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Design of low impact development in the urban context considering hydrological performance and life-cycle cost

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Abstract
The pressures on water system are increasing in cities. Rapid urbanisation caused by booming population leads to more impervious area and less infiltration, with the consequence of larger runoff volume and higher flood risk. Launched in 2014, the low impact development (LID), an important part of Sponge City in China initiative, invests in projects that aim to restore the water cycle in the urban area. A comprehensive understanding of the performance of LID measures at watershed scale under different rainfall scenarios and life cycle costs is necessary. The objectives of this study are to assess the hydrological performance and to identify the optimal LID design by using SWMM model and life cycle cost (LCC) method. This study found that LID practices, including bioretention, grass swale, and permeable pavement, showed good performance on urban storm mitigation at watershed scale under different rainfall scenarios. Furthermore, the rates of surface runoff reduction were largely insusceptible to the change of rainfall volume and duration. Regarding the cost-effectiveness, the priority was grass swale > bioretention > permeable pavement in the study area. The optimal LID scenario was the combination of these three types of LID. The proposed approach can help the decision-makers to determine the preferable LID plan suitable for the local communities.

KEYWORDS
life cycle cost, optimization, sponge city, SWMM, urban hydrology

1 | INTRODUCTION

The rapid urban development has increased the percentage of impervious area and changed original hydrological processes in cities. As a result, pressures on urban water management are intensifying, for example, the increasing urban flood risk (Wheater & Evans, 2009; Yang, Flower, & Thompson, 2013). This situation is very likely to accelerate in the near future due to the increase of extreme weather under climate change (Hu et al., 2017; Liu Kattel, Arp, & Yang, 2015; Yi et al., 2006). Since traditional urban rainwater management practices have exhibited the ineffectiveness in some extreme events such as western Japan heavy downpours in 2018, some source control alternative approaches have become popular (Fletcher et al., 2015). In China, a sponge city plan has been proposed to mitigate floods and improve water quality (Xia et al., 2017; Yang, Xie, Ni, & Flower, 2012). This plan has been applied in 30 pilot cities, for example Tianjin city, with 3–4 years of development. As an important component of this sponge city program, Low Impact Development (LID) is an approach to land development that works with nature to manage stormwater as close to its source as possible (Prince George's County, 1999). It was first proposed in North America, which was described as a land planning and engineering design approach to manage stormwater runoff. Due to its nature of replicating the predevelopment hydrologic regime of watersheds through infiltrating, filtering, storing, evaporating, and detaining runoff close to its source, it has gained popularity in urban planning and water resources management in recent years (Davis, 2005; Huang, Li, Niu, & Zhou, 2014; Maniquiz, 2012).

The effects of LID components on the hydrologic processes are of great interest for planners, designers and decision-makers for their potential to aid in the city sustainability (Li, Deng, Li, Li, & Song, 2017). A number of studies have shown that implementation of LID practices are proven to substantially influence flood control and water balance, including the volume of storm runoff (Dietz & Clausen, 2008; Jennings & Jarnagin, 2002), ratio of runoff to precipitation (Rushton, 2001), peak flow rate (Guo & Cheng, 2008), and lag time (Hood, Clausen, & Warner, 2006). In the LID design for the urban catchment, grass swale (GS), permeable pavement (PP), bioretention (BIO) pits and other facilities were widely adopted. Many types of research on these facilities have been done (e.g., Hu et al., 2017; Hu et al., 2018). Ahiablame, Bernard, and Indrajeet (2013) made an assessment of the application of rain barrel/rain harvest and porous pavement as retrofitting technologies in the urban areas. It was found that 50% implementation of either can reduce 2–12% runoff volume. Bioretention has the ability to diminish the effects of urbanisation by increasing interception and infiltration while reducing 25% overflow volume and mitigating the costs of stormwater management (Brown & Hunt, 2012; Hunt, Jarrett, Smith, & Sharkey, 2006). Porous pavements allow stormwater to drain through them and into a stone reservoir, where it is infiltrated into the underlying native soil or temporarily detained (Ferguson, 2005). Grassed swales and other vegetative controls, which can remove an average of 69, 46, and 56% of the total loads of total suspended solid (TSS), total phosphorus (TP), and total nitrogen (TN), respectively, have often been mentioned as vital components of any integrated stormwater management programs (Deletic & Fletcher, 2006). Infiltration trenches are used for a single block application, which can be implemented at the ground surface to intercept overland flow and show a higher ability in runoff reduction for small storm events (Maniquiz-Redillas, Geronimo, & Kim, 2014). The hydrological performance of LIDs varies significantly in various precipitation (Qin, Li, & Fu, 2013). Pyke et al. (2011) proved that runoff volume is most affected by changes in impervious area, followed by changes in total precipitation volume and rainfall intensity.

Although many studies have reported that LIDs could mitigate water-related problems, the flood mitigation capabilities are not well understood in the built-up watersheds. Are LIDs effective in all storms? What are the impacts of rainfall temporal distribution, duration, and intensity on LIDs performance at watershed scale? Moreover, the sponge city is at the infant stage in China and it requires more studies in various cities with different rainfall characteristics.

In addition, the economic cost is an important factor for the widespread application of LIDs. Different LIDs have different hydrological performance and economic costs. It is significant and necessary to evaluate the cost-effectiveness of LIDs selections in sponge city construction. However, few studies have investigated this issue at the watershed scale (Chui, Liu, & Zhan, 2016). Life cycle cost (LCC) analysis is a method to identify the most cost-effective option by taking all the combined costs that the object will face or can be assumed to face over its lifespan (Curran, 1996). It has been adopted in the field of water supply system inventory (Lee, Shin, Rasheed, & Kong, 2017), evaluation of green and grey combined sewer overflow control strategies (De Sousa, Montalto, & Spatari, 2012) and permeable pavements design (Rehan, Qi, & Werner, 2018). Spatari, Yu, and Montalto (2011) explored the use of sensitivity analysis in traditional LCC approaches. It demonstrated that greenhouse gas (GHG) emissions of different LID plans can relate to the materials used. Wang et al. (2016) identified environmental tradeoffs for urban low impact development in the term of effectiveness of bioretention and future climate change. In this study, LCC analysis was used to evaluate the economic costs of all LIDs. Then a cost-effectiveness framework for LIDS based on cost analysis results and hydrological performance was proposed.

The research aims of the current study are (a) to evaluate the hydrological performance of different LID plans under different storms; (b) to estimate the cost-effectiveness of LID scenarios and identify the most suitable one; (c) to offer a guideline and build a more robust and cost-effectiveness framework for the LID design. The remainder of the paper is organised into four sections: Section 2 describes the methodology. Sections 3 and 4 present the simulation results and discussions. The conclusion is reported in Section 5.

2 | STUDY AREA AND MATERIALS

The study area is the Tianjin Airport Economic Area, located in the Binhai New Area in Tianjin, north China (Figure 1). Tianjin is one of 30 pilot sponge cities in China. The average annual precipitation at Tianjin Station is nearly 550 mm (1981–2010) according to China Meteorological Administration. Total annual renewable water resource of Tianjin is only 180 m^3 per capita, less than 1/10 of the national average and less than 1/36 of the world average. However, due to the monsoon climate, the rainfall is unevenly distributed within 1 year. About 78.5% of the annual precipitation falls in the summer from June to August, while about 58.6% of the total annual rainfall occurs in only 1 month, from the second half of July to the first half of August. This has caused large flooding risks. In addition, the change of rainfall pattern, particularly moving forward of peak rainfall, exacerbates the flooding risks. Flooding in Tianjin has become the bottleneck for the sustainable development. The study area, one of the experimental sites for sponge city constructions in Tianjin, is a typical urbanised area with the total area at 22.78 km^2. A detailed land use classification map (10 m × 10 m) of the study area and imperviousness of each land use type were provided by Planning and Construction Management Bureau of Tianjin Airport Economic Area (shown in Table 1). There are 30 types with exclusive land use codes from the standard for classification of urban land GB50137-2011 issued by Ministry of Housing and Urban–Rural Development (2011). The multi-functional land uses could be fell into four groups: industrial (55%), commercial (10%), residential (16%) and others (19%). The pipeline data was also provided by Planning and Construction Management Bureau of Tianjin Airport Economic Area.

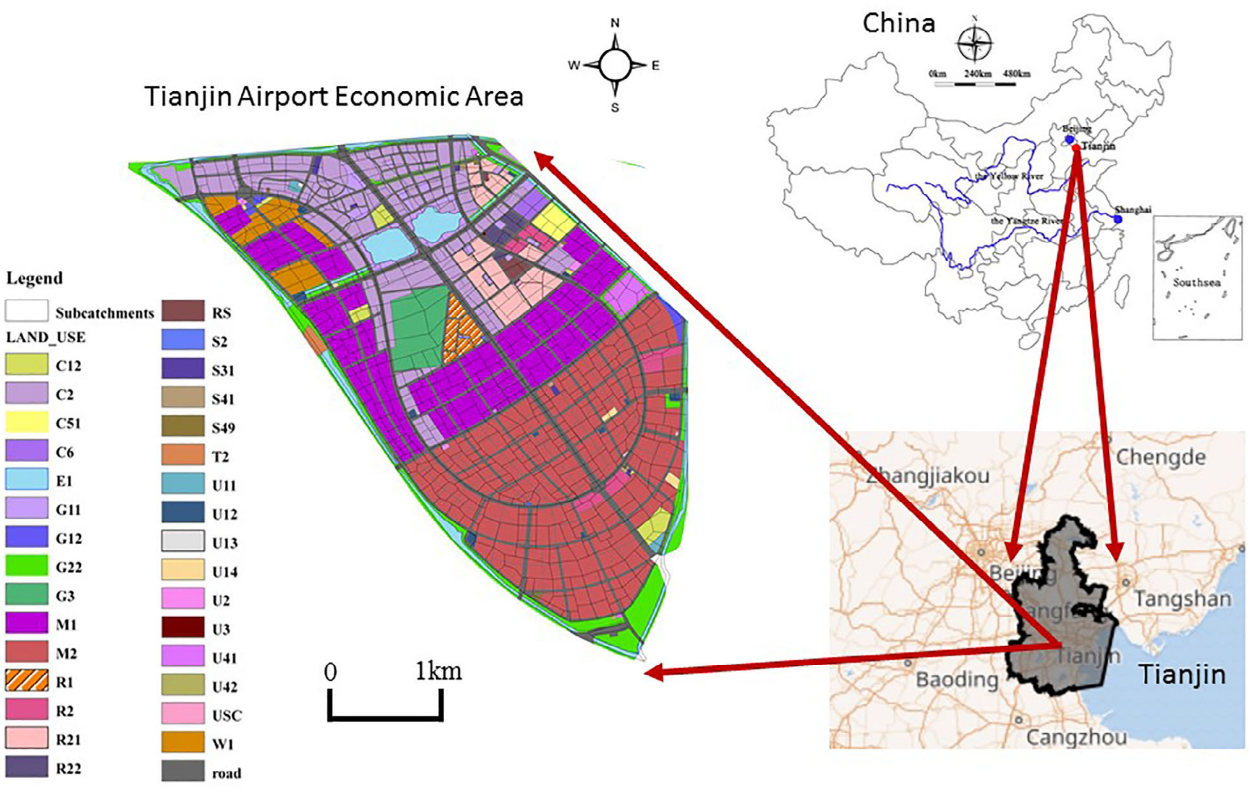

FIGURE 1 The study area and land use types at Tianjin Airport Economic Area in Tianjin, north China

TABLE 1 Land use type in the study area in Tianjin, north China

Land use code	Land use type	Impervious rate	Land use code	Land use type	Impervious rate
E1	Water	0	C2	Commercial and financial area	80
G22	Green space for street	10	M1	First class industrial land	80
G11	Park	25	M2	Second class industrial land	80
G12	Green buffer	25	S2	Square	80
G3	Golf land	25	S31	Parking lot	80
G11	Park	25	S41	Public transportation	80
G12	Green buffer	25	S49	Transportation facility	80
R1	First class residential land	55	T2	Highway	80
R2	Residential land	55	U11	Utility for water supply	80
C6	Education and research land	60	U12	Utility for electricity	80
R21	Second class residential	60	U13	Utility for gas	80
C12	Office building	65	U14	Utility for heat	80
C51	Hospital	70	U2	Fire service land	80
R22	Public service	70	U41	Rainwater and sewage treatment land	80
RS	Middle school, primary school and kindergarten land	70	Road	Road	100

Source: Planning and Construction Management Bureau of Tianjin Airport Economic Area.

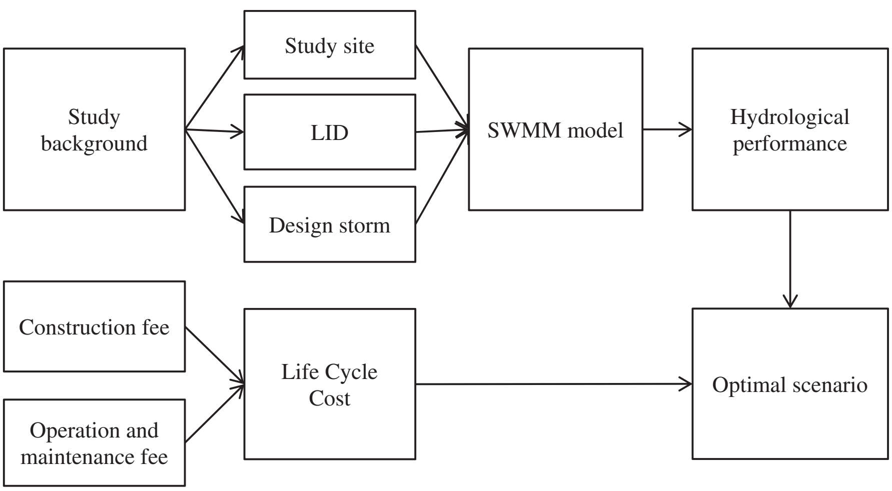

FIGURE 2 Flowchart of life cycle cost (LCC)-based low impact development (LID) design

3 | METHODOLOGY

The study could be divided into three main stages: basic information collection, hydrological performance analysis and life cycle cost analysis. The schematic diagram is shown in Figure 2. First, according to the local conditions of study sites, hydrological performance of various LID implementation scenarios was evaluated in SWMM model under different rain storms. Then the life cycle costs of various LID plans were calculated based on construction fee and operation/maintenance fee. Finally, the optimal LID scenario was obtained by taking hydrological and life cycle cost into consideration.

3.1 | Design rainfall scenarios

The performance of each LID varies with rainfall intensity and duration (Qin et al., 2013). Thus, various types of rainstorms designed by the intensity-duration-frequency

(IDF) curve of Tianjin were used in this study. The IDF curve and corresponding parameters were generated using two data sampling methods. This curve can be presented as (Jun & Yanjuan, 2012):

$$I = \frac{49.586 + 39.846 * \log(10 * T)}{(d + 25.334)^{1.012}} \quad (1)$$

where I is rainfall intensity (mm/min), T is return period (year) and d is rainfall duration (min).

In addition, rainfall temporal distribution is a key issue for urban hydrology. It has a strong influence on the detention of rainfall on site/within a watershed and runoff generation and it also has an impact on the water balance and water budget. According to the previous studies (Fan, 2011; Yin, Xie, Nearing, Guo, & Zhu, 2016), Huff rainfall distribution (Huff, 1967) can present the characteristics of typical rainfall events in Tianjin. Thus, three periods (2-, 10-, and 100-year) and two rainfall durations (3- and 6-hr) were calculated using Equation (1) and Huff rainfall distribution. The rainfall amounts of 3 hr events were 50.6 mm, 73.5 mm and 106.3 mm at 2-, 10-, and 100-year, respectively. The rainfall amounts of 6 hr events were 53.6 mm, 77.8 mm, and 112.5 mm at 2-, 10-, and 100-year. The differences of the rainfall total volumes at the same return period between 3 hr event and 6 hr event is relatively small based on formula (1). The hyetograph of all designed storms are shown in Figure 6. Three hours duration design storms are early bursting events and 6 hr duration design storms are relatively centred events in the term of the timing of the precipitation burst. Normally an early bursting event which means less response time for the locals to deal with the flood issue may lead to higher peak flow discharge and more critical consequence (Bezak, Šraj, & Mikoš, 2018).

3.2 | SWMM model and LID scenarios

In this study, Storm Water Management Model 5 (SWMM5) was used to simulate urban hydrological processes with and without LIDs. SWMM is a stormwater/wastewater and watershed modelling tool developed by US EPA with hydrology and hydraulics capabilities. It is a distributed model for urban watersheds that involve run-on flows or cascade runoff flows from the impervious area onto the pervious area (Niazi et al., 2017). More important, it has a LID module with six kinds of LID technical contents which can represent LID facilities (Mogenfelt, 2017). And the LID contents have maximum five layers: surface, soil, pavement, storage and underdrain. Each layer has different storage and functions differently. SWMM can be used to set different LID types and design parameters facilities in the research, so as to make it convenient for the research on the effects of different LID facilities for water balance (Guo, 2017). SWMM model is more suitable for urban water system and LID evaluation compared with other models. And it has been widely used in LID related studies (Lee, Nietch, & Panguluri, 2018). For example, Limos et al. (2018) employed EPA (Environmental Protection Agency)'s SWMM to determine that green roofs significantly affect rain water in urban areas. Huang et al. (2014) utilised SWMM to study bioretention, porous pavement, grass swales, infiltration trenches, and rain harvest systems.

The study area was delineated into 604 subcatchments in ArcGIS 10.2 (ESRI, Redlands, CA: ESRI, 2014) based on the information of land use type and pipelines (Figure 3). Depression storage values of various land cover were as follows: 2–8 mm for roof, 2–4 mm for paved area, 5–10 mm for lawn grass, and 6–13 mm for open fields. Manning's roughness values were 0.2 for the pervious surfaces and 0.013 for the impervious surfaces (McCuen, Johnson, & Ragan, 1996). The Green-Ampt infiltration method was used (Rossman, 2010). Permeable pavement, bioretention and grass swale were chosen as potential appropriate LID faculties. Some parameters of these three LID controls are shown in Table 2. Three indices of SWMM outputs (outflow volume, peak flow and flood volume) were used to evaluate the hydrological performance of LID scenarios. The changes in flood volumes indicate the effects of LIDs on flood mitigation. And the variations in peak flow and surface runoff represent the impact on rainfall-runoff processes. The model.

The construction area of different scenarios (each LID and their combination) was decided based on the technical guideline for the sponge city construction (Ministry of Housing and Urban–Rural Development, 2014). The total available LID implementation area is 0.99 km^2. There are 0.07 km^2 available for bioretention (BIO) and permeable pavement (PP), 0.06 km^2 available for BIO and grass swale (GS), 0.07 km^2 available for GS and PP, and 0.01 km^2 available for three facilities (shown in Figure 4). The potential maximum implementation areas of BIO, GS and PP are 0.21 km^2, 0.32km^2, and 0.65km^2, respectively. Eight scenarios were constructed with different combinations of LID practices (listed as follows). The reasonability of LID combination acreage is discussed in “Optimal LID implementation scenario.”

Baseline: no LID
Scenario 1: Implementation of BIO (0.21km^2)
Scenario 2: Implementation of GS (0.32km^2)
Scenario 3: Implementation of PP (0.65km^2)

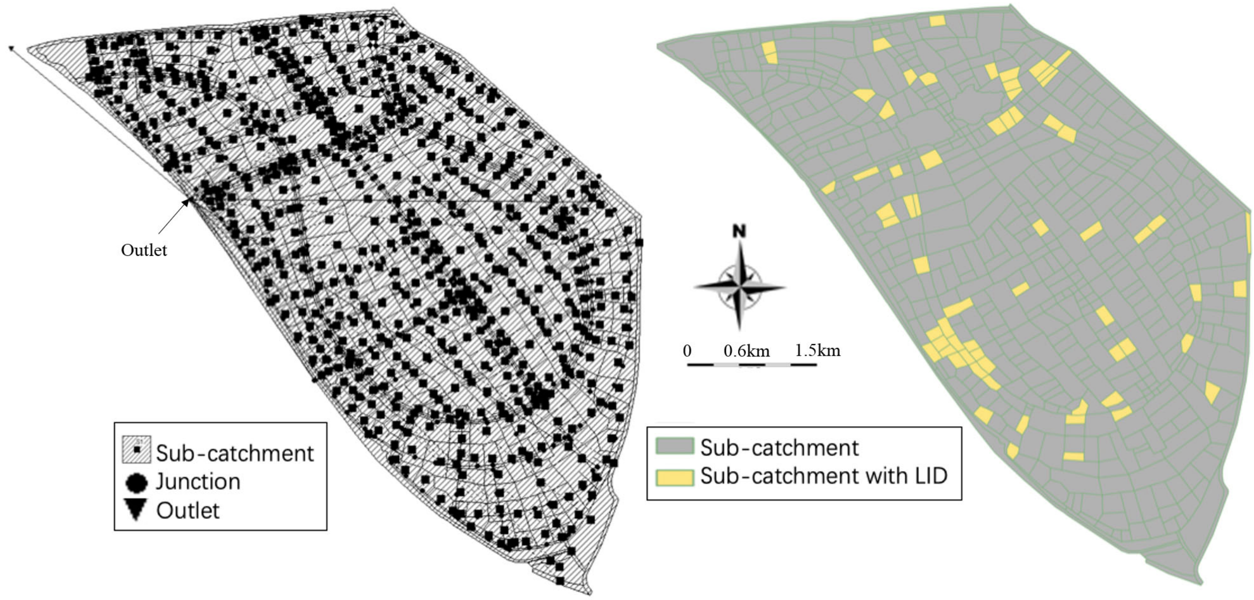

FIGURE 3 The sketch of study area (left) and potential spatial allocation of subcatchments with LIDs (right) in SWMM model

TABLE 2 Parameters of low impact development (LID) controls

Layer	Parameter	Bioretention	Grass swale	Permeable pavement
Surface	Berm height (mm)	25	200	10
	Vegetative cover fraction	0.1	0.1	0
	Surface roughness (Manning *n*)	0.1	0.3	0.013
	Surface slope (%)	2	2.5	3
Soil	Thickness (mm)	450–500	—	—
	Porosity (volume fraction)	0.5	—	—
	Field capacity (volume fraction)	0.2	—	—
Pavement	Thickness (mm)	—	—	120–180
	Void ratio (voids/solids)	—	—	0.15
	Clogging factor	—	—	0
Storage	Thickness (mm)	500	—	300
	Void ratio (voids/solids)	0.45	—	0.33
	Clogging factor	0	—	0
Underdrain	Flow coefficient	0.5	—	0.5
	Flow exponent	0.5	—	0.5

Scenario 4: Implementation of BIO (0.15km^2) + GS (0.32km^2)

Scenario 5: Implementation of BIO (0.21km^2) + PP (0.58km^2)

Scenario 6: Implementation of GS (0.32km^2) + PP (0.58km^2)

Scenario 7: Implementation of BIO (0.15km^2) + GS (0.32km^2) + PP (0.52km^2)

3.3 | Cost-effectiveness analysis

Life cycle cost (LCC) analysis is a widely used analysis technique to estimate the total cost of a system over its life span (Farreny, Gabarrell, & Rieradevall, 2011). It could be presented as follows (ISO, 2008):

$$E = C - C * \mathrm{sv} + D \quad (2)$$

$$\text{PV} = E + \text{OM} * \frac{(1+i)^n - 1}{i * (1+i)^n} \quad (3)$$

where E is economic capita, C is construction fee, sv is salvage value, D is design fee, PV is present value of LID, OM is operation and maintenance fee, n is the years of service, and i is discount rate.

The LCC for each LID design is calculated based on Equations (2) and (3). The life span of BIO and GS are assumed to be 20 years (Liu et al., 2018), and the life span of PP is assumed to be 8 years (Ministry of Transport of the People's Republic of China, 2014). Though some studies reported the infiltration rates of PP decline obviously with several years of use due to clogging (Hu et al., 2018; Kumar et al., 2016), maintenance could reclaim part of the lost infiltration rates. Thus, the impact of clogging on life span and performance of PP was neglected in this study. The discount rate (i) and salvage value (sv) are recommended at 5% and 4% in China (Hu, 2012; Mei et al., 2018). The initial and maintenance costs per capita are set according to previous studies (Chui et al., 2016; Hu, Sayama, & Zhang, 2013; Montalto et al., 2007; Wang et al., 2016; Xie et al., 2017) and project quoted price by technical guideline for the sponge city construction (Ministry of Housing and Urban–Rural Development, 2014). The values are shown in Table 3.

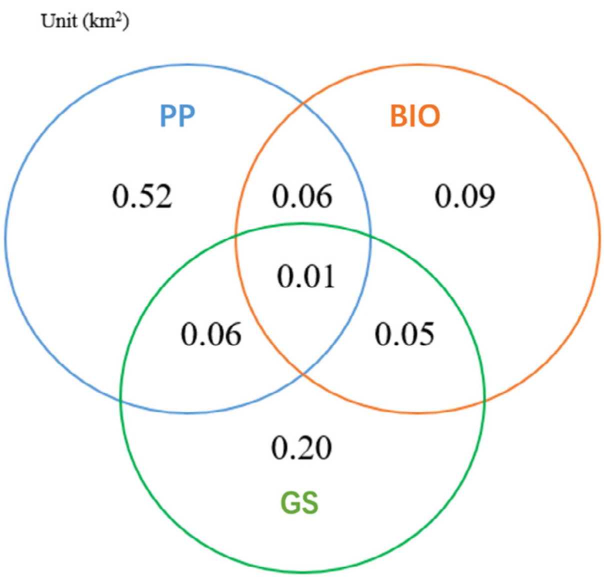

FIGURE 4 Suitable application area for three types of LID

When comparing the three LID practices with respect to their overall performance, the overall performance of LID is defined as the average across percentage of peak flow reduction per million dollars, percentage of outflow volume reduction per million dollars and percentage of flooding volume reduction per million dollars. The formula can be expressed as below

$$\text{Overall cost effectiveness} = \frac{(P_p + O_p)/2}{PV} \quad (4)$$

where P_P is the percentage of peak flow reduction by LID application, O_P is the percentage of runoff volume reduction by LID application, and PV is present value of LID.

4 | RESULTS

4.1 | Model calibration and validation

SWMM model was calibrated and validated by comparing the simulated and observed surface runoff at the watershed outlet using the index of Nash–Sutcliffe model efficiency coefficient (NSE) (Nash & Sutcliffe, 1970). It is defined as follows:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{mean}\right)^2} \quad (5)$$

where Q_i^{obs} is the i observed value, Q_i^{sim} is the corresponding i simulated value, Q_i^{mean} is the mean of all the observed value and n is the total number of the observations. The NSE value can range between $-\infty$ and 1 and NSE = 1 means a perfect fit. For the SWMM model, the NSE value larger than 0.5 suggests that the performance of the model is acceptable (Dongquan et al., 2009).

TABLE 3 Life-cycle costs of low impact development (LID) during the service period

LID	Construction fee (US\$/m²)	Design fee (US\$/m²)	Operation and maintenance fee (US\$/m²)	Years of service
BIO	102.72	3.39	3.55	20
GS	26.25	0.36	0.26	20
PP	59.00	3.36	1.28	8

The rainfall event on 25th August 2007 was used for calibration and rainfall events on 16th August 2008 and 26th July 2012 were selected for validation. The rainfall amounts were 46 mm, 53 mm, and 181 mm, respectively. Figure 5 shows the simulated and observed surface runoff at the watershed outlet without any LID placement. The NSE value of calibration is 0.93 and the values of validation were 0.84 and 0.80, respectively. Thus, model performance is well in the study area.

4.2 | Hydrological performance of LID facilities

Figures 6 and 7 indicate hydrological performances of all scenarios in six designed storms. It was found that LID facilities had significant effects on rainfall-runoff processes. Total surface runoff decreased by 4–23%. And peak flow decreased by 4–39%, also there was time delay of peak flow observed in some events so that LID facilities could effectively mitigate urban flood. For single LID facility, PP had highest hydrological performance, followed by BIO and GS. The application area of different types of LID concentrated in a limited area may explain that theses hydrographs with LID share the similar trend.

4.3 | Impact of rainfall amounts on LID performance

In the same rainfall duration, the reduction ratios of flood volume decreased as rainfall amounts increased in all LID scenarios. The runoff coefficient is an index relating the amounts of runoff to the amounts of precipitation received. For example, the runoff coefficients were minimum (0.652–0.760) at 2-year, followed by 10-year (0.818–0.879) and 100-year (0.842–0.882) in 3 hours' duration storms (Table 4). There were similar findings in

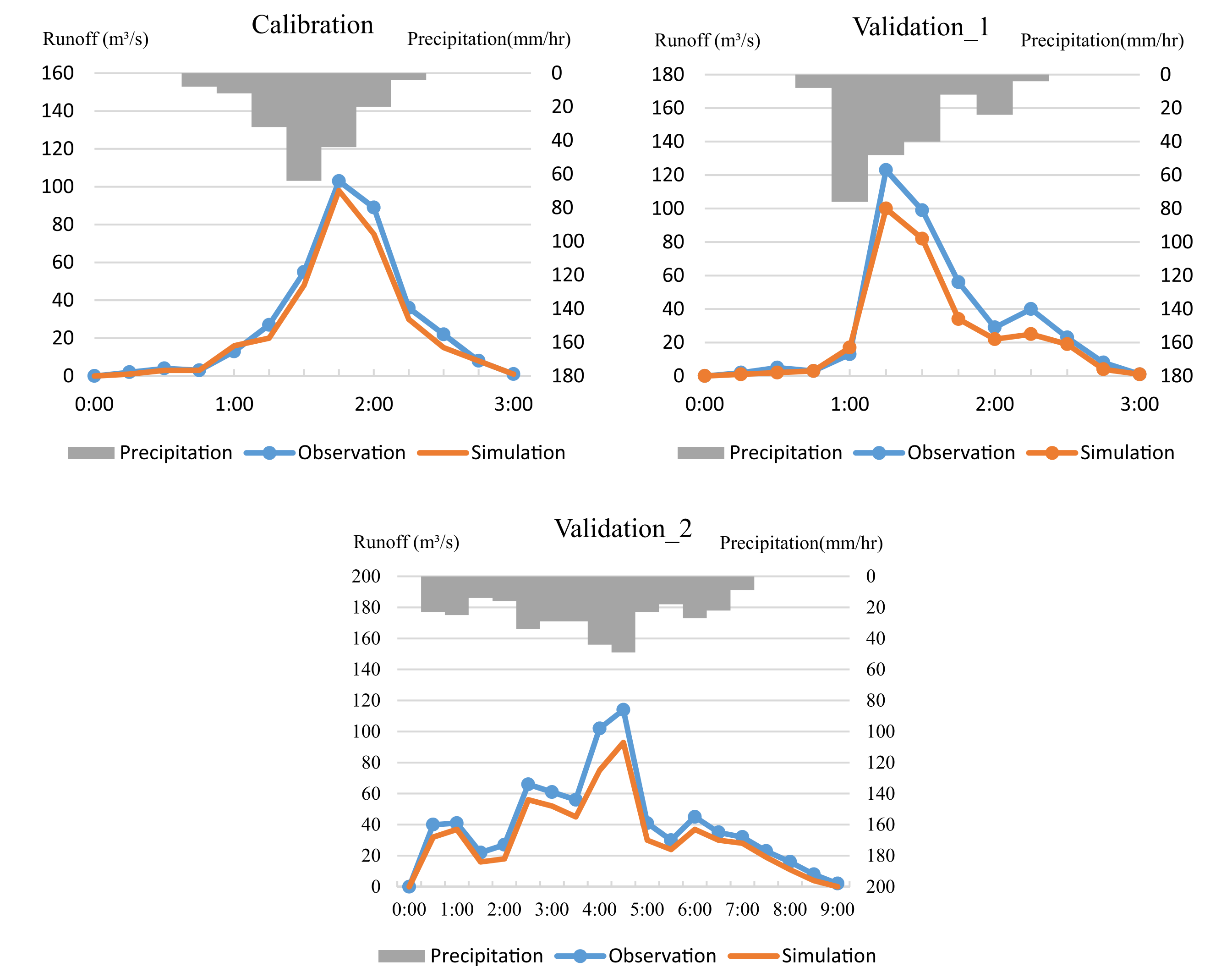

FIGURE 5 Comparison of simulated and observed surface runoff at the study area outlet

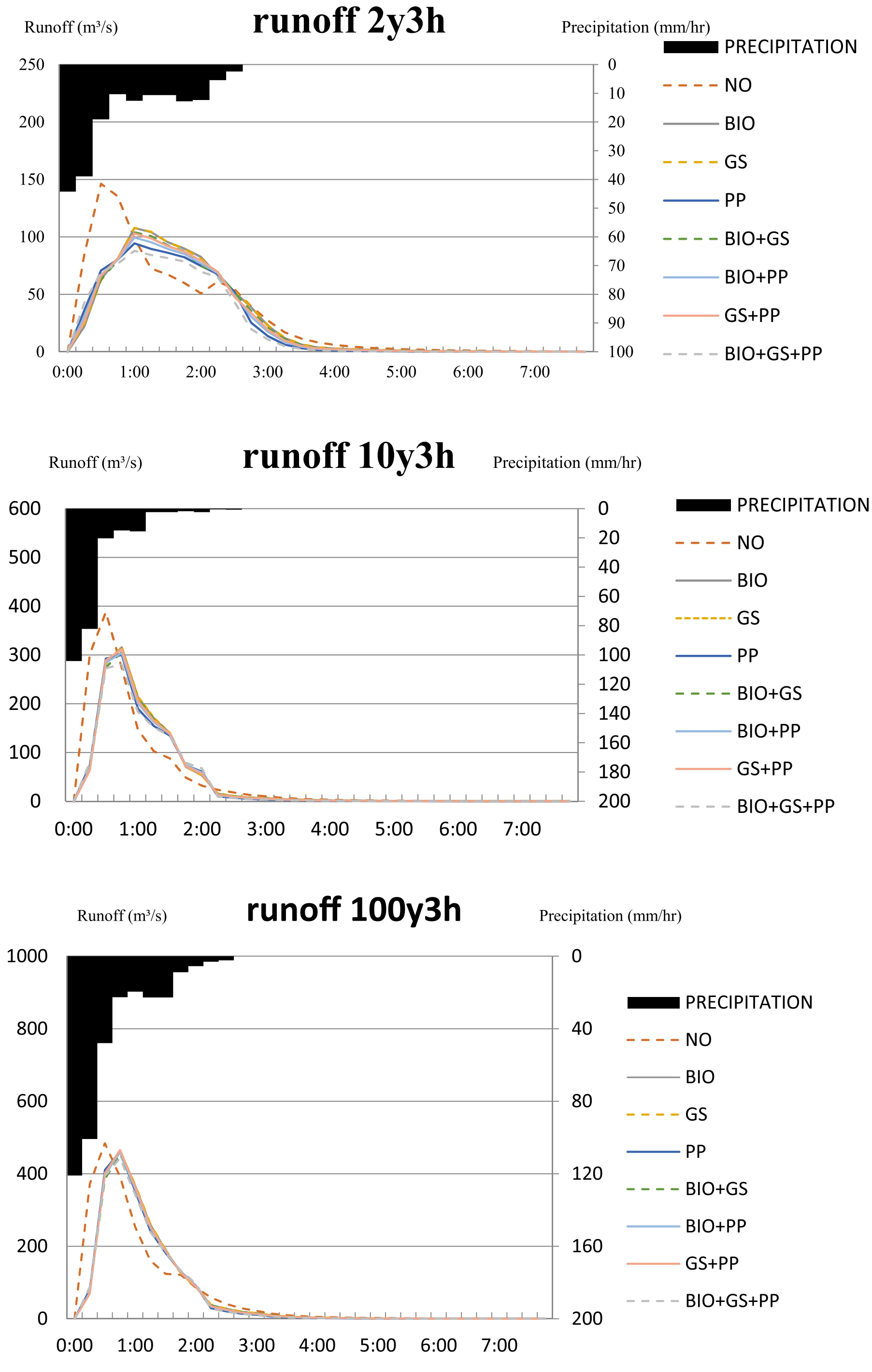

FIGURE 6 Hyetograph and hydrograph of the rainfall-runoff of designate low impact development (LID) scenarios

6 hours' duration storms. Thus, the flood mitigation performance decreased with the increase of rainfall amounts.

4.4 | Cost-effectiveness of LID

Table 5 shows the present costs of each scenario and the reduction values of flood volumes per million dollar in the storm of 100-year and 6 hours' duration. For single LID facilities, the costs of GS were cheapest (0.461 million dollar) in the study area, followed by BIO (1.536 million dollar) and PP (5.547 million dollar). Figure 8 indicates the overall cost-effectiveness of LID facilitates per million dollar in different storms. In terms of cost-effectiveness, the order is GS > BIO + GS > BIO > PP > PP + BIO + GS > PP + GS > PP + BIO. Overall, LID

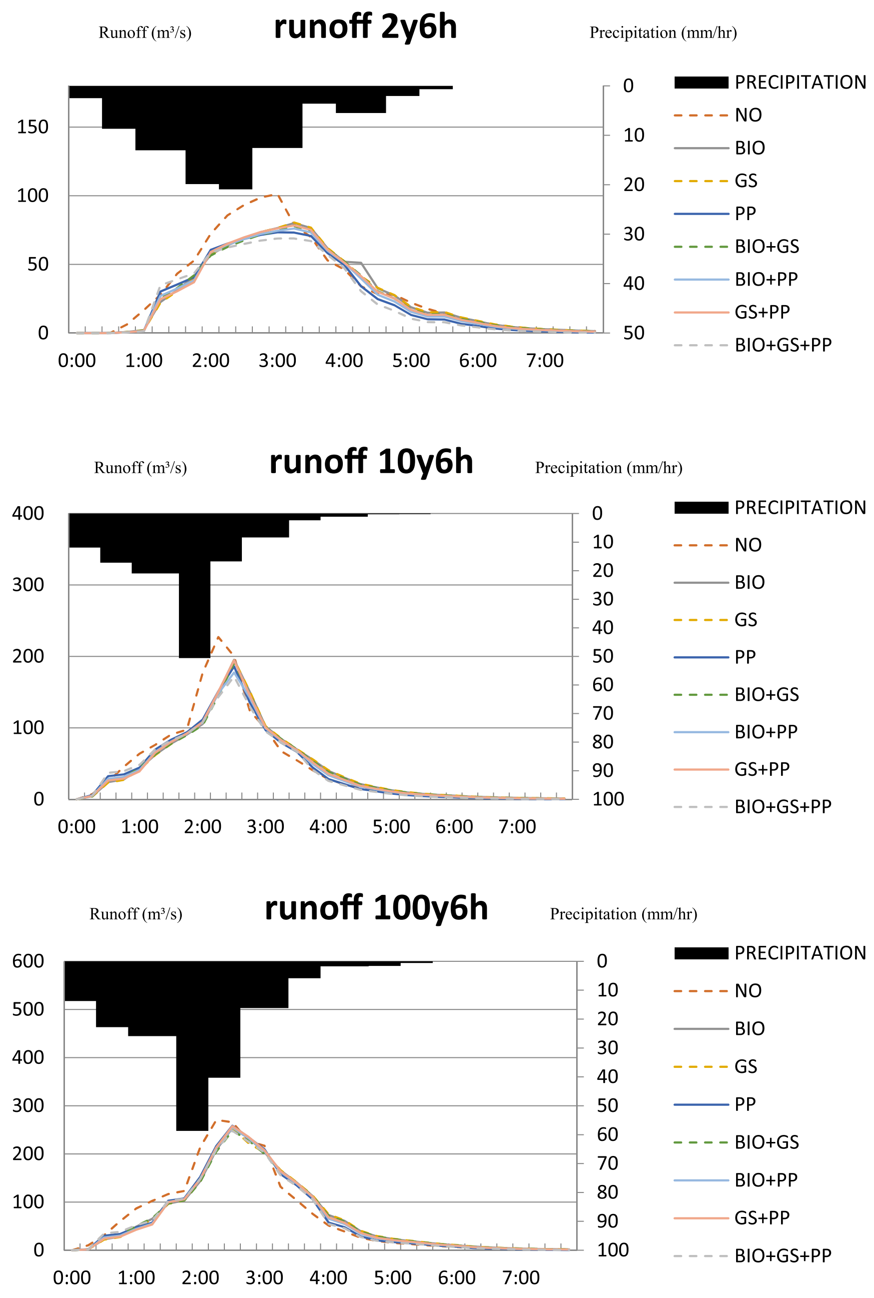

FIGURE 6 (Continued)

facilities had better cost-effectiveness in shorter and smaller rainfall events.

5 | DISCUSSION

5.1 | Optimal LID implementation scenario

At the watershed scale, high hydrological performance does not mean high cost-effectiveness for LID facilities. In this study, PP had highest hydrological performance but lowest cost-effectiveness among the three single LID facilities. This is because LID hydrological performance is high related with implementation areas and locations. In a built-up watershed, the available locations and areas are always limited. In the study area, the available land for PP was 0.65 km^2, much larger than the lands for BIO (0.21km^2) and GS (0.32 km^2). Cost-effectiveness is the hydrological performance per unit cost, which has excluded the impact of implementation area. Thus, PP had lowest cost-effectiveness but highest hydrological performance. And GS has the highest cost-effectiveness. Similarly, Hu, Sayama, Zhang, et al. (2017) reported PP

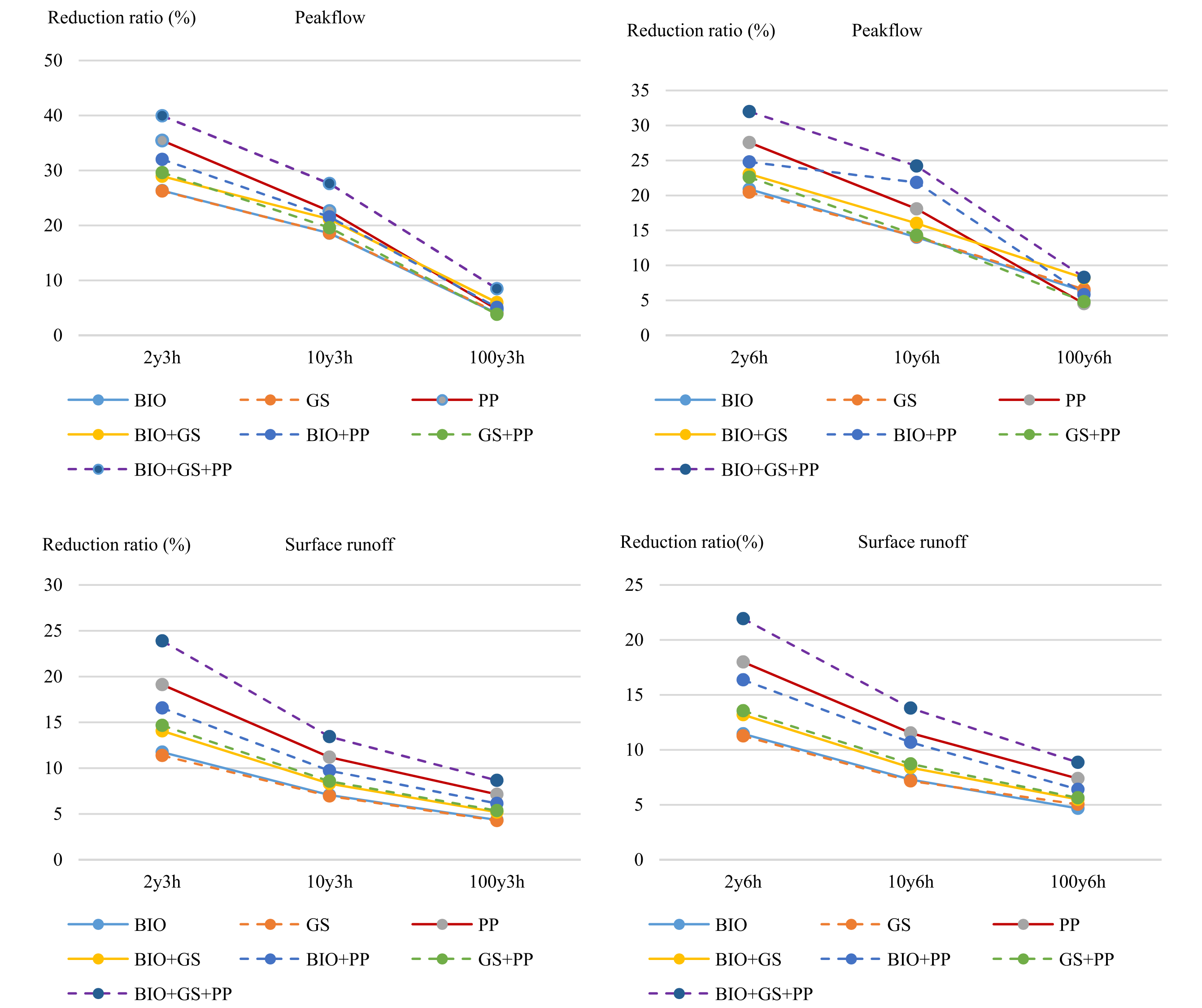

FIGURE 7 Hydrological performance of designate low impact development (LID) scenarios

TABLE 4 Runoff coefficient of the basin in each LID plan and no LID plan

	BIO	GS	PP	BIO + GS	BIO + PP	GS + PP	BIO + GS + PP	No
2y3h	0.757	0.760	0.693	0.737	0.715	0.732	0.652	0.857
10y3h	0.878	0.879	0.839	0.866	0.853	0.864	0.818	0.945
1003h	0.882	0.882	0.856	0.874	0.865	0.872	0.842	0.922
2y6h	0.680	0.681	0.630	0.666	0.642	0.664	0.599	0.768
10y6h	0.766	0.767	0.731	0.757	0.738	0.755	0.713	0.827
100y6h	0.809	0.806	0.786	0.802	0.795	0.801	0.774	0.849

has highest performance on flood mitigation by a study in Nanjing, China. Liu, Bralts, and Engel (2015) indicated that grass swale is the most cost-effective way to reduce runoff and pollutants in a highly urbanised area. As mentioned in “SWMM model and LID scenarios,” there were some lands with a total area of 0.18 km^2 suitable for more than one type of LID facility. In these areas, the priority is GS > BIO > PP according to their cost-effectiveness. For example, in the combination of BIO and GS, the both available area of 0.06 km^2 should be covered by GS. The

TABLE 5 Present values of LID scenarios and cost-effectiveness of flood mitigation in the 100-year and 6 hr storm

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Present value (million US dollar)	1.536	0.461	5.547	1.558	6.485	5.411	5.995
Flood reductions (mm/million US dollar)	17.8	42.9	9.4	19.4	7.2	8.1	9.1

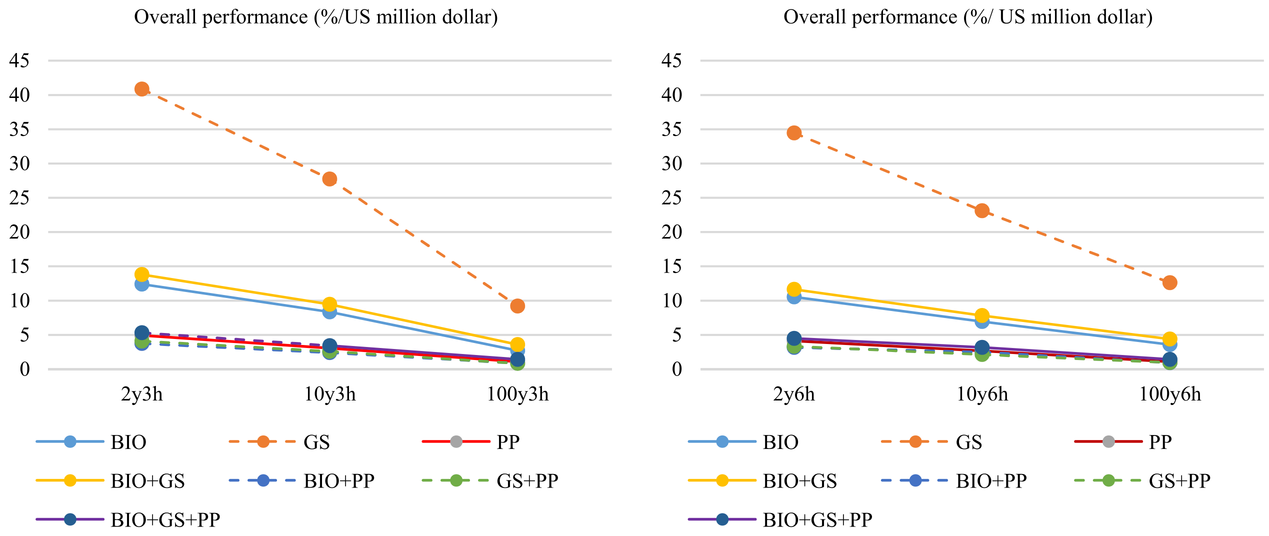

FIGURE 8 Overall cost-effectiveness of designate LID scenarios

combination area should be 0.32km^2 of GS and 0.15 km^2 of BIO. Under this criterion, the combination scenarios were designed in this study (Scenarios 4–7). In addition, one of main purposes of Chinese sponge city construction is to mitigate urban flooding. It is recommended that all available lands are used for LID implementation (Mei et al., 2018). Thus, scenario 7 (PP 0.52km^2 + BIO 0.15 km^2 + GS 0.32 km^2) was the optimal one. Similarly findings has been demonstrated by Mao, Jia, and Shaw (2017) that the multi-types of LID which contain green roofs, biological retention, porous pavements, were the most cost-effective solution to achieve control goals.

5.2 | Implication of rainfall characteristics

The changes in the reduction ratio of flood volume under different storms indicate that flood mitigation performance of LID facilities decreased with the increase of rainfall amounts. Similar findings have been reported by Hu, Zhang, Li, Yang, and Tanaka (2019) that LID facilities are less effective in heavier storms. Some studies (Mei et al., 2018; Qin et al., 2013) found that there were significant variations in the reduction ratios of peak flow and surface runoff in different storms, which was not found among six designed storms in this study. One reason is due to the different rainfall distribution pattern in Tianjin. Chicago hyetograph is commonly used in LID related studies in China (Mei et al., 2018; Qin et al., 2013). Here, Huff hyetograph was used, which has early bursting in short rainfall events and centred bursting in long rainfall events. The differences in bursting resulted in different rainfall-runoff process. Another reason is the rainfall intensities designed in this study are relatively low compared with the potential drainage capacity of the study area with LID implementation.

6 | CONCLUSION

Based on SWMM model and life-cycle cost analysis, an integrated LID evaluation system was proposed and applied in the Tianjin Airport Economic Area to estimate the hydrological performance and life cycle cost of LID scenarios under different storms. The main findings can be summarised as follows.

1. Urban flood could be effectively mitigated by the implementation of LID facilities. However, flood

mitigation performance decreased with the increasing rainfall amounts. LID facilities were more effective in smaller storms.

2 Permeable pavement had the highest hydrological performance, while grass swale had the greatest cost-effectiveness for single LID facility. The optimal LID scenario was the combination of PP (0.52 km^2), BIO (0.15 km^2) and GS (0.32 km^2).
3 The proposed integrated LID evaluation framework is useful for the LID design.

As a case study, the findings of LID facilities with highest hydrological performance and lowest costs may not be perfectly applicable in other regions with different characteristics. But the proposed LID evaluation system is useful for identifying the optimal scenario by assessing hydrological performance and life cycle cost of LID facilities in sponge city construction. In addition, parameters of LID facilities lacked experimental values, though all the parameters were from the published literature. Thus, future studies including experimental values or filed observations from pilot cities are necessary to improve the accuracy of evaluation of cost-effectiveness of LID facilities. In order to do the cost risk analysis, the benefit curve and the damage curve with resulting flood costs under a large range of return periods of rainfall are also necessary. In this study due to the limitation of information on damage costs, only the effectiveness on hydrological performance including rainfall collection under 2-, 10-, 100-year return period with 3-, 6-hr duration by different LID plans were discussed. For the future work, simulation under more return period design rainfall will be done and the damage cost information will be collected to generate the cost risk analysis.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Planning and Construction Management Bureau of Tianjin Airport Economic Area. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of Planning and Construction Management Bureau of Tianjin Airport Economic Area.

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