Simulating the effects of low impact development approaches on urban flooding: a case study from Tehran, Iran

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ABSTRACT

Low impact development (LID) methods have been shown to be efficient in reducing the peak flow and total volume of urban stormwater, which is a top priority for effective urban stormwater management in many municipalities. However, decision-makers need information on the effects of LIDs and their associated costs before allocating limited resources. In this study, the Storm Water Management Model (SWMM) was used to investigate the effects of five different LID scenarios on urban flooding in a district in Tehran, Iran. The LID scenarios included rain barrel (RB) at two sizes, bio-retention cell (BRC), and combinations of the two structures. The results showed that significant node flooding and overflow volume would occur in the study area under the existing conditions, especially for rainfall events with longer return periods. BRC and combinations of BRC and RBs were the most effective options in reducing flooding, while the smaller-size RB was the cheapest alternative. However, normalized cost, obtained through dividing the total cost by the percent reduction in node flooding and/or overflow volume, was smallest for BRC. The results of this study demonstrate how hydraulic modeling can be combined with economic analysis to identify the most efficient and affordable LID practices for urban areas.

Key words | bio-retention cell, economics, rain barrel, SWMM

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INTRODUCTION

Urban runoff has turned into a serious problem in many municipalities around the world due to accelerated urbanization and population growth (Rech *et al.* 2018). Urbanization causes numerous changes in the natural environment, putting more stress on conventional stormwater management systems (Chen *et al.* 2016). Urban development changes the hydrological characteristics of basins by reducing water infiltration, concentration time, and evapotranspiration capacity. Increased coverage of impervious surfaces, which affect runoff quantity and quality, can significantly increase the total outflow and flow peak of runoff from the basin (Liao *et al.* 2013). In addition, the elevated risk of flooding caused by a suite of natural and anthropogenic factors has made flood planning and management more challenging, especially in developing countries such as those in south Asia (Abbas *et al.* 2016; Nguyen-Tien *et al.* 2018). In Bangladesh, for instance, it was found that all dimensions of comprehensive integrated water resources management to address flood issues were considered in major policies, but some dimensions were ignored at institutional and project levels (Gain *et al.* 2017). Another study reported that most developing countries lack an integrated urban flood management plan, responding reactively to flood incidents (Tingsanchali 2012).

The low impact development (LID) approaches can provide effective tools for resolving urban flood management problems by maintaining and/or restoring natural hydrological conditions and improving environmental conditions in a given basin (Lee *et al.* 2012). In order to achieve the intended stormwater management objectives, LID approaches rely heavily on infiltration and evapotranspiration and attempt to incorporate natural features into

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their design. Compared with traditional urban stormwater management, LID alternatives have several benefits of reducing runoff volume (Liao *et al.* 2015), improving infiltration, reducing peak flow due to reduced impervious surfaces (Drake *et al.* 2013), extending lag time, decreasing pollutant loads (Liu *et al.* 2015), and increasing base flow (Hamel *et al.* 2013). Providing economic, environmental, and aesthetic benefits are among other advantages of implementing LIDs. Considering the wide range of benefits offered by LIDs (Liao *et al.* 2015; Liu *et al.* 2015) and the fact that they can be effectively included in integrated urban flood management plans and projects, their implementation is strongly suggested for developing countries.

Different types of LIDs have been developed in the past, including but not limited to bio-retention cells, infiltration trenches, continuous porous pavement, rain barrels (or cisterns) and vegetative swales. It should be noted that rain gardens, street planters, and green roofs are all variations of BRCs (Chen *et al.* 2018).

Among different LID types mentioned above, two have been widely used in urban areas: bio-retention cells (BRC) and rain barrels (RB). BRC is an area in the landscape lowered to reduce stormwater runoff and peak flow and is beneficial in both residential and commercial settings. Chapman & Horner (2010) reported that a street-side BRC system in Washington could achieve 26–52% runoff retention. BRC can also be implemented for agricultural water quality improvement. With a range of 40–97% reduction in runoff volume and peak flow, BRC has been identified as a promising approach for stormwater management by Chapman & Horner (2010) and DeBusk & Wynn (2011). The RB is a structure to collect and store rainwater for later use. The collected rainwater can be used for different purposes such as non-potable indoor uses (toilet flushing) and landscape irrigation. This system can be constructed with different capacities and installed above or underground, inside or outside the building. RB has several characteristics that make it the preferred choice in many areas, such as ease of construction and installation, preventing stormwater from reaching the sewer system, and reducing the water demand and associated costs (Gunderson *et al.* 2011).

Several previous studies have investigated different aspects of the LID practices mentioned above. For example, Jennings *et al.* (2012) reported that a 189 L (50 gallon) RB that collected rainwater from 25% of a 186 m^2 residential roof and served a 14 m^2 garden in Ohio, USA, reduced the total roof runoff by 2.4–5.4% during the growing season and by 1.4–3.1% during the entire year, depending on the irrigation strategy applied. Other studies have reported much larger reductions in runoff depending on the type, size and extent of LID projects investigated. In Germany, Jackisch & Weiler (2017) found that a combination of LID practices captured 735 of all rainfall events and that there was a 66–87% reduction in runoff volume. In another study, various LID structures (i.e., RB, green roof, BRC, and porous pavement) were modeled to quantify the impact on runoff and non-point source (NPS) pollution in Chicago, USA. The results revealed that these structures could have a noticeable impact on annual runoff and NPS carried by the runoff (Martin *et al.* 2015). Many other studies have documented the effects of implementing LID approaches on reducing runoff volumes, peak flow, and pollutant loads in cities and urban watersheds (Walsh *et al.* 2014; Huang *et al.* 2015; Palla *et al.* 2017).

Conducting field studies on the impacts and effectiveness of LID structures requires significant financial, technical, and human resources. Hence, computer models have been employed in many applications to simulate the performance of these structures. In addition, many urban municipalities are interested in using computer models to estimate the costs and benefits of adopting LID approaches prior to allocating funds and resources. A widely used model in hydraulic and hydrologic studies of urban catchments is the Storm Water Management Model (SWMM). Zaghloul & Al-Mutairi (2010) applied SWMM to estimate runoff for urban areas in Kuwait and found it a powerful tool for developing a more accurate design of an urban drainage network. In another study, Yazdandust *et al.* (2013) examined the effects of different combinations of rainfall and climate change scenarios on urban flooding in Tehran, Iran, using the SWMM model. Their results indicated an increase in flood volume and node flooding due to a changing climate.

In 2009, the US Environmental Protection Agency (USEPA) updated the SWMM model with explicit LID controls. This enabled SWMM to simulate five LID structures: BRC, infiltration trench, porous pavement, RB, and vegetated swale. Since then, the SWMM model has been used in a variety of urban LID and flood management studies. Li *et al.* (2015) used the SWMM model to study the effects of different LID structures on the reduction of runoff and peak flow at different locations in Longyan, China. They reported that the performance of a certain LID was similar at different locations, but the reduction effect on runoff and peak flow varied, especially in the case of RBs and green roofs. Other examples of using SWMM LID applications can be found in Xie *et al.* (2017) and Xu *et al.* (2017).

Despite extensive previous research on the use of computer models to assess the performance of LID approaches, there is still a great need for additional research projects and case studies in large urban municipalities of developing countries. In this study, the results of SWMM simulations were combined with economic analysis to identify the most effective and affordable LID practices for reducing urban runoff and flooding in a district in eastern Tehran, Iran, for variable rainfall return periods. The more specific objectives were: (i) to collect the required input data and convert them to the appropriate electronic format for computer simulation; (ii) to run the SWMM model for the current drainage network of the study area to identify areas with flooding issues; (iii) to assess the potential impacts of implementing different combinations of BRC and RB on reducing runoff volume and flooding; and (iv) to estimate the cost of implementing each LID scenario.

MATERIALS AND METHODS

Study area

The study area covered parts of District 13 in eastern Tehran, Iran, with an area of about 50 hectares. The study area was occupied predominantly by residential, followed by commercial and green areas (Figure 1). The average slope was 0.5% with a nearly north–south aspect. Data were extracted from existing maps on a scale of 1:2,000. The area was considered highly developed, since alleys, main streets, and sidewalks have impervious surfaces mostly covered with asphalt. The storm water system is mainly composed of open or closed channels and continuous or discontinuous green spaces with variable widths along the streets.

SWMM model

SWMM is a dynamic model to simulate the quality and quantity of runoff in urban areas. Extensively adopted for designing and analyzing drainage systems in urban areas, this model has also been employed to assess the performance and efficacy of LID structures. SWMM simulates storms based on the given rainfall hyetograph, meteorological data, basin characteristics, and drainage network to produce an output hydrograph. The model uses the continuity and Manning equations for routing the basin as a non-linear reservoir on sub-basins and channels. The Saint-Venant equations, derived from the equations of mass conservation and momentum, can be used for hydraulic modeling of flow through open channels and pipes. The continuity equation for each sub-basin can be

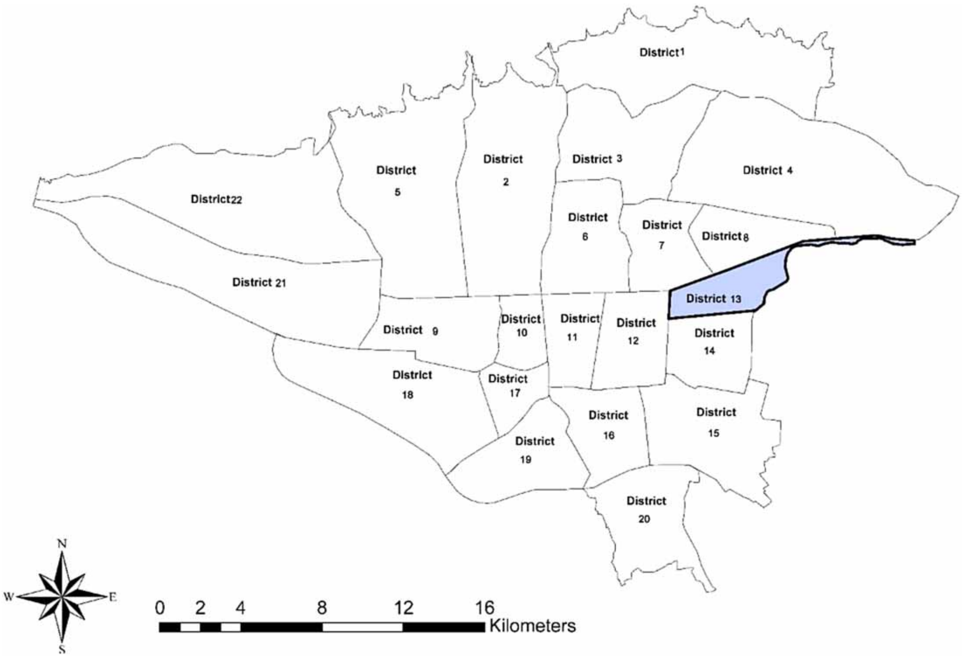

Figure 1 | The study area was located in District 13, Eastern Tehran, Iran.

expressed as Equation (1):

$$\frac{\partial d_x}{\partial t} = P - E - F - q \tag{1}$$

where d_x is the depth of water (m); P is the precipitation rate (m sec^{-1}); E is the evapotranspiration rate (m sec^{-1}); F is the rate of infiltration (m sec^{-1}); and q is water flow in each sub-basin per unit area (m sec^{-1}) obtained through dividing the flow rate from the Manning equation (Equation (2)) by the surface area of the same sub-basin:

$$Q = W.\frac{1}{n}(d - d_p)^{5/3} S^{1/2} \tag{2}$$

where W is the width of the sub-area (m); n is Manning's roughness coefficient; d_p is the depth of pothole storage (m); and S is the slope of the sub-basin.

Equation (3), which is a nonlinear reservoir equation, is obtained by combining the above two equations and by solving for the unknown parameter d:

$$\frac{dd_x}{dt} = P - E - F - \alpha d_x^{5/3},\ \alpha = \frac{W.S^{1/2}}{A_S.n} \tag{3}$$

where A_S is the area of the subcatchment (m^2).

These equations are solved through numerical analysis in the SWMM model. The model also takes into account several other factors such as rainfall–runoff, technical/statistical considerations, as well as common laws and regulations used in many countries for selecting rainfall continuity. From the technical perspective, the design minimum rainfall continuity must be equal to or greater than the total basin concentration time, so that the effects of each basin component in producing flood outflows can be duly considered (Tehran Municipality 2012).

A review of concentration time within Tehran sub-basins (Tehran Municipality 2012; Yazdandust *et al.* 2013) indicated that under all circumstances, the sum of total concentration time of the individual basins and the concentration-time required for water flow through the flooding channel to reach the outlet was less than six hours. Thus, the rainfall–runoff in the model was duly calculated, and the local rainfall pattern was obtained based on the intensity–duration–frequency (IDF) curves across Tehran, using the alternating block method. According to the results of previous studies in Tehran (Tehran Municipality 2012), rainfall is most severe towards the middle of the rainy period (October to April) for events taking three hours and longer. This fact was included in the development of the local rainfall pattern for Tehran. The runoff hydraulics were simulated for return periods of two, five, and ten years given the importance of floods in the design of hydraulic structures, particularly the surface water collection channels, and given the urban considerations concerning Tehran's District 13 (based on the rainfall data available at weather stations). The Horton equations were employed to determine the infiltration rate. The surface water collection network in District 13 was mathematically modeled for each of six scenarios, as discussed in the following sections.

Research approach and scenarios

In this research, six scenarios were defined and modeled, including the existing surface water collection network in the study area and five combinations of rain barrels at two sizes and bio-retention cells. These scenarios are listed in Table 1.

In order to simulate the first scenario (EXST), numerous site visits were made to collect the required data on location, coordinates, and characteristics of the existing surface water collection network to create a geographic information system (GIS) database. Separate vector layers were added to this database for streets, northward/southward buildings, and northward/southward yards, to distinguish between impervious and non-impervious surfaces as well as between effective and non-effective areas. The non-effective areas refer to rooftops of northward buildings and yards of southward buildings because the rooftop runoff in northward buildings is discharged directly into the absorbing wells and the yards of southward buildings are not connected to the storm water network. Accordingly, the existing network was divided into 235 sub-basins in the GIS database. The data for each sub-basin were then fed to the SWMM model, and the relevant processes were subsequently defined and executed.

In the second and third scenarios, RB with two sizes of small and large (RBS and RBL) were considered. RB is one

Table 1 | Research scenarios and their descriptions

No.	Scenarios	Description
1	EXST	Existing conditions (no LID)
2	RBS	Rain Barrel, Small ($D = 1.0$ m)
3	RBL	Rain Barrel, Large ($D = 1.5$ m)
4	BRC	Bio-Retention Cell
5	BRC + RBS	BRC with Rain Barrel, Small
6	BRC + RBL	BRC with Rain Barrel, Large

of the most practical LID methods in the study area due to social acceptance, minimum legal requirements, availability of material, low cost, and ease of installation. The two different sizes of RB considered in this study included diameters of 1.0 m (RBS) and 1.5 m (RBL). These two sizes are most common in the market, according to several local dealers and manufacturers. Both RBs were assumed to have a height of 2.0 m. RBs are similar to flood adjustment tanks in function, except that they are decentralized. Hence, the routing of RBs was similar to that of flood adjustment tanks. In modeling RBs, the rainwater was first directed from the roof surfaces toward the RB through downpipes. Once the RB was full, the excess water was discharged as an overflow to the surface water collection system. As a result, the outflow hydrograph had reduced flood volume and delayed peak flow. Based on the developed GIS

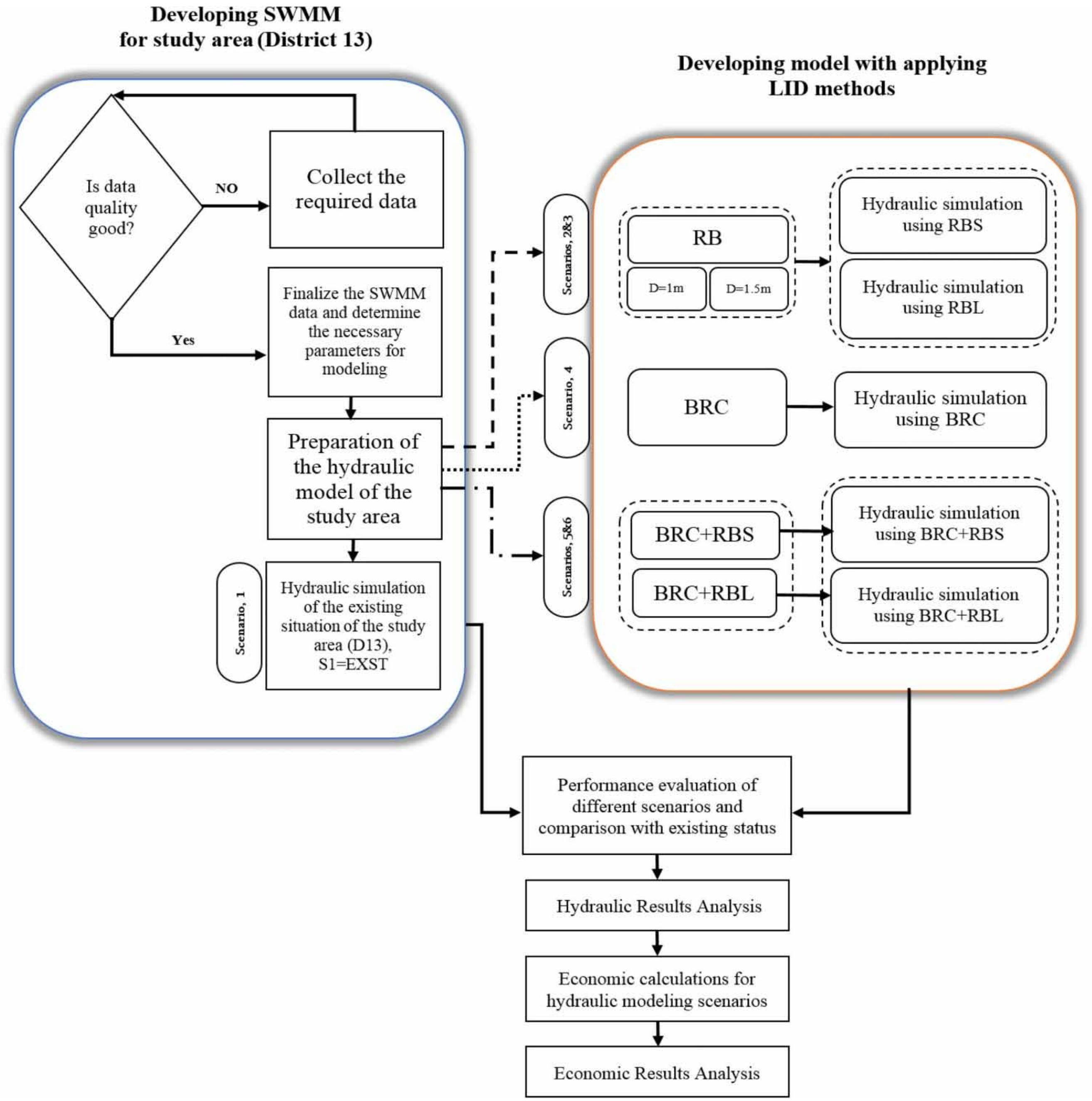

Figure 2 | Flowchart of the research procedure.

database, a total of about 1,000 barrels were determined and assumed to be installed in limited parking spaces depending on the specific conditions in each building.

The fourth scenario was the use of BRC within the existing green spaces. The hydrologic soil group in the study area was determined as B and C. Given the local conditions, the width of BRC was assumed to be 1.0 m, its length equal to that of the adjacent urban structure, and the upper edge of the unit 0.2 m. The specifications of soil and retention layers including thickness, wilting point, field capacity, saturated hydraulic conductivity, and hydraulic gradient were determined for the sandy loam soil based on Rossman (2017). Through evaporation, transpiration, and infiltration, BRCs can reduce runoff volume and improve its quality. Depending on the infiltration rate into the soil and physical limitations in the region, BRCs may be designed with or without underground drainage. In this study, the retention system was assumed to be without drainage, since this type of BRC has a higher chance of being considered by local managers for future implementation. After evaluating the GIS database, 234 locations were identified for BRC installations at the margins of streets and alleys, where the available surface area was adequate. The BRCs were positioned in the east–west and north–south directions in each side of the street adjacent to the streets and sidewalks at a slope of 0.1%. The total length of BRCs was about 24 km in the study area.

The fifth scenario consisted of simultaneous implementation of BRC and RBS, while the sixth scenario included BRC and RBL to monitor the combined effects of these two LID structures. The flowchart of the research methodology employed in the present study is presented in Figure 2. The SWMM simulations were run for each scenario under three rainfall return periods of two, five, and ten years.

Economic analysis

The economic evaluation is one of the most important elements in studying the feasibility of any urban infrastructure project, especially in regions with limited financial resources. Such information assists decision-makers with comparing different alternatives (e.g., the scenarios explained above) and allows them to choose the most appropriate alternative based on their specific circumstances. In the present study, an economic analysis was conducted for all scenarios. The costs of purchasing and installing each of the two RB sizes was estimated through requesting quotes from several local dealers and technicians, and the total cost was estimated according to the modeling scenario, which designated one RB per each south-facing building. In the case of BRC, the same approach was implemented in determining the costs of a unit length of these structures, and this estimate was multiplied by the total length of BRC structures.

RESULTS AND DISCUSSION

SWMM results

The surface water collection network, developed in the GIS environment, consisted of 137 nodes and 136 conduits (canals). The total amount of simulated six-hour rainfall events was calculated at 17, 22 and 26 mm for return periods of two, five and ten years, respectively. The SWMM results revealed that under existing conditions (EXST) and a two-year return period, the network was not able to convey the whole flood and 10% node flooding would occur. Increasing the return period to five and ten years exacerbated the problem and resulted in 26% and 42% node flooding, respectively. The simulated volume of overflow was 19, 24, and 27% of the total flow for the return periods of two, five, and ten years, respectively. Therefore, the results demonstrate the inefficiency of the existing network in the timely

Table 2 | Simulated results of node flooding and overflow volume for each of the studied scenarios and rainfall return periods in the study area

Return period	Scenarios	Node flooding	Reduction in node flooding (%)[a]	Overflow volume (%)	Reduction in overflow volume (%)[a]
2 years	EXST	13	–	19	–
	RBS	5	62	10	47
	RBL	5	62	10	47
	BRC	0	100	0	100
	BRC + RBS	0	100	0	100
	BRC + RBL	0	100	0	100
5 years	EXST	36	–	24	–
	RBS	17	52	19	21
	RBL	6	83	15	36
	BRC	3	92	6	74
	BRC + RBS	0	100	0	100
	BRC + RBL	0	100	0	100
10 years	EXST	57	–	27	–
	RBS	43	25	24	10
	RBL	9	84	17	39
	BRC	8	86	13	52
	BRC + RBS	2	97	1	97
	BRC + RBL	1	98	1	97

[a] Compared to EXST scenario.

transfer of urban runoff, a limitation that can negatively affect urban infrastructures and services such as emergency response. The modeling results also show that the entire study area would be affected by flooding under existing conditions, but node flooding would be more severe in the southern and eastern regions.

Under the second scenario (RBS), node flooding was about 4% for the two-year return period, which was a decrease of about 62% compared with the EXST scenario. Node flooding with a return period of five years was about 13%, which was 52% smaller than the EXST scenario. The longest return period (ten years) resulted in 32% node flooding, which was 25% smaller than the existing conditions. The percentage of overflow volume was also significantly reduced compared with the EXST scenario, with estimates of 10%, 19% and 24% of total flow for the return periods of two, five and ten years, respectively. Larger decreases were obtained under the third scenario (RBL), which was expected due to the larger storage volume of the implemented RB. The occurrence of node flooding in this scenario was 4%, 5%, and 7% for the return periods of two, five and ten years, respectively. The percentage of overflow volume was 10%, 15%, and 17% under the same return periods, respectively. Table 2 summarizes the estimated node flooding and overflow volume for each studied scenario and return period, as well as the magnitude of reductions in each parameter under each LID scenario (compared with existing conditions).

Installing BRC structures (fourth scenario) led to no node flooding following the events with a return period of two years. Increasing the return period to five and ten

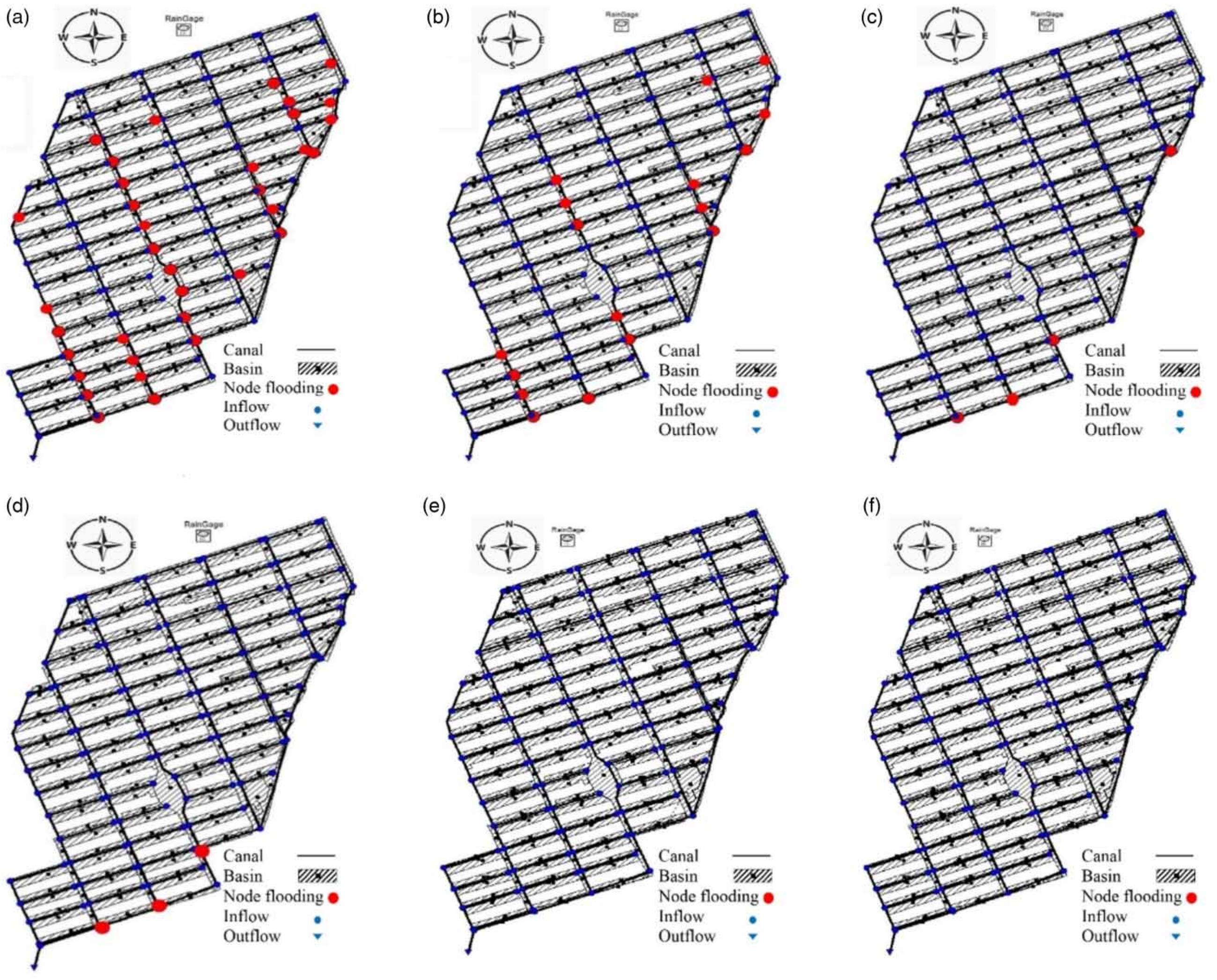

Figure 3 | The occurrence of node flooding after an event with five-year return period for scenarios: (a) EXST; (b) RBS; (c) RBL; (d) BRC; (e) BRC + RBS; (f) BRC + RBL.

years resulted in flooding of 2% and 6% of all nodes, respectively. Percentage of overflow volume was 0%, 6%, and 13% for the return periods of two, five, and ten, respectively. This indicates that BRC was more efficient than RBS and RBL in reducing flooding issues in the study area. As expected, combining BRC and RB had a larger impact on node flooding and overflow volume to the point that the values of both parameters were zero for BRC + RBS and BRC + RBL under two- and five-year return periods. For the most intensive rainfall (ten-year return), 1% node flooding and overflow volume were found for BRC + RBS and BRC + RBL scenarios (Table 2).

Figures 3 and 4 demonstrate the graphical representation of the results of SWMM simulations. These types of output are valuable to city managers and in identifying areas to be prioritized when urban flood control projects are implemented. The information can also be combined with existing GIS databases of early responders in case emergency conditions occur following extreme floods.

Economic analysis

The estimated costs for each studied LID scenario are presented in Table 3. According to the obtained estimates, the implementation of the second scenario (RBS) was the cheapest option. Use of a larger-size rain barrel (RBL, third scenario) would increase the cost by 2.25 times. This significant increase is mainly due to the higher cost of the larger RB. Construction of BRC along the streets (about 24 km) was the second cheapest option, with a total cost that was only about 11% larger than that of RBS. Combining BRC and RBS (fifth scenario) would have a cost close to the

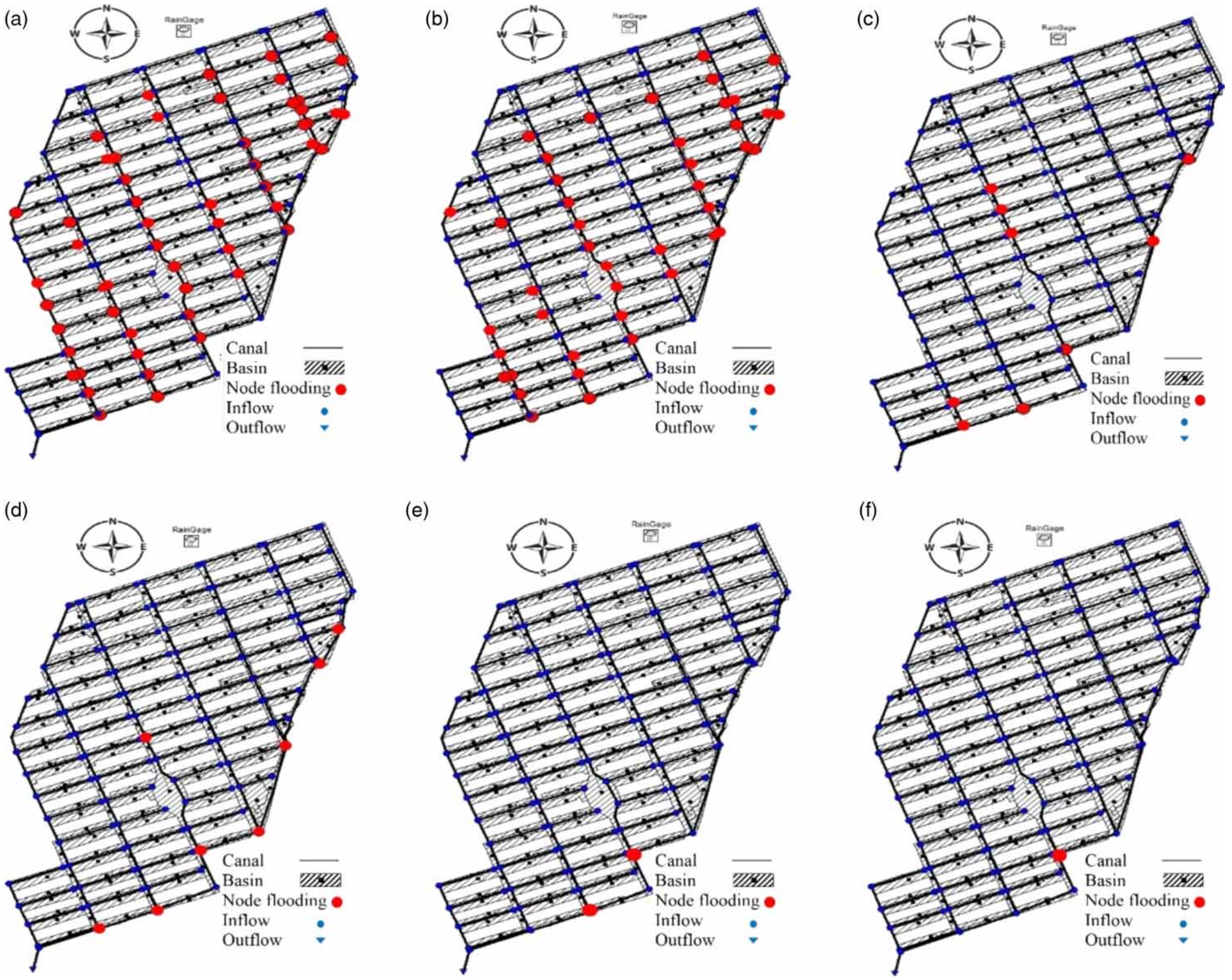

Figure 4 | The occurrence of node flooding after an event with ten-year return period for scenarios: (a) EXST; (b) RBS; (c) RBL; (d) BRC; (e) BRC + RBS; (f) BRC + RBL.

Table 3 | Cost of implementing each LID scenario

Scenarios	Total cost (USD)[a]
RBS	380,952
RBL	857,143
BRC	423,810
BRC + RBS	804,762
BRC + RBL	1,280,953

[a] 1 USD = 42,000 IRR.

cost of the RBL scenario (6% cheaper). Finally, the sixth scenario (BRC + RBL) was the most expensive option.

Although the total cost estimates would provide decision-makers with valuable information on the economic feasibility of each scenario and the financial resources that must be secured, cost estimates normalized based on the level of reduction in flooding issues that they can achieve may be a more appropriate piece of information. Table 4 presents the normalized costs, estimated through dividing the total costs (Table 3) by the percent reduction in node flooding and overflow volume achieved under each studied scenario and rainfall return period. In other words, the estimates in this table represent the cost of reducing each flooding variable by 1%.

Before normalizing the costs, the RBS scenario was the most affordable option. After normalizing, however, BRC was always the cheapest option with the smallest expense per every 1% reduction in node flooding and overflow volume for all return periods. RBS had the second lowest normalized price based on node flooding and for return periods of two and five years. For the ten-year return period, BRC + RBS was the second cheapest option.

Table 4 | Normalized cost per unit reduction in node flooding (NCNF) and unit reduction in overflow volume (NCOV)

Return period	Scenarios	NCNF (USD)[a]	NCOV (USD)[a]
2 years	RBS	6,144	8,175
	RBL	13,825	18,198
	BRC	4,238	4,238
	BRC + RBS	8,048	8,048
	BRC + RBL	12,810	12,810
5 years	RBS	7,326	18,141
	RBL	10,327	23,810
	BRC	4,607	5,712
	BRC + RBS	8,048	8,048
	BRC + RBL	12,810	12,810
10 years	RBS	15,238	38,095
	RBL	10,204	21,978
	BRC	4,928	8,150
	BRC + RBS	8,297	8,331
	BRC + RBL	13,071	13,206

[a] 1 USD = 42,000 IRR.

CONCLUSIONS

Six low impact development (LID) scenarios were simulated for their impact on reducing node flooding and overflow volume following rainfall events with return periods of two, five and ten years in District 13 of Tehran, Iran. The results showed the significant flooding issues that would occur under the existing conditions (no LID) for each of the return periods. Installing small and large rain barrels (RBS and RBL, respectively) had the smallest impact on reducing flooding. The remaining three scenarios, which included implementing bio-retention cells (BRC) or combinations of BRC and RBS/RBL, all resulted in over 86% reduction in node flooding and 52% reduction in overflow volume under the most intense rain event (ten-year return period). The combination scenarios (BRC + RBS and BRC + RBL) were able to eliminate node flooding and overflow under events with two- and five-year return periods.

A major factor in evaluating and implementing LID projects in urban municipalities is the financial costs of different alternatives. This is especially the case in developing countries, where financial resources may be more limited. The results of the cost analysis conducted in the present study showed RBS was the cheapest option, followed by BRC (11% more expensive). However, dividing the total costs by the percent reduction in node flooding and overflow volume revealed that BRC always had the smallest normalized price, followed by RBS or BRC + RBS depending on the rainfall return period. For longer return periods, BRC + RBS had the smallest cost per each percent reduction in node flooding, and overflow volume achieved. The present study was conducted for one district in Tehran, but the results would most probably be applicable to other districts due to similarities in urban settings and characteristics of underlying soils. Local decision-makers can use the results to evaluate different alternatives along with the impact on controlling flooding issues in this megacity.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abbas, A., Amjath-Babu, T. S., Kächele, H., Usman, M. & Müller, K. 2016 An overview of flood mitigation strategy and research support in South Asia: implications for sustainable flood risk management. *International Journal of Sustainable Development & World Ecology* **23** (1), 98–111.

Chapman, C. & Horner, R. R. 2010 Performance assessment of a street-drainage bioretention system. *Water Environment Research* **82** (2), 109–119.

Chen, Y., Samuelson, H. W. & Tong, Z. 2016 Integrated design workflow and a new tool for urban rainwater management. *Journal of Environmental Management* **180**, 45–51.

Chen, T., Zhang, B., Li, J. & Han, M. 2018 Process and influencing factors of N removal in grassed paving system by ^{15}N tracing analysis. *Water Science & Technology* **78** (3), 611–621.

DeBusk, K. M. & Wynn, T. M. 2011 Storm-water bioretention for runoff quality and quantity mitigation. *Journal of Environmental Engineering* **137** (9), 800–808.

Drake, J. A. P., Bradford, A. & Marsalek, J. 2013 Review of environmental performance of permeable pavement systems: state of the knowledge. *Water Quality Research Journal* **48** (3), 203–222.

Gain, A. K., Mondal, M. S. & Rahman, R. 2017 From flood control to water management: a journey of Bangladesh towards integrated water resources management. *Water* **9** (1), 55.

Gunderson, J., Roseen, R., Janeski, T., Houle, J. & Simpson, M. 2011 Economical CSO management. *Stormwater* **12** (3), 10–25.

Hamel, P., Daly, E. & Fletcher, T. D. 2013 Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: a review. *Journal of Hydrology* **485**, 201–211.

Huang, C.-L., Hsu, N.-S., Wei, C.-C. & Luo, W.-J. 2015 Optimal spatial design of capacity and quantity of rainwater harvesting systems for urban flood mitigation. *Water* **7** (9), 5173–5202.

Jackisch, N. & Weiler, M. 2017 The hydrologic outcome of a low impact development (LID) site including superposition with streamflow peaks. *Urban Water Journal* **14** (2), 143–159.

Jennings, A. A., Adeel, A. A., Hopkins, A., Litofsky, A. L. & Wellstead, S. W. 2012 Rain barrel–urban garden stormwater management performance. *Journal of Environmental Engineering* **139** (5), 757–765.

Lee, J.-m., Hyun, K.-h., Choi, J.-s., Yoon, Y.-j. & Geronimo, F. K. F. 2012 Flood reduction analysis on watershed of LID design demonstration district using SWMM5. *Desalination & Water Treatment* **38** (1–3), 255–261.

Li, P., Liu, J., Fu, R., Liu, X., Zhou, Y. & Luan, M. 2015 The performance of LID (low impact development) practices at different locations with an urban drainage system: a case study of Longyan, China. *Water Practice & Technology* **10** (4), 739–746.

Liao, Z. L., He, Y., Huang, F., Wang, S. & Li, H. Z. 2013 Analysis on LID for highly urbanized areas' waterlogging control: demonstrated on the example of Caohejing in Shanghai. *Water Science & Technology* **68** (12), 2559–2567.

Liao, Z. L., Zhang, G. Q., Wu, Z. H., He, Y. & Chen, H. 2015 Combined sewer overflow control with LID based on SWMM: an example in Shanghai, China. *Water Science & Technology* **71** (8), 1136–1142.

Liu, Y., Ahiablame, L. M., Bralts, V. F. & Engel, B. A. 2015 Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff. *Journal of Environmental Management* **147**, 12–23.

Martin, A. R., Ahiablame, L. M. & Engel, B. A. 2015 Modeling low impact development in two Chicago communities. *Environmental Science: Water Research & Technology* **1** (6), 855–864.

Nguyen-Tien, V., Elliott, R. J. R. & Strobl, E. A. 2018 Hydropower generation, flood control and dam cascades: a national assessment for Vietnam. *Journal of Hydrology* **560**, 109–126.

Palla, A., Gnecco, I. & La Barbera, P. 2017 The impact of domestic rainwater harvesting systems in storm water runoff mitigation at the urban block scale. *Journal of Environmental Management* **191**, 297–305.

Rech, A. S., Rech, J. C., Caprario, J., Tasca, F. A., Recio, M. Á. L. & Finotti, A. R. 2018 Use of shrimp-shell for adsorption of metals present surface runoff. In: *New Trends in Urban Drainage Modelling* (G. Mannina, ed.), Springer, Cham, Switzerland, pp. 25–29.

Rossman, L. 2017 *Storm Water Management Model Reference Manual Volume II – Hydraulics*, EPA/600/R-17/111. US Environmental Protection Agency, Washington, DC, USA.

Tehran Municipality 2012 *Summary Report of the Master Plan for Surface Water Management*, Volume 11. Tehran Municipality, Tehran, Iran.

Tingsanchali, T. 2012 Urban flood disaster management. *Procedia Engineering* **32**, 25–37.

Walsh, T. C., Pomeroy, C. A. & Burian, S. J. 2014 Hydrologic modeling analysis of a passive, residential rainwater harvesting program in an urbanized, semi-arid watershed. *Journal of Hydrology* **508**, 240–253.

Xie, J., Wu, C., Li, H. & Chen, G. 2017 Study on storm-water management of grassed swales and permeable pavement based on SWMM. *Water* **9** (11), 840.

Xu, T., Jia, H., Wang, Z., Mao, X. & Xu, C. 2017 SWMM-based methodology for block-scale LID-BMPs planning based on site-scale multi-objective optimization: a case study in Tianjin. *Frontiers of Environmental Science & Engineering* **11** (4), 1.

Yazdandust, F., Pourshushtari, M. & Tahmasebi Birangani, Y. 2013 Investigating the effect of climate change on urban flooding and the function of drainage system. In: *National Conference on Flood Management, Tehran, Iran*.

Zaghloul, N. A. & Al-Mutairi, B. L. 2010 Water harvesting of urban runoff in Kuwait. *Scientica Iranica: Transactions on Civil Engineering (A)* **17** (3), 236–243.

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