Assessing the performances of low impact development alternatives by long-term simulation for a semi-arid area in Tianjin, northern China

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ABSTRACT

For areas that are urbanized rapidly, the practice of low impact development (LID) has gained an important place in stormwater management and urban planning due to its capability and beneficial effects in restoring the original hydrological cycle. The performances of LID alternatives can vary substantially due to different climate conditions. This study investigated the performances of five LID alternatives under a semi-arid climate in northern China on water balance and flood control. A numerical model, Storm Water Management Model version 5 (US Environmental Protection Agency), was employed to run 10 years' rainfall events for these objectives. Two evaluation methods were proposed in this study: the efficiency index for water balance and a performance radar chart. The investigation of the five LID alternatives revealed that these LID alternatives functioned differently in flood control and water balance, and porous pavement performed best in all indices except the lag time. The two evaluation methods, in conjunction with the long-term numerical simulation, can facilitate design and decision making by providing a clear picture of the performance and functions for these LID alternatives.

Key words | flood control, hydrological cycle, low impact development, SWMM5, water balance

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INTRODUCTION

With rapid urban developments, the pressures on ecosystems are intensifying as a result. Development typically follows a course of removal of natural vegetation, construction of impervious areas and modification of original land use with less ecological service value. These processes have changed the mechanism of generation and convergence of runoff in the original ecological conditions (Booth & Jackson 1997; Liao *et al.* 2013). Urbanization has been proved to have substantial impacts on flood control and water balance, including the volume of storm runoff (Jennings & Jarnagin 2002; Dietz & Clausen 2008), ratio of runoff to precipitation (Rushton 2001), peak flow rate (Guo *et al.* 2010) and decreased lag time (Hood *et al.* 2007).

In response, the practice of low impact development (LID) is gaining its place in stormwater management and urban planning (Davis 2005). The LID practice is an integrated watershed management strategy which provides natural retention, treatment and source protection capabilities.

It utilizes natural processes to capture, treat, absorb and infiltrate stormwater runoff that has increased in peak rate and volume with more pollutant contents.

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Research on LID facilities such as bio-retention, porous pavement, grass swale, infiltration trench and cistern system has also increased and has documented promising findings in recent years. Bio-retention has the ability to diminish the effects of urbanization by increasing interception and infiltration while reducing runoff and mitigating the costs of stormwater management (Hunt *et al.* 2006; Brown & Hunt 2012). As a filter and infiltration practice, bio-retention temporarily stores, treats and infiltrates runoff. 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; Hunt *et al.* 2006). Grassed swales and other vegetative controls have often been mentioned as vital components of any integrated stormwater management programs (Bäckström *et al.* 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 *et al.* 2012). The cistern system is widely used as one of the LIDs for commercial and public buildings. It is the process of intercepting and storing rainfall for later use (Petrucci *et al.* 2012; Walsh *et al.* 2013).

The effects of LID practices on the hydrologic cycle have been well documented (Maniquiz *et al.* 2012). However, the performances of LID practices can vary substantially due to different climate conditions. Studies on numerical modeling have been done to simulate the design and performance of LIDs (Pitt 1999; Elliott & Trowsdale 2007; Damodaram *et al.* 2010). The utilization of an appropriate modelling tool, which can simulate the full processes in LID practices, would provide a means to evaluate the LID performance in the design phase and provide guidance for decision making. In this study, Storm Water Management Model version 5 (SWMM5) (Rossman 2010; USEPA 2012) developed by the US Environmental Protection Agency (USEPA), was selected for this purpose.

This study evaluated five LID design alternatives selected in the planning and design of the new campus of Tianjin University in northern China. The overall objectives of this study were to assess the performances of these LID alternatives on flood control and water balance restoration and to identity the most effective practice. Ten years' continuous meteorological data (2003–2012) were used to simulate the semi-arid climate conditions. Due to different functionalities provided by the LID alternatives, two new evaluation methods, namely, the efficiency index for water balance and performance radar chart (PRC) were proposed to consistently assess the performance of each LID alternative.

MATERIALS AND METHODS

Study area

The new campus of Tianjin University is located on the north shore of the middle reach of the Haihe River basin in the northeast part of China (Figure 1).The new campus has an area of 2.5 km^2, which will be built block by block for each college. Soil types are predominantly gravel and sandy soil with high infiltration rates. The distribution of the study area is as follows: buildings 21%, courtyard 21%, roads 4%, green space 37% and water 17%. The total impervious area is 40%. The impervious area includes buildings (student dormitories, lecture halls, etc.), roads (including sidewalks, driveways, etc.) and paved courtyards.

The average annual precipitation of Tianjin City is nearly 550 mm; however, it is very unevenly distributed. 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 one month, from the second half of July to the first half of August. Due to the limitation of the storages provided by the LID facilities and the turnover rates of the storage, the temporal rainfall pattern may have significant impacts on the performance of the LID facilities. Therefore, in the present study, 10-year rainfall data were employed to evaluate the LID performance in terms of peak flow reduction and water balance restoration.

Figure 1 | Geographical location of the study area.

SWMM5 models the hydrological and hydraulic processes occurring in each LID facility by dividing the facility into three layers: surface layer, soil or pavement layer and storage layer. All three layers have different storages and they function differently (Figure 2). For example, the bio-retention system has the storage on the surface layer (depression storage) accounting for the effect of vegetation, storage in the void space of the soil layer and the storage in the underlying gravel or crushed rocks layer (note that the cistern system only has one layer). All these layers have different hydraulic conductivities or draining

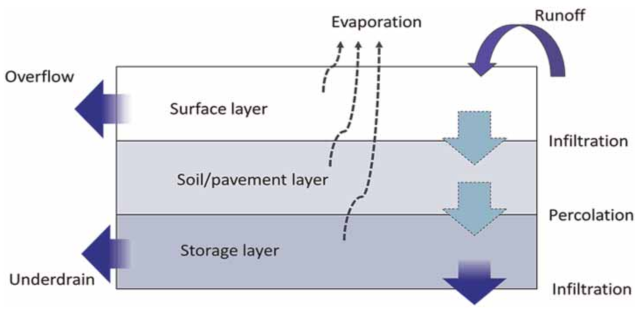

Figure 2 | Conceptual model of a LID process (*Source:* USEPA 2012).

rate. The storage of a LID facility was a main factor which determined how much rainfall could be captured and stored in the LID facility. In order to compare with the rainfall depth, the storage volume is converted to depth over the catchment area by Equation (1).

$$d = \frac{V_{tp}}{A} \quad (1)$$

in which d is the storage in depth, mm; V_{tp} is the total storage volume of the LID practices, m^3; A is the area of the catchment area, m^2.

The information about the storages provided by these LID alternatives is shown in Table 1.

The SWMM5 model was used to simulate the performance of the selected LID practices in this study. In the SWMM5 model, sub-catchments were delineated by the grading of the site plan and the land use data. Thirty-six sub-catchments were determined with areas ranging from 3.1 to 9.1 ha by using ArcGIS. Land surface slopes for these sub-catchments were between 0.2 and 3.9%. Manning's roughness values were set to 0.2 for the pervious surfaces and 0.013 for the impervious surfaces. Depression storages of the pervious and impervious surfaces were set to 2.5 and 1.0 mm, respectively. The slopes and lengths of conduits were provided by the storm sewer network design. The roughness of the conduit was set as 0.013 for circular, concrete pipes.

Table 2 lists the design characteristics of these LID alternatives selected for the new campus and the associated parameters implemented in the SWMM5 model.

LID design characteristics

The model was run for two scenarios (with and without LID implementations) using SWMM5 for the 10-year continuous rainfall data. The following indices were used to evaluate and assess the performances of the LID alternatives on flood control and water balance: the change of average runoff, change of peak flow, rainfall capture on site, ratio of runoff to precipitation, change of lag time, the water balance and the efficient index for water balance. Rainfall captured by LID on site was defined as the difference of saved rainfall on site between alternatives with and without LID implementations. Since these LID alternatives provide different volumes of storage, for comparison purpose, a new index, efficiency index for water balance, was proposed

$$Iw = \frac{R}{d} \quad (2)$$

in which Iw is the efficiency index for water balance; R is the total storage volume of the LID practices, m^3; d is the storage in depth, mm

RESULTS

Since LID facilities have limited storage, they are normally designed for frequent rainfall events. A LID normally does not function well for extreme events. In Tianjin City, based on a previous investigation of 56 years' rainfall records (Zhang *et al*. 2013), 77% of rainfall events were less than 25.4 mm rainfall depth, which is the 1-inch rainfall usually used in the United States. Hence, this study focused on the rainfall events with less than 25.4 mm to evaluate the performance of these design alternatives. There were 261 rainfall events identified in the 10-year rainfall records. The hydrological responses for cases with and without LID implementations were evaluated for the 261 rainfall events, and the results for these rainfall events are presented in Table 3.

From Table 3, it can be seen that without LID implementations, the average runoff for each rainfall event (in depth, unit mm) and the peak flow from the site were 3.39 mm and 0.003 $m^3/(s \cdot ha)$ respectively. The ratio of runoff to precipitation was 0.36 at the imperviousness

Table 1 | The storage provided by each type of LID alternative

	LID practice					
	Unit	Bio-retention	Grass swales	Infiltration trench	Porous pavement	Cistern system
Surface layer	m^3	17.40	1500.00	35.40	15.00	–
Soil/pavement layer	m^3	588.24	–	–	225.00	–
Storage layer	m^3	1102.95	–	3540.96	1875.00	180.00
Total storage depth (d)	mm	18.74	16.45	39.22	23.19	1.97

Table 2 | Characteristics of the selected LID facilities

LID practice	Modeling parameters
Bio-retention	• Thicknesses of the surface and storage layers were 20 and 500 mm respectively • 0.1 for vegetation factor • 0.45 for void ratio • 0.15 for slope
Grass swale	• 2.5:1 for side slope for surface layer • Depth of 500 mm • 0.1 for vegetative cover fraction • Depth of 500 mm for swale layer • 0.3 for surface roughness
Infiltration trench	• 1200 mm for height • 0.5 of void ratio • Site slops between 0.10 and 0.15 • Soil infiltration capacity: 200 mm/hr • 0.1 for surface roughness
Porous pavement	• Void ratio of 0.45 for the storage layer, 0.31 for the pavement layer • 0.04 for surface slope • 0.1 for surface roughness • 1.30 m for bedrock depth from base of system • Situated 3.1 m from building foundations
Cistern system	• Size of 10 m^3 for each cistern system • Drain delay of 24 hours for underdrain

level of 40% for the site. For total runoff, porous pavement had the smallest value of 2.185 mm. For peak flow, bio-retention, grass swale and porous pavement had the value of 0.002 $m^3/(s \cdot ha)$, while infiltration trench and cistern system were 0.003 $m^3/(s \cdot ha)$, the same as the value for no LID implementations.

The effects of each LID implementation on the restoration of hydrological cycle in terms of water balance and peak flow are also presented in Table 3. It can be seen that the porous pavement provided remarkable reduction in total runoff with a reduction rate of 35.58%, followed by infiltration trench of 30.80%. Bio-retention had minimal effect on average runoff with a rate of 9.1% reduction. In terms of the ratio of runoff to precipitation, among the five LID facilities, porous pavement had the best effect by reducing the ratio to 0.232, whereas considering the efficiency index for water balance (Iw), the cistern system had the best value of 0.221, and the indices for all the other four alternatives ranged between 0.017 and 0.052, about 4–10 folds lower than the cistern system.

The change of peak flow rate and the change of lag time are two valuable indicators for flood control measures. It was found that the bio-retention provided the best performance for both peak flow reduction with a rate of 41.65% reduction and a lag time of 21 minutes delay on average. The other four LID alternatives provided reduction rates ranging from 13 to 28% for peak flow reduction and ranging from 7 to 18 minutes of delay for average lag time for 261 rainfall events.

Since the performances for peak flow and water balance were different from each other for each LID, it was a challenge to compare their performances by a single value. In order to evaluate the LID alternatives in an integrated way, the PRC was proposed for the evaluation purpose.

The LID PRC shown in Figure 3 provides a clear view of how these LIDs function in different ways under the storm events of less than 25.4 mm. The areas enclosed in this radar chart represent the LID performance for five LIDs on flood control and water balance in five dimensions: change of peak flow, change of lag time, change of average runoff, rainfall captured by LID on site and the ratio of saved rainfall on site to precipitation.

The top of the polygon in Figure 3 is the change in average runoff; the two wings of the polygon in the middle are the indices regarding flood control, namely, change of lag

Table 3 | Hydrological responses for rainfall events (<25.4 mm)

Hydrological variables	No LID	Bio-retention	Grass swale	Infiltration trench	Porous pavement	Cistern system
Average runoff (mm)	3.39	3.08	3.07	2.35	2.19	2.96
Change of total runoff (%)		9.10	9.60	30.80	35.58	12.85
Peak flow (0.01 $m^3/(s \cdot ha)$)	0.32	0.19	0.25	0.26	0.23	0.31
Change of peak flow (%)		41.65	23.56	19.44	28.66	13.00
Change of lag time (min)		21	18	12	7	10
Ratio of runoff to precipitation	0.36	0.33	0.33	0.25	0.23	0.31
Rainfall captured by LID on site (mm)		0.31	0.33	1.05	1.21	0.44
Iw		0.017	0.020	0.027	0.052	0.221

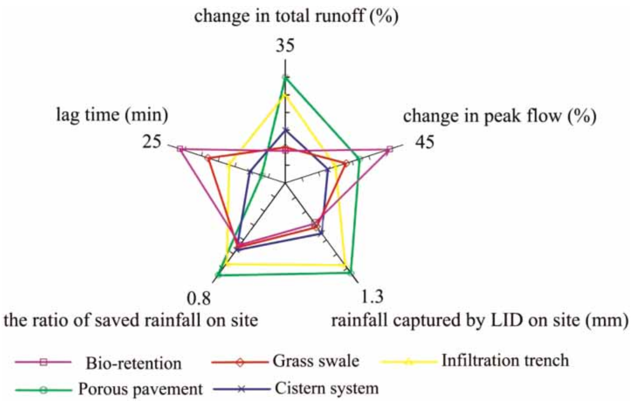

Figure 3 | LID performance radar chart for small storm events (<25.4 mm).

time and peak flow. The two indices at the bottom reflect the performance of LID alternatives on water balance.

The purple lines with a square show that bio-retention performed the best in the change of lag time and peak flow for flood control. The red line with a rhombus indicated that grass swale functioned poorly in the reduction of average runoff and all water balance indices; however, it is the second best in delaying the lag time. The green line with a square and the yellow line with a triangle are for porous pavement and infiltration trench, respectively. The two alternatives performed well for water balance indicators, including the change of average runoff, rainfall captured by LID on site and the ratio of saved rainfall on site to precipitation. The cistern system as the blue line with a cross did not perform well for all the indicators; similarly for grass swale, represented by the red line with a circle. Its performances on the water balance indicators were the worst, while the performance on peak flow was in the middle.

DISCUSSION

Table 1 shows that infiltration trench provides the largest storage, followed by porous pavement and bio-retention. Since the cost of each alternative is normally closely associated with the storage, the less storage that is required, the less the cost for the construction and hence a higher cost-benefit ratio. The storage provided by bio-retention is less than half of that by infiltration trench; however, it performed the best in terms of flood control as shown in Table 3. For water balance, the cistern system had the best *I*w value of 0.221, which means that the cistern system is the most cost-effective way to control and restore water balance.

The PRC chart has yielded four important findings for design considerations.

(1) In this study, porous pavement performs the best in four indices, namely, change in total runoff (%), change in peak flow rate (%), rainfall captured by LID on site (mm) and the ratio of saved rainfall on site to precipitation amount (%). Its performance is the best overall for the four indices except lag time.
(2) For water balance in terms of the three indices, namely, the change in total runoff (%), rainfall captured by LID on site (mm), and the ratio of saved rainfall on site (%), porous pavement is the best performer followed by infiltration trench.
(3) For flood control, the bio-retention performs the best in both peak flow reduction (%) and delaying of lag time (min) for peak flow. The second best for peak flow reduction is porous pavement, while the second best for delaying lag time is grass swale.
(4) For comparison purposes, it can be seen clearly that infiltration trench performs much better than a cistern system in all five indicators, while bio-retention performs better than grass swale.

As indicated in Table 1, the infiltration trench provides the largest storage followed by porous pavement. However, most of the storage in the infiltration trench is provided in the storage layer with very high infiltration rate (hydraulic conductivity), while porous pavement has the paved layer on top with less hydraulic conductivity. This feature may allow porous pavement to function better in reducing peak flow and capturing runoff on site for small rainfall events (less than 25.4 mm) as well as draining the captured runoff slowly to the under drain at the bottom. However, due to its smoother surface than other LIDs (smaller value for Manning's n), it does not perform well in lag time.

CONCLUSIONS

To restore the hydrological cycle in an effective way requires the designers and the decision makers to understand clearly the functions of each LID alternative. The information about the performances of each LID alternative can help them develop a better storm management strategy.

In this study, the SWMM 5 model was applied to simulate the performances on water balance and flood control of these LID alternatives under 10 years' rainfall events for Tianjin City. Two evaluation methods were proposed in this study – the efficiency *I*w and the PRC. Five LID alternatives were evaluated by using the above methodology. It was found that porous pavement provided the best performance overall except for lag time under small rainfall events (less than 25.4 mm, 77% of rainfall events in Tianjin City) from the assessment by PRC, while the cistern system provided the most effective way to capture rainfalls on site in order to restore the water balance by the indicator *I*w. The investigation of the five LID alternatives revealed that they function differently in flood control and water balance. It is therefore necessary to have a consistent way to evaluate their long-term performances in the design phase and operational phase. The two evaluation methods (*I*w and PRC) in conjunction with the long-term numerical simulation can facilitate design and decision making in an efficient and effective manner.

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