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Comparisons of Retention and Lag Characteristics of Rainfall–Runoff under Different Rainfall Scenarios in Low-Impact Development Combination: A Case Study in Lingang New City, Shanghai

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Abstract: An increasing focus has been given to stormwater management using low-impact development (LID), which is regarded as a "near-nature" concept and is utilized to manage and reduce surface runoff during the rainfall–runoff process. According to the hydrological monitoring data, we evaluated the retention and lag characteristics of rainfall–runoff in LID combination under three rainfall-intensity scenarios (light–moderate, heavy, and torrential rainfall) in Lingang New City in Shanghai. LID facilities have been constructed for three years in the target study area, including rain gardens, retention ponds, green parking, porous pavement, and grass swales. The average runoff retention was 10.6 mm, 21.3 mm, and 41.6 mm under light–moderate, heavy, and torrential rainfall scenarios, respectively, and the corresponding runoff retention rate was 72.9%, 64.7%, and 76.1% during the study period. By comparing rainfall, runoff retention, runoff retention rate, cumulative rainfall, and lag times, it becomes evident that the ability to retain runoff can be greatly improved in the LID combination. The average runoff retention was significantly enhanced by nearly two times and four times under the heavy and torrential rainfall scenarios compared to the conditions under the light–moderate rainfall scenario. Furthermore, the lag time from the end of rainfall to the end of runoff (t_2) and the lag time between the centroid of rainfall and the centroid of runoff (t_3) showed a significantly negative correlation with rainfall intensity. Meanwhile, t_3 presented an incredibly positive correlation with rainfall duration. In this study, the LID combination demonstrated superior benefits in extending the duration of runoff in rainfall events with lower rainfall amounts, and demonstrated significant overall lag effects in rainfall events with longer durations and lower rainfall amounts. These results confirmed the vital role of the LID combination in stormwater management and the hydrologic impact of the LID combination on rainfall-induced runoff retention and lag effects. This work has provided valuable insights into utilizing LID facilities and can contribute to a better understanding of how runoff retention and lag characteristics respond to different rainfall intensity scenarios.

Keywords: Sponge City; low-impact development; stormwater management; retention time; lag time; Lingang New City

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1. Introduction

Urban development has modified land use types and occupied large areas of natural green lands, which leads to the rise of impervious surfaces [1] and the rapid increase in runoff volume [2,3]. Increasing focus has been given to stormwater management using low-impact development (LID), which is regarded as a "near-nature" concept [4] and aimed to manage stormwater runoff and reduce surface runoff [5–7]. Common LID practices mainly include bioretention, green roofing, permeable pavement, bioswales, rain barrels, rain gardens, and so on [8], which manage stormwater through infiltration, detention, storage, and purification [9,10]. In particular, LID practices play a vital role in reducing rainfall runoff volumes and peaks [5,11].

The LID practices have been evaluated in various geographical regions [7,12]. However, the construction and operation of LID have been widely applied in developed countries, although there are insufficient practices and studies in developing countries [7,13,14]. Therefore, there is an immediate requirement for experimental data on LID that accurately represent the specific local and environmental conditions in developing nations [15,16]. A "Sponge City" is a concept that utilizes nature as a sponge, intending to enhance the capacity of LID to improve the effective control of urban peak runoff and increase the effectiveness of stormwater management [17]. Since 2015, the Chinese government has carried out "Sponge City" construction projects [18], with LID as one of the critical approaches to stormwater management [19]. Effectively reducing runoff volume by using LID has become one of the primary goals of "Sponge City" [20], and has been piloted in 30 large-scale Sponge Cities across the whole country [21].

Numerous studies have evaluated the retention effect of certain individual LID practices [7,22–24]. For example, rain gardens could mitigate direct runoffs by 23.6–98.4% [22], detention ponds could reach a total runoff reduction by 45% [23], and porous pavement parking could reduce flood volume by 93% compared to asphalt parking [24]. Meanwhile, there is a lag effect of LID practices on urban flooding events, and LID practices can reduce the risk of urban flooding [25,26]. LID could minimize peak discharge depths, runoff coefficients, and discharge volumes and increase lag times and runoff thresholds compared with traditional residential development [26]. For example, Davis [25] found that the peak time of runoff in retention ponds can be lagged twice or even more compared with the rainfall process. Xia [27] showed that the outflow peaks in bioretention were delayed for at least 13 min and lowered at least 52% under high, medium, and low inflow rate conditions. The magnitude of the time delay and flood detention of peak flow using green roofing could be enhanced by 22–70% [28].

But even here, many studies have indicated that LID combinations with various characteristics may provide more effective performance than certain individual LID practices [29–31]. For instance, the simulation of individual LID practices led to a 3–40% reduction in average annual flood volumes, whereas LID combinations could reduce annual flood volumes by 16–47% [31]. Overall, green infrastructures could lessen total rainfall runoffs by 85–100% and decrease peak flows by 92–100% [30]. In contrast, the reduced flood capacity of a single infrastructure was limited [30]. However, there is still a lack of sufficient studies on the lag effect of LID practices in China. This topic holds significant importance and requires in-depth investigation, particularly concerning the study on the lag effect in combination of LID practices [16,19,30].

Shanghai is located at the intersection of the coastline and the Yangtze River Estuary (Figure 1), with a mean elevation of approximately four meters. There is continuous rainy weather annually in the Yangtze River Delta from late spring to early summer, commonly called the plum rain season. The plum rain season usually begins in mid-June and ends at the beginning of July, lasting approximately 20-plus days [32]. Shanghai is among the 30 pilot cities of China's second round of the national "Sponge Cities" project [22]. Due to rapid urbanization, a large population, and climate change, the high probability of heavy rainfall risk is rising in Shanghai, increasing the potential dangers of pluvial flooding events in Shanghai [22,33–35]. However, how retention and lag characteristics in the LID combination respond to different rainfall scenarios is still not well known and needs to be stressed.

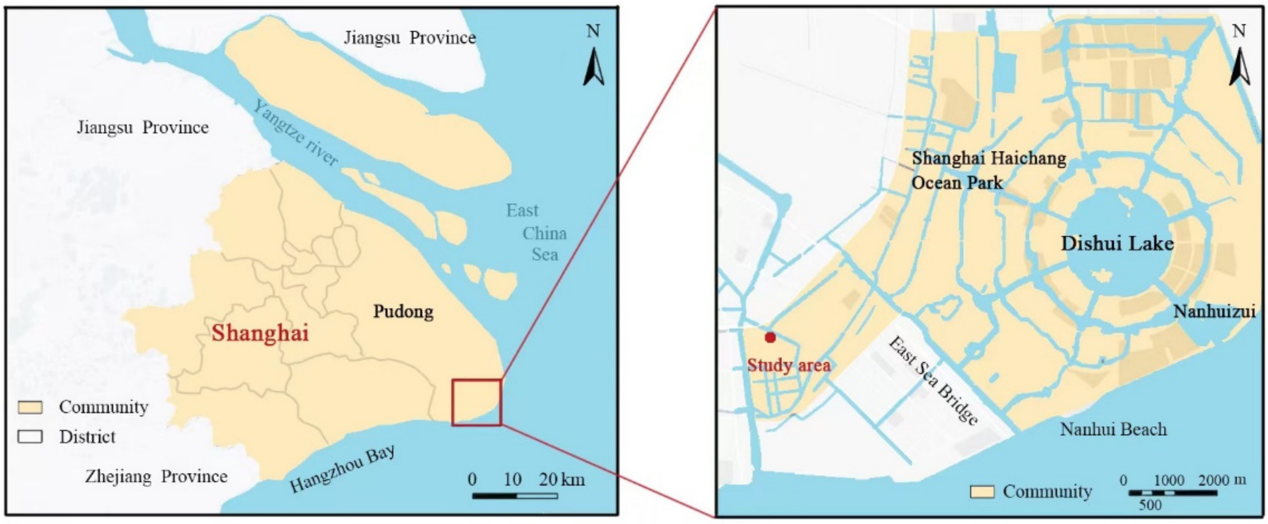

Figure 1. Location of the study area.

In this study, based on the continuous hydrological monitoring data, we selected a residential area of Lingang New City in Shanghai with a LID combination, which has been constructed for three years, and specifically addressed the following aims: (1) compare retention and lag characteristics of runoff in LID combination; (2) stress the different retention and lag characteristics of runoff in LID combination under different rainfall intensity scenarios; (3) discuss the correlation between rainfall characteristics and retention or lag characteristics during the rainfall–runoff process.

2. Materials and Methods

2.1. Study Area

Lingang New City, situated at the southeastern tip of Shanghai, is the largest “Sponge City” pilot area among the 30 pilot cities in China, spanning a pilot area of 79 km^2 (Figure 1). It is approximately 50 km away from the urban area of Shanghai [36]. Lingang New City has been focused on developing and expanding advanced manufacturing industries for nearly 20 years, contributing to its economic growth [37].

There have been considerable changes in the landscape because of sediment deposition, erosion, sand excavation, dam construction, and land reclamation in the history of Lingang New City [38]. Due to the low elevation and extensive land use of tidal flats in this area, Lingang New City is frequently threatened by pluvial flooding and freshwater shortages [39].

The land terrain in Lingang New City is predominantly flat, as it is located within the impact plain of the Yangtze River Delta. The land, for the most part, has been formed through beach reclamation [40]. The area has a stable and modern Quaternary sedimentary structure, with no occurrences of geological disasters such as new active faults or landslides in the pilot area. The foundation soil layer mainly consists of clay, silty, and sandy soil compositions [40]. The surface layer of the soil is composed of blown fill soil with a thickness ranging from 0.5 to 3.5 m. This layer primarily consists of clay, silt, and other similar materials. The soil in the surface layer is characterized by its uneven nature, loose structure, and poor permeability. Beneath the surface layer lies a layer of sandy silt, which exhibits more favorable soil properties. This bottom layer possesses relatively higher bearing capacity and permeability capabilities than the surface layer [40].

The soil permeability coefficient in Lingang New City can be found in Table 1 [40]. In general, the undisturbed soil in the pilot area is characterized by low permeability, high salinity–alkalinity, and soil depletion. These soil properties can affect water infiltration and drainage capabilities in the area. Additionally, Lingang New City experiences an average annual rainfall of 1228.1 mm. A significant portion of this rainfall occurs from May to

October, accounting for more than 70% of the annual rainfall. During this period, there is a higher occurrence of typhoons accompanied by heavy rainfall and high tide phenomena. These weather conditions can contribute to increased precipitation levels during these months [40].

Table 1. Soil permeability coefficient in Lingang New City.

Soil Type	Permeability Coefficient k (cm/s)
Sandy silt	1.54×10^{-4}~1.83×10^{-4}
Silt	2.63×10^{-4}~2.77×10^{-4}
Mucky clay	1.54×10^{-5}~1.55×10^{-5}
Clay	1.38×10^{-5}~1.54×10^{-5}

The target study area (Xinluyuan F residential district) is a resettlement community built in 2006. In 2021, the annual rainfall in the target study area was recorded as 1948.6 mm. The area has recently been constructed and equipped with LID facilities since late 2017. The target study area is in the southwestern part of Lingang New City, as shown in Figure 1. The study area encompasses a total land area of 3.36 hm^2 with a designated green area covering 1.33 hm^2. The greening rate of the study area is approximately 40%.

In this study area, the comprehensive runoff coefficient for the underlying surface of the land parcel is about 0.65. The design recurrence interval for the rainwater pipe network is once every 5 years. Surface runoff from rainwater within this target residential community is collected through various LID facilities and directed into the on-site rainwater pipe network. The rainwater pipe network is designed to discharge into the municipal rainwater pipe network on the east side of Chao Le Road. The outflow pipe has a diameter of DN800, and the bottom elevation inside the pipe is at an absolute height of 1.92 m (using the Wu Song elevation system).

The primary purpose of this sponge engineering construction is to reduce emissions at the source, implement total stormwater runoff control from the source of runoff production and confluence, reduce the peak and flow of runoff, delay the runoff time, and improve the drainage capacity of the original drainage facilities in the target study area of Lingang New City. Five LID facilities were selected considering the Sponge City's goals and the study area's characteristics, including retention ponds, rain gardens, green parking, grass swales, and porous pavement (Figure 2). LID facilities were set up in an independent and parallel manner, and the characteristics of different LID facilities in the study area are shown in Table 2.

Table 2. Characteristics of different LID facilities in the study area.

LID	Area	Number
Retention pond	25 m^3	25
Rain garden	773.3 m^2	75
Green parking	2631.6 m^2	58
Grass swale	50.12 m^2	47
Porous pavement	158 m^2	2

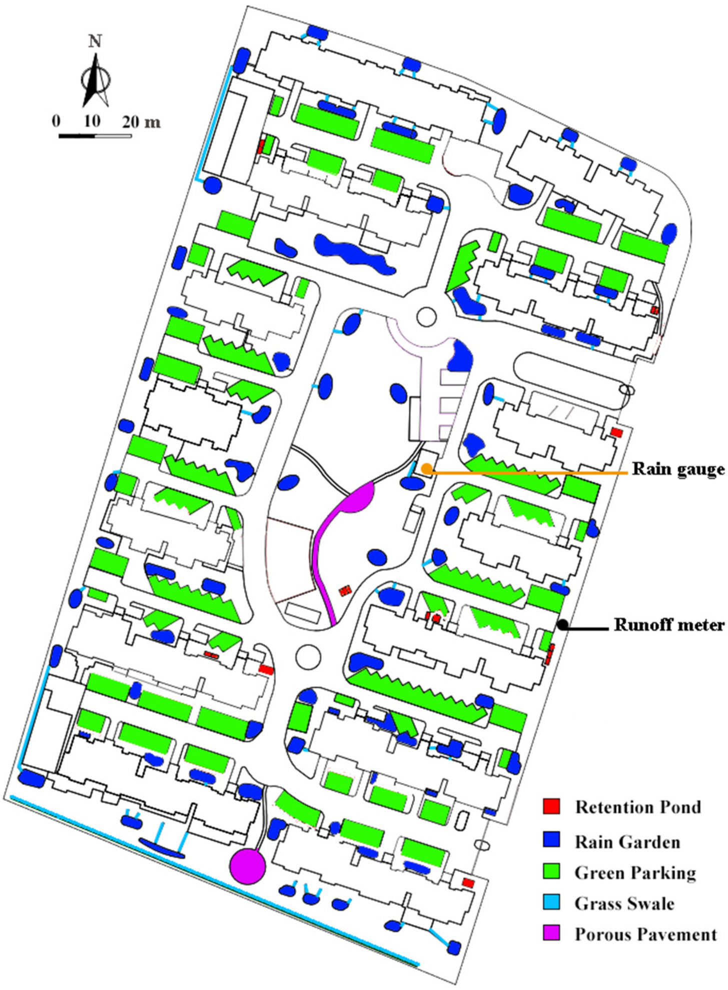

Figure 2. The layout of LID facilities and their combination in the study area.

2.2. Data Acquisition and Analysis

In this study, the rainfall and runoff data were collected from the Lingang Sponge City Management Platform, established in 2019. Through the Lingang Sponge City Management Platform, total rainfall and runoff data were continuously recorded and uploaded in the study area. Rainfall data were collected using a tipping bucket rain gauge of type L99-YL with a precision of ±2% to ±4% mm. The rain gauge was strategically positioned near the center of the study area (Figure 2). On the other hand, runoff data were collected using an acoustic doppler flowmeter of type ISCO 2150 with a precision of ±0.03 m/s (−1.5 m to 1.5 m/s). The runoff meter was strategically positioned near the main outlet in the study area (Figure 2). The data were recorded at intervals of 15 min for rainfall and 10 min for runoff.

The rainfall and runoff data used in this study were collected from fifteen valid rainfall events during 2021. The criterion for distinguishing a new valid rainfall event was based on two conditions: (1) no rainfall observed for at least 30 min prior to the commencement of rain; (2) no runoff outflow detected from the LID facilities during this period as well [16]. The rainfall data can be divided into four groups based on the intensity of rainfall [34]. These groups are determined as follows: (i) light rainfall: cumulative rainfall less than 10 mm/day ($r < 10$ mm/day); (ii) moderate rainfall: cumulative rainfall between 10 mm/day and 25 mm/day ($10 \leq r < 25$ mm/day); (iii) heavy rainfall: cumulative rainfall between 25 mm/day and 50 mm/day ($25 \leq r < 50$ mm/day); and (iv) torrential rainfall: cumulative rainfall exceeding 50 mm/day ($r > 50$ mm/day). Additionally, for ease of interpretation, the categories of light and moderate rainfall have been combined into a single group referred to as "light-moderate rainfall".

In the study, the retention effect was analyzed using indicators such as total retention, retention rate, cumulative rainfall (A_0), and retention time (t_1), along with their changes under different rainfall intensity scenarios. Among these indicators, runoff retention and retention rate were used to assess the regulation effect of the LID combination on runoff. Runoff retention represents the difference between rainfall and runoff, while retention rate is the retention ratio to rainfall. A_0 was measured to indicate the cumulative rainfall from the beginning of rainfall to the beginning of runoff.

T_1 represents the time interval from the beginning of rainfall (t_{p0}) to the beginning of runoff (t_{r0}) (as shown in Figure 3). In addition, our study investigated three other indices to represent the lag characteristics during the process of rainfall and runoff (Figure 3): (1) t_2: the lag time from rainfall end (t_{p3}) to the runoff end (t_{r3}); (2) t_3: the lag time from the centroid of rainfall (t_{p2}) to the centroid of runoff (t_{r2}); and (3) t_4: the time from the peak rainfall intensity (t_{p1}) to the peak runoff (t_{r1}). In the study, we collected data on the total lag times of t_2, t_3, and t_4, as well as their changes, under various rainfall intensity scenarios.

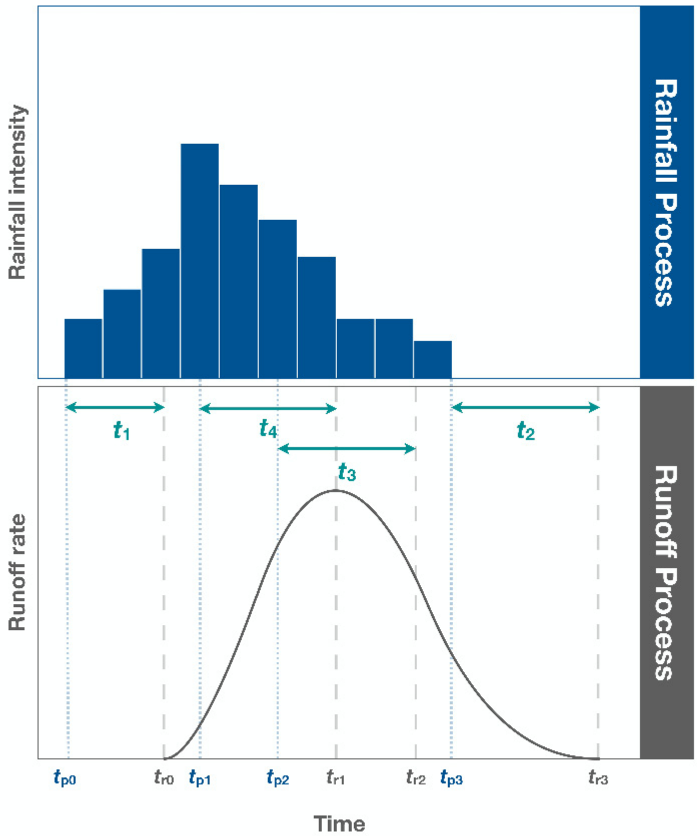

Figure 3. Schematic diagram illustrating indices of retention and lag effects for rainfall and runoff (Based and modified on Hood et al., 2007 [26] and Yin et al., 2022 [16]).

The centroid of rainfall and runoff were calculated as follows, respectively [26]:

$$t_{p2} = \frac{\sum_{i=1}^{n} W_i \times t_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

where t_{p2} = centroid of rainfall, W_i = rainfall for period i, and t_i = time for period i.

$$t_{r2} = \frac{\sum_{i=1}^{n} A_i \times t_i}{\sum_{i=1}^{n} A_i} \quad (2)$$

where t_{r2} = centroid of runoff, A_i = runoff for period i, and t_i = time for period i.

The differences in runoff retention, runoff retention rate, A_0, and runoff retention and lag time among different rainfall intensity scenarios were analyzed using non-parametric comparison (Kruskal–Wallis test) for pairwise multiple comparisons. Spearman's test was used to examine the relationship between characteristics of rainfall events and indicators representing the runoff retention and lag effects.

All data analyses were performed in R (version 4.0.2) through RStudio (version: 2022.12.0+353; https://posit.co/download/rstudio-desktop/, accessed on 31 January 2023). The Kruskal–Wallis non-parametric comparison procedure was performed using the R package 'PMCMRplus' [41]. Statistically significant differences were identified when $p < 0.05$, unless otherwise stated in this study.

3. Results

3.1. Rainfall Runoff Retention Effect

Among the fifteen rainfall events studied, the total rainfall and runoff retention were 427.4 mm and 296.2 mm, respectively. Specifically, the average rainfall amounts were 14.6 mm, 33 mm, and 54.6 mm under the light–moderate, heavy, and torrential rainfall scenarios, respectively. The average rainfall under the heavy and torrential rainfall scenarios was 2.3 and 3.7 times higher, respectively, compared to the light–moderate rainfall scenario. The maximum recorded rainfall was 21 mm, 41 mm, and 55 mm under the light–moderate, heavy, and torrential rainfall scenarios, respectively.

The average runoff retention values were 10.6 mm, 21.3 mm, and 41.6 mm under the light–moderate, heavy, and torrential rainfall scenarios, respectively (Figure 4). The maximum runoff retention values recorded were 15.8 mm, 35.1 mm, and 42 mm under the light–moderate, heavy, and torrential rainfall scenarios, respectively. The retention showed a significant increase of approximately two and four times under the heavy and torrential rainfall scenarios, respectively, in comparison with the light-moderate rainfall scenario (p = 0.026 and 0.003, respectively) (Figure 4). However, no significant difference in runoff retention was observed between heavy and torrential rainfall scenarios (p = 0.108) (Figure 4).

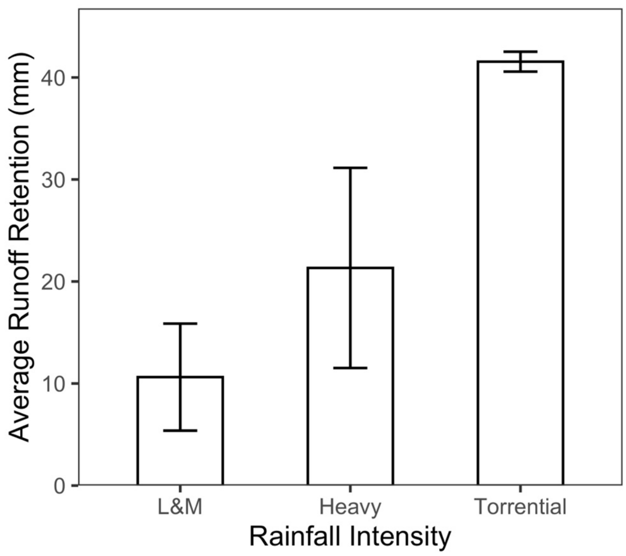

Figure 4. The average runoff retention of LID combination under three different rainfall intensity scenarios. The data in the bar plot represent the mean ± standard deviation for each rainfall intensity scenario. Abbreviations: L&M—light and moderate rainfall.

As described in Figure 5, the rainfall and retention values are nearly equal under lower rainfall scenarios and closely aligned along the 1:1 diagonal line. However, as the rainfall intensity increases, the retention values become gradually lower than the corresponding rainfall values. This is evident from the increasing deviation from the 1:1 diagonal line. The observed trend indicates that the difference between rainfall and retention increases as rainfall intensity increases.

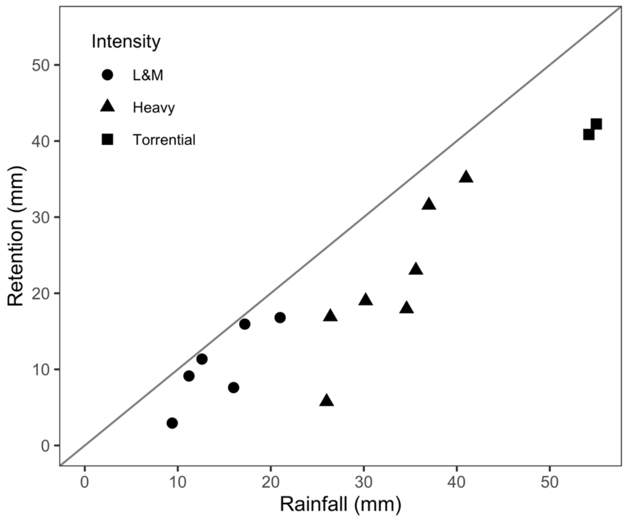

Figure 5. Discrete distribution of rainfall and runoff retention under different rainfall intensity scenarios. Abbreviations: L&M—light and moderate rainfall.

The total runoff retention rate was calculated as 69.3% among the fifteen rainfall events. The average runoff retention rates were 72.9%, 64.7%, and 76.1% under the light–moderate, heavy, and torrential rainfall scenarios, respectively (Figure 6). Despite the slight decrease in the total runoff retention rate under the heavy rainfall scenario compared to the light–moderate and torrential rainfall scenarios, no significant relationship was found between the runoff retention rates among different rainfall intensity scenarios (Figure 6). The maximum runoff retention rates recorded were 92.7%, 85.7%, and 76.8% under the light–moderate, heavy, and torrential rainfall scenarios, respectively (Figure 6).

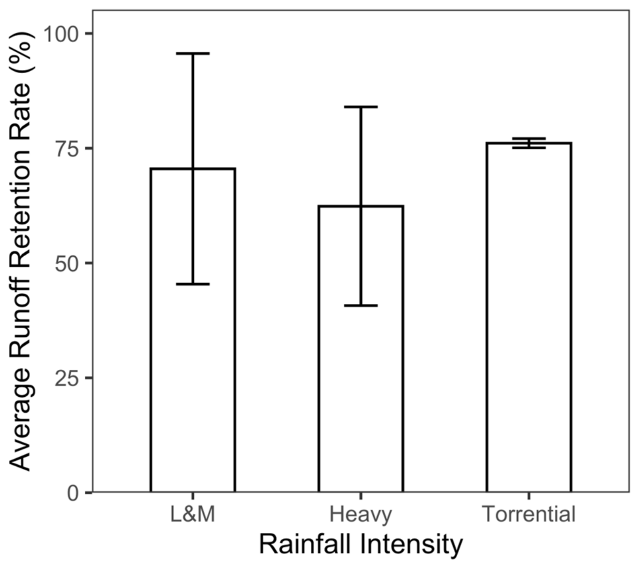

Figure 6. The retention rate of LID combinations under three different rainfall intensity scenarios. The data in the bar plot represent the mean ± standard deviation for each rainfall intensity scenario. Abbreviations: L&M—light and moderate rainfall.

The average A_0 values were 3.4 mm, 9.7 mm, and 7.0 mm under the light–moderate, heavy, and torrential rainfall scenarios, respectively (Figure 7). Among the scenarios, the average A_0 value was highest under the heavy rainfall scenario. Furthermore, the average A_0 values were nearly three and two times higher under the heavy and torrential rainfall scenarios, respectively, compared to the light–moderate rainfall scenario (Figure 7). However, no significant differences in A_0 were observed under different rainfall intensity scenarios (Figure 7). The maximum A_0 values recorded were 9.4 mm, 23.8 mm, and 10 mm under the light–moderate, heavy, and torrential rainfall scenarios, respectively (Figure 7).

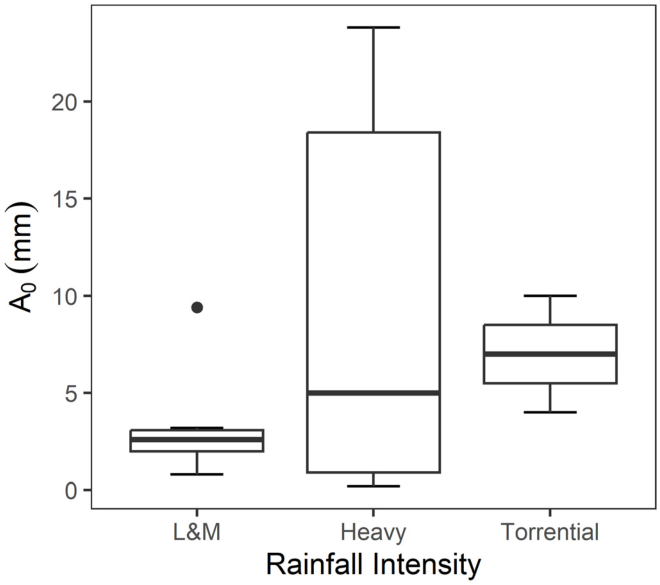

Figure 7. Distribution of cumulative rainfall (A_0) from the beginning of rainfall to runoff in LID combination. In the box plot, the horizontal line within each box represents the median value for each rainfall intensity scenario. The black dot on the plot indicates data outlier. Abbreviations: L&M—light and moderate rainfall.

3.2. Rainfall–Runoff Lag Effect

No significant differences in retention and lag time were observed under different rainfall intensity scenarios within each group, as shown in Figure 8. The average values for t_1, t_2, t_3, and t_4 were 26 min, 43 min, 34 min, and 20 min, respectively. Among the different rainfall scenarios, the range of values was 5 to 60 min for t_1. For t_2, the values varied between 10 to 115 min. For t_3, the vaues ranged from 8 to 73 min. For t_4, the values exhibited a wider range from −60 to 100 min.

Specifically, under the light–moderate rainfall scenario, the average values for t_1, t_2, t_3, and t_4 were 28 min, 57 min, 34 min, and 24 min, respectively. The range of values for t_1, t_2, t_3, and t_4 under the light–moderate rainfall scenario were 5 to 60 min, 25 to 115 min, 8 to 88 min, and 10 to 50 min, respectively. Under the heavy rainfall scenario, the average values for t_1, t_2, t_3, and t_4 were 25 min, 36 min, 34 min, and 15 min, respectively. The ranges for t_1, t_2, t_3, and t_4 under the heavy rainfall scenario were 10 to 40 min, 10 to 85 min, 9 to 70 min, and −60 to 100 min, respectively. Under the torrential rainfall scenario, the average values for t_1, t_2, t_3, and t_4 were 20 min, 30 min, 30 min, and 28 min, respectively. The ranges for t_1, t_3, and t_4 under the torrential rainfall scenario were 10 to 30 min, 19 to 40 min, and 15 to 40 min, respectively. It is noteworthy that t_2 was consistently 30 min under the torrential rainfall scenario (Figure 8).

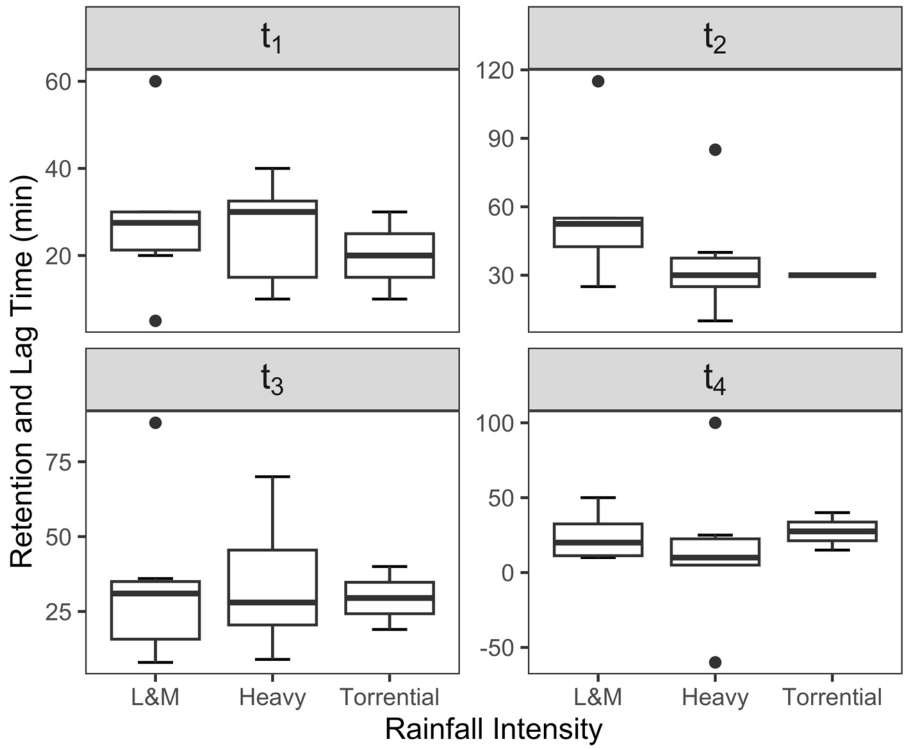

Figure 8. Patterns of retention and lag time under different rainfall intensity scenarios. t_1 represents the retention time from the beginning of rainfall to the beginning of runoff; t_2 indicates the lag time from the end of rainfall to the end of runoff; t_3 represents the lag time between the centroid of rainfall and the centroid of runoff; t_4 indicates the lag time from the peak rainfall to the peak runoff. In the box plots, the horizontal line within each box represents the median value for each rainfall intensity scenario. Black dots on the plots indicate data outliers. Abbreviations: L&M—light and moderate rainfall scenario.

3.3. Effects of Rainfall Characteristics on Retention and Lag Effects

The runoff retention effect exhibited a significant positive correlation with rainfall amount and intensity ($p < 0.001$ and $p = 0.005$, respectively, as shown in Table 3). Additionally, there was a significant negative correlation between the runoff retention rate and rainfall duration ($p = 0.013$, Table 3). On the other hand, the correlation between A_0 and rainfall intensity was only marginally positive ($p = 0.067$, Table 3).

Table 3. Results of Spearman's correlation tests between rainfall characteristics and retention effects. The table presents the correlation coefficients, and the corresponding *p*-values are listed in parentheses. Significant correlations are indicated in bold.

Retention Effect	Rainfall Duration	Rainfall Amount	Rainfall Intensity
Runoff retention	−0.227(0.417)	**0.932 (<0.001)**	**0.704 (0.005)**
Runoff retention rate	**−0.622 (0.013)**	0.107 (0.705)	0.446 (0.097)
A_0	−0.317 (0.250)	0.414 (0.126)	0.489 (0.067)

According to Table 4, neither t_1 nor t_4 exhibited significant correlations with rainfall duration, amount, or intensity. However, t_2 and t_3 showed significant negative correlations with rainfall intensity ($p = 0.003$ and $p = 0.011$, respectively, Table 4). Additionally, t_3 demonstrated a significant positive correlation with rainfall duration ($p = 0.022$, Table 4).

Table 4. The results of Spearman's correlation tests between rainfall characteristics and retention and lag time. The table presents the correlation coefficients, and the corresponding p-values are listed in parentheses. Significant correlations are indicated in bold.

Retention and Lag Time	Rainfall Duration	Rainfall Amount	Rainfall Intensity
t_1	0.228 (0.413)	−0.084 (0.766)	−0.301 (0.275)
t_2	0.496 (0.060)	−0.507 (0.054)	**−0.706 (0.003)**
t_3	**0.585 (0.022)**	−0.147 (0.602)	**−0.633 (0.011)**
t_4	0.141 (0.616)	−0.332 (0.226)	−0.303 (0.271)

4. Discussion

Generally, the effectiveness of LID combination tends to exceed that of individual LID facilities, as the performance of LID combination may not be equally obtained from individual LID facilities [7,29]. LID combination often exhibit varying degrees of impact in managing stormwater, and the overall retention effect of LID combination can provide more prominent advantages compared to the simple superposition of individual LID facilities [16]. During the rainfall–runoff process, the runoff retention and lag effects of LID combinations are influenced by a variety of factors [7,8], including soil type, rainfall amount, rainfall duration, timing of peak rainfall intensity, antecedent rainfall, and the conditions of the constructed area [26,42]. All these comprehensive factors collectively contribute to the overall performance of runoff retention and lag effects in LID combination.

In this study, the runoff retention effect exhibited a significant positive correlation with both rainfall amount and intensity because it is widely recognized that both rainfall amount and intensity have a considerable impact on the hydrological behavior of permeable surfaces [42]. In particular, rainfall intensity and amount can influence soil infiltration and runoff production [42–44]. It is expected that soil infiltration would increase with higher rainfall intensity, mainly due to the spatial heterogeneity in soil infiltration characteristics. When rainfall exceeds the maximum infiltration rate, soil moisture does not reach saturation, resulting in a higher soil infiltration rate [45]. Consequently, the proportion of water transitioning from rainfall to runoff would also increase with increasing rainfall intensity [45]. Additionally, the soil could stabilize the infiltration rate and sustain infiltration even after soil moisture reaches saturation under higher rainfall intensity conditions [45]. However, some other studies have reported that spatial heterogeneity in the infiltration characteristics of the soil surface may decrease with increasing rainfall intensity, even for the same duration of rainfall [45]. In particular, the land terrain in Lingang New City is predominantly flat, and the pilot area is characterized by low permeability, leading to a significant decrease in soil infiltration volume with increasing rainfall intensity scenarios. Some studies, such as those by Römkens [46] and Parsons [47], have also found a potential decrease in runoff and an increase in retention with increasing rainfall intensity.

In addition, previous studies have indicated a threshold of rainfall amount that can trigger a change in the hydrological behavior of a catchment [48–50]. However, it has been observed that rainfall intensity has a more significant influence on determining the threshold value compared to rainfall amount [42]. Primarily, we found that the retention showed a substantial increase of approximately two and four times under the heavy and torrential rainfall scenarios, respectively, in comparison with the light-moderate rainfall scenario. Moreover, the difference between rainfall intensity and retention increases as rainfall intensity increases. This suggests that the retention capacity of the LID combination tends to stabilize and gradually reach saturation as rainfall intensity rises.

The average runoff retention rate was not significantly affected by increasing rainfall intensity in the LID combination. This is probably because the changes in A_0 under different rainfall intensity scenarios reflect the site-specific soil conditions, vegetation type, the prior rainfall conditions, as well as the retention effect in the study area [8,51]. This coincides with the soil condition in the pilot area mentioned previously. The soil in the study area has low permeability, making it difficult for water to penetrate through the soil layers. Furthermore, a significant negative correlation was observed between the runoff retention rate and rainfall duration. It has been shown that LID facilities with porous surfaces are more effective in reducing floods during shorter rainfall durations [7], which chould be partly explained by the fact that A_0 does not vary with increases in rainfall duration.

Retention and lag time are considered critical indices, as they encompass various aspects of runoff generation [26,52]. This study selected four characteristic indices (t_1, t_2, t_3, and t_4) to represent retention and lag time. First, t_1 represents the lag time from the start of rainfall to the initiation of runoff. During this process, the rainfall is primarily absorbed by vegetation, infiltrated into the soil, and fills the soil macropores [44]. In this study, it did not show any significant response under different rainfall intensity scenarios and no significant correlation with rainfall duration, amount, or intensity. This could correspond to the response of A_0 mentioned earlier under the various rainfall intensity scenarios, which can be primarily attributed to the antecedent soil moisture conditions prior to the onset of rainfall [16,26]. Nevertheless, the influence of antecedent soil moisture on soil infiltration was more noticeable under relatively lower rainfall intensity. But this effect diminished gradually as the rainfall intensity increased [53]. Additionally, the impact of vegetation coverage during the rainfall–runoff process may also contribute to the response of t_1 [44].

Second, t_2 represents the lag time from the end of rainfall to the end of runoff. While the rainfall process concludes, the LID facilities continue to generate runoff during this period. It was observed that t_2 decreased with increasing rainfall intensity scenarios, and the findings of this study also revealed a significant negative correlation between t_2 and rainfall intensity. This result can be attributed to the relationship between rainfall intensity and soil infiltration, which is highly influenced by rainfall intensity [42,54,55]. The delay between the end of rainfall and the end of runoff has a buffering effect on storing rainwater and can effectively conserve urban water resources. During the study period, this delay between the rainfall and runoff could be due to the decrease in soil infiltration volume with increasing rainfall intensity scenarios, resulting in the gradual decrease in t_2 in the LID combination. Therefore, in this study, the LID combination demonstrates superior benefits in extending the duration of runoff in rainfall events with lower rainfall amounts.

Third, t_3 represents the time delay between the centroid time of rainfall and runoff. The lag effect of the centroid time can be used to assess the overall lag effect of LID combination during the rainfall and runoff production processes. In this study, a significant positive correlation between t_3 and rainfall duration indicates that the overall lag effect in the LID combination could be more pronounced with prolonged rainfall. However, t_3 showed a significant negative correlation with rainfall intensity, suggesting that the centroid time might occasionally be longer due to the extended duration of runoff generation under short-duration rainstorms. Thus, in this study, the LID combination demonstrates significant overall lag effects in rainfall events with longer durations and lower rainfall amounts.

Fourth, t_4 represents the lag time from the peak rainfall to the peak runoff, commonly used to characterize the lag effect of LID combination under different instantaneous rainfall intensity scenarios. The peak value is an immediate value, and the peak effect of rainfall in runoff generation is quickly reflected. Typically, when the rainfall reaches its peak, the corresponding peak in runoff generation will also occur rapidly in theory. In this study, we found no significant correlation between t_4 and rainfall in the various rainfall intensity scenarios. The lack of correlation and differences in t_4 can be partly attributed to the shifting positions of the peak rainfall and peak runoff. This shift often depends on the different intensities of rainfall throughout the entire process. The peak rainfall can occur either early on or after the rainfall period, leading to a delay in peak runoff. In addition, negative values for t_4 can be encountered in this study, where the peak runoff occurs before the peak rainfall. This is because, in certain rainfall events, the average rainfall intensity in the early stages is high, but the peak rainfall occurs later in the rainfall process. As a result, the peak runoff primarily responds to the earlier rainfall process rather than the later peak rainfall.

5. Conclusions

This study investigated the response of rainfall–runoff retention and lag effects in an LID combination under three different rainfall intensity scenarios in a resettlement community in Lingang New City. We compared various parameters in the LID combination along a rainfall gradient, including rainfall, runoff retention, runoff retention rate, cumulative rainfall, and different lag times in the LID combination. The results showed a gradual reduction in runoff retention within the LID combination during heavier rainfall intensity scenarios, accompanied by an increasing difference between rainfall and runoff retention. Additionally, the average runoff retention was significantly enhanced, by nearly two times and four times, under heavy and torrential rainfall events compared to light–moderate rainfall. Moreover, the runoff retention effect positively correlated with rainfall amount and intensity. However, we only found a significant negative correlation between runoff retention rates and rainfall duration, but not with rainfall and rainfall intensity.

No significant differences in A_0 were observed between different rainfall intensities. Additionally, no significant differences in the lag effect were observed under different rainfall scenarios in each group. However, t_2 and t_3 showed a significant negative correlation with rainfall intensity. On the other hand, t_3 exhibited a strong positive correlation with rainfall duration. The findings from this study provide a valuable case study using observational data to analyze rainfall retention and lag effects in the LID combination. This study contributes to the existing empirical evidence in stormwater management using the LID combination. However, due to limitations and uncertainties, it is recommended that future studies consider long-term monitoring analysis and explore other influencing factors to improve the accuracy of evaluation.

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References

1. Brown, J.N.; Peake, B.M. Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff. *Sci. Total Environ.* **2006**, *359*, 145–155. [CrossRef] [PubMed]
2. de Macedo, M.B.; Rosa, A.; do Lago, C.A.F.; Mendiondo, E.M.; de Souza, V.C.B. Learning from the operation, pathology and maintenance of a bioretention system to optimize urban drainage practices. *J. Environ. Manag.* **2017**, *204*, 454–466. [CrossRef] [PubMed]
3. O'Sullivan, A.D.; Wicke, D.; Hengen, T.J.; Sieverding, H.L.; Stone, J.J. Life cycle Assessment modelling of stormwater treatment systems. *J. Environ. Manag.* **2015**, *149*, 236–244. [CrossRef] [PubMed]
4. Zhu, Z.H.; Chen, Z.H.; Chen, X.H.; Yu, G. An assessment of the hydrologic effectiveness of low impact development (LID) practices for managing runoff with different objectives. *J. Environ. Manag.* **2019**, *231*, 504–514. [CrossRef]
5. Tredway, J.C.; Havlick, D.G. Assessing the potential of low-impact development techniques on runoff and streamflow in the templeton gap watershed, Colorado. *Prof. Geogr.* **2017**, *69*, 372–382. [CrossRef]
6. Sohn, W.; Kim, J.H.; Li, M.H. Low-impact development for impervious surface connectivity mitigation: Assessment of directly connected impervious areas (DCIAs). *J. Environ. Plan. Manag.* **2017**, *60*, 1871–1889. [CrossRef]
7. Pour, S.H.; Wahab, A.K.A.; Shahid, S.; Asaduzzaman, M.; Dewan, A. Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. *Sustain. Cities Soc.* **2020**, *62*, 102373. [CrossRef]
8. Golden, H.E.; Hoghooghi, N. Green infrastructure and its catchment-scale effects: An emerging science. *Wiley Interdiscip. Rev. Water* **2018**, *5*, e1254. [CrossRef]

9. Dong, X.; Guo, H.; Zeng, S.Y. Enhancing future resilience in urban drainage system: Green versus grey infrastructure. *Water Res.* **2017**, *124*, 280–289. [CrossRef]
10. Jia, H.F.; Wang, Z.; Zhen, X.Y.; Clar, M.; Yu, S.L. China's sponge city construction: A discussion on technical approaches. *Front. Environ. Sci. Eng.* **2017**, *11*, 18. [CrossRef]
11. Ahmed, K.; Chung, E.S.; Song, J.Y.; Shahid, S. Effective design and planning specification of low impact development practices using Water Management Analysis Module (WMAM): Case of Malaysia. *Water* **2017**, *9*, 173. [CrossRef]
12. Chang, N.B.; Lu, J.W.; Chui, T.F.M.; Hartshorn, N. Global policy analysis of low impact development for stormwater management in urban regions. *Land Use Policy* **2018**, *70*, 368–383. [CrossRef]
13. Wang, M.; Zhang, D.Q.; Su, J.; Dong, J.W.; Tan, S.K. Assessing hydrological effects and performance of low impact development practices based on future scenarios modeling. *J. Clean. Prod.* **2018**, *179*, 12–23. [CrossRef]
14. Bedan, E.S.; Clausen, J.C. Stormwater runoff quality and quantity from trational and low impact development watersheds. *J. Am. Water Resour. Assoc.* **2009**, *45*, 998–1008. [CrossRef]
15. Chen, Y.; Tan, M.; Wan, J.H.; Weise, T.; Wu, Z.Z. Effectiveness evaluation of the coupled LIDs from the watershed scale based on remote sensing image processing and SWMM simulation. *Eur. J. Remote Sens.* **2021**, *54*, 77–91. [CrossRef]
16. Yin, Y.X.; Qin, H.P.; Yu, S.Q.; Zheng, Y.Y.; He, K.M. Retention and lag effects of rainfall runoff in a low impact development area. *J. Shenzhen Univ. Sci. Eng.* **2022**, *39*, 142–151. (In Chinese) [CrossRef]
17. Song, C. Application of nature-based measures in China's sponge city initiative: Current trends and perspectives. *Nat.-Based Solut.* **2022**, *2*, 100010. [CrossRef]
18. Liu, D.S. China's sponge cities to soak up rainwater. *Nature* **2016**, *537*, 307. [CrossRef]
19. Guo, X.C.; Guo, Q.Z.; Zhou, Z.K.; Du, P.F.; Zhao, D.Q. Degrees of hydrologic restoration by low impact development practices under different runoff volume capture goals. *J. Hydrol.* **2019**, *578*, 124069. [CrossRef]
20. Ding, L.; Ren, X.Y.; Gu, R.Z.; Che, Y. Implementation of the "sponge city" development plan in China: An evaluation of public willingness to pay for the life-cycle maintenance of its facilities. *Cities* **2019**, *93*, 13–30. [CrossRef]
21. Li, Z.M.; Xu, S.Y.; Yao, L.M. A systematic literature mining of sponge city: Trends, foci and challenges standing ahead. *Sustainability* **2018**, *10*, 1182. [CrossRef]
22. Du, S.Q.; Wang, C.X.; Shen, J.; Wen, J.H.; Gao, J.; Wu, J.P.; Lin, W.P.; Xu, H. Mapping the capacity of concave green land in mitigating urban pluvial floods and its beneficiaries. *Sustain. Cities Soc.* **2019**, *44*, 774–782. [CrossRef]
23. Shannak, S.d.A.; Jaber, F.H.; Lesikar, B.J. Modeling the effect of cistern size, soil type, and irrigation scheduling on rainwater harvesting as a stormwater control measure. *Water Resour. Manag.* **2014**, *28*, 4219–4235. [CrossRef]
24. Dreelin, E.A.; Fowler, L.; Ronald Carroll, C. A test of porous pavement effectiveness on clay soils during natural storm events. *Water Res.* **2006**, *40*, 799–805. [CrossRef]
25. Davis, A.P. Field performance of bioretention: Hydrology impacts. *J. Hydrol. Eng.* **2008**, *13*, 90–95. [CrossRef]
26. Hood, M.J.; Clausen, J.C.; Warner, G.S. Comparison of stormwater lag times for low impact and traditional residential development. *J. Am. Water Resour. Assoc.* **2007**, *43*, 1036–1046. [CrossRef]
27. Xia, J.; Wang, H.P.; Stanford, R.L.; Pan, G.Y.; Yu, S.L. Hydrologic and water quality performance of a laboratory scale bioretention unit. *Front. Environ. Sci. Eng.* **2018**, *12*, 14. [CrossRef]
28. Alfredo, K.; Montalto, F.; Goldstein, A. Observed and modeled performances of prototype green roof test plots subjected to simulated low- and high-intensity precipitations in a laboratory experiment. *J. Hydrol. Eng.* **2010**, *15*, 444–457. [CrossRef]
29. Gao, J.; Wang, R.S.; Huang, J.L.; Liu, M. Application of BMP to urban runoff control using SUSTAIN model: Case study in an industrial area. *Ecol. Model.* **2015**, *318*, 177–183. [CrossRef]
30. Huang, C.L.; Hsu, N.S.; Liu, H.J.; Huang, Y.H. Optimization of low impact development layout designs for megacity flood mitigation. *J. Hydrol.* **2018**, *564*, 542–558. [CrossRef]
31. Ahiablame, L.; Shakya, R. Modeling flood reduction effects of low impact development at a watershed scale. *J. Environ. Manag.* **2016**, *171*, 81–91. [CrossRef]
32. Zhou, L.; Ye, B.; Xia, S. Assessing membrane biofouling and its gel layer of anoxic/oxic membrane bioreactor for megacity municipal wastewater treatment during plum rain season in Yangtze River Delta, China. *Water Res.* **2017**, *127*, 22–31. [CrossRef] [PubMed]
33. Huang, Q.Y.; Wang, J.; Li, M.Y.; Fei, M.L.; Dong, J.G. Modeling the influence of urbanization on urban pluvial flooding: A scenario-based case study in Shanghai, China. *Nat. Hazards* **2017**, *87*, 1035–1055. [CrossRef]
34. Yuan, Y.; Xu, Y.S.; Arulrajah, A. Sustainable measures for mitigation of flooding hazards: A case study in Shanghai, China. *Water* **2017**, *9*, 310. [CrossRef]
35. Yin, J.; Yin, Z.E.; Hu, X.M.; Xu, S.Y.; Wang, J.; Li, Z.H.; Zhong, H.D.; Gan, F.B. Multiple scenario analyses forecasting the confounding impacts of sea level rise and tides from storm induced coastal flooding in the city of Shanghai, China. *Environ. Earth Sci.* **2011**, *63*, 407–414. [CrossRef]
36. Zheng, S.J.; Meng, C.; Xue, J.H.; Wu, Y.B.; Liang, J.; Xin, L.; Zhang, L. UAV-based spatial pattern of three-dimensional green volume and its influencing factors in Lingang New City in Shanghai, China. *Front. Earth Sci.* **2021**, *15*, 543–552. [CrossRef]
37. Shen, J.; Luo, X.; Wu, F.L. Assembling mega-urban projects through state-guided governance innovation: The development of Lingang in Shanghai. *Reg. Stud.* **2020**, *54*, 1644–1654. [CrossRef]

38. Yin, J.; Zhao, Q.; Yu, D.P.; Lin, N.; Kubanek, J.L.; Ma, G.Y.; Liu, M.; Pepe, A. Long-term flood-hazard modeling for coastal areas using InSAR measurements and a hydrodynamic model: The case study of Lingang New City, Shanghai. *J. Hydrol.* **2019**, *571*, 593–604. [CrossRef]
39. Xu, H.S.; Chen, L.; Zhao, B.; Zhang, Q.Z.; Cai, Y.L. Green stormwater infrastructure eco-planning and development on the regional scale: A case study of Shanghai Lingang New City, East China. *Front. Earth Sci.* **2016**, *10*, 366–377. [CrossRef]
40. Zhang, C.; Lv, Y.P. *Research on Sponge City Construction Technology in Plain River Network Area and Case Study in Lingang New City*; China Architecture & Building Press: Beijing, China, 2022.
41. Pohlert, T. PMCMRplus: Calculate Pairwise Multiple Comparisons of Mean Rank Sums Extended. 2021. Available online: https://cran.r-project.org/web/packages/PMCMRplus/index.html (accessed on 24 August 2023).
42. Guan, M.F.; Sillanpää, N.; Koivusalo, H. Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. *Hydrol. Process.* **2016**, *30*, 543–557. [CrossRef]
43. Dunkerley, D. Effects of rainfall intensity fluctuations on infiltration and runoff: Rainfall simulation on dryland soils, Fowlers Gap, Australia. *Hydrol. Process.* **2012**, *26*, 2211–2224. [CrossRef]
44. Mu, W.B.; Yu, F.L.; Li, C.Z.; Xie, Y.B.; Tian, J.Y.; Liu, J.; Zhao, N.N. Effects of rainfall intensity and slope gradient on runoff and soil moisture content on different growing stages of Spring Maize. *Water* **2015**, *7*, 2990–3008. [CrossRef]
45. He, L.; Li, S.; Cui, C.H.; Yang, S.S.; Ding, J.; Wang, G.Y.; Bai, S.W.; Zhao, L.; Cao, G.-L.; Ren, N.Q. Runoff control simulation and comprehensive benefit evaluation of low-impact development strategies in a typical cold climate area. *Environ. Res.* **2022**, *206*, 112630. [CrossRef]
46. Römkens, M.J.M.; Prasad, S.N.; Parlange, J.Y. Surface seal development in relation to rainstorm intensity. *Catena* **1990**, *17*, 1–11.
47. Parsons, A.J.; Stone, P.M. Effects of intra-storm variations in rainfall intensity on interrill runoff and erosion. *Catena* **2006**, *67*, 68–78. [CrossRef]
48. Burton, G.A., Jr.; Pitt, R.E. *Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2002.
49. Said, A.; Downing, H. Estimating connected impervious areas as function of rainfall depth. In Proceedings of the AWRA2010 Spring Specialty Conference, Orlando, FL, USA, 29–31 March 2010.
50. Sillanpää, N.; Koivusalo, H. Impacts of urbanization and event magnitude on runoff contributing area and runoff coefficients. In Proceedings of the 13th International Conference on Urban Drainage, Sarawak, Malaysia, 7–12 September 2014.
51. Boyd, M.J.; Bufill, M.C.; Knee, R.M. Pervious and impervious runoff in urban catchments. *Hydrol. Sci. J.* **1993**, *38*, 463–478. [CrossRef]
52. Leopold, L.B. Lag times for small drainage basins. *Catena* **1991**, *18*, 157–171. [CrossRef]
53. Liu, H.; Lei, T.W.; Zhao, J.; Yuan, C.P.; Fan, Y.T.; Qu, L.Q. Effects of rainfall intensity and antecedent soil water content on soil infiltrability under rainfall conditions using the run off-on-out method. *J. Hydrol.* **2011**, *396*, 24–32. [CrossRef]
54. Hawke, R.M.; Price, A.G.; Bryan, R.B. The effect of initial soil water content and rainfall intensity on near-surface soil hydrologic conductivity: A laboratory investigation. *Catena* **2006**, *65*, 237–246. [CrossRef]
55. Assouline, S.; Mualem, Y. Modeling the dynamics of seal formation and its effect on infiltration as related to soil and rainfall characteristics. *Water Resour. Res.* **1997**, *33*, 1527–1536. [CrossRef]