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Flood mitigation performance of low impact development technologies under different storms for retrofitting an urbanized area

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ABSTRACT

Low impact development technologies (LIDs) have been reported as alternatives to mitigate urban water-related hazards, particularly for urban flooding. However, the effectiveness of LIDs on flood mitigation is still not well understood. This study assessed the mitigation extent of urban flooding by LIDs for retrofitting an urbanized area at a feasible level using a hydrological model. A range of storms with different rainfall durations and amounts from intensity-duration-frequency curves were used to evaluate the hydrological performances of LIDs. The results indicated that LIDs were effective alternatives to mitigate urban flooding in the urbanized area. Surface runoff and peak flow decreased by 18.6–59.2% and 8.0–71.4%, respectively. However, the flood mitigation performance decreased markedly with the increase of rainfall amount. Although LIDs were less effective in flood mitigation during shorter and heavier storms, the performance was better with the increase of rainfall duration. This research provides an insight into flood reduction capabilities of LIDs under different rainfall characteristics for retrofitting built up areas, which is useful for urban storm management.

1. Introduction

Urban flood risks have been increasing due to rapid urbanization and climate change in many cities around the world (Abebe et al., 2018), such as Minneapolis in the U.S.A. (Hettiarachchi et al., 2018) and Nanjing in China (Du et al., 2012). And this trend is very likely to continue or accelerate in the near future though uncertainty remains regarding future climate change (IPCC, 2013). Traditional urban rainwater management practices are designed to meet performance standards (Pyke et al., 2011) and have exhibited the ineffectiveness in some extreme events such as the Tohoku tsunami in 2011 (Hu et al., 2017a). Meanwhile, some alternative approaches that control storm water at the source have become popular in the use of terms such as low impact development (USEPA, 2000; Xu et al., 2017; Wang et al., 2018) and best management practices (Ice, 2004; Fletcher et al., 2015; Petit-Boix et al., 2017).

The most commonly adopted low impact development technologies (LIDs) include rain cisterns, permeable pavements (PP), vegetated swales (VS), green roof and bio-retention (Ahiablame and Shakya, 2016). The benefits of these technologies on flood mitigation have been substantially documented in scientific literature (Damodaram et al., 2010; Gao et al., 2013), e.g. reduction in peak flow (Palanisamy and Chui, 2015), runoff (Baek et al., 2015), flood volume (Mei et al., 2018), inundation area (Hu et al., 2017b) and others. Palla and Gnecco (2015) found that the combinations of PP and green roof could reduce 23% of runoff and 45% of peak flow. Ahiablame and Shakya (2016) reported that flood flow events were maximally reduced by 40% with the implementation of rain barrel, rain garden and PP in an urban watershed in central Illinois. In China, Xie et al. (2017) found that PP could reduce 24.7% of peak flow in a designed five-year storm in a tourist village in Jurong, east China. Meanwhile, some studies indicated that the performances of

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these technologies on flood control were significantly different in various storms (Lee et al., 2012; Qin et al., 2013). For example, the lag times to peak of LIDs were significantly larger than the traditional watershed for small storms in Southeastern Connecticut (Hood et al., 2007). Wang et al. (2016) reported that the hydrological performances of bio-retention on peak runoff reduction were different in 2-year and 10-year designed storms in Singapore. Surface runoff was reduced by 15%, 27% and 38% for 2, 5 and 10-year storms with the application of rain gardens in Columbia (Morsy et al., 2016).

Although it is widely recognized that runoff volume and peak flow are reduced by LIDs, their flood control capabilities are not well understood in urbanized watersheds. Few studies (Pickerill and Maxey, 2009) concern the available space for implementation of LIDs in urbanized areas. Implementation area assumption was typically used in the earlier studies on flood mitigation of LIDs (Ahiablame et al., 2013; Luan et al., 2017). In fact, the retrofitting spaces are restricted in built-up areas due to the limitation of land, resident orientation, and complex urban environment (Talen, 2011). It is of significance to know which level of retrofitting technologies could be implemented in urbanized areas. Under the available level, is it effective on flood mitigation? And what are the mitigation extents of urban flooding under different storms? In addition, China proposed a sponge city construction plan in 2014, attempting to find ecologically suitable alternatives to mitigate water-related problems such as urban floods (MHURD, 2014). LIDs are an important component of sponge city construction. The sponge city plan is still at the infant implementing stage in 30 pilot cities of China. It requires more studies on LIDs and urban hydrology in various cities with different rainfall characteristics.

The main objectives of this study are to 1) evaluate the performance of LIDs on flood mitigation at an investigated feasible implementation level for retrofitting an urbanized area, and 2) investigate flood mitigation performance under designed storms with different rainfall durations and frequencies from the intensity-duration-frequency (IDF) curve of the study area. The results provide important implications for understanding the hydrological performance of LIDs for retrofitting an urbanized watershed. This study will be helpful for urban storm management and Chinese sponge city construction.

2. Method

2.1. Study area

The study area is located at Hexi district in Nanjing, east China (Fig. 1). The choice of this study area was driven by severe waterlogging problems. Hexi district is surrounded by the Qinhuai River and the Yangtze River. During the rainy season, water levels in both rivers are higher than the Hexi district's average height of terrain, so it is difficult to discharge surface runoff into the rivers, with the consequence of serious waterlogging. The study area is one of the areas with high vulnerability to waterlogging in Nanjing (Zhang et al., 2012). The distribution of land uses is shown in Table 1. The total area is 0.58 km^2, with around 73.8% impervious underlying surfaces.

2.2. Modeling approach overview

A model proposed by Hu et al. (2018) was used to evaluate the effectiveness of LIDs on flood mitigation. The model details and setup were reported in the previous study (Hu et al., 2018). Brief summary is provided here. The model consists of impervious module with the soil conservation service (SCS) curve number (CN) method, and pervious module with Horton's infiltration method (Horton, 1941). The SCS-CN method, empirically developed for runoff evaluation (Mishra and Singh, 2013), has been widely applied in low impact development related studies with acceptable performance (Ahiablame et al., 2013; Zhang et al., 2016). It estimates runoff (RF, mm) for a given precipitation depth (P, mm) as:

$$RF = \frac{(P-I)^2}{P-I+S} \qquad P > I \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

where S is soil moisture retention; I is the initial abstraction (i.e. infiltration, interception and surface storage), equals to 0.2S. The value of CN is set as 94 according to a published study (Zhang et al., 2016). A description of the development of pervious module based on Horton's infiltration model is provided by Hu et al. (2018). It estimates surface runoff (Rs) for given precipitation duration (x) and intensity (q) as:

$$R_s = \int_0^x h_s dx \tag{3}$$

$$h_s = \begin{cases} 0, & q \le f_0\left(1-\frac{W(t)k}{f_0}\right) + f_c\frac{W(t)k}{f_0} \\ q - f_0\left(1-\frac{W(t)k}{f_0}\right) - f_c\frac{W(t)k}{f_0}, & q > f_0\left(1-\frac{W(t)k}{f_0}\right) + f_c\frac{W(t)k}{f_0} \end{cases} \tag{4}$$

$$W(t) = \int_0^t f_0 e^{-kt} dt \tag{5}$$

where f_c and f_0 are the minimum and maximum infiltration; $W(t)$ is soil moisture at time t; k is a decay constant. The values of f_c, f_0 and k are 12 mm/h, 199.8 mm/h and 1.98, respectively (Table 2). Initial soil moisture is set as half of maximum soil water capacity for all designed rainfall events (Gao, 2010; Hu et al., 2018).

2.3. Designed rainstorms

Various types of rainstorms were designed according to the empirical formula of rainfall IDF relationship in Nanjing, which was developed by the Nanjing Meteorological Bureau. The formula has

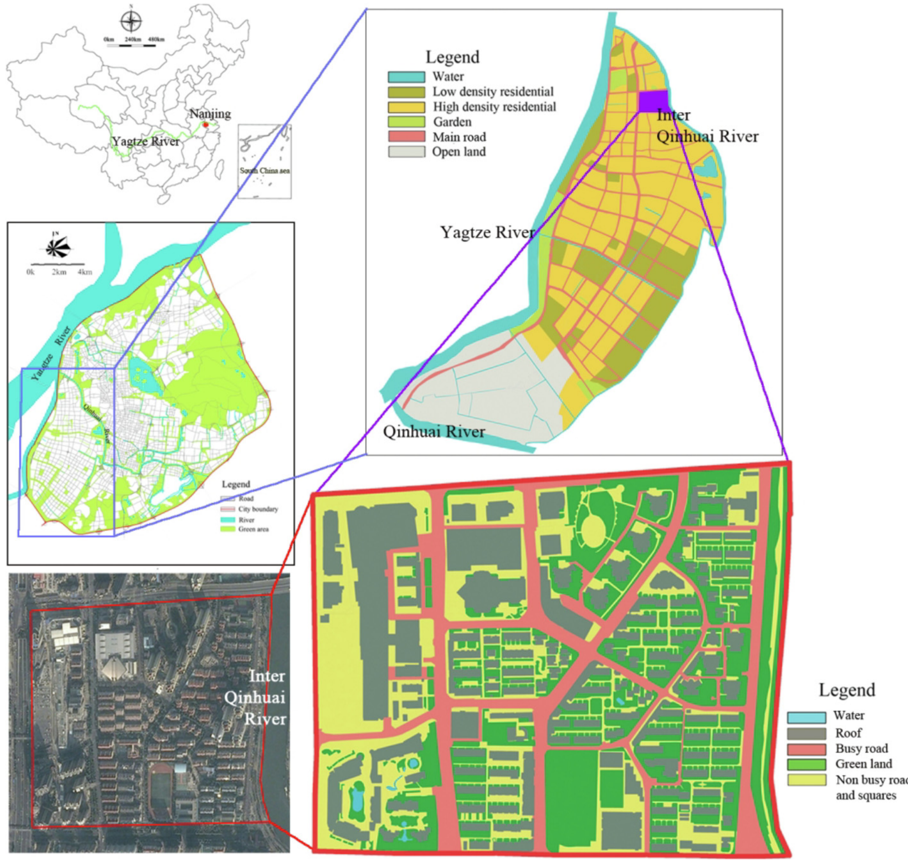

Fig. 1. Location and land use map of the study area in Nanjing, China.

Table 1
Land use and land cover in the study area.

Type	Roof	Non-busy road and squares	Busy road	Green land	Water	Total
Area (km^2)	0.153	0.131	0.143	0.150	0.001	0.578
Percentage (%)	26.4	22.7	24.7	26.0	0.2	100

Table 2
Mandatory parameters values for model simulation.

	Impervious surfaces	Green lands	PP	VS
f_0 (mm·h^{-1})	–	199.8	15000	199.8
k	–	1.98	104.17	1.98
f_c (mm·h^{-1})	–	12	–	12
CN	94	–	–	–

PP: permeable pavements; f_0: maximum infiltration; k: a decay constant; VS: vegetated swales; f_c: minimum infiltration; CN: curve number.

been widely used in Nanjing city where the study area located at (Rui et al., 2015; Shi et al., 2017). It is described as:

$$q = \frac{64.3 + 53.8lgT}{(r + 32.9)^{1.011}} \quad (6)$$

where q is rainfall intensity (mm/min); T is return period, and r is rainfall duration (min). Chicago hyetograph method (Keifer and Chu, 1957) was used for rainstorm design (Qin et al., 2013). The ratio of time to peak point r was set as 0.4 (Jia et al., 2014; Silveira, 2016). Four return periods (2-, 10-, 50-and 100-year) and three rainfall durations (2- 4- and 6-h) were considered. Storms are named as mhTn, where m and n are numbers of duration time and return periods. For example, 2hT2 is the storm of 2 h duration and 2 year return period. The rainfall amounts of all designed storm events are shown in Table 3 and the distribution of rainfall intensities are shown in Fig. 2.

Table 3
Reduction in surface runoff and peak flow with the application of LIDs under different storms.

	Rainfall (mm)	Depth of surface runoff (mm)		Runoff reduction		Peak flow reduction	
		Original Case	LIDs	(mm)	%	(mm)	%
2hT2	59.8	31.9	13.0	18.9	59.2	11.9	71.4
2hT10	87.7	59.0	39.5	19.5	33.1	11.6	41.6
2hT50	115.6	86.0	67.0	19.0	22.1	5.8	15.0
2hT100	127.7	97.8	78.9	18.9	19.3	3.5	8.0
4hT2	66.6	36.2	16.2	20.0	55.2	12.6	72.0
4hT10	97.6	65.4	45.3	20.1	30.6	12.8	44.1
4hT50	128.7	95.2	75.1	20.1	21.1	8.2	20.0
4hT100	142.1	108.2	88.1	20.1	18.6	6.2	13.5
6hT2	69.1	37.9	16.4	21.5	56.7	12.0	71.7
6hT10	101.3	67.8	45.6	22.2	32.7	12.5	44.3
6hT50	133.6	98.4	75.5	22.9	23.3	10.6	27.1
6hT100	147.5	111.7	88.5	23.2	20.8	8.9	20.2

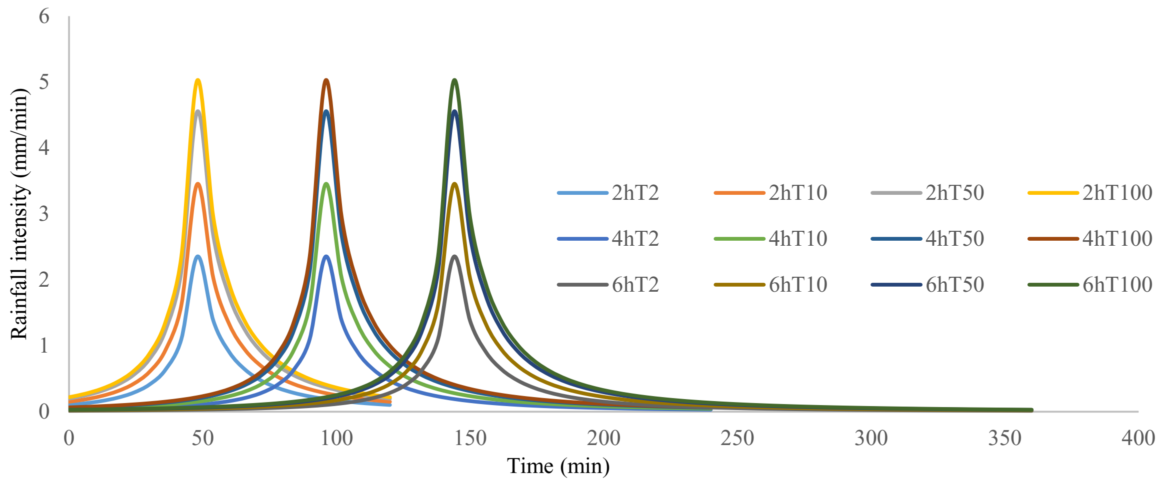

Fig. 2. Intensity patterns of designed rainstorms.

2.4. Implementation level of low impact development technologies

2.4.1. Rooftop rainwater harvesting

The potentials of rooftop rainwater harvesting are limited by tank capacity and available land space for tank setting. In this study, the tank capacity was calculated by specified rainstorm. The capacity equals to the rooftop surface runoff during the specified rainfall events. All rooftop runoff is collected into rainfall tanks when rainfall amount is less than the tank capacity. A designed rainfall intensity with 2-year return period and 2-h durations was used. The tank capacity is 0.044 m^3 (hereafter mentioned as 44 mm) per unit roof area (1 m^2). The rationality of the selected rainfall intensity is discussed in "Rainwater tank capacity". In addition, an *in situ* investigation on available land space for rainwater tank set-up was conducted and the results indicated that there were 55% of rooftops available for rainwater harvesting with aboveground cisterns in or around buildings (Zhang et al., 2012). The total implementation area of rooftops for rainwater harvesting is 0.08 km^2. Four criteria were considered in this investigation, including available places on plazas or parks without impact on facilities usage, on greenbelts without impact on the function and view, outside the construction site in the building area, and in the construction sites (Zhang et al., 2012).

2.4.2. Permeable pavements and vegetated swales

Replacement of existing impervious pavements is a large project and it affects traffic and daily life. Thus, in this study, PP are planned to be implemented on non-busy roads and parking lots. Non-busy roads are community internal roads and city branch roads with low traffic. The total retrofitting area of PP is 0.13 km^2. Various kinds of PP have different hydrological performance (Collins et al., 2008; Fassman and Blackbourn, 2010). Permeable concretes are used in this study, which have the best performance on flood mitigation compared with other types (Hu et al., 2018). According to previous studies (Hu et al., 2018; Kumar et al., 2016), the parameter values for permeable concretes are shown in Table 2. Also, VS are planned to be built on concentrated green lands except greenbelts between dwelling areas and roads. The total area is about 0.02 km^2. The height of swales is 10 mm lower than the surrounding ground surfaces. VS have same infiltration rates and soil moisture as green lands in this study, and the mandatory parameters are shown in Table 2.

3. Results

3.1. Performance of low impact development technologies on flood mitigation

Table 3 shows the simulated surface runoff and peak flow (in depth, mm) of original case and LIDs under different designed rainfall events. It was found that LIDs could reduce 19.3–59.2% of surface runoff and 8.0–71.4% of peak flow in the 2 h storms. There was an 18.6–55.2% decrease in surface runoff and a 13.5–72% decrease in peak flow in the 4 h storms. Surface runoff and peak flow reduced by 20.8–56.7% and 20.2–71.7% in the 6 h storms, respectively. With the exception of the 6hT10 storm, there was no time delay of peak flow observed in all events (Fig. 3).

3.2. Impact of rainfall amount on flood mitigation performance of low impact development technologies

In the same rainfall duration, the reduction ratios of surface runoff decreased with the increase of rainfall amount. For instance, the reduction ratio of surface runoff was maximum at the storm of 2hT2, followed by the storm of 2hT10, 2hT50 and 2hT100. Similarly, the reduction ratios of peak flow decreased with the increase of rainfall amount in the same rainfall duration. For instance, the reduction ratio of peak flow was maximum at the 6hT2 storm, followed by the 6hT10, 6hT50, and 6hT100 storms. However, changes in reduction values varied with the changes of rainfall amount in different rainfall duration. For 2-h rainfall events, reduction values of surface runoff increased from the 2-year event to the 10-year event and decreased when rainfall amount was larger than the 10-year rainfall amount. For 4-h and 6-h rainfall events, reduction values of surface runoff slightly increased with the increase of rainfall amount. Reduction values of peak flow decreased with the increase of rainfall amount for 2-h rainfall events. For 4-h and 6-h rainfall events, reduction values of peak flow increased when rainfall amount was lower than the 10-year return period rainfall amount, but they decreased when rainfall amount was higher than the 10-year return period rainfall amount.

3.3. Impact of rainfall duration on flood mitigation performance of low impact development technologies

To evaluate the impact of rainfall duration on flood mitigation, three storms were designed. They had the same rate of time to peak

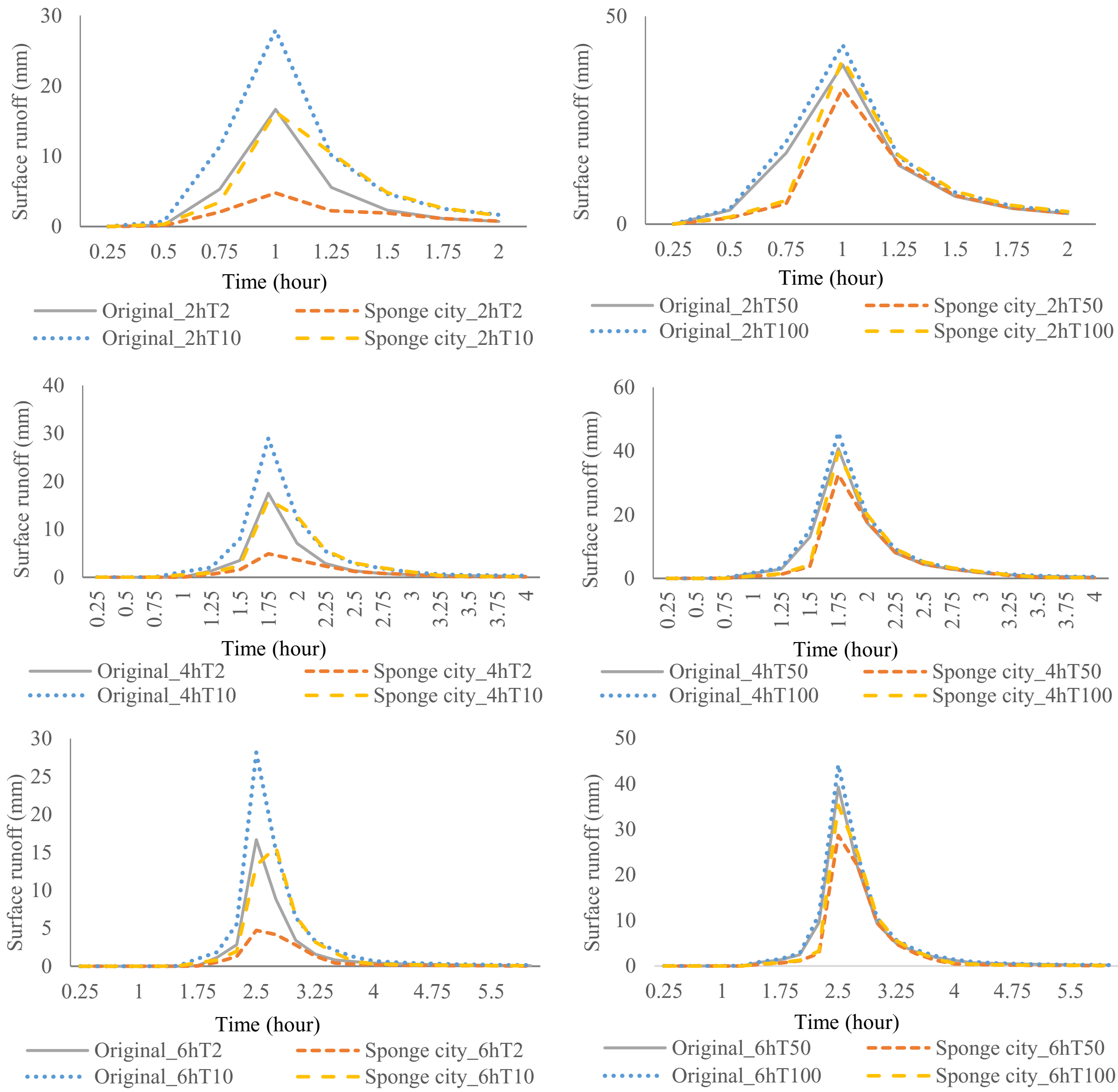

Fig. 3. Simulated surface runoff of original case and LIDs applied under the rainstorms with different return periods and durations.

Table 4
Reduction in surface runoff and peak flow with the application of LIDs under the rainstorms with same rainfall amount and different duration.

	Depth of surface runoff (mm)		Runoff reduction		Peak flow reduction	
	Original Case	LIDs	(mm)	%	(mm)	%
2hR115.6	86	67.01	18.99	22.08	5.72	14.95
4hR115.6	82.59	62.55	20.04	24.27	10.1	28.25
6hR115.6	81.26	58.81	22.45	27.63	12.9	39.16

point (0.4) and the rainfall amount (115.6 mm) in different rainfall duration (2, 4 and 6-h) named 2hR115.6, 4hR115.6 and 6hR115.6 (Table 4). With the same rainfall amount, as the rainfall duration increased, both surface runoff and peak flow declined. The reduction ratio of surface runoff was minimum (22.08%) at the 2hR115.6 storm, followed by the 4hR115.6 and 6hR115.6 storms. Similarly, the reduction ratio of peak flow increased from 14.95% to 39.16%. When rainfall duration was longer, the performance of LIDs on flood mitigation was better. In addition, there was no time delay of peak flow with the increase of rainfall duration (Fig. 4).

4. Discussion

4.1. Rainwater tank capacity

Walsh et al. (2014) suggested that the performance of rooftop rainwater harvesting dependent highly on tank storage size. Larger tank capacity has better performance in rainfall harvesting (Hu et al., 2017b). However, large tanks require lots of land space and big investment. Huang et al. (2014) found that compared with other LIDs, rainwater harvesting produced the smallest change in the peak flow, mainly because the implementation area and tank capacity were restricted in urbanized areas. Some studies have estimated sizes and performances of rainwater harvesting systems using approaches such as water balance simulation (Ghisi and Schondermark, 2013; Zhang and Hu, 2014) and designed rainstorm intensity (Zhang et al., 2012). In general, storage capacity cannot be standardized, affected by site-specific variables (Campisano and Modica, 2012). In this study, a designed rainfall intensity with 2-year return period and 2-h rainfall duration was adopted. The reason is that 2hT2 rainfall storms frequently occur

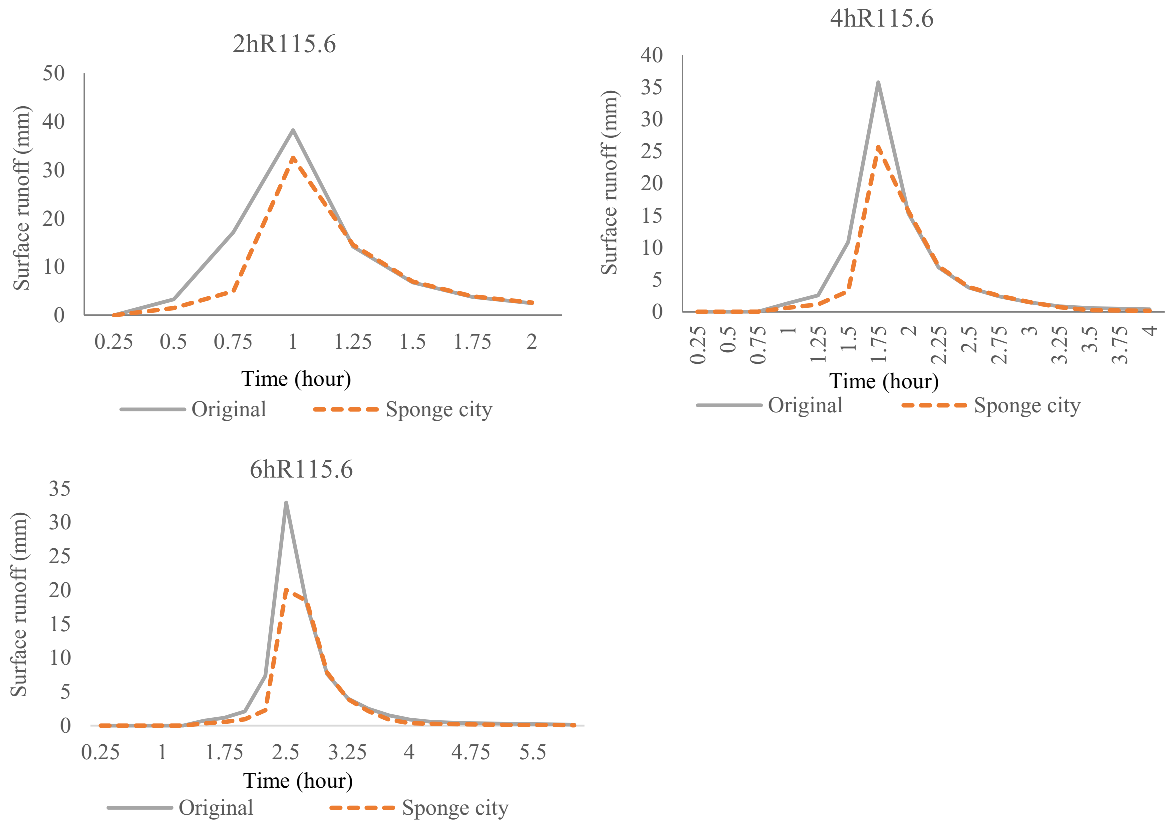

Fig. 4. Simulated surface runoff of original case and LIDs applied under the rainstorms with same rainfall amount and different duration.

and it is necessary to eliminate the flood risks caused by this kind of rainfall storms. Also, rainwater tanks have a relative low vacancy rate for water storage at this size compared with higher criterion. Based on the index of rainwater utilization rate and financial costs using water balance simulation and life cycle cost analysis, Hu (2012) found that the suitable rainwater tank capacity in the study area is between 26.2 and 78.5 mm. The value of designed tank capacity (44 mm) is in the range.

4.2. Clogging of permeable pavements

Kumar et al. (2016) reported that the measured *in-situ* infiltration rates of PP declined markedly due to clogging of pores after two-year using. Nanjing is a city suffering from high concentrations of particulate matter. The PP performance will degrade due to particle deposition on pavement surfaces. A previous study at the study area (Hu et al., 2018) has proved that clogging could reduce the performance of PP by 62–92%. However, this problem could be tackled to some extent by maintenance. Bean et al. (2007) found that maintenance significantly improved the infiltration rates of PP on 40 PP sites in Maryland, Virginia, North Carolina, and Delaware, the U.S.A. Kamali et al. (2017) found that PP could function hydraulically when they were annually cleaned. In this study, clogging was not considered during simulation. The evaluated performance of LIDs will degrade when the using period extends. However, this degradation could be slowed down with good maintenance.

4.3. Implications of low impact development technologies

Retrofitting projects in urbanized area are always restricted by limited land space, fund, resident orientation and complex urban environment. This study estimated the potential implementation level of LIDs considering land space, environment and traffics. There are maximum about 14.5% of total area (55% of roof area) available for rainwater harvesting and 22.7% of total area available for PP. The full using of this potential level could reduce 18.6–59.2% of surface runoff. However, flooding cannot be completely eliminated by LIDs. The reduction ratios of surface runoff and peak flow decreased with the increasing of rainfall amount. LIDs are less effective in flood mitigation during shorter and heavier storms. Despite the effectiveness of LIDs for mitigating urban flood, it is still indispensable to combine traditional grey infrastructures with LIDs for urban flood prevention. As a case study, this research identified the appropriate implementation level for the study area, which may not be applicable in other watersheds with different characteristics. Sustainable managing and using water resource has been a big challenge in the world, particularly in China (Yang et al., 2013; Yang, 2014). Therefore more researches are still needed for region-specific implementation of LIDs for flood control.

4.4. Limitations and future research

In line with numerous other studies, the current research has some limitations. Due to lack of observed runoff data, no effort was made to calibrate the model. Model parameter values were obtained from the published literature and the main conclusions were from multi-scenarios. Therefore, to the best of our knowledge, marked changes are unlikely caused by the uncertainties of model. Also, calibration can be done with field observed data in the future study. So the accurate evaluation of the effectiveness of LIDs can be further improved. In addition, this study discussed the designed rainfall events by Chicago hyetograph method with $r = 0.4$. The storms with different patterns may have different impacts on low impact development performance. Therefore, researches on various rainfall patterns are also needed in the future researches. Moreover, the investigation on implementation level of LIDs did not consider resident orientation and economic considerations, which may overestimate the potentials of the implementation level.

5. Conclusion

This study analysed the effectiveness of LIDs on flood mitigation at a feasible implementation level under various designed storms for retrofitting an urbanized area. The main findings are summarized as follows:

1) LIDs are effective alternatives to mitigate urban flooding for retrofitting the study area. With the implementation of LIDs, surface runoff and peak flow decreased by 18.6–59.2% and 8.0–71.4% under different storms.
2) The flood mitigation performance decreased obviously with increasing rainfall amount. The reduction ratios of surface runoff decreased markedly from 32.7-59.2% to 18.6–20.8% with the increase of rainfall amount from a 2-year event to a 100-year event. And the reductions in peak flow declined from 11.9-12.8 mm to 3.5–8.9 mm (from 71.4-72% to 8–20.2%).
3) LIDs are more effective on flood mitigation as the rainfall duration increases, but it is less effective in shorter and heavier storms. Surface runoff reduction ratio increased from 22.08% to 27.63% and peak flow reduction ratio increased from 14.95% to 39.16% as the rainfall duration increases from 2 h to 6 h.

The study provides valuable insight for decision making regarding flood reduction capabilities of LIDs under different rainfall characteristics for retrofitting built up areas.

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