Analysis on LID for highly urbanized areas' waterlogging control: demonstrated on the example of Caohejing in Shanghai

Z. L. Liao, Y. He, F. Huang, S. Wang and H. Z. Li

ABSTRACT

Although a commonly applied measure across the United States and Europe for alleviating the negative impacts of urbanization on the hydrological cycle, low impact development (LID) has not been widely used in highly urbanized areas, especially in rapidly urbanizing cities in developing countries like China. In this paper, given five LID practices including Bio-Retention, Infiltration Trench, Porous Pavement, Rain Barrels, and Green Swale, an analysis on LID for highly urbanized areas' waterlogging control is demonstrated using the example of Caohejing in Shanghai, China. Design storm events and storm water management models are employed to simulate the total waterlogging volume reduction, peak flow rate reduction and runoff coefficient reduction of different scenarios. Cost-effectiveness is calculated for the five practices. The aftermath shows that LID practices can have significant effects on storm water management in a highly urbanized area, and the comparative results reveal that Rain Barrels and Infiltration Trench are the two most suitable cost-effective measures for the study area.

Key words | cost-effectiveness, low impact development (LID), storm water management model (SWMM), urbanized areas, waterlogging

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INTRODUCTION

As a problem that any city in any country has to encounter in the fast urbanizing processes, the rapid increase in impervious surfaces is occurring in many Chinese cities because of the large-scale, high-speed urbanization ongoing in China. Consequently, this problem can bring great changes to the natural hydrological regime. In particular, the augmentation of volume and frequency of runoff can cause waterlogging during storm periods (Fletcher *et al.* 2007; O'Driscoll *et al.* 2010; Gao *et al.* 2012; Ashbolt *et al.* 2013). The mitigation and adaptation to hydrological changes arising from urban development have now attracted serious concern in China.

There are many ways to alleviate the negative impacts of urbanization on the hydrological cycle, such as urban water sensitive designs, sustainable urban drainage systems, or low impact development (LID) (Brown & Hunt 2012). Amongst them, LID is a relatively new concept for stormwater management, which first appeared in Prince George's County, Maryland, USA in the 1990s. LID is a site design strategy to maintain the pre-development hydrological regime by the use of integrated and distributed micro-scale stormwater retention and detention basins. Unlike traditional stormwater management, LID principles are based on controlling stormwater at the source, being more cost effective and more aesthetically pleasing than traditional, structural stormwater conveyance systems (Coffman 2000). LID is more commonly implemented in newly developed areas and has shown promising results in applications across the United States and Europe (Brattebo & Booth 2003; Bengtsson *et al.* 2005; Dietz & Clausen 2008). However, LID has not been widely implemented in highly urbanized areas, especially in rapidly urbanizing cities in developing countries like China.

In order to make the design and application of LID more efficient, modeling tools are required to specifically support the selection and evaluation of viable LID options (Artina *et al.* 2005; Elliott & Trowsdale 2007; Lai *et al.* 2007). The storm water management model (SWMM) is a model which can explicitly simulate five different generic types of LID control: Bio-Retention, Infiltration Trench, Porous Pavement, Rain Barrels, and Green Swale.

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In SWMM, controls are represented by a combination of vertical layers whose properties are defined on a per-unit-area basis. This allows LIDs with the same design but different areal coverage for the purpose of being easily placed within different sub-catchments of a study area (Rossman 2010). In addition, cost control is another important concern in the process of promoting LID.

Typically, there are many constructions and reconstructions in highly urbanizing areas during their high-speed development periods. If LID controls are embedded into their constructions and reconstructions, negative impacts of urbanization on the hydrological cycle can be reduced significantly. Prior to the use of LID, it is necessary to know how to select the most cost-effective measures. In this paper, a case in Shanghai, China is used to show how to choose the most appropriate LID measures in a highly urbanized area. An SWMM model is employed, and effects and costs of different LID measures are compared. The purpose of this study is to provide a reference to the methodology, comparisons, and technical and economic parameters for the analyses on LID measures in highly urbanized regions.

METHODOLOGY

Study area description

The Caohejing drainage system is located in Xuhui District, Shanghai, China, which occupies an area of 3.74 km^2. Land use in Caohejing includes green spaces, industrial land, residential areas, roads and squares, etc. The system was constructed in 1986. The storm recurrence interval of this system is 1 year and the runoff coefficient is 0.5. Tianlin Pumping Station is the flood control pumping station for the system. It is equipped with six axial flow pumps that discharge water to the Puhui River. Due to the large quantity of dry weather flow, it is equipped with two additional sewage interception pumps.

Based on the digital elevation model (DEM) of the system, the whole area is divided into 58 sub-catchments through ArcGIS, and there are 560 nodes and 566 pipes (see Figure 1).

Model's principle

The US Environmental Protection Agency's SWMM was selected to track the quantity of runoff generated within each sub-catchment. In SWMM, the Extended Transport module provides the SWMM with dynamic wave simulation capability (Roesner *et al.* 1988). Dynamic wave routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results (Huber *et al.* 1988). The Saint Venant equations represent the principles of conservation of momentum (Equation (1)) and conservation of mass (Equation (2)):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{Q}{gA}\frac{\partial}{\partial x}\left(\frac{Q}{A}\right) + \frac{\partial h}{\partial x} = S_0 - S_f \tag{2}$$

where, A is area of the pipe flow cross section, m^2; Q is flow, m^3/s; t is time, s; x is the length of the pipe along the flow direction, m; g is gravitational acceleration, m/s^2; h is the depth of water, m; S_0 is pipe slope, dimensionless; S_f is friction slope, dimensionless.

Model calibration and validation

Rain and pump station data were obtained from the online drainage comprehensive application system of the Shanghai Municipal Sewerage Company Ltd (see http://www.smsc.sh.cn/oa_index/). The rain gauge is set up in the pump station. Because the study area is only 3.74 km^2, the rain data are accurate enough to establish the model (Dong & Liu 2012).

The parameters of the model are listed in Table 1. Among them, some fixed physical parameters are extracted from ArcGIS or on-site research. An initial estimate of the characteristic width is calculated from the sub-catchment area divided by the average maximum overland flow length. The maximum overland flow length is the length of the flow path in terms of the furthest drainage point of the sub-catchment before the flow becomes channelized. The Manning's roughness coefficient was taken from the SWMM user's manual. The routing time is 10 s and the infiltration model selected in the model is Horton's model. The routing model selected in the research work is the dynamic wave model. With reference to previous literature, other parameters were selected to calibrate using the monitoring data. Manning coefficient (N-Imperv, N-Perv), storage (Dstore-Imperv, Dstore-Perv), parameters in Horton's model, and roughness of conduit are calibrated parameters. Initially, they take values based on the listed references (*a*, *b*, *c*, *d*, *e*, *f*). The confirmed results of these parameters after calibration and validation are also shown in Table 1.

In total, 11 selected rainfall events from 2009 to 2012 with maximum precipitation of 108.6 mm and minimum

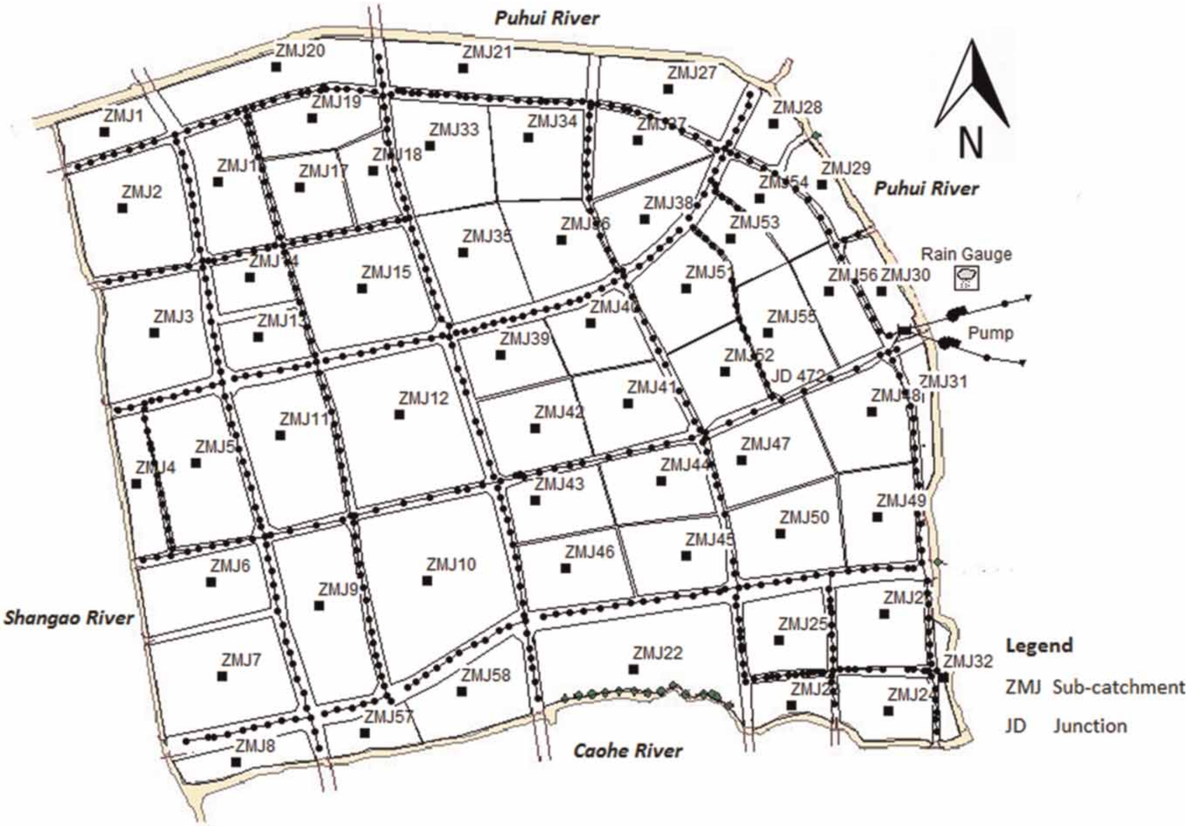

Figure 1 | Sub-catchments of the study area.

precipitation of 21.2 mm were employed for calibration and validation (nine for calibration and two for validation). Flow and water level were measured in the pumping installation and in the pipe network. The relative errors of the simulation flow and real flow ranged from 2.81 to 13.53%. The relative errors of the simulation water level and real water level ranged from 14.51 to 16.99%. Thus, the validated model is acceptable. Some of the results from the calibration and validation are shown in Figure 2.

Design storms

Since rainfall causes waterlogging, the design of rainstorm has a direct impact on the occurrence of waterlogging. The design formula of storm intensity in this study is shown as Equation (3) (Shanghai Urban Construction Design and Research Institute & Shanghai Meteorological Centre 2004):

$$i(\mathrm{mm/min}) = \frac{9.45 + 6.7932\lg P}{(t + 5.54)^{0.6514}} \tag{3}$$

While i is storm intensity, mm/min; P is storm recurrence interval, year; t is rainfall duration, min.

The Chicago hyetograph is suitable for the design storms in Shanghai and the value of r (ratio of time before the peak occurs to the total duration time) selected is 0.375 (Ning 2006). Therefore, the continuous curves of the hyetograph are computed in terms of the times before (t_b) or after (t_a) the peak intensity by the two equations (Equations (4) and (5)) (Keifer & Chu 1957):

$$\text{Before the peak: } i_b = \frac{(9.45 + 6.7932\lg P)\left[\dfrac{(1-0.6514)t_b}{0.375} + 5.54\right]}{\left(\dfrac{t_b}{0.375} + 5.54\right)^{0.6514+1}} \tag{4}$$

$$\text{After the peak: } i_a = \frac{(9.45 + 6.7932\lg P)\left[\dfrac{(1-0.6514)t_a}{1-0.375} + 5.54\right]}{\left(\dfrac{t_a}{1-0.375} + 5.54\right)^{0.6514+1}} \tag{5}$$

Table 1 | Main parameters for the catchment

	Parameters	Unit	Value		Source
			Range	Validated	
Sub-catchment properties	Area	ha	2.44–16.9	–	ArcGIS
	Width	m	131–532	–	ArcGIS
	% Slope	–	0.04–1.15	–	ArcGIS
	% Imperv	–	25–100	–	ArcGIS
	N-Imperv	–		0.013	*a. b. f.*
	N-Perv	–		0.15	
	Dstore-Imperv	mm	1–5	1.27	*c. f.*
	Dstore-Perv	mm	3–15.3	7.62	
	% Zero-Imperv	–	31%–97%	–	ArcGIS
Horton model	The maximum infiltration rates	mm/h	7.62–254	67.2	*a. d. e. f*
	The minimum infiltration rates	mm/h	0.69–177.04	0.69	
	Decay coefficient	h^{-1}	2–7	2	
Junction properties	Inflows	l/s	0–38	–	
	Max. depth	m	3–5	–	ArcGIS
	Initial depth	m	0	–	Default
	Invert el.	m	−2.4–6	–	ArcGIS
Conduit properties	Shape		Circular	–	ArcGIS
	Max. depth	mm	350–2,400	–	ArcGIS
	Length	m	8–81	–	ArcGIS
	Roughness	–	0.009–0.017	0.012	*a.*

a: Rossman (2010).
b: McCuen *et al*. (1996).
c: Bartlett (1981).
d: Zoppou (2001).
e: Liong *et al*. (1991).
f: Choi & Ball (2002).

Because the design return period of the stormwater drainage system in Shanghai is 1 year mostly, and with reference to the 10 year rainfall data distribution of Shanghai, the design storm recurrence intervals selected in this research are 1, 2 and 5 y and the rainfall durations selected are 60, 360 and 1,440 min. Figure 3 shows the intensity-duration-frequency (IDF) curves of the nine design storm events. The nine design storm events were used to analyze the waterlogging situation without and with LID.

RESULTS AND DISCUSSION

Design of LID practices

The geographic information system (GIS) map database of the study region shows that the impermeability of each sub-catchment area ranges from 25 to 100%. According to the design principles of LID, the sub-catchments whose impermeability is greater than 80% are selected as subjects to impose LID practices, and a total of 23 sub-catchments satisfy this condition. The area of each sub-catchment ranges from 2.44 to 16.49 ha.

In order to compare the waterlogging reduction and peak discharge reduction effects of different LID practices, five LID practices including Bio-Retention, Infiltration Trench, Permeable Pavements, Rain Barrels and Grass Swale were applied to those sub-catchments separately. According to the previous literature, the area covered by LID practices accounts for 9.3%–15.2% of each sub-catchment (Roldin *et al*. 2012).

Results of different scenarios and discussion

In order to select the best LID practices suitable for the study area, five scenarios with different LID practices were set to simulate runoff reduction. The five scenarios were simulated by using nine rainfall events designed previously. The waterlogging volume is the amount of water poured out of inspection wells. Hydraulic conductivity of the soils is around 0.1–0.5 m/d, and the groundwater situation is 2.6 meters below the ground surface. The area is surrounded by channels. It cannot be affected by other drainage systems.

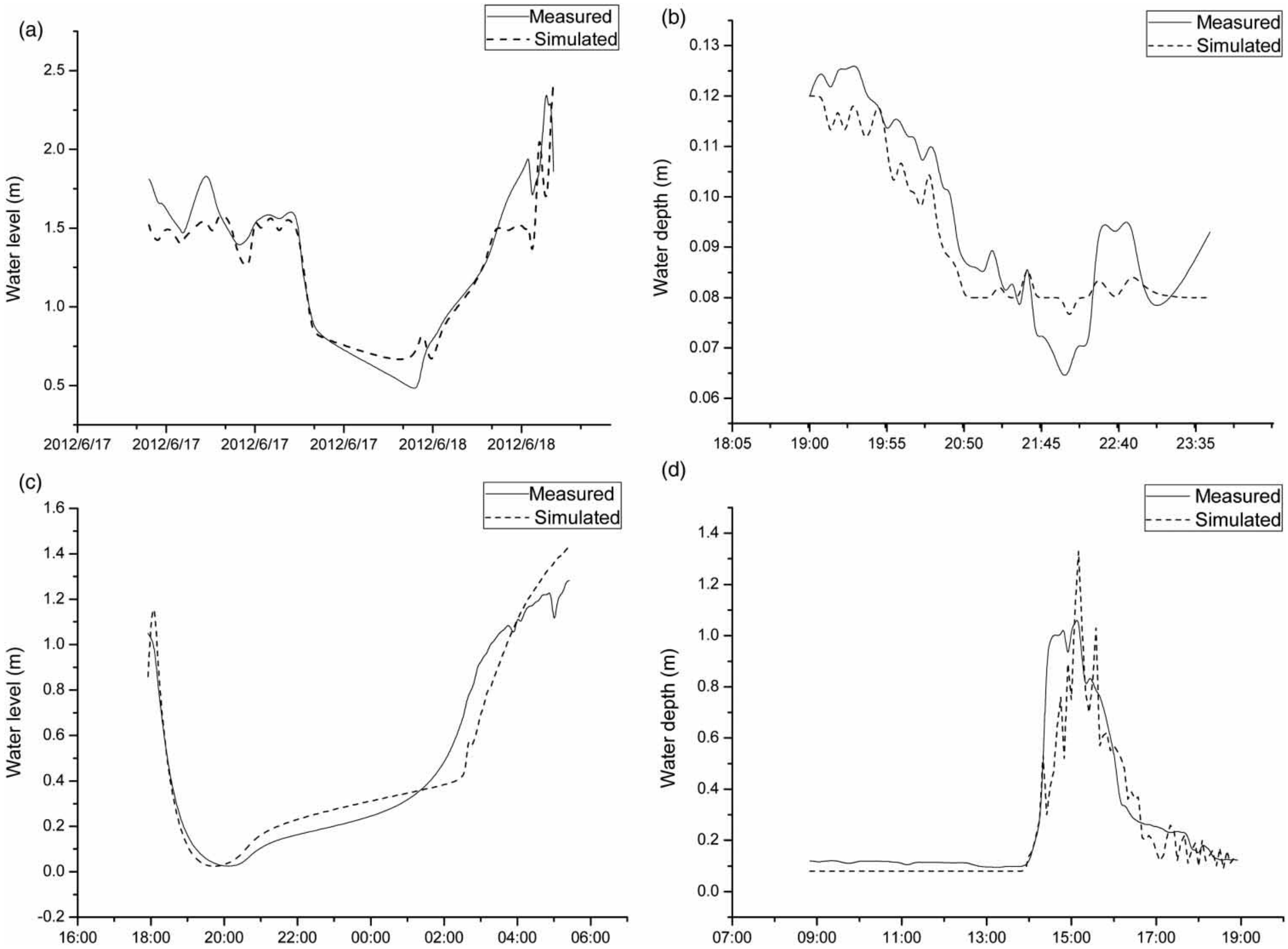

Figure 2 | (a) Water level of forebay for the event 17/6/2012 (calibration), (b) water level of junction JD472 for the event 27/6/2009 (calibration), (c) water level of forebay for the event 10/6/2011 (validation), (d) water level of junction JD472 for the event 27/6/2009 (validation).

The simulated results are listed in Tables 2–4. It can be seen from these tables that, with increasing rainfall duration, the processing efficiency of each LID practice is significantly reduced, and the total waterlogging reductions of Infiltration Trench, Permeable Pavements and Rain Barrels are significantly greater than the Bio-Retention and Grass Swale. In particular, although the design rainfall recurrence period of the system is 1 year, the simulation results of 1 year show occurrences of waterlogging.

Furthermore, three sub-catchments were selected to analyze the effect of peak discharge reduction and runoff coefficient reduction. They are the ZMJ10 (the largest one, $A = 16.49$ ha), ZMJ7 (medium in size, $A = 10.95$ ha), and ZMJ57 (a small one, $A = 2.77$ ha). Simulation results are shown in Figure 4.

These graphs show the following:

1. LID measures in urbanized areas contribute to the decrease of peak flow and runoff coefficient. They can reduce the negative effects on the natural hydrological cycle.
2. There is a big difference between different LID measures in the reduction of peak flow and runoff coefficient. Therefore, it is necessary to choose the most appropriate measures in different regions.
3. Infiltration Trench and Rain Barrels play a strong role in reducing flood peak and runoff coefficient, followed by Bio-Retention and Permeable Pavements. The least effective is Grass Swale because the measure does not have infiltration and storage modules in the current edition of SWMM.

Cost-effectiveness of LID

Benefit–cost ratio is often used in public investment analysis. However, it is not easy to accurately quantify the public benefits of waterlogging abatement. Therefore, a LID rapid

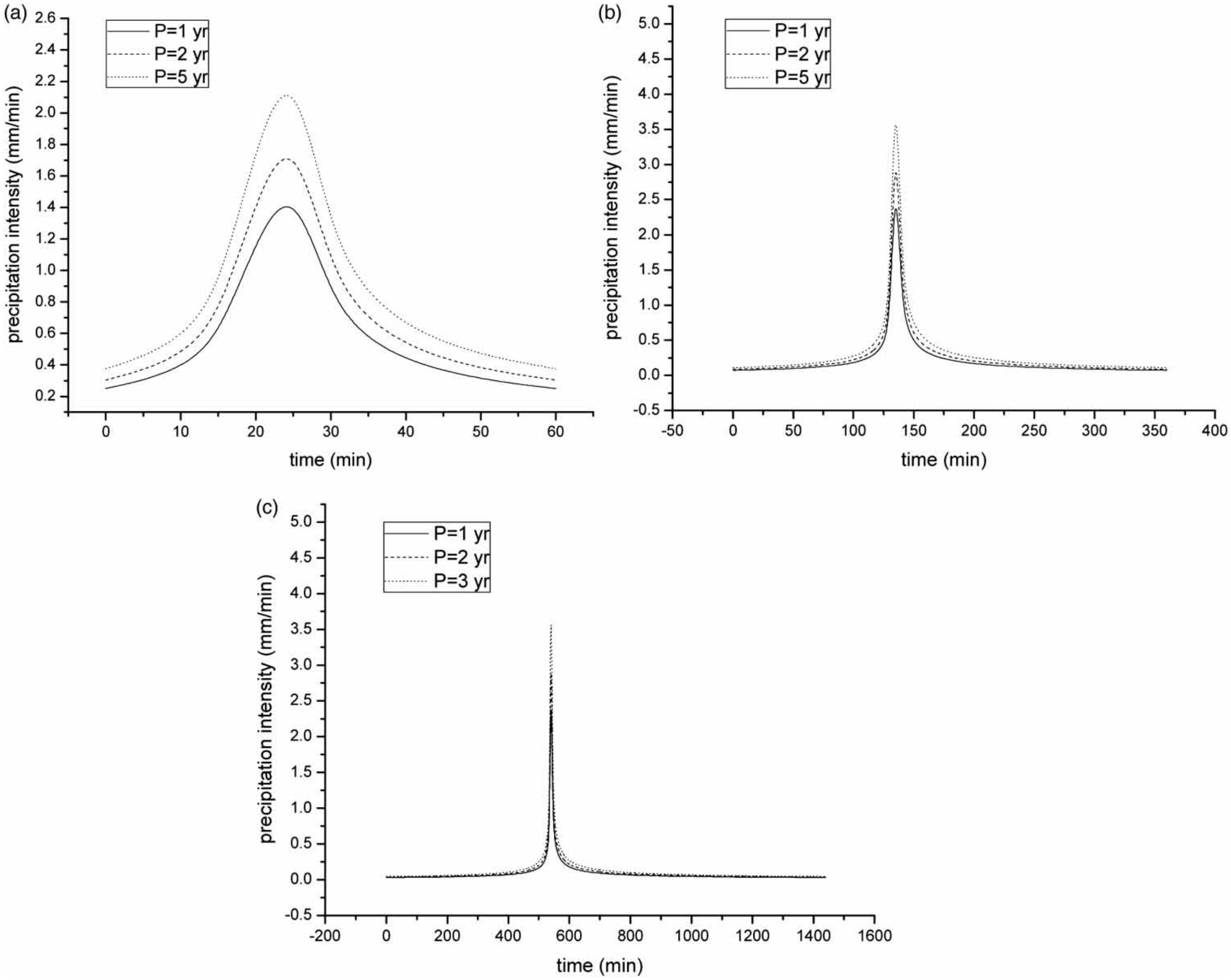

Figure 3 | IDF curves (a) rainfall duration = 60 min, (b) rainfall duration = 360 min, (c) rainfall duration = 1,440 min.

Table 2 | Comparison of waterlogging reduction of five LID practices ($P = 1$ y, $t = 60,360,1,440$ min)

			With LID				
		Without LID	Bio-Retention	Infiltration Trench	Permeable Pavements	Rain Barrels	Grass Swale
$t = 60$ min	Total waterlogging volume (m^3)	18,088	4,077	4,004	4,351	4,003	12,035
	Waterlogging reduction rate (%)	–	77.46	77.86	75.95	77.87	33.46
$t = 360$ min	Total waterlogging volume (m^3)	62,636	40,549	28,790	33,835	28,783	59,272
	Waterlogging reduction rate (%)	–	35.26	54.04	45.98	54.05	5.37
$t = 1,440$ min	Total waterlogging volume (m^3)	74,209	63,312	37,758	42,867	37,731	71,455
	Waterlogging reduction rate (%)	–	14.68	49.12	42.23	49.16	3.71

Table 3 | Comparison of waterlogging reduction of five LID practices ($P = 2$ y, $t = 60,360,1,440$ min)

		Without LID	With LID Bio-Retention	Infiltration Trench	Permeable Pavements	Rain Barrels	Grass Swale
$t = 60$ min	Total waterlogging volume (m^3)	35,139	12,900	12,718	14,756	12,729	27,378
	Waterlogging reduction rate (%)	–	63.29	63.81	58.01	63.78	22.09
$t = 360$ min	Total waterlogging volume (m^3)	62,636	40,549	28,790	33,835	28,783	59,272
	Waterlogging reduction rate (%)	–	35.26	54.04	45.98	54.05	5.37
$t = 1,440$ min	Total waterlogging volume (m^3)	117,450	109,935	68,788	78,360	68,825	113,481
	Waterlogging reduction rate (%)	–	6.40	41.43	33.28	41.40	3.38

Table 4 | Comparison of waterlogging reduction of five LID practices ($P = 5$ y, $t = 60,360,1,440$ min)

		Without LID	With LID Bio-Retention	Infiltration Trench	Permeable Pavements	Rain Barrels	Grass Swale
$t = 60$ min	Total waterlogging volume (m^3)	60,598	33,833	29,956	36,047	29,957	51,030
	Waterlogging reduction rate (%)	–	44.17	50.57	40.51	50.56	15.79
$t = 360$ min	Total waterlogging volume (m^3)	156,298	135,960	92,990	109,290	93,013	154,460
	Waterlogging reduction rate (%)	–	13.01	40.50	30.08	40.49	1.18
$t = 1,440$ min	Total waterlogging volume (m^3)	179,620	173,779	113,787	130,156	113,771	178,373
	Waterlogging reduction rate (%)	–	3.25	36.65	27.54	36.66	0.69

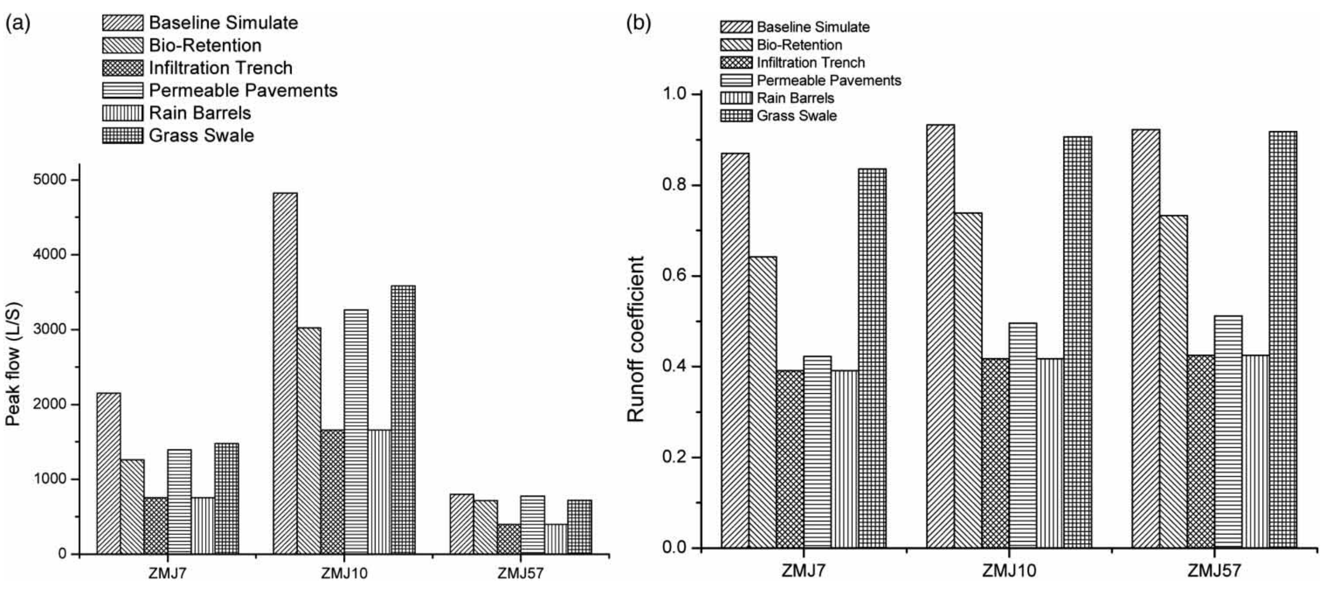

Figure 4 | Simulation results of different LID measures for three selected sub-catchments: ZMJ7, ZMJ10, ZMJ57. (a) Peak flow reduction, (b) runoff coefficient reduction.

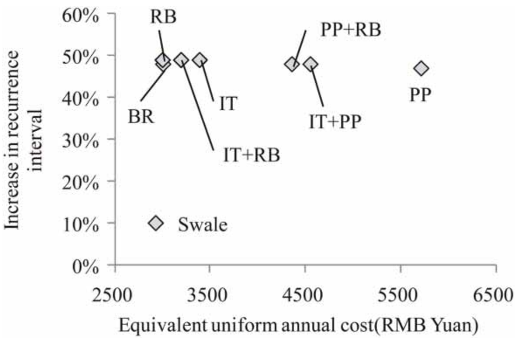

Figure 5 | Cost-effectiveness of individual and combined LID strategies: BR – Bio-Retention, RB – Rain Barrels, IT – Infiltration Trench, PP – Porous Pavement.

assessment (LIDRA) (Montalto *et al*. 2007) that assesses cost-effectiveness using hydrological effectiveness and cost estimation was adopted here. The hydrological component of LIDRA represents LID effectiveness in terms of a simulated change in bearable storm recurrence interval without waterlogging. For cost estimation, life cycle cost analysis is necessary because the LID strategies differ in initial cost, annual operation and maintenance cost, salvage value and particularly, lifespan. Under such circumstances, we can compare the equivalent uniform annual costs (EUAC) computed for alternatives based on their own service lives (Newnan *et al*. 2009). The financial data are collected by our estimation and comparison with comparable literature (USEPA 1999; California Department of Transportation 2004; Houdeshel *et al*. 2011).

Figure 5 shows a graphic representation of the comparison between individual and combined LID strategies. The cost-effectiveness of Rain Barrels is the highest, followed by Bio-Retention and Infiltration Trench with Rain Barrels. Simulation results, however, show that when the recurrence interval of rainfall increases, the effectiveness of Bio-Retention declines sharply. Therefore, the two most suitable LID measures for the study area are Rain Barrels and Infiltration Trench.

CONCLUSIONS

The results of the study show the following:

1. LID practices can have significant effects on storm water management in a highly urbanized area. Therefore, LID controls can be embedded into new cities' construction and old cities' rehabilitation to reduce urbanization's negative effects on the natural hydrological cycle.
2. In this case, when the rainfall recurrence period is 1 year and the rainfall duration is 60 min, the waterlogging reduction rate of LID practices is highest. Rain Barrels can be up to 77.87%, followed by Infiltration Trench, Bio-Retention and Permeable Pavements. They can be up to 77.86, 77.46 and 75.95% respectively. The least effective is Grass Swale (up to 33.46%).
3. With increasing rainfall duration or return period, the effects of the various measures decline, and the waterlogging reduction effect of Bio-Retention is very unstable.
4. Through comparisons between the hydrological effectiveness resulting from various LID practices and their life cycle costs, Rain Barrels and Infiltration Trench are considered as suitable waterlogging abatement strategies for the Caohejing drainage system.

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