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Optimizing stormwater low-impact development strategies in an urban watershed considering sensitivity and uncertainty

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Abstract Stormwater management in an urban environment is beset by uncertainties about future development. Dynamic strategies must be devised to cope with such uncertain environment. This work proposes a simulation–optimization model that minimizes the costs of low-impact development (LID) measures for mitigating impacts of future urban development on runoff. This paper's methodology is tested in an urban watershed in Tehran, Iran, relying on the stormwater management model (SWMM) coupled with the genetic algorithm (GA) to function as a simulation–optimization method for urban–runoff control by means of LID stormwater control measures. A sensitivity analysis of the calculated optimal solution revealed the impacts the most sensitive LIDs would have on runoff considering a set of plausible future development scenarios in the urban catchment. A comparison of the results from two different scenarios of future development with the existing stormwater system's performance shows the cost increase in redesigning the existing system to make it LID sensitive would equal 20% of the existing system's cost. The additional cost of redesigning the existing system without LID features would be 45% of the existing system's cost. These results demonstrate the importance of assessing the sensitivity of designed units in a stormwater management system and studying the trade-offs between possible decisions and future uncertainties concerning development in the watershed.

Keywords Stormwater management model · Simulation · Optimization · Genetic algorithm · Low impact development · Uncertainty

Introduction

The rise of urbanization in watersheds and concomitant increase of impervious areas lead to heightened urban runoff rates and runoff pollution (Davis and Birch 2009; Brown and Peake 2006; Sadeghi et al. 2017). Low-impact development practices have been adopted to cope with the increasing threat by urban runoff in urban watersheds (Loáiciga et al. 2015; Sadeghi et al. 2017). These low-impact development (LID) practices focus

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on runoff retention and infiltration, aiming to replicate the predevelopment hydrological characteristics of the catchment (Davis and Birch 2009).

LIDs have been implemented by several researchers under multiple scenarios (i.e., Ackerman and Stein 2008; Zhang et al. 2006, Zhang 2009; Cheng et al. 2009; Lee et al. 2012). Li et al. (2009) investigated the hydrologic performance of six bio-retention cells in Maryland and North Carolina. Their results indicated bio-retention facilities achieve substantial hydrologic benefits through delaying and reducing peak flows and decreasing runoff volume. Roseen et al. (2011) examined the performance of porous pavements for stormwater management in cold climates. Dudula and Randhir (2016) assessed the potential impacts of climate change on watershed hydrologic processes and effectiveness of best management practices (BMPs). Bio-retention and rain gardens were modeled for the Ipswich watershed (USA), and the results demonstrated the effectiveness of these BMPs in mitigating the impact of climate change on storm runoff.

Many authors have reported a variety of approaches for the selection and placement of LIDs in urban catchments. Montaseri et al. (2015) developed a simulation–optimization model of stormwater management involving a combination of the MUSIC simulation model and the genetic algorithm (MUSIC-GA). They applied their model to cost-effective design of a stormwater treatment system in Australia. Sebti et al. (2015) developed an optimization model for selecting and placing best management practices (BMPs) to control water quality and quantity by means of linear programming (LP). Sebti et al. (2016) compared their LP model with results obtained by coupling the GA and the simulated annealing (SA) algorithm, with the LP model serving as a reference solution. The results validated a slightly better performance by SA than that obtained by the GA. Dai et al. (2016) reported an internal-fuzzy possibilistic programming (IFPP) method and applied it to the optimal placement of BMPs to control nutrient pollution in the Baoxianghe River watershed in China. Sadeghi et al. (2017) reported a mixed integer programming (MIP) model for the optimal selection, sizing, and placement of LID stormwater control measures (SCMs) that retain runoff by percolation and retention in permeable soils in the City of Los Angeles, CA.

Methods used for optimizing the design and implementation of LIDs in the catchments are classified as classical or EAs (evolutionary algorithms) based approaches. Classical methods such as LP are useful tools for optimizing design but these methods have shown some shortcomings in optimization problems (Rani and Moreira 2010). Furthermore, traditional algorithms are effective in small scale problems with limited number of variables. Thus, where there are large numbers of decision variables, they have not performed well (Bozorg-Haddad et al. 2013). EAs, however, are independent of the problem type (linear, nonlinear, discontinuous, high dimensionality, etc.) and have gained acceptance owing to their accuracy, effectiveness, and not having the limitations inherent to classical methods. The GA in particular has been applied to a wide range of water resources management problems including reservoir operation (Afshar et al. 2007; Bozorg-Haddad et al. 2006, 2015, 2018; Bahrami et al. 2017), water distribution networks (Ghajarnia et al. 2012; Beygi et al. 2012), cultivation rules (Moradi-Jalal et al. 2007), and site selection of infrastructures (Karimi-Hosseini et al. 2011). The results of these studies have confirmed the reliability of GA in finding the optimal solution in water resources problems. In recent years, the GA has been applied successfully in finding the optimal design of stormwater management measures (Harrell and Ranjithan 2003; Reichold et al. 2009; Damodaram and Zechman 2010; Montaseri et al. 2015).

The cited studies focused on the cost-effectiveness of the design and implementation along with quality and quantity control capabilities of LID systems for urban runoff control, which produced stormwater management systems capable of coping with the present urban setting and future development extensions. Considering the fast pace of urbanization and the increase in impervious surfaces, it is evident there are future uncertainties about future development in urban subcatchments. LIDs are usually constructed with a life cycle of 30 years, which means that many changes may take place during the life time of a LID. Another sensitive issue is the maintenance of these units that might not be performed in the most effective manner. These facts call for a design that takes into account future urban development and related uncertainties. This develops a simulation–optimization model for LID selection and placement to control runoff quantity. The optimization model produces an adaptive plan to cope with the worst-case possible scenarios affecting designed LIDs by future development in the study area. This paper's simulation–optimization model relies on the stormwater management model (SWMM) for simulation and is coupled with the GA for optimization. The

SWMM-GA model is applied to an urban case study in Tehran, Iran. Figure 1 depicts the methodology implemented in this study.

Simulation–optimization methodology

The proposed methodology integrates the simulation model and the optimization algorithm for selecting and placing LIDs in the study catchment. Figure 2 illustrates the flowchart of the simulation–optimization model. The U.S. Environmental Protection Agency's (EPA) SWMM version 5.1 was implemented to simulate the runoff process with a study catchment. SWMM 5.1 is a dynamic rainfall–runoff model for catchment-wide simulations of hydrologic events including rainfall and surface runoff which also includes a LID editor for modeling the impacts of these measures on hydrologic response of the catchment (Rossman 2010). SWMM has been applied in numerous studies, which have demonstrated its capacity in modeling LIDs (Rosa et al. 2015; Campisano et al. 2017; Peng and Stovin 2017). SWWM represents LIDs as layered structures with distinct properties. SWMM performs a moisture balance during simulation that keeps track of how much water moves between and is stored within each LID layer.

The input data to SWMM includes a catchment map along with land use specifications, catchment slopes, percentage of impervious lands, manning's roughness, design hyetograph for a 25-year design period, and the layer specifications of the LIDs. Dynamic wave was implemented for flow routing. Infiltration was modeled with Horton's method. The optimal size and placement of the LIDs within the study catchment are obtained with the simulation–optimization model herein developed.

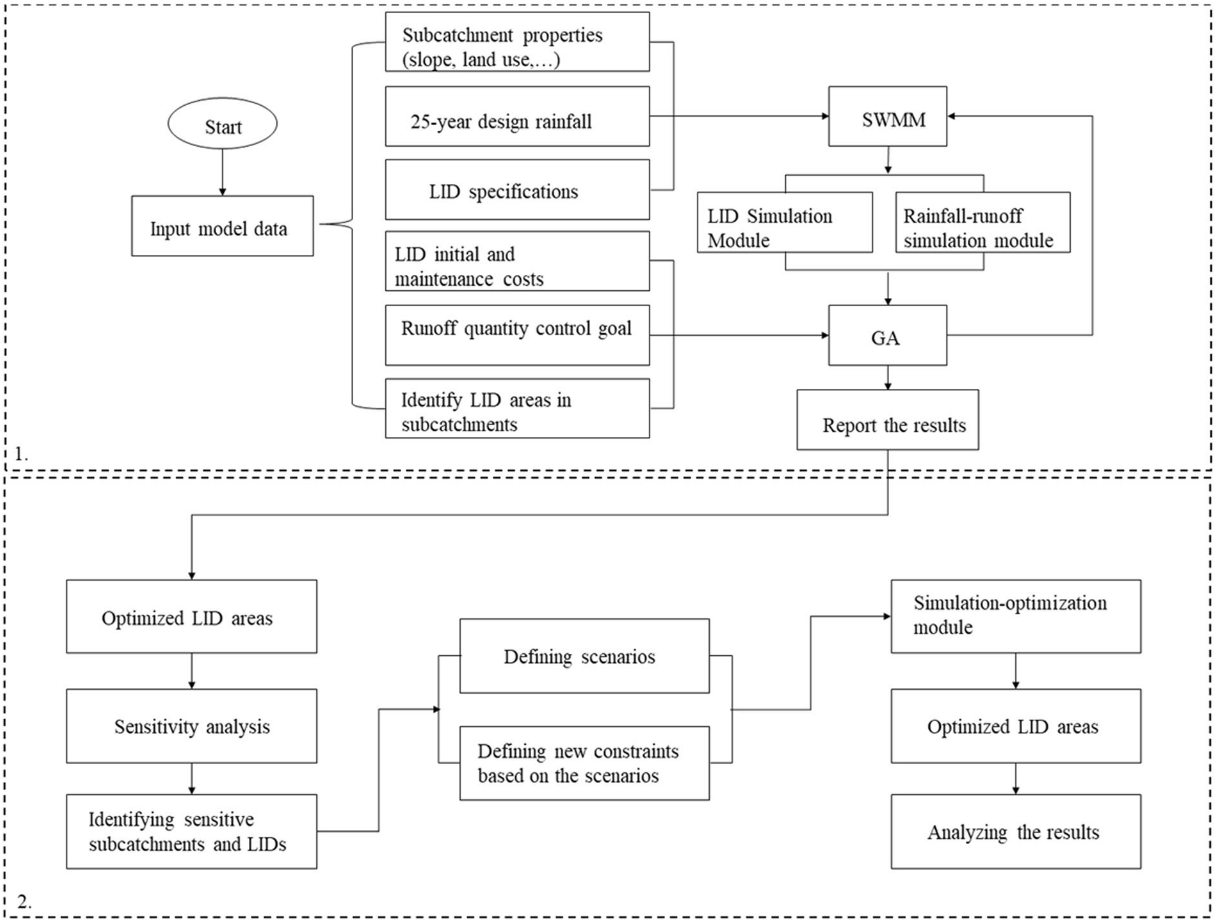
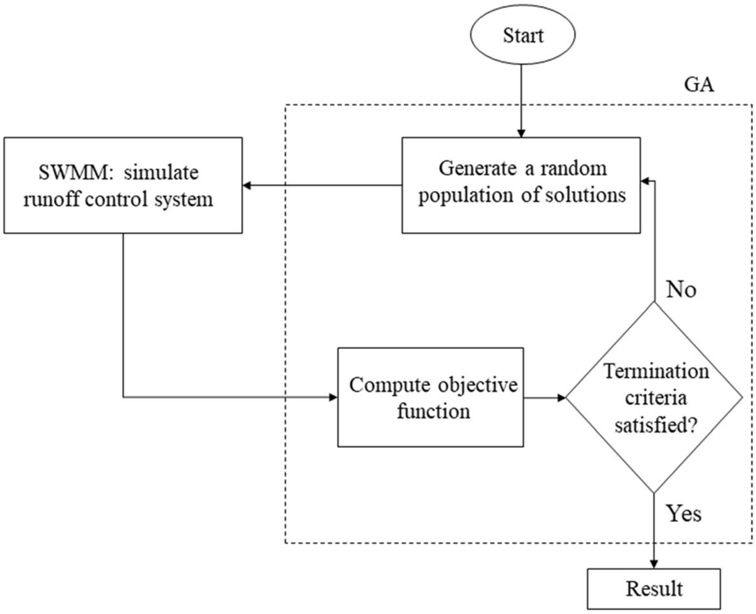


Fig. 1 Methodology applied in this study

Fig. 2 Flowchart for the simulation–optimization method



Case study

District 6 of Tehran municipality

District 6 of Tehran municipality is chosen as the study area. It is located in downtown Tehran with an area of 21.37 km^2, as shown in Fig. 3. The catchment area was obtained with a digital elevation model (DEM). This catchment is comprised of 45 subcatchments which are homogenous in their hydrological and physical characteristics as indicated by runoff measurements in each subcatchment. The outlet nodes are also depicted in Fig. 3. Most of these subcatchments have an impervious percentage of 100% due to urbanization, with the exception of areas consisting of parks. Their slopes range between 0.01 and 0.04. The highest and the lowest elevations in the catchment are 1460 and 1214 m, respectively. The study area slopes towards the south with an average slope of 0.05. Tehran has a semi-arid climate with an average precipitation of 300 mm per year. Temperatures in urban areas of Tehran varies between a maximum of 41 °C and a minimum of −40 °C with an average temperature of 10 °C.

Simulations for a 25-year return rainfall were conducted and the simulated runoff volumes were extracted from the simulation results. The results indicated the 25-year rainfall flooded four nodes in the catchment. The total volume of flooding in the catchment equaled 136 cubic meters. Table 1 lists the flooded nodes in the catchment and the flooding volume and times of occurrence at each flooded node. This work applies two LID types (bio-retention cells and porous pavement) for runoff control in the study area based on the area's availability and other catchment specifications. Table 2 summarizes the specification for the LID bio-retention cells and porous pavement used in this study.

Design rainfall

Gibb (1975) obtained the intensity–duration–frequency (IDF) curve for short term rainfalls in Tehran as follows:

$$I = C_{AltPR} \times D^{-0.645} \tag{1}$$

in which I = rainfall intensity (mm/h), D = rainfall duration (minutes), and C_{AltPR} = coefficient determined by the return period and average elevation of the study area. The average elevation of the study area is 1300 m; thus, the value of C_{AltPR} is equal to 237 for a 25-year return period. The concentration time for entire city of Tehran equals

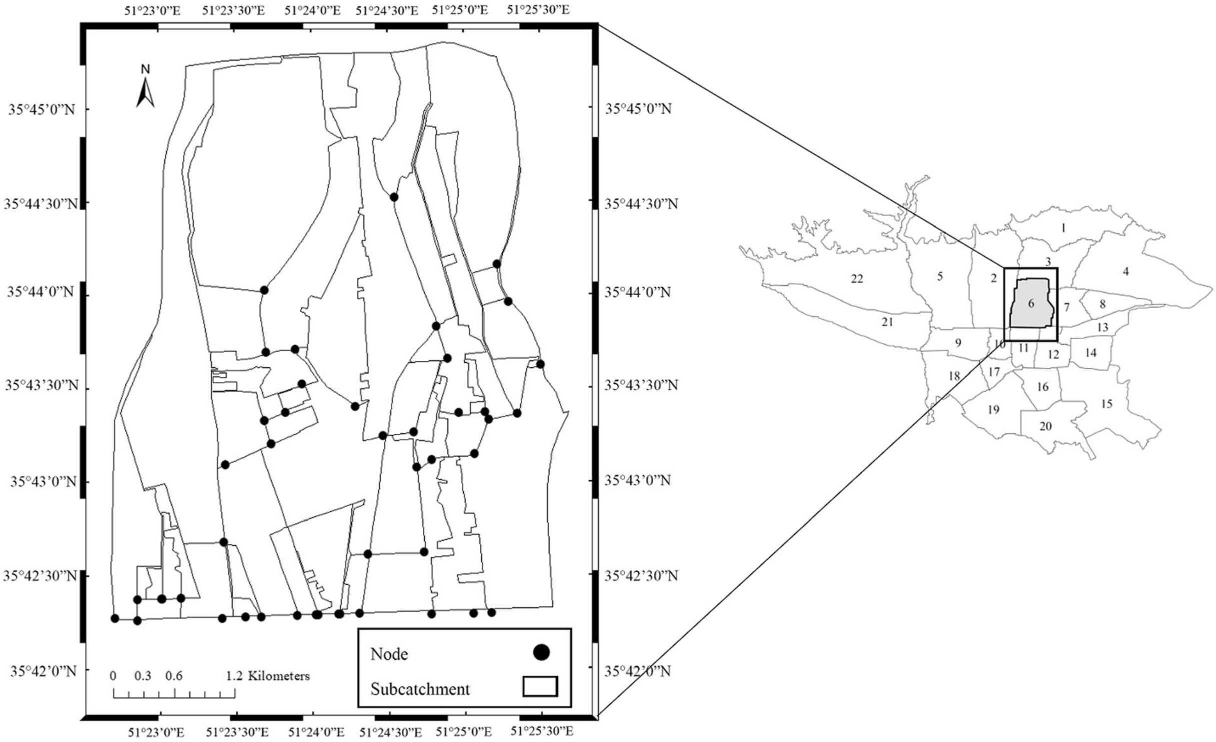


Fig. 3 District 6 of Tehran municipality located in Tehran, Iran

3 h according to the Tehran Surface Water Master Plan (Mahab and Pöyri 2010). Therefore, the concentration time for the study area is less than 3 h. The Qodds and Pöyri's (2010) report recommended rainfall with a 25-year return period, and a duration of 6 h is suitable for simulating rainfall–runoff events within Tehran. This study uses the recommended rainfall event for LID design in the study area.

The rainfall intensity for each time increment (10 min) is calculated with Eq. (1). The precipitation depths are ordered so that the maximum rainfall block falls in the middle of the hyetograph; the next largest block is placed to the right of the maximum block, the third largest block is placed to the left of the maximum block, and so on and so forth. The resulting hyetograph for a 25-year rainfall with a duration of 6 h is depicted in Fig. 4.

Optimization model

The optimization model implemented in this study is based on the GA, which starts with a randomly generated population of solutions, and through selection, crossover, and mutation, an offspring population of solutions is created. The members of the offspring population are ranked according to their objective function values. Consecutive, improved populations of solutions are generated until predefined stopping criteria are met (Cai et al. 2001). This study sets the objective function of

Table 1 Flooded nodes in the study area

Node number	Flooding time (h)	Peak flow (m^3/s)	Runoff volume (m^3)
10	0.69	5.01	10,200
16	3.41	7.57	78,424
31	2.74	11.70	42,400
41	0.26	1.70	5152

Table 2 LID specifications used in this study

Layer	Parameter	LID	
		Bio-retention cell	Porous pavement
Surface	Berm height (mm)	250	80
	Vegetation volume fraction	0.1	0
	Manning's *n*	0.03	0.01
	Surface slope (%)	0	1
Pavement	Thickness (mm)	–	100
	Void ratio	–	0.15
	Permeability (mm/h)	–	125
Soil	Thickness	900	–
	Porosity	0.35	–
	Conductivity (mm/h)	250	–
Storage	Thickness (mm)	150	350
	Void ratio	0.7	0.2
	Conductivity (mm/h)	44	44

the optimization model as the minimization of the lifetime cycle costs (F) of LIDs for runoff control. Equations (2) through (5) state the objective function and its constraints:

Cost minimization:

$$\text{Min } F = \sum_{i=1}^{n}\sum_{k=1}^{m} C_k A_{ki} \tag{2}$$

Constraint on LID area sizes:

$$0 \le A_{ki} \le A_{M_{ki}} \quad i = 1, \ldots, n \text{ and } k = 1, \ldots, m \tag{3}$$

Constraint on runoff volume:

$$V_T \le V_{\max} \tag{4}$$

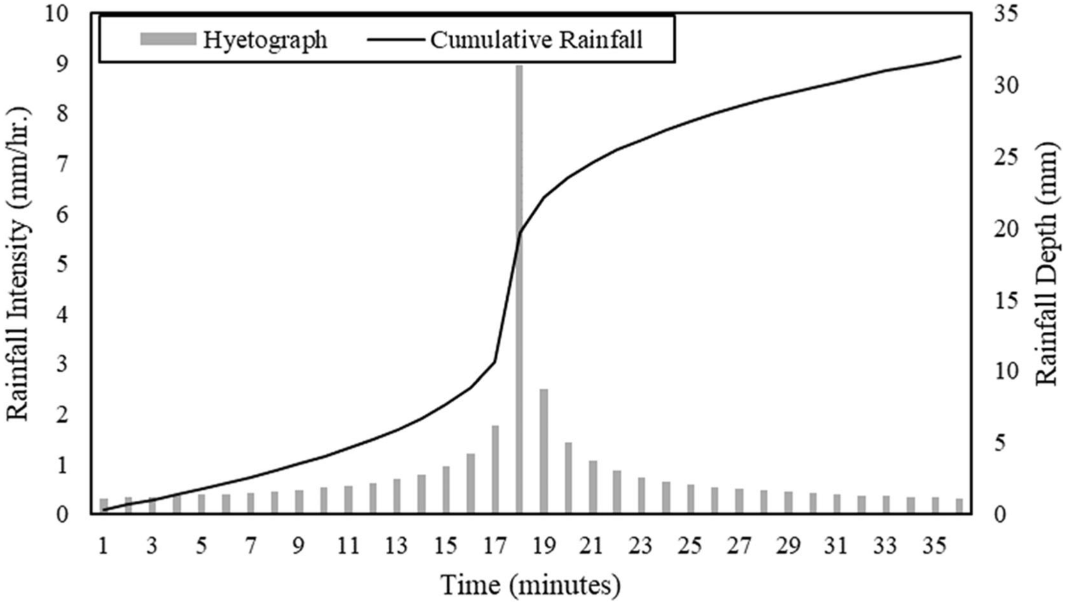


Fig. 4 Twenty-five-year design rainfall for District 6 of Tehran municipality

in which n = total number of subcatchments; m = total number of LIDs in each subcatchment; A_{ki} = area of LID type k in subcatchment i (the decision variables); A_{Mki} = maximum available area for the kth LID in subcatchment i; V_T = cumulative runoff volume at flooded nodes (m^3); $V_{\max}$ = maximum cumulative runoff volume which is allowable at flooded nodes (m^3); and C_k = life cycle costs of LID type k, which is calculated as follows (Sebti et al. 2015):

$$C_k = C_{k_0} + \sum_{t=1}^{T} \frac{C_{k_t}}{(1+r)^t} \tag{5}$$

in which C_{k0} = construction costs for LID type k (\$/m^2), C_{kt} = lifetime maintenance costs for LID type k in year t (\$/m^2), T = LID lifetime, and r = annual discount rate.

The simulation–optimization model was applied to the study area in Tehran for a 30-year period and the 25-year, 6-h, design rainfall, with the objectives of minimizing the objective function while keeping the cumulative runoff volume within admissible value. The GA was coupled with SWMM by means of MATLAB 8.6. The obtained results from GA satisfied the constraints and the algorithm minimized the lifetime cost. Table 3 lists the flooding volume at each flooded node after optimization. It is seen in Table 3 the flood volume at flooded nodes is reduced, with node number 41 completely relieved from flooding after LID deployment.

Sensitivity analysis

Simulations were performed to investigate the impacts of omitting LIDs within the study area with the purpose of assessing the sensitivity of the designed stormwater management system. Sensitivity was calculated omitting each of the prospective LIDs, one at a time, from one of the subcatchments, and simulating catchment runoff without the omitted LID under future development in the study catchment. This means that for 2 types of LIDs in 45 subcatchments, we have ran the simulation 90 times and the change in the runoff volume was calculated by simulating runoff in the study area to better understand the effect of each LID unit in the whole design. The results of the sensitivity analysis are displayed in Fig. 5. The results in Fig. 5 indicate six of the prospective LIDs in the catchment induce high sensitivity under future conditions. Therefore, omitting them would exacerbate future flood damages. The six high-sensitivity LIDs are summarized in Table 4. It is deduced from the results of Table 4 that LIDs placed in subcatchment numbers 15, 16, and 31 are associated with the highest sensitivity of the runoff control system. These subcatchments are upstream of flooded nodes 16 and 31 which explain their high induced sensitivity. Figure 6 displays the sensitive subcatchments and their location compared to the flooded nodes. The increases in cumulative flood volume at flooded nodes due to omission of a sensitive LID from the designed stormwater management model are shown in Fig. 7. It is inferred from Fig. 7 that omission of LID number 61 from the runoff control system would increase by 15,000 m^3 the total flood volume at flooded nodes. This represents a 22% runoff increase in the study area.

Table 3 Runoff volume at flooded nodes

Node number	Runoff volume (m^3)				Cumulative
	10	16	31	41	
Without LIDs	10,200	78,424	42,400	5152	136,176
With LIDs	3186	45,431	19,482	0	68,085

Having identified the sensitive areas for stormwater control system, we considered probabilities of future developments in the catchment. The sensitivity analysis results signal that future changes in subcatchments 15, 16, or 31 would cause severe impacts on the hydrologic response of the catchment to rainfall. To cope with the likelihood of such impacts, this work entertained two approaches for designing stormwater control measures in the study area. These approaches are presented in the following sections.

Redesigning the stormwater control system

Twelve new runoff control optimizations were performed for the study area based on two approaches. In the first approach (A), one of the six sensitive LID units was omitted completely by setting its size equal to 0 (Fig. 8a). This omits the LID from the simulation–optimization algorithm, thus forcing a search for

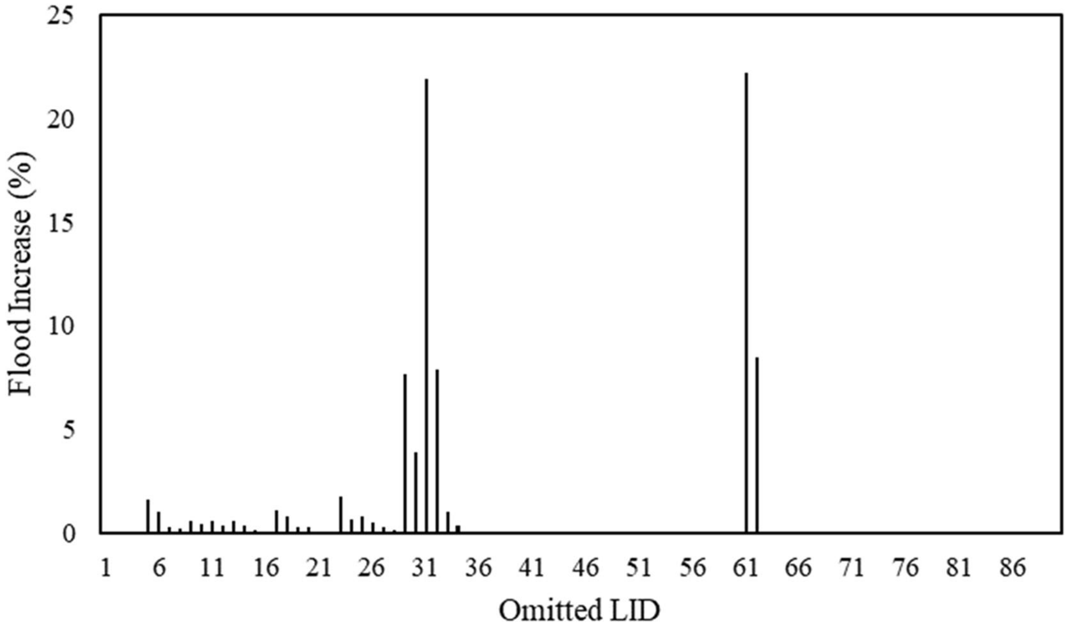


Fig. 5 Sensitivity analysis of the designed LIDs in the study area

alternative optimal LID designs in the catchment. The constraints for the approach A with LID number 29 being omitted are as follows:

$$0\le A'_{ki}\le A_{M_{ki}} \quad i=1,\dots,n \quad \text{and} \quad k=1,\dots,m \tag{6}$$

$$A'_{29}=0 \tag{7}$$

in which A'_{ki} = the new area of LID type k in subcatchment *I* and A'_{29} = the new area for LID number 29, which is set equal to 0.

Our second approach (B) for optimizing the LIDs consists of searching for alternatives to reduce the effects of omitting a LID from the designed system. Thus, any future development changes requiring the removal of a sensitive LID is countered by improving and changing the LIDs in other subcatchments. The optimal change in the design of LIDs in case LID number 29 is removed is formulated as follows (Fig. 8b):

$$A_{ki}\le A''_{ki}\le A_{M_{ki}} \quad i=1,\dots,n \quad \text{and} \quad k=1,\dots,m \tag{8}$$

in which A''_{ki} = the new area LID type k from subcatchment i would have to mitigate the adverse runoff impacts.

Results and discussion

Optimal designs of the stormwater control measures for approaches A and B were obtained with the GA. The results for approach A are reported in Table 5, which show an increase in the total cost of runoff control by

Table 4 Sensitive subcatchments and LIDs

LID number	LID type	Subcatchment	Flood variation (%)
29	Porous pavement	15	7.7
30	Bio-retention cell	15	3.9
31	Porous pavement	16	21.9
32	Bio-retention cell	16	7.9
61	Porous pavement	31	22.2
62	Bio-retention cell	31	8.5

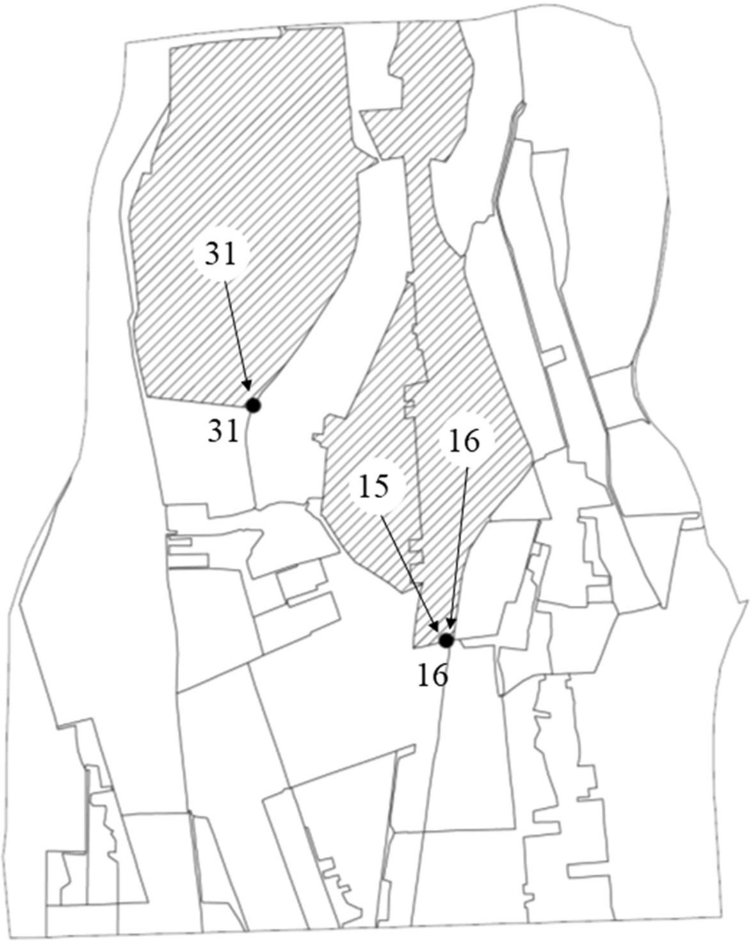


Fig. 6 Most sensitive subcatchments and their outlet nodes in the study area

20% and an increase of 22% in the areas dedicated to LID implementation. The GA found the optimal design for four among six optimizations. Replacement of LIDs number 31 and 61 was not feasible, and the GA could not solve for an optimal answer in this instance. The former two LIDs are porous pavements to be deployed in subcatchments 16 and 31. This would raise the sensitivity of the designed stormwater control system. Any

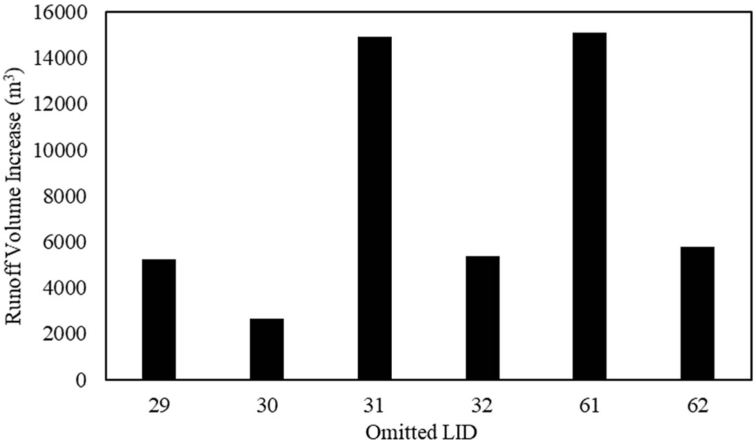


Fig. 7 Increase in total runoff volume due to omitting LIDs in the sensitive subcatchments

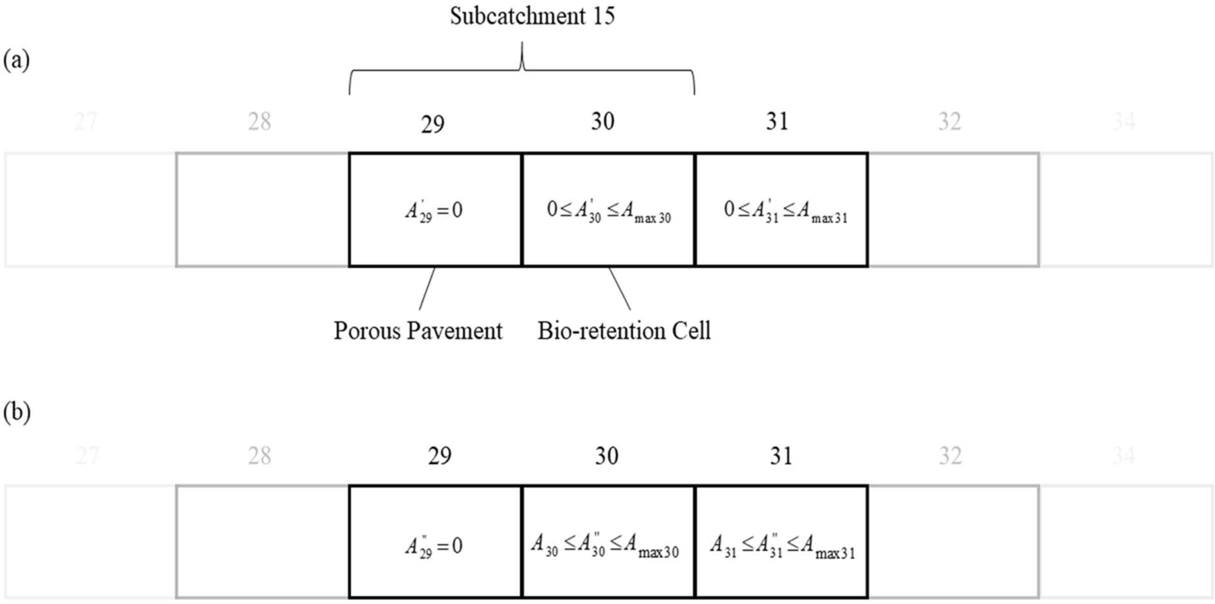


Fig. 8 Schematic of a solution associated with (**a**) scenario A and (**b**) scenario B

changes to these LIDs in the initial design or long-term developments in the subcatchments would have a large adverse impact on urban runoff in the catchment caused by the 25-year, 6-h rainfall. This in turn limits the ability to responds to future changes on the part of decision makers. By accepting a design with sensitive and unremovable units, it would be costly to modify these areas in the future. Also, the maintenance of these units is of utmost important because otherwise they may cause heavy damage to the catchment.

Approach B increases the areas of the designed and implemented LIDs such that would diminish the impact caused by omitting a LID from the runoff control system. The omission of sensitive LIDs could occur during future development in the catchment. The results for approach B are reported in Table 6. In this instance, the largest increases in LID areas and costs equal 43% and 45% for LID number 29, which also had the largest increase in approach A.

Figure 9a, b demonstrates the increase in costs and LID areas associated with approaches A and B, respectively. It is inferred from these figures that in order to avoid an 8.5% rise in total flood volume due to the omission of LID number 62, which is a bio-retention cell in subcatchment 31, using approach B would cause 38% and 36% increases in costs and LID areas, respectively. Whereas by applying approach A and adding 4% to the LID areas, the total costs would only raise for 10%. This means that by applying approach A, one can diminish the effects of an 8.5% rise in total flood volume and save 28% and 32% in costs and LID areas, respectively. By limiting the optimization model and through

Table 5 Choices obtained for approach A

Omitted LID	Choice	Increase in costs (%)	Increase in LID areas (%)
29	A1	20%	22%
30	A2	14%	14%
31*	–	–	–
32	A3	14%	12%
61*	–	–	–
62	A4	10%	4%

*Not feasible

Table 6 Choices obtained for approach B

Omitted LID	Choice	Increase in costs (%)	Increase in LID areas (%)
29	B1	45%	43%
30	B2	35%	35%
31*	–	–	–
32	B3	44%	43%
61*	–	–	–
62	B4	38%	36%

*Not feasible

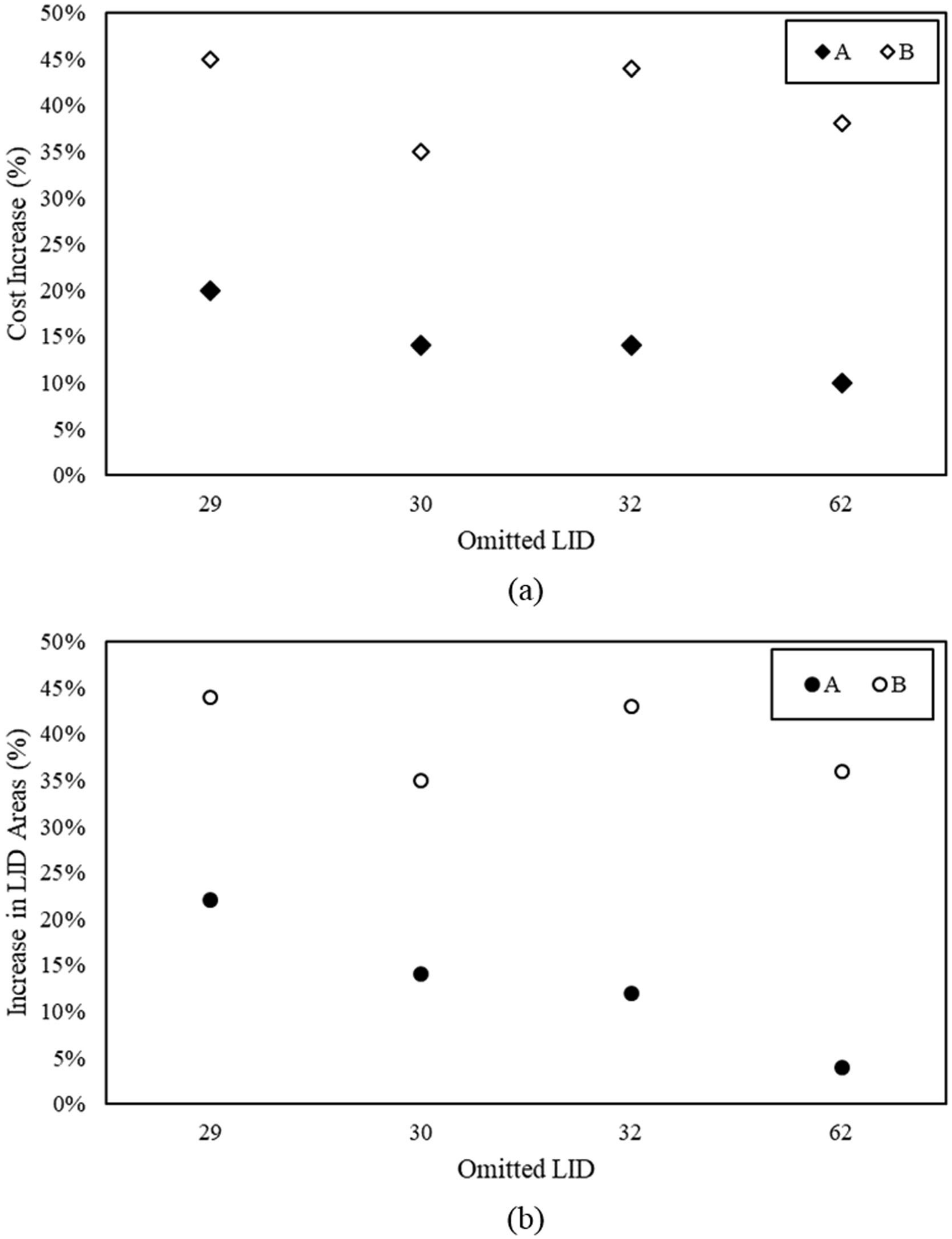


Fig. 9 The difference in (**a**) costs and (**b**) areas of LIDs associated with approaches A and B

reruns of the algorithm, it was possible to find alternative design models in which the algorithm did not focus on designs involving highly sensitive units. This means the newer designs would be more expensive than the optimal design without considering future development, but in the long run, they can assist decision makers avoid larger financial losses than those incurred with the optimal current design.

The GA searches for optimal selection of LIDs in other subcatchments to compensate for the omission of sensitive LIDs. Figure 10 shows the subcatchments that were chosen by GA to accommodate LIDs in approaches A and B. Before applying the approaches, GA chose to deploy more LIDs in subcatchments 15, 16, and 31, which are located upstream of the flooded nodes 16 and 31. After applying approaches A and B, the GA dedicated more LID areas to subcatchments 3, 9, 32, and 39. These subcatchments are located upstream of flooded nodes 10 and 41. Adding more LIDs upstream of node 10 would decrease the total flood volume at flooded nodes. However, flooded node number 36 is upstream of node 41, which means the GA has chosen LIDs in subcatchments upstream of this node to avoid flooding at node 36. These results indicate omitting a sensitive LID from the main runoff control design causes the GA to distribute runoff control among other subcatchments and LIDs, which, in turn, mitigates the effect one sensitive LID would have on the entire stormwater control system.

Concluding remarks

This paper presented a method for finding the most reliable system for stormwater control affected by uncertain future development in urban catchments. The method consists of a simulation–optimization model that couples the SWMM (simulation) with the GA (optimization) using MATLAB. The model finds the optimal design of LIDs necessary to decrease 50% of the total runoff volume in an urban catchment.

This study implements two approaches for optimization of LIDs in the catchment which are based on identifying the most sensitive LIDs for runoff control. Each approach redesigns the urban runoff control system such that the effects of sensitive LIDs are reduced by distributing the runoff control measures among other subcatchments within the study area. These approaches consider the probable omission of LIDs from the runoff control

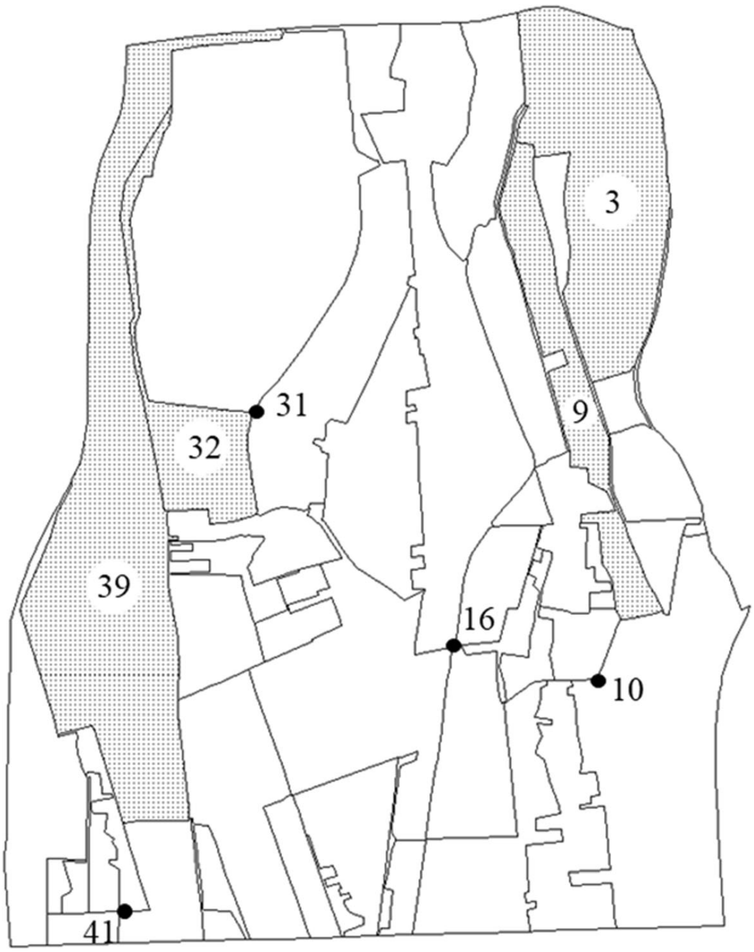


Fig. 10 Alternative subcatchments to deploy LIDs

system due to future development in the catchment and attempt to diminish the hydrologic effects of their removal by (a) redesigning the runoff control system such that the sensitive LIDs are omitted and the LIDs are distributed throughout the catchment and (b) increasing the area dedicated to the LIDs in the main design to mitigate the removal of sensitive LIDs.

The optimal solutions were obtained for four out of six LIDs, with two of them being impossible to remove from the designed system due to the infeasibility of the problem. Comparing the results from approach A with the main designed system shows that the maximum increase in redesigning the system, in a way that a sensitive LID which in case of omission increases the flood volume 7.7%, is equal to 20%. But this value is greater for approach B scenarios, where the increase in cost goes up to 45%. This means that replacing one LID can cause a lot more cost than just distributing it throughout the whole system. These results demonstrate the importance of investigating the sensitivity of designed units in a system and studying the trade-offs between different possible decisions that could be taken against the uncertainties in future developments and changes in the watershed. The sensitivity methodology used in this study can also be used in already designed stormwater systems. Identifying the sensitive units can assist designers to evaluate various stormwater management approaches based on conditions in the study area. This would assist decision makers making risk-free developments plans through understanding of the effectiveness of each designed element.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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