Low Impact Development) systems. Based on the hydrological analysis of this mountain region, SWMM (Storm Water Management Model) software is used to model and compare the runoff control effects of two LID systems schemes, namely segmental detention and retention and terminal detention and retention. The study's findings demonstrate that the terminal detention and retention scheme can effectively delay the time of peak flooding and partly reduce peak discharge. In contrast, the segmental detention and retention scheme has a limited delay effect on flood peaks but significantly reduces the peak discharge. This research breaks through the limitations of the previous construction of a single LID scheme for mountainous regions in built-up urban areas. It serves as a theoretical model and technical reference for selecting LID scenarios in response to different mountain conditions.

Keywords: low impact development; mountainous urban regions; stormwater management; SWMM simulation; effect assessment

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1. Introduction

Extreme weather events are becoming more common and occurring globally due to global warming, especially in China [1]. Intense storms and torrential rains have been more common in China in recent decades [2], leading to numerous occurrences of severe flooding, which has become another major "urban disease" related to traffic congestion and pollution [3]. In response to a range of rain and flood-related issues associated with its urbanization process, China has actively promoted the construction of a new urban construction model dubbed "sponge cities" [4]. Low impact development (LID) is one of the theoretical foundations for sponge cities [5]. It is critical towards systematically solving water-related environmental problems of urbanities while boosting their long-term sustainability. LID is one of China's most recent and commonly used stormwater management tools, having been previously employed in theoretical research and practical applications in the United States, Germany, New Zealand, and other countries. In the past decade, LID research trends have shifted from focusing on singular cases and technical designs to broader urban planning research and cost-benefit analysis [6,7]. The underlying concept of sustainable development is also being expanded to various fields and aspects, and more emphasis is being placed on the employment of creative models or methods to solve the problem of total utilization of resources [8–11]. China has made significant efforts to theoretically research and physically explore the LID subject with the advent of sponge city construction. In terms of theoretical research, the emphasis has frequently been placed on quantitative assessments of the overall advantages and LID policies. Various information technologies (IT) are utilized to depict stormwater management processes and the collaborative planning of urban green space systems [12–14]. In terms of practical applications, efforts have primarily been directed toward addressing urban droughts and floods, including the construction of LID municipal roads in sponge cities, LID-based residential space planning, and design, optimizing the stormwater-collection capacities of green spaces, and the restoration of urban water systems and wetland ecosystems [15–17].

In China, mountain regions are vast, with complex and diverse ecological types that have long-term and varied interactions with mountain ecological succession [18]. Raised landforms, such as mountains and hills, are the vital component of many urban green spaces and are more complex than other types of green spaces in terms of their associated topographic and hydrological processes [19]. They are among the significant items in the development of sponge cities and stormwater management. In the event of flash floods, unlike in the city's relatively flat areas, there can be a rapid convergence of stormwaters in the mountainous regions of urban areas, which can easily result in landslides, downstream flooding, and other disasters [20,21]. In return, these effects pose threats to surrounding urban roads and construction areas' safety and place great pressure on municipal pipeline networks. As such, establishing an effective LID system for the mountainous regions of built-up urban areas may significantly affect the mountain environment itself its urban surroundings. Thus, it has a significant positive effect become a new focus area of LID and stormwater management research.

Derdour Abdessamed [22] employed a parameterization method to assess urban, mountainous areas with a high flood risk under arid conditions, demonstrating the necessity to research and design LID systems for such places. Liu Enxi et al. [23] investigated multi-scale stormwater management techniques for small mountain communities using quantitative and visual methodologies. Ambika Khadka et al. [24] analyzed and compared various stormwater management measures, concluding that water storage could be used as an indicator of flood resilience. M. Johst, S. Uhlenbrook et al. [25] enhanced the model TACD (tracer aided catchment model) and performed a good runoff simulation of the Loehnersbach watershed in the kitbueheler mountain area of the Austrian Alps. According to Sami Towsif Khan et al. [26], dispersed, retrofitted, and small-scale solutions could dramatically reduce impermeable surface runoff during frequent, less violent storm occurrences and delay peak surface runoff. These and other previous studies have looked at the impacts of hydrological changes on mountain habitats, the construction of mountain drainage systems, and simulated and forecasted mountain stormwater runoff, among other areas. Their technological approaches and simulation methods are extremely useful for this paper. In terms of previous literature in this field, Liu Jialin et al. [27] have explored the mountain parks' stormwater management based on the comprehensive performance of hydrological cost-effectiveness of their varying landscape system design strategies. Liu Jun et al. [28] summarized the characteristics and functions of the four types of sponge green spaces in mountainous cities. They proposed a way to construct three-dimensional sponge green spaces in mountainous cities. Meanwhile, Hou Qinghe, Yuan Yangyang, et al. [29] investigated the hydrological characteristics and processes of mountain parks' and put forward several partitioned and hierarchical LID systems design strategies. Černohous V. et al. [30] compared the impacts of different drainage systems on stormwater runoff in mountainous areas and discovered that both static and dynamic retention systems would function effectively. The above researches focus on the simulation of rainfalls in a mountain environment and different LID system construction schemes. The performance assessment focuses on comparing and selecting various scheme proposals for a single LID system, not the control effects of stormwater runoff in specific LID scenarios. However, there is a large diversity of urban mountain types and forms, and their surroundings are quite complex. In contrast, the same mountain can often have varying runoff yields and flow convergence conditions across different areas. Therefore, to cope with the requirements of constructing multiple types of mountain LID systems, it is necessary to compare stormwater runoff flow, peak outflow, and the time to flood peak to evaluate the performance of stormwater runoff regulation and storage in different LID scenarios.

This paper investigates this issue by comparing the effects of two LID system schemes: segmental detention and retention (Scheme S) and terminal detention and retention (Scheme T) on mountain runoff in a developed urban area. A quantitative comparison of the two schemes is conducted for stormwater runoff outflow and peak runoff characteristics during various rainfall return periods. The remaining sections of this paper are: Section 2 introduces the experimental platform, the specific case, methods for this study, and explains the SWMM (Storm Water Management Model) modeling process. The Section 3 examines and contrasts the simulation results of the two LID schemes. The Section 4 discusses the study's findings. This study's findings may support a robust theoretical foundation for projects involving the construction of mountain LID systems in built-up urban areas.

2. Materials and Methods

The study site has been chosen as Lijia Mountain in Nanjing City, China. The hydrology is analyzed using ArcGIS software. Then the pre-design model and simulation of the LID scheme are completed in the SWMM software. Finally, combined with the actual situation of the study site, the two LID schemes of the "segmental detention and retention" and "terminal detention and retention" LID system schemes (Scheme S and Scheme T, respectively) are designed. SWMM software is used to simulate and compare the performance of the two LID schemes on runoff detention and retention.

2.1. SWMM

This study utilizes urban hydrological and hydraulic models, focusing on the urban hydrological system's temporal and spatial changes. It is used to analyze the runoff yield and flow of surface convergence and infiltration of the catchment area and determine the ideal spatial distribution type and scale of the LID scheme [31]. The STORMWATER MANAGEMENT MODEL (SWMM) is a dynamic rainfall-runoff simulation model primarily used for single-event or long-term stormwater quantity and quality simulations in urban areas [32]. It is the most researched and widely applied urban hydrological and hydraulic model globally. As such, SWMM supports a robust theoretical foundation for designing LID systems.

SWMM software provides the Horton model, Green-Ampt model, and SCS curve to simulate the stormwater infiltration [33]. In dynamic simulations, the Horton model is most commonly used to represent the change in stormwater infiltration rates over time and predict the infiltration rates for saturated and unsaturated soils. The Horton model is also used for long-period simulations of rain. It involves several parameters, including the initial infiltration rate, saturated infiltration rate, and attenuation coefficient [34]. The Horton model provides three calculation methods for flow convergence and movement simulation: steady flow, kinematic wave, and dynamic wave. The dynamic wave equations are used to solve de Saint-Venant equations and thereby model flow routing. In theory, its results are also the most accurate and widely applicable [35]. Thus, this study's modeling and simulation used the dynamic waves equations.

2.2. Research Area

Nanjing, China, is a hilly city in a coastal plain region with relatively flat terrain and good natural conditions, located at 31°14″ N–32°37″ N and 118°22″ E–119°14″ E. Nanjing has a subtropical monsoon climate and average annual precipitation of 1106 mm. Rainfall is abundant but varies seasonally, with short-term heavy rain seen frequently in the summer. In this study, Lijia Mountain, located in Nanjing's Qixia District, is selected as the case study site. The mountain area encompasses 370,000 square meters, has a maximum altitude of 86.5 m. It is located in the low foothills of the adjacent Nanjing-Zhenjiang Mountains. With a maximum gradient of 45%, the terrain and slope vary significantly over the Lijia Mountain area. Despite the flat areas at the foot of the mountain, there are several valleys and hills. Many developed residential, educational, and commercial areas surround Lijia Mountain. This combination of features shows that Lijia Mountain is a typical mountainous region of a built-up urban area.

2.3. Research Methods

The technical research approach of this study, as indicated in Figure 1, covers three main segments: the hydrological investigation of the mountainous terrain, model creation and simulation, and comparison of the two LID systems. For the first segment, basic environment data was collected regarding the site's precipitation, soil type, vegetation coverage, and underlying surface type. Then, using ArcGIS software, a topographical and hydrological analysis of the site was performed, as well as an exploration of the hydrological characteristics of Lijia Mountain. According to the study's objectives and the terrain conditions, the current catchment was determined as the basis for constructing the SWMM model. For the second segment, prior to designing the LID models in SWMM, a combined mountain and stormwater model was constructed, including a mountain and precipitation model. Then, LID models were generated via the following three steps: (1) The SWMM software was used to generate the research area's sub-catchment, cut-off ditch, and outfall, and configure essential parameters such as the Manning coefficient, pipe roughness coefficient, infiltration rate, and attenuation coefficient; (2) Rainfall models for different return periods were built according to the Chicago rainstorm method; (3) Model validation was completed through the runoff coefficient. The grass gutter and wetland detention and retention models were selected for the third research segment to design and construct the two LID schemes of the "segmental detention and retention" and "terminal detention and retention" LID system schemes (Scheme S and Scheme T, respectively). The SWMM software was used to build relevant models, which were utilized to simulate and compare the outflow and peak runoff characteristics under different rainstorm conditions.

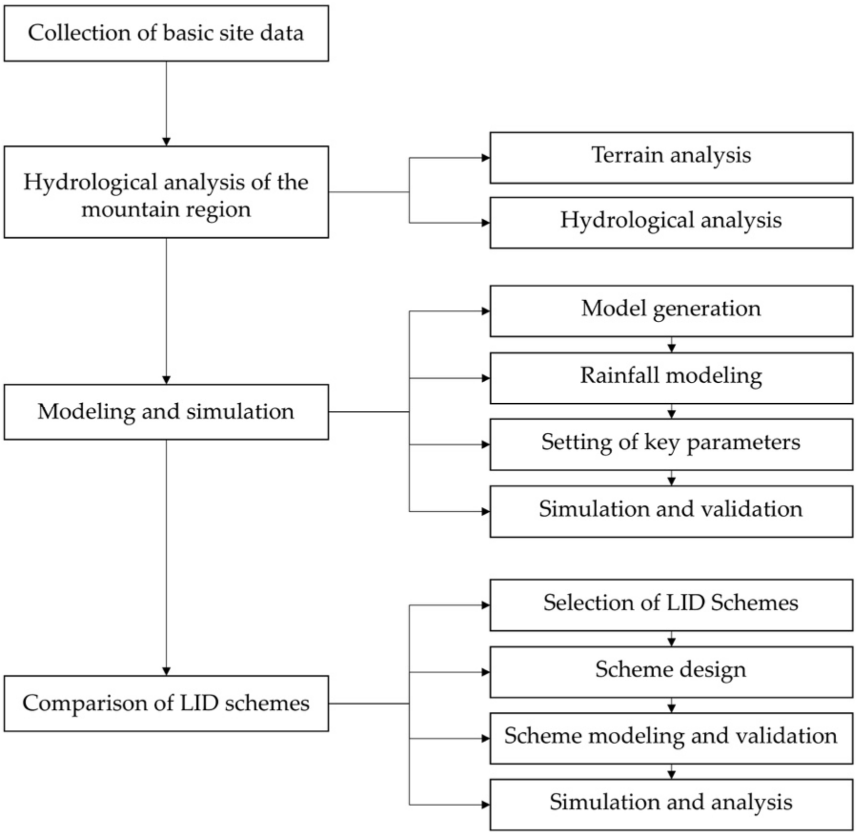


Figure 1. Overview of Technical Research Approach.

2.4. Modeling Process of SWMM

2.4.1. Construction of the Digital Model

ArcGIS software was used to analyze and process elevation data, generate a digital elevation model (DEM) for the study area, and analyze slope gradients and directions. Water flow directions and accumulation were computed using this data. Other significant hydrological information, such as runoff courses and pour points, was also analyzed and determined using ArcGIS. The mountain topography model was combined with the catchment partition data to produce 13 sub-catchment areas. ArcGIS was further used to analyze and determine other important hydrological information, including runoff paths and pour points (Figure 2).

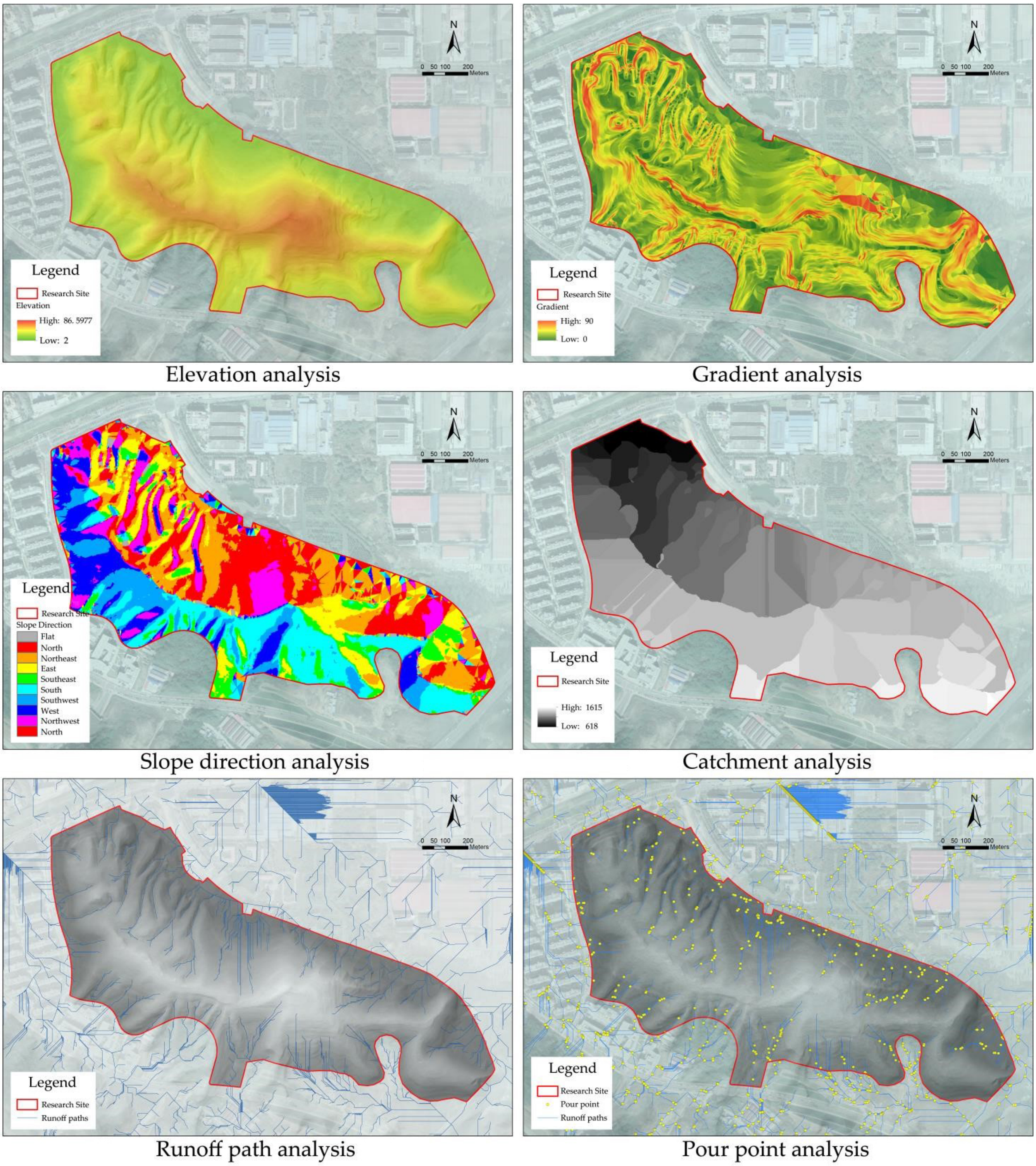


Figure 2. Topographical and Hydrological Analysis of Lijia Mountain.

It is necessary to convert the site's data into parameters recognized by the SWMM software before generating the SWMM model. According to the original runoff data of the mountain, the site's information was converted into the following parameters and input into the SWMM software: sub-catchments, conduit, and outfall. Figure 3 shows how a cut-off ditch (referred to as a conduit in the model) connects the 13 sub-catchments in the study area to achieve direct outflow without the need for LID schemes.

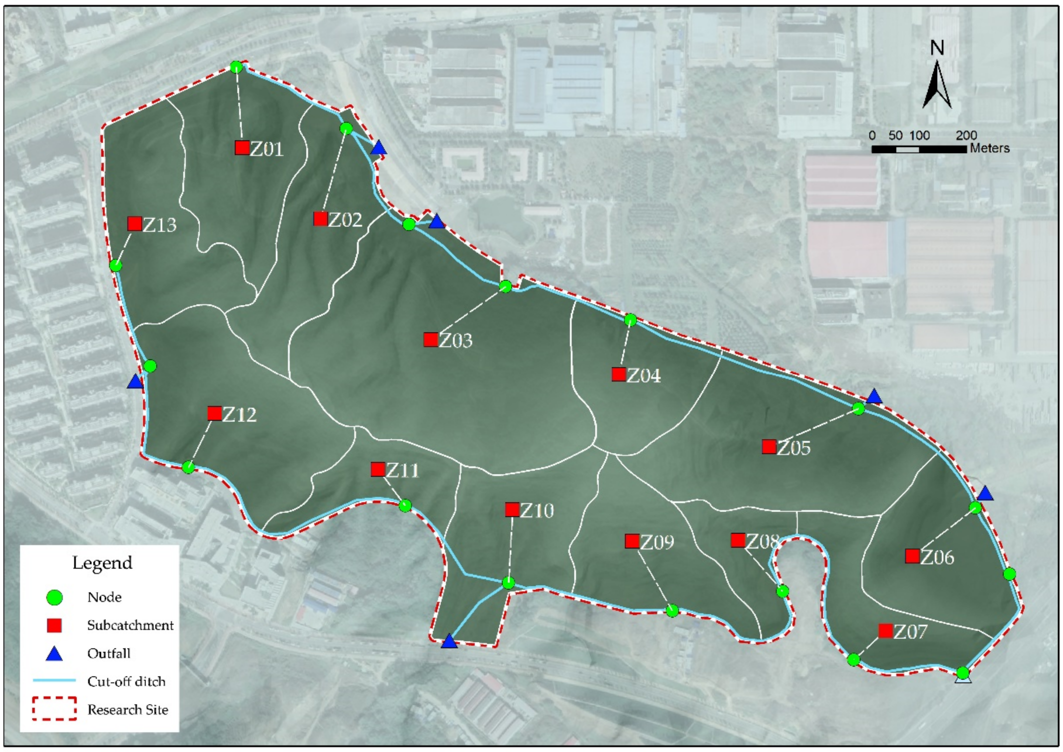


Figure 3. Subcatchment Partitions and Model Generation Pre-LID Schemes.

This study used the Chicago rainstorm method, a short-duration rainstorm pattern, for rainfall modeling. Based on the Nanjing Rainfall Intensity Formula published by Nanjing Urban Management Bureau in 2014 [36], the city's return periods for heavy rains are 2, 5, 10, and 20 years, with a rainfall duration of 2 h. The mean rainfall intensities are 0.498 mm/min, 0.630 mm/min, 0.731 mm/min, and 0.831 mm/min, respectively. The comprehensive rainfall peak coefficient for Nanjing is 0.4. A short-duration Chicago rainstorm method-based pattern was calculated for return periods of 2, 5, 10, and 20 years using these parameters and the Chicago rainfall method, as shown in Figure 4.

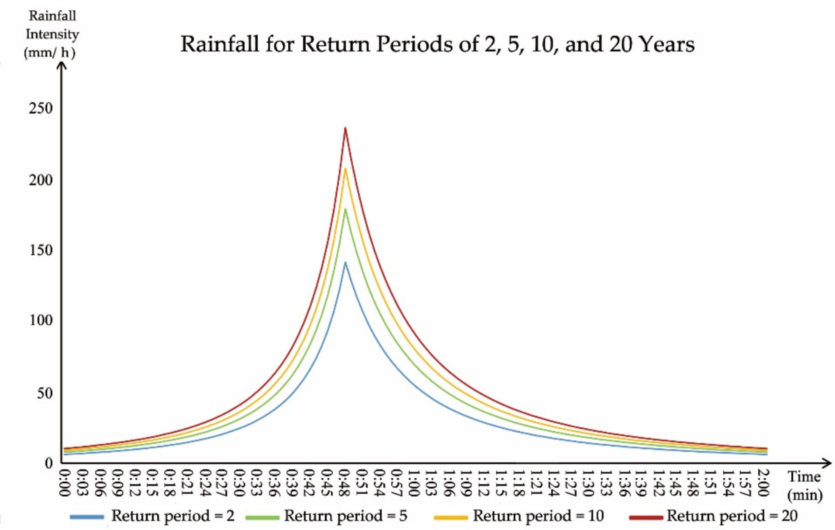


Figure 4. Rainfall Hydrograph for Nanjing with Return periods of 2, 5, 10 and 20 years.

The formula for calculating rainfall intensity is as follows:

$$i = \frac{(A_1 + ClgP)}{(t + b)^n} \quad (1)$$

where:

i—the average rainfall intensity (min/min);

t—rainfall duration (min);

P—return period (a);

n—rainfall attenuation coefficient;

A_1, C and b—local parameters.

Subsequently, the rainfall intensity formula for Nanjing is as follows:

$$i = \frac{(64.300 + 53.800lgP)}{(t + 32.900)^{1.011}} \quad (2)$$

where:

i—the average rainfall intensity (min/min);

t—rainfall duration (min);

P—return period (a).

The sponge system scheme for mountainous regions in built-up urban areas was designed for and confirmed with the 2 h rainfall intensity model for a five-year return period, according to China's Ministry of Housing and Urban-Rural Development's Technical Guide for Building a Sponge [37,38]. Meanwhile, the annual runoff control rate for the study site was set at 85%. Based on the site's total area, the entire stormwater detention and retention volume is approximately 5390 m^3.

For the SWMM modeling and simulation, key parameters were set, including those that were determined and underdetermined. Spatial attribute data required for modeling were obtained via ArcGIS software, including sub-catchment areas, average gradients of each catchment, pipe length, and node elevation. The impermeable/permeable areas, Manning coefficient, pipe roughness coefficient, maximum/minimum infiltration rates, attenuation coefficient, and other underdetermined parameters were determined based on the physical significance of the parameters or by referencing existing research results [39]. As applied to the Lijia Mountain study area, their values are shown in Tables 1 and 2. The values of the selected parameters in the soil-related parameter table are derived from the soil look-up table in the SWMM official manual. According to the site survey, the soil in the case site is loam, and the parameters in the loam selection table are used as the experimental simulation parameters. The model and calibration table parameters are derived from the measured data of various materials in the official SWMM manual. They refer to the data of similar experiments with this paper [40].

Table 1. List of Soil-related Parameters.

Parameter	Value
Saturated hydraulic conductivity (K)	0.13 in/h
Waterhead (ψ)	3.5 in
Porosity (φ)	0.463
Water-yielding capacity (FC)	0.232
Shrinkage point (WP)	0.116

Table 2. List of the Model's Parameters Set By Reference to Research.

Parameter	Parameter Range	Value Set
Impervious Manning coefficient(s/m$^{1/3}$)	0.011–0.014	0.013
Pervious Manning coefficient(s/m$^{1/3}$)	0.15–0.8	0.4
Pipe roughness coefficient	0.011–0.4	0.2
Maximum infiltration rate(mm/h)	30–200	36
Minimum infiltration rate(mm/h)	0.1–20	10
Attenuation coefficient(1/h)	0–30	4

2.4.2. Stormwater Model Simulation and Validation Pre-LID Schemes

As determined through the simulation, in the case of a rainfall event during the return period of 2, 5, 10, or 20 years, the model's original stormwater runoff coefficients are 0.4487, 0.544827 0.597674, 0.639386, respectively. The results reveal that the higher the precipitation is, the bigger the runoff coefficient is, which conforms with the measurement results of other relevant experiments [41]. According to the Code for Design of Outdoor Wastewater Engineering GB50014-2006 (2016 Version) [42], the park runoff coefficient should be between 0.10 and 0.20. Still, the runoff coefficient in this simulation is higher mainly due to the larger slope gradients of Lijia Mountain. Previous field studies have shown that under the same rainfall event, the larger the slope gradient is, the higher the runoff coefficient [43]. Considering relevant experimental measurements and the results of simulation experiments [44], when a green space has a slope with a gradient below 25%, the runoff coefficient tends to be between 0.21 and 0.42 depending on the varying intensities of different rainfall events. Lijia Mountain's average gradient is 35.86% on average, with a maximum of 45.06%, resulting in a runoff coefficient of 0.45 to 0.64, which is in line with surface runoff characteristics of a mountain environment.

2.4.3. LID Scheme Designs

This study used grass gutter and distributed detention and retention wetland models to design the study's two LID system schemes. The construction principle of the segmental detention and retention scheme is to "promote infiltration at the source". Based on the hydrological analysis of the mountain, including rainwater runoff and sub-catchments areas, the site is divided into smaller sub-catchments. Small-scale detention and retention wetland areas are subsequently set up along the respective runoff paths according to their size and pour points. The detention and retention wetlands are connected by grass gutters, which form a complete set of upstream and downstream flow paths. When upstream detention and retention wetland overflows, the water will flow downstream through the grass gutters to a larger detention and retention wetland. Stormwater can flow into the nearest wetland under the segmental detention and retention scheme to achieve local infiltration of mountain-based stormwater runoff. In contrast, the construction principle of the terminal detention and retention scheme is to "utilize terminal retention". Instead, the grass gutter and detention and retention wetlands are primarily set up at the runoff paths' terminal points of confluence. Stormwater runoff flows along the grass gutters towards the terminal wetlands for centralized detention and retention to preserve the mountain site's original hydrological characteristics. Compared with the terminal detention and retention scheme, the segmental detention and retention scheme requires a more precise LID layout, thus requiring a more detailed analysis of the hydrological characteristics of the study area. The ArcGIS-based analysis of the catchment, catchment area, watersheds, runoff paths, pour points and other information combined with the knowledge of the site's topographical and hydrological features are to determine the design and location of the detention and retention wetlands such that they are set up at the "source, middle and end" of each sub-catchments main runoff paths. Some sub-catchments have no wetlands set downstream due to their steep falling gradients. Instead, grass gutters are built to guide the stormwater to their adjacent sub-catchments' detention and retention wetland. In such a case, if the downstream detention and retention wetlands of adjacent sub-catchments are relatively close to each other, they may be combined. Following these principles, the distributed detention and retention wetlands of the segmented LID scheme include 62 pour points. Each sub-catchment was then further subdivided based on the catchment range of each pour point. Finally, the appropriate water volumes for each detention and retention wetland were computed in proportion to their areas based on the entire study area's total stormwater detention and retention volume. To facilitate modeling, the depth of each wetland was fixed at 1.5 m, from which the area of each detention and retention wetland was obtained, as shown in Table A1. Grass gutters were developed to connect the terminal detention and retention wetlands at their source, middle, and end, according to the direction of the runoff paths. The terminal detention and retention wetlands were then connected to their adjacent municipal pipe network, which functioned as the whole sponge system (Figure 5). The sub-catchments and LID scheme in the SWMM model were used to generate the segmental detention and retention model. At the same time, the relevant parameters were input into the rainfall model of a five-year return period. Figure 6 depicts the final LID scheme layout and SWMM model for the segmental detention and retention scheme.

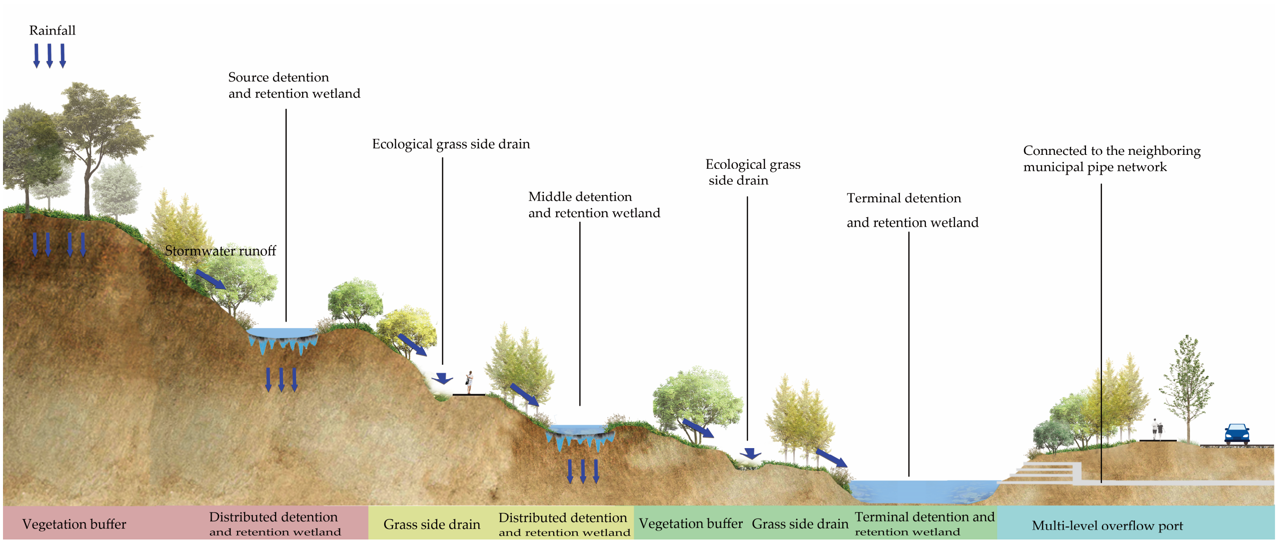


Figure 5. Schematic diagram of LID Scheme S.

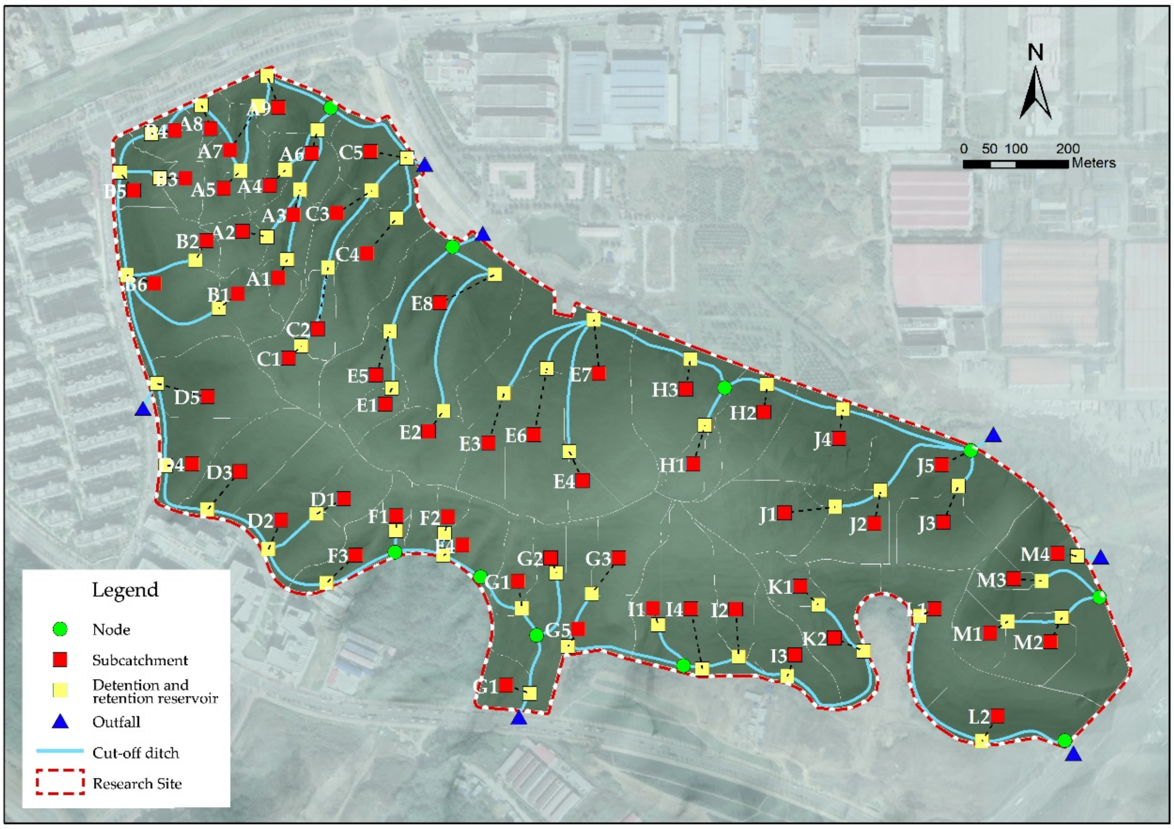


Figure 6. Division of Scheme S's sub-catchments and layout of detention and retention wetlands.

The study site is located within a built-up urban area, where the mountainous region is surrounded by municipal roads and seven municipal pipe network connection points. As a result, the terminal detention and retention scheme (Scheme T) its complexity by consolidating the original model's 14 sub-catchments into seven catchments. One of which has a very steep gradient and is therefore unsuitable for building a detention and retention wetland, and thus only has grass gutters set up to channel rainwater flow. The detention and retention wetlands in each of the other six catchments were designed to align with their particular flow conditions. The amount of water detention and retention necessary for each sub-catchment is calculated based on its proportion to its area, which is taken as the detention and retention volume of the wetland and kept consistent with Scheme S. The depth of the detention and retention wetlands were uniformly set to 1.5 m. The area of each of the scheme's wetlands is shown below in Table A2. To effectively divert the mountain runoff into this scheme's detention and retention wetlands, circularly connected grass ditches were arranged at the foot and middle-height area of the mountain along its contour lines. Stormwater can be collected and diverted to the scheme's terminal detention and retention wetland in this way (Figure 7). To complete the model, required parameters were input after the terminal detention and retention scheme model was generated, and the rainfall model was loaded into the SWMM software (Figure 8).

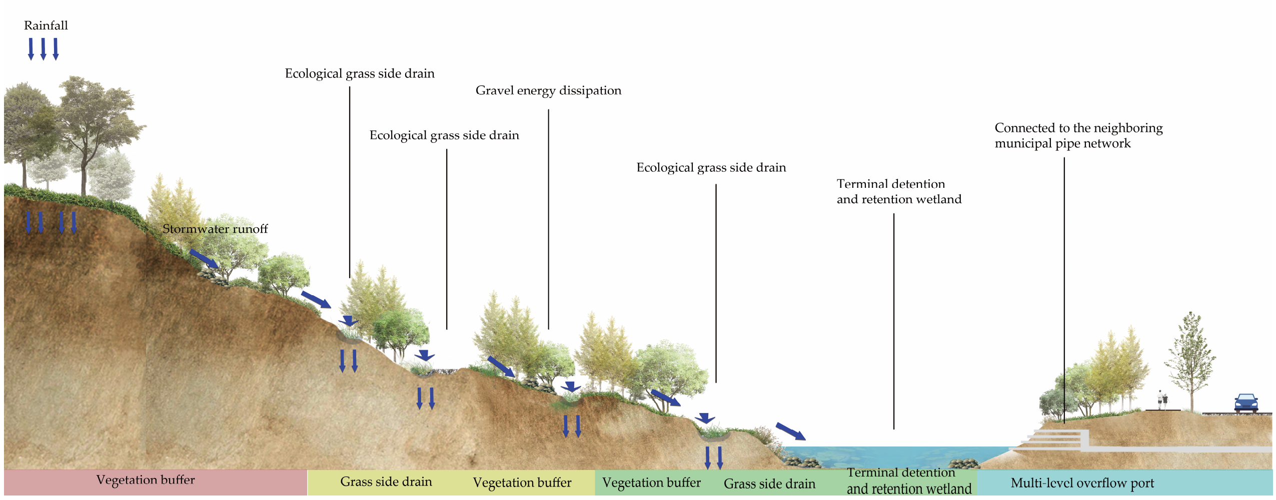


Figure 7. Schematic diagram of LID Scheme T.

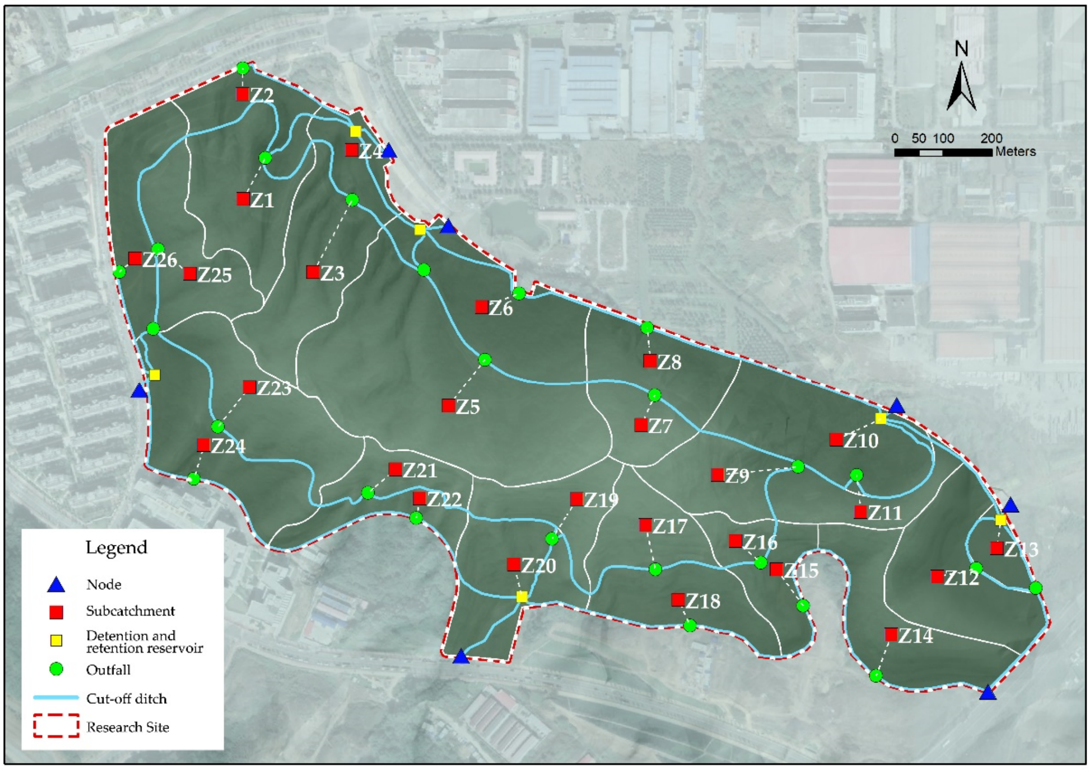


Figure 8. Division of Scheme T's sub-catchments and layout of detention and retention wetlands.

2.5. SWMM Runoff Simulations

The Horton model was utilized to simulate the stormwater infiltration process in this study. Also, the calculation interval was set to 1 s to control for errors. Before running simulations, each return period's rainfall intensity curves were inputted respectively, while associated rainfall events were selected throughout the experiment. Afterward, the SWMM models were run for Schemes S and T of detention and retention. Following the law of conservation of mass, the continuity errors of surface runoff and flow routing checking were used as the criterion for verifying the rationality of the models' operations. Through the simulation of rainfall events, the results of both models showed continuity errors of less than 5%, which is within a reasonable range and thereby indicates that the SWMM models operate reasonably and validly.

3. Results and Discussion

The sub-catchment runoff coefficient, final system outflow, and peak runoff under the rainfall events of different return periods were obtained by running the SWMM models of the pre-design, segmental detention and retention sponge system, and terminal detention and retention sponge system scheme, as shown in Table 3.

Table 3. Simulations results of the Pre-design Model, Scheme S, and Scheme T under rainfall events of different return periods.

	Total Outflow (m³)				Peak Outflow (m³/min)				Peak Time (h: min)		
Return Period	**y = 2**	**y = 5**	**y = 10**	**y = 20**	**y = 2**	**y = 5**	**y = 10**	**y = 20**	**y = 2**	**y = 5**	**y = 10**
Pre-design	9306	14,147	17,832	21,531	3290	5270	6790	8330	1:06	1:02	1:00
Terminal detention & retention	5828	10,776	13,119	14,827	1630	2980	3300	3530	1:43	1:30	1:25
Segmental detention & retention	1467	2840	3904	4979	740	1520	2120	2730	1:16	1:06	1:02

3.1. Comparison of Stormwater Runoff and Outflow

Under 2 h rainfall events in return periods of 2 years, 5 years, 10 years, and 20 years, the total outflow of the pre-design model increases from 9306 m^3 to 21,531 m^3. However, the total outflow of Scheme S and Scheme T is less than that of the pre-design model during all return periods. Scheme S and Scheme T have average total outflows of 20.2% and 70.3% of the pre-design model, respectively. After a 2-h rainstorm event, the total outflow of the pre-design model reached 14,147 m3 using 5-year return period data as a sample period. In contrast, for Scheme T the outflow under the same conditions reduces to 10,776 m^3, an approximate 24% reduction. Meanwhile, Scheme S' effect is even more significant, reducing total outflow under the same conditions to 2840 m^3. (Figure 9).

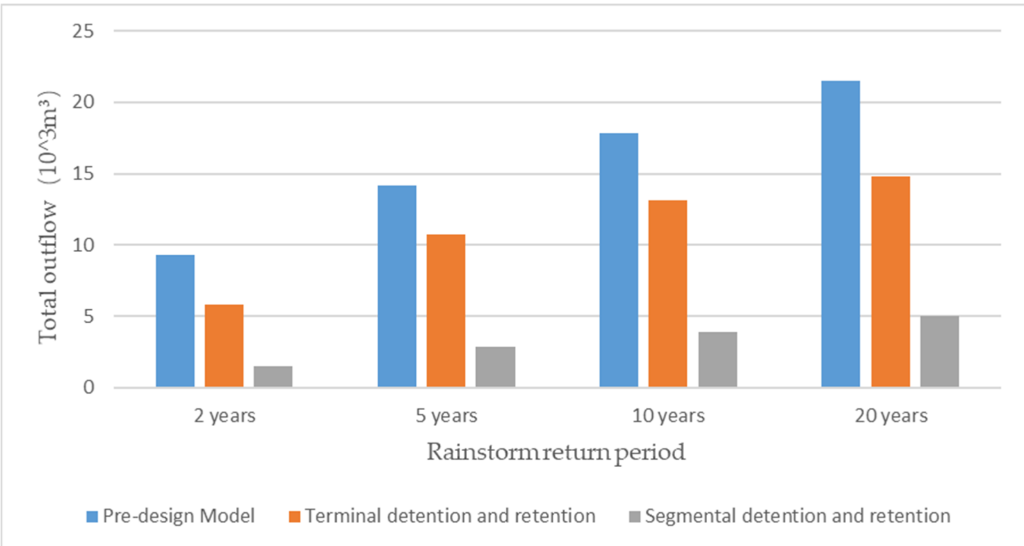


Figure 9. Comparison of Total Outflows between the Pre-design Model, Scheme S and Scheme T under rainfall events in different return periods.

The average gradient of the site and the impervious Manning coefficient of the underlying surface are the two important factors affecting the results of stormwater runoff in mountainous regions [30]. For this study, the underlying surface conditions of the research site were generalized. As such, the average gradient coefficient becomes the most important component to consider. Two representative outfalls will be selected to compare the different LID scheme effects. It can be seen that the average gradients of their corresponding catchments are quite different (Figure 10).

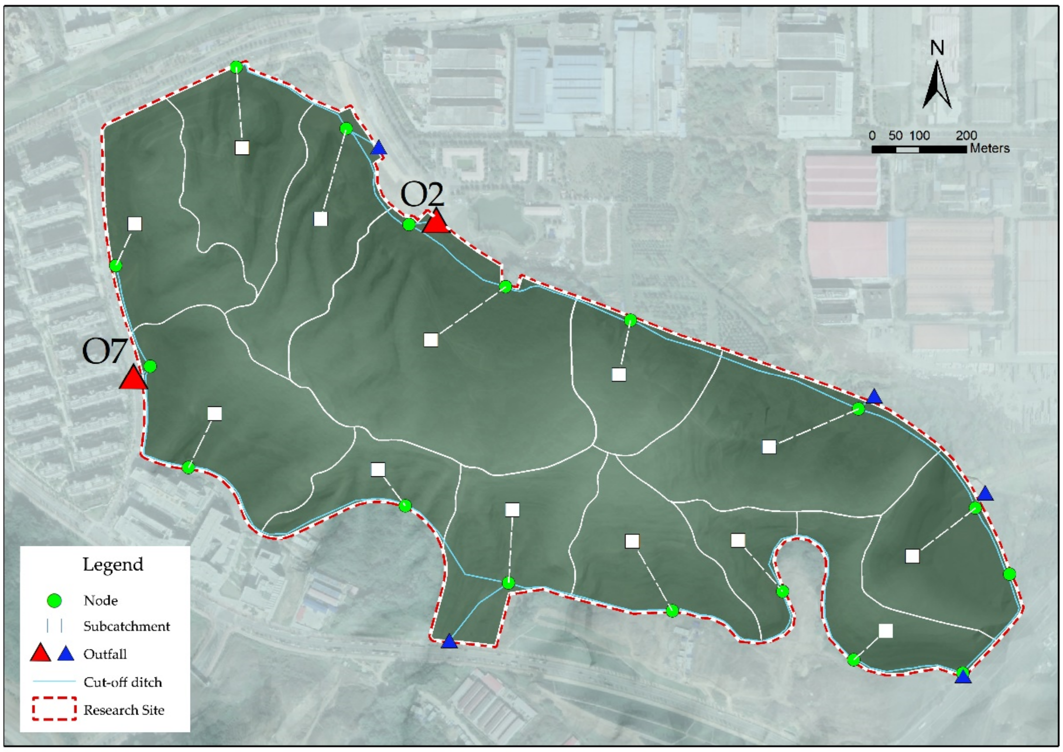


Figure 10. Schematic diagram of the representative outfalls O2 and O7.

The location of outfall O2 has a flat terrain with a mountainous gradient of approximately 20%. Outfall O7, on the other hand, is situated in a steeper terrain with a mountainous gradient of up to 45%. Take these outfalls, O2 and O7, as an example in the 5-year return period. The total outflow of O2 under the pre-design model conditions is 1761 m^3, that of Scheme T is 1614 m^3. This example shows that Scheme T has a limited reduction effect on the outfall O2. In contrast, the total outflow of O2 under Scheme T reduces significantly to only 607 m^3 (Table 4). Outfall O7 demonstrates Scheme S' greater effectiveness even more strikingly, with total outflows of 2354 m^3 and 1920 m^3 under the pre-design model and Scheme T conditions, respectively, but only 319 m^3 with Scheme S (Table 5).

Table 4. Total outflow of outfall O2 (gradient = 20%) under the pre-design model, Scheme S, and Scheme T over different return periods.

Return Period	Total Outflow at Outfall O2 under Pre-Design Model (m^3)	O2 Outflow in Scheme T (m^3)	O2 Outflow in Scheme S (m^3)
2 years	1105	838	305
5 years	1761	1614	607
10 years	2276	1896	841
20 years	2801	2096	1077

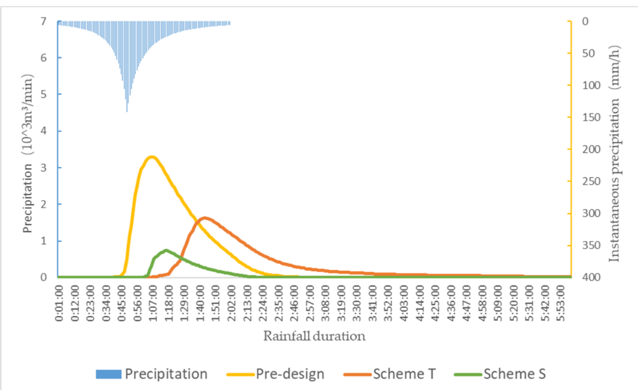
Table 5. O7 Outflow in the pre-design scheme, Scheme S and Scheme T under rainfall events of different return periods.

Return Period	Total Outflow at Outfall O7 under Pre-Design Model (m^3)	O7 Outflow in Scheme T (m^3)	O7 outflow in Scheme S (m^3)
2 years	1544	1054	174
5 years	2354	1920	319
10 years	2983	2243	431
20 years	3621	2481	545

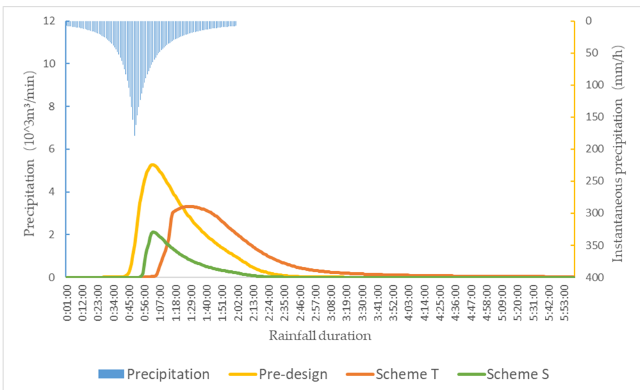
The above simulation results indicate that constructing LID systems in the mountainous regions of built-up urban areas can effectively reduce the total outflow from the site under a rainstorm. A further comparison of representative outfalls O2 and O7 indicates that, within a specific range, the construction of a LID system has a greater impact on runoff reduction in areas with steep gradients. According to the comparison of two LID system solutions, Scheme T can reduce the outflow to a certain degree. Scheme S, on the other hand, the segmental detention and retention scheme, has a clearly greater impact on runoff reduction.

3.2. Comparison of Peak Runoff Characteristics

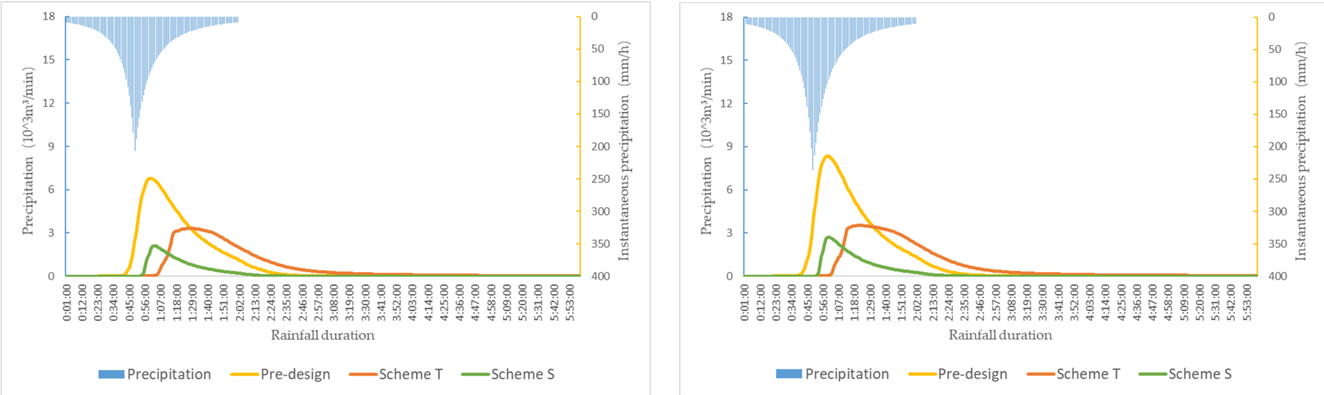
The effects of Scheme S and T, as compared to that of the pre-design model, in the time it took to reach flood peak under the conditions of an assumed 2 h rainfall event with 2-year, 5-year, 10-year, and 20-year return periods, the peak value and duration of time to reach flood peak were also compared. According to the comparison between the pre-design model and Scheme S, the time it took to reach a flood peak in the system was not significantly delayed. However, for Scheme S, the flood peak's outflow per unit time (the volumetric flow rate) decreases significantly, with an average decrease of about 80%. As the rainstorm return period extended, Scheme S's outflow relative reduction compared to the pre-design model declines. For example, for the case of rainfall with a 20-year return period, the unit outflow of peak flood peak is only reduced by about 32.77%. Meanwhile, it can be seen that when Scheme T is applied, the relative time to flood peak of the system is gradually advanced as rainfall intensity increases, as compared to the pre-design mode, which is consistent with the features of the site's stormwater bearing capacity. However, through the construction of Scheme T, the time to flood peak was delayed in different return periods, with a maximum delay time occurring in the 2-year return period. Similar to the effect of Scheme S, as the return period gets extended, the delayed effect Scheme T provides to reach a flood peak is gradually shortened. However, even if in the event of rainfall with a 20-year return period, the data shows that construction of such a LID system would still significantly affect the delay of flood peak. (Figure 11).



(**a**)



(**b**)



(**c**) (**d**)

Figure 11. Time to the flood peak and outflow of in the event of a rainstorm with different return periods: (**a**) Total outflow from the outfall in a 2-year return period based on time; (**b**) Total outflow from the outfall in a 5-year return period based on time; (**c**) Total outflow from the outfall in a 10-year return period based on time; (**d**) Total outflow from the outfall in a 20-year return period based on time.

Two representative outfalls, O2 and O7, were again selected to compare the instantaneous outflow for different return periods throughout the pre-design model and Schemes S and T. When Scheme T is applied to the immediate outflow at O2 and O7 during a five-year return period, the peak outflow at O2 remains near that of the pre-design model, but flood peak time is delayed. Meanwhile, the peak outflow of Scheme S is about half of that of the pre-design model, but the delay effect of the time to flood peak is more limited (Table 6). The peak outflow at O7 under Scheme T is about 50% of the pre-design model's, while the time to flood peak remains delayed. In contrast, the peak outflow at O7 with Scheme S decreases drastically, with only approximately 1/5 the pre-design model, although the time to flood peak remains relatively the same (Table 7). The relative effect of runoff detention and retention in Scheme S is superior to that in Scheme T, based on the simulated results of these two outfalls. However, for areas with steeper mountains, the stormwater runoff detention and retention effects of two LID system schemes have their unique features and tradeoffs, so the optimal detention and retention schemes could be selected based on the practical needs of an actual case. In most cases, the peak outflow under Scheme T is less than 50% of the pre-design model. In comparison, Scheme S can reduce peak outflow to 25% of the pre-design scheme, indicating that the construction of these LID systems can effectively reduce the flood peak and delay the time to the flood peak.

Table 6. Peak outflow at O2 and time to the peak outflow of the pre-design scheme, Scheme T and Scheme S in different return periods.

	Peak Outflow (m³/min)				Peak Time (h: min)		
Return Period	**y = 2**	**y = 5**	**y = 10**	**y = 20**	**y = 2**	**y = 5**	**y = 10**
Pre-design	354.7	573.8	755	945.9	1:07	1:05	1:03
Terminal detention & retention	379.7	547.2	547.2	547.2	1:38	1:20	1:16
Segmental detention & retention	165.1	313.4	430.1	325.9	1:17	1:08	1:04

Table 7. Peak outflow at O7 and time to the peak outflow of the pre-design scheme, Scheme S and Scheme T in different return periods.

	Peak Outflow (m^3/min)				Peak Time (h: min)		
Return Period	**y = 2**	**y = 5**	**y = 10**	**y = 20**	**y = 2**	**y = 5**	**y = 10**
Pre-design	639.6	1006.8	1301.3	1606.6	1:03	1:01	0:59
Terminal detention & retention	332.8	547.2	547.2	547.2	1:44	1:23	1:16
Segmental detention & retention	112.2	197.9	262	325.9	1:08	1:01	0:58

In conclusion, the mountainous-region LID systems enable the detention and retention of short-duration rainfall in different situations for certain ranges of total detention and retention. In terms of delaying the time to flood peak, Scheme T can do this more effectively while also having a notable effect on runoff control. In terms of reducing peak outflow of the flood peak, Scheme S has a more significant effect while having a more limited delay effect. This verifies the effectiveness of the LID systems' construction by demonstrating "reduction at the source and in-situ infiltration promotion".

4. Conclusions

This paper focuses on the control performance of the mountain LID (Low Impact Development) systems in different urban built-up areas on stormwater runoff. Specifically, we compared the stormwater runoff and peak characteristics of the terminal and segmental detention and retention schemes in the built-up areas through digital model construction and simulation. The peak value and peak time of typical outflow points are also discussed. We conclude this work as below:

(1) Due to the different physical mechanisms of the two LID systems on mountain runoff, their effects also vary. According to the findings of this study, the segmental detention and retention scheme can reduce total and peak outflow more effectively than the terminal detention and retention scheme. In addition, the segmental detention and retention scheme appears more suitable for areas with steeper mountains. In contrast, the terminal detention and retention scheme can play a more significant role in delaying the onset of flood peaks. Therefore, if a mountainous or hilly region is not steep and the stormwater pipe network of the surrounding plots is relatively good, both schemes would meet the requirements for runoff detention and retention. In this case, the terminal detention and retention scheme can effectively delay the time to the flood peak. The amount of construction of new wetland areas for detention and retention needed in this scheme is significantly less than that of the segmental detention and retention scheme. Hence, it may be relatively convenient or cost-effective for actual construction. However, suppose the mountainous region is steep, and the surrounding stormwater pipe network is not ideal. In that case, flash torrential rainfall will lead to larger runoff of water and soil loss and bring huge pressure to the drainage of the stormwater pipe network in the built-up areas surrounding such regions. Based on this logic and the current situation, it seems priority should be usually given to segmental detention and retention schemes to improve the water-holding capacity of the mountain regions, increase the amount of runoff control, and thereby effectively reduce outflow and peak outflow.

(2) This paper focuses on the construction and simulation comparison of the terminal and segmental detention and retention schemes. It belongs to the theoretical model stage and can provide certain theoretical support and technical reference for constructing

suitable LID systems in the mountainous areas of urban built-up areas. The development level of the mountainous region in built-up urban areas and surrounding areas leads to differences in soil, hydrology, and topography. Since this can significantly impact the LID system's construction,, accurate data concerning the types of underlying surfaces, distribution of surrounding stormwater pipe networks, and the site's topography are required to improve the simulation's accuracy and planning. The soil type, infiltration rate, and other factors used in this paper primarily depend on existing data from adjoining areas of Lijia Mountain due to the constrained conditions. Appropriate calibration and corrections to the parameters have been carried out in the study's simulation experiment, so there are certain limitations. The case in this paper is an actual project completed by the research team. In future research on this topic, the accuracy of these parameters may be improved in combination with field research and experimental determination and other techniques of obtaining genuine data, thus optimizing the research of this paper. Research samples can also be further expanded. Specifically, several mountains in built-up areas will be selected as the case studies to research combined with multiple types of LID schemes, thus improving the general applicability of this study's conclusions.

(3) Previously, stormwater simulation of parts of the mountain environment and the implementation of mountain LID systems were the main focus of research on urban mountain stormwater management. The performance evaluation compares and selects different facility schemes with a single LID system. It does not involve comparing the control effects of stormwater runoff in specific LID scenarios. This study contrasts and evaluates the stormwater regulation and storage performance of two LID schemes; the terminal and segmental detention and retention scheme in built-up areas. The study's research supports the construction of the LID system for mountainous urban regions and may be used to provide references for relevant practices. According to the findings of this paper, in practical applications, single or combined segmental and terminal detention and retention LID system schemes may be selected based on local conditions. Various types of LID systems should be designed in different elevations and areas to realize effective stormwater detention and retention in the mountain environment of built-up areas. This will optimize mountains' water environment, improve the landscape effect, and reduce the pressure of urban stormwater pipe networks, thus helping urban flood control and disaster reduction. Furthermore, upon completion of the project, the runoff control performances of LID system schemes can be evaluated with sensors and compared to the digital simulation results to verify the effectiveness of the LID system schemes.

Author Contributions: Y.Y. (Yangyang Yuan) designed and conducted the experiments, Y.Y. (Yue Yin) collected the data. Y.G. organized the paper and analyzed the data. Y.X., Q.X., Y.S. wrote the paper. Y.Y. (Yangyang Yuan) checked the paper. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Wetland parameters of the segmental detention and retention scheme (Scheme S).

Subarea	Corresponding Subcatchment Numbers	Wetland Design Area Volume (m³)	Design Area (m²)	Average Depth (m)
	A1	28	19	1.5
1	A2	41	28	1.5
	A3	60	41	1.5

	A4	19	13	1.5
	A5	32	22	1.5
	A6	58	39	1.5
	A7	59	40	1.5
	A8	22	15	1.5
	A9	76	51	1.5
2	B1	53	36	1.5
	B2	13	9	1.5
	B3	32	22	1.5
	B4	44	30	1.5
	B5	51	35	1.5
	B6	203	136	1.5
3	C1	59	40	1.5
	C2	52	35	1.5
	C3	59	40	1.5
	C4	125	84	1.5
	C5	87	59	1.5
4	D1	55	37	1.5
	D2	159	107	1.5
	D3	118	79	1.5
	D4	79	53	1.5
	D5	135	91	1.5
5	E1	32	22	1.5
	E2	101	68	1.5
	E3	59	40	1.5
	E4	34	23	1.5
	E5	80	54	1.5
	E6	143	96	1.5
	E7	282	189	1.5
	E8	314	210	1.5
6	F1	20	14	1.5
	F2	18	13	1.5
	F3	67	45	1.5
	F4	98	66	1.5
7	G1	53	36	1.5
	G2	23	16	1.5
	G3	87	59	1.5
	G4	37	25	1.5
	G5	199	133	1.5
8	H1	34	23	1.5
	H2	90	61	1.5
	H3	176	118	1.5
9	I1	25	17	1.5
	I2	67	45	1.5
	I3	79	53	1.5
	I4	171	115	1.5
10	J1	124	83	1.5
	J2	91	61	1.5
	J3	95	64	1.5

	J4	141	95	1.5
	J5	180	121	1.5
11	K1	43	29	1.5
	K2	124	83	1.5
12	L1	114	77	1.5
	L2	140	94	1.5
13	M1	50	34	1.5
	M2	71	48	1.5
	M3	23	16	1.5
	M4	215	144	1.5

Table A2. Wetland parameters of the termina detention and retention scheme.

Wetland No.	Wetland Design Area Volume (m^3)	Design Area (m^2)	Average Depth (m)
1	774	516	1.5
2	1157	772	1.5
3	881	587	1.5
4	359	239	1.5
5	942	628	1.5
6	939	626	1.5

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