Evaluating the performance of low impact development practices in urban runoff mitigation through distributed and combined implementation

Sina Samouei and Mehmet Özger

ABSTRACT

Rapid urbanization and increasing impervious surfaces in cities lead to a serious reduction in infiltration rate of the surface and cause challenges in stormwater management. The Low Impact Development (LID) concept is considered as a potential solution for sustainable urban growth by contributing in urban flood mitigation. However, its effects on hydrologic response of the urbanized catchments, especially in broad scale implementation, are not fully understood and practically examined. In this study a hydrologic-hydraulic model of a small catchment was developed in EPA storm water management model (SWMM) program and calibrated and validated through field measurements. The hydrologic response of the catchment was investigated after replacing proportions of impervious surfaces with combinations of LID practices such as green roof, permeable pavement and bio-retention cell, through four land cover conversion scenarios and under five different designed storm events. The simulation results which are derived by comparison of outflow hydrographs between each scenario and conventional drainage system indicated that implementing 5–20% of LIDs has a noticeable impact on runoff peak flow and volume reduction, especially in storm events with shorter return periods. Also the runoff reduction trends show a linear response due to the increase in LID implementation ratio in the study area.

Key words | bio-retention cell, green roof, low impact development (LID), permeable pavement, storm water management model (SWMM), urban hydrology

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HIGHLIGHTS

- Developing a physically based hydrologic-hydraulic model for an urbanized catchment by using high resolution spatial data and a calibration process based on field measurements.
- Distributed and combined implementation of green roof, permeable pavement and bio-retention cell as three types of LID practices in the study area.
- Evaluating the performance of LID practices in a group, under different storm events and different implementation scenarios.
- Observing significant reductions in urban runoff peak and volume and flood risk as simulation results.

INTRODUCTION

The rapid expansion of cities and urban areas, especially during the last centuries and decades, is an inevitable response to the population growth occurring all over the world. The ratio of population living in the cities has risen from 30% in 1950 to 50% nowadays and will increase to 80% by the end of 2050 (Bettencourt & West 2010).

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Urbanization may cause some positive effects on the living conditions and welfare of the population at the first look, but also has some disadvantages and side effects. By expansion of the cities, more impervious surfaces have been replaced with natural and pervious surfaces like pastures, forests, wetlands, etc. This modification on the ground surface drastically disrupts the hydrologic response of the region and its natural flow regime (Leopold 1968; Poff *et al.* 1997).

Surface runoff in urban areas is generally conducted by hydraulically connected impervious areas to drainage system inlet points. These types of surfaces, which are known as effective impervious areas (EIA), have a major contribution in increasing the urban runoff volume and rate (Shuster *et al.* 2005; Sankalp & Sahoo 2018). Flash floods, which are considered as one of the outcomes of high intensity and short duration rainfalls, occur because of infiltration excess mechanisms in the soil (Vojinovic & Abbott 2012). Growing EIA in urban areas, which is accompanied by reducing the limited pervious surfaces, will facilitate the occurrence of these kind of floods which have higher volume and velocity and shorter concentration time in urban areas (Ahiablame & Shakya 2016; Wang *et al.* 2017a, 2017b).

As a conventional response to this challenge in urban areas, a complex infrastructure system which acts as a centralized and single oriented approach in flood management and is known as grey infrastructure is presented (Alves *et al.* 2018). Some components of this system include channels, ducts, pipelines, manholes, etc. Although grey infrastructure has been widely preferred by decision makers in urban planning due to their high conveyance capacities, this solution seems to be unsustainable due to the continuous urban growth and is incompatible with increasing rainfall intensities through climate change (Hanak & Lund 2012; Dong *et al.* 2017). On the contrary, a sustainable urban infrastructure system is supposed to meet the presently expected functionality and be adaptive to future uncertainties. So there is an increasing need for more sustainable solutions in urban runoff management (Qin *et al.* 2013; Kong *et al.* 2017).

By considering sustainability in urban growth and in the context of hydro-meteorological risk reduction, various stormwater management strategies have been developed and implemented to date in some countries and regions and have been cited in scientific literature (Debele *et al.* 2019; Ruangpan *et al.* 2020) such as: Low Impact Development (LID) and Best Management Practices (BMP) in US (USEPA 2000; Liu *et al.* 2016), Water Sensitive Urban Design (WSUD) in Australia (Zimmer *et al.* 2007), Green Infrastructure (GI) in US and UK (Naumann *et al.* 2011), Sustainable Drainage Systems (SuDS) in UK (Scholz & Grabowiecki 2007), Nature-based Solutions (NBS) in Europe (European Commission 2015; Nesshöver *et al.* 2017), Ecosystem-based Adaptation (EbA) in Canada and Europe (CBD 2009) and sponge cities in China (Li *et al.* 2017). All of these methods and strategies are based on reducing EIA from urban areas and replacing them with more natural structures in order to increase surface permeability and retention capacity.

LID strategies have been presented as one of the probable alternative approaches to conventional drainage systems in urban storm water management (Kong *et al.* 2017). This approach tries to rebuild the pre-development condition of the ground by disconnecting or reducing large EIAs in the urban areas and giving back some of the soil and surface critical characteristics such as infiltration, evaporation and retention capacities (Dietz 2007; Epps & Hathaway 2019). Among various types of LID practices, green roofs, permeable pavements and bio-retention cells have been considered as the most effective approaches in urban runoff mitigation (Qin *et al.* 2013; Randhir & Raposa 2014; Eckart *et al.* 2017). The main concern in the utilization of LIDs and examining their performance is how to model them regarding highly complex drainage and sewer systems in urban areas and different interactions between water movements and urban facilities and components (Kaykhosravi *et al.* 2018).

Among various hydrological models which have been developed for urban runoff management purposes such as Storm Water Management Model (SWMM), Model for Urban Sewer (MOUSE), Soil Water Assessment Tool (SWAT) and Soil Conservation Service (SCS) (Mishra & Singh 2003; Douglas-Mankin *et al.* 2010; Rossman 2010), SWMM has shown the highest suitability for hydrological modeling in urban areas, especially in the case of different land cover variation, LID implementations, flood depth determination in specific points, adaptive sub-catchment delineation and obtaining time varying hydrologic results

(Bosley 2008; Wang & Altunkaynak 2012; Kong *et al.* 2017; Gülbaz *et al.* 2019; Niemi *et al.* 2019).

Numerous studies have been carried out to investigate the effectiveness of LID strategies on urban runoff reduction. Dietz (2007) stated that a green roof has the capacity for precipitation retention up to 60–70% in comparison with a conventional rooftop by carrying out research on the retention performance of green roofs in different locations. Palla & Gnecco (2015) reported that by replacing up to 36% of EIA, which corresponds to all rooftops and parking lot areas in a small urbanized area, with two types of LID source control elements such as green roof and permeable pavement, runoff peak flow and volume will decrease respectively up to 45 and 23% in an urbanized catchment. Qin *et al.* (2013) investigated the reduction in flood volume in the case of implementing three types of LIDs including green roof, permeable pavements and swales under different rainfall characteristics. Although they used three different types of LIDs in their study, the implementation scenarios were based on using a single type of mentioned LID with a constant implementation ratio within the catchment area in each try. They noticed that although these LIDs have a significant impact on runoff volume reduction, their performance is also related to the storm event characteristics. Miao *et al.* (2019) and Bae & Lee (2020) indicated that although implementation of LID control elements such as rain barrels, rain gardens and swales have significant impacts on runoff peak flow reduction and peak flow delay in urban areas, still it is not as much as the pre-development condition and may not prevent the occurrence of flooding.

In the majority of performed researches for investigating the hydrologic impacts of LID practices in urban areas, the implementation scenarios are based on replacing a constant or specific proportion of existing impervious surfaces with LIDs, i.e. all or half of the total conventional roof tops or parking lots with green roofs or permeable pavements, without considering the real condition of the site for applicability of these LID practices or without prioritizing the locations of implementations. However, in some urbanized catchments it is impossible to apply green roofs for all rooftop areas or similarly replace all roads and parking lots with permeable pavements. This perspective seems to be exaggerated and far from reality. Also, without site dependent application of LID practices it is highly probable that these practices will be subjected to malfunctions such as early filling of their retention capacity or not operating in full capacity which in return will affect the study results in a negative way.

In this study, a hydrologic-hydraulic model was developed for investigating the effects of LID implementations on the hydrologic response of a traditionally developed area in the city catchment scale. For this purpose, Istanbul Technical University's main campus was selected as the case study area. The hydrologic-hydraulic model of the study area, which was developed in EPA SWMM 5.1 program, is based on high resolution spatial data which is obtained by a construction plan of the university campus and GIS based data. Focusing on the comparison of runoff peak flow and runoff volume values in simulations, the hydrologic response of the study area for different land cover conversion scenarios and different storm events was investigated in this study. The aims of this study are as follows: (1) creating a hydrologic-hydraulic model of the study area, calibrating and validating via field measurements and integrated simulations; (2) investigating the change in runoff peak flow and runoff volume at the study area after implementing a combination of LIDs including green roofs, permeable pavements and bio-retention cells through four impervious area replacement scenarios of 5, 10, 15 and 20%; (3) evaluating the performance of these implemented LID combinations in simulation with five different synthetic storm events corresponding to return periods of 2, 5, 10, 25 and 50 years; (4) obtaining the potential relationship between the LID implementation ratios and the hydrologic response of the catchment for each storm event. The present study attempted to design LID implementation scenarios based on the real condition of the study area and according to the applicability of roof tops and availability of parking lots to reach reliable results. Additional to the applicability, the priority in implementation of LIDs was given to the subcatchments that had the highest contribution in producing surface runoff due to their higher ratio of imperviousness. Furthermore, a combination of green roofs, permeable pavements and bio-retention cells were used at the same time within each scenario to create an environment to assess their performance simultaneously in a group.

The study results aim to assist decision makers in urban planning, disaster management and related areas to manage and mitigate storm waters in a more sustainable way and also to help fill the gap between mathematical modeling and socio-environmental, socio-technical concerns in water-related problems and to be in compliance with the holistic concept of hydroinformatics (Abbott 1991; Abbott & Vojinovic 2009).

MATERIALS AND METHODS

Site description

As shown in Figure 1, Istanbul Technical University's main campus was selected for investigating the changes in hydrologic response of the catchment due to the LID implementation scenarios under different designed storm events.

As a small city catchment, the university campus is located at the European side of Istanbul province in Turkey (41°05′–41°06′N, 29°00′–29°02′E). The study area has a Mediterranean climate with a mean annual temperature of 14.4 °C and an average annual precipitation of 814.4 mm. The soil type of the study area is mainly categorized as sandy clay. According to the university authorities, there have been two flood events that occurred in the years 2009 and 2011 which caused damage to the buildings and faculties in the central and southern parts of the campus. Despite the damage being mostly negligible, it demonstrated that the traditional drainage system of the university campus may be inadequate in the case of storm events with accumulated precipitation higher than 50 mm. Additional to the statement of authorities and in compliance with them, Samouei & Özger (2020), by developing an inundation model of the study area, reported that in the case of a storm event with a return period of 25 years and accumulated precipitation of 57.9 mm, there will be local inundations mostly at the central parts of the university campus. The university campus has a total area of 106 ha consisting of 54% pervious and 46% impervious surfaces. A high resolution land cover map of the study area was created by using the planning map in CAD format and aerial photo of the campus together in Arc GIS program. The study area was divided into nine different land cover types including roads, buildings, parking lots, stony surfaces, cobblestone surfaces, water bodies, lawns, moderately wooded areas and wooded areas. Figure 2(a) shows the land cover map of the study area. Table 1

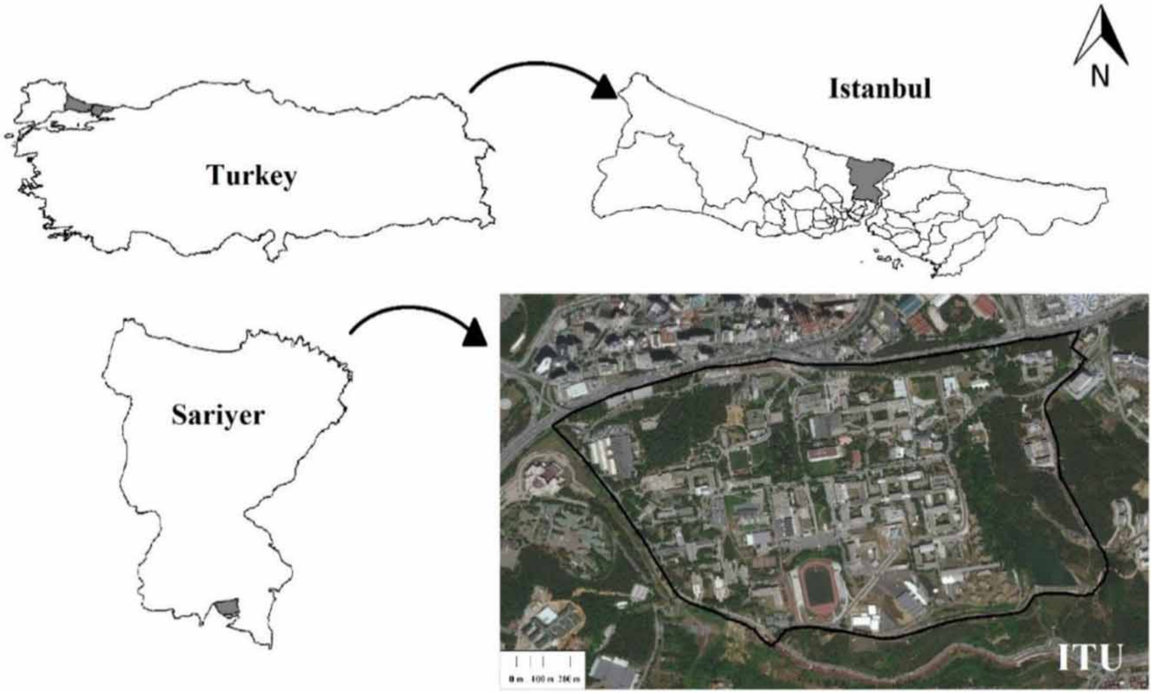

Figure 1 | Location of the study area.

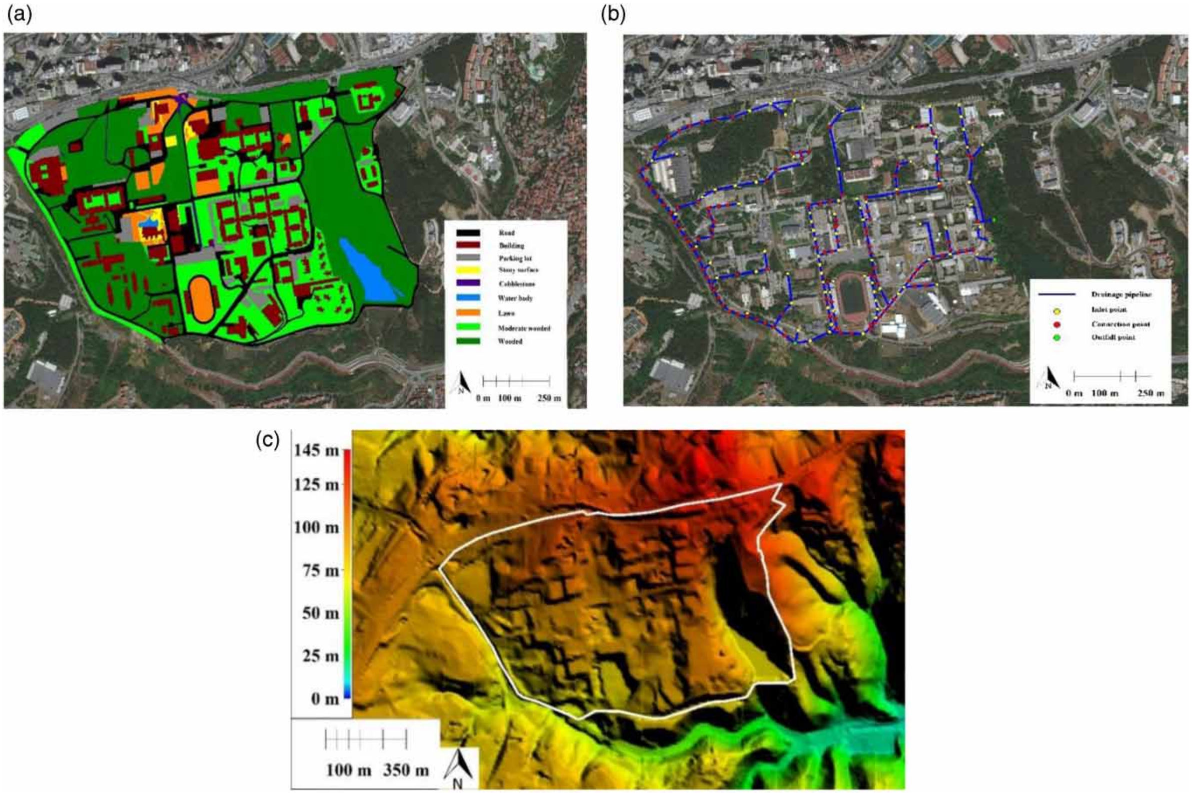

Figure 2 | (a) Land cover map of the study area; (b) drainage system of the study area; (c) DEM of the study area.

Table 1 | Land cover characteristics of the study area

	Area	
Land Cover	**(ha)**	**%**
Road	17.45	17
Building	16.97	15
Parking lot	5.45	5.2
Stony surface	0.9	1.5
Cobblestone	0.5	1.1
Water body	2.08	2
Lawn	4.06	3.87
Moderate wooded	22.82	21.33
Wooded	35.14	33

shows the occupied area and percentages of different land cover types of the study area.

The university campus infrastructure facilities include separate drainage and sewer systems which have been constructed by binary pipelines. Stormwater management is addressed with a traditional drainage system constructed by pipes with circular cross-sections and diameters of 0.3–0.6 m. The main outfall point of the drainage system is located in the south of study area. Also, there are three derivative outfall points in the east side of the study area where their drained water deposits at the site and does not leave the catchment. Conducted drained water after reaching the main outfall point will be directed to release into the Marmara Sea at Bosporus. Figure 2(b) shows the different components of the drainage system including pipeline, inlet points, connection points and outfall points.

A digital elevation model (DEM) of the study area with resolution of 5×5 m has shown that the general slope of area is equal to 4.1% and is toward the south of the campus. The elevation of the highest and lowest points of the area were obtained respectively as 135 and 62 m above sea level. Figure 2(c) shows the DEM of the study area.

The EPA SWMM model

In this study EPA Storm Water Management Model (SWMM) Version 5.1, which provides a module for LID controls design and implementation, was used for model development and implementation of LIDs during land cover conversion scenarios. SWMM is a dynamic rainfall-runoff model for simulating and analyzing the quality and quantity of runoff, generally in urban environments. Some of the main components of a hydrologic-hydraulic model in SWMM and their functions are: rain gauge for providing the rainfall data, sub-catchment for illustrating a divided part of surface with predetermined physical parameters and for conducting surface water to a specified outlet point, junctions for connecting conduits and drainage system inflow points and conduits for conducting water in a conveyance system (Rossman 2010).

In the present study, a nonlinear reservoir model was used for calculating the surface runoff. Additionally, a dynamic wave routing method was selected for the flow routing process in conduits and also a modified Green Ampt method was employed for infiltration calculations.

Sub-catchment discretization was carried out by using DEM of the study area and by considering the flow directions and elevation analysis. The Arc GIS program was used for topographic analysis. In addition to DEM of the study area, land cover map and locations of the drainage system inlet points were used in the sub-catchments boundary delineation process. Further field observations and controls were also carried out for ensuring the site condition and accuracy of the sub-catchment's discretization. Finally, the study area was divided into 77 sub-catchments.

Characteristics of the drainage system, including locations of manholes and outlet points, length and diameter of the pipes, slope and invert elevations, were obtained by using the university campus infrastructure map and DEM of the study area. Also, field observations were performed for ensuring the accuracy of the drainage system nodes locations and their conditions. The SWMM model of the study area consists of 197 conduits, 196 junction nodes and four outlet nodes. Figure 3 shows the SWMM model of the study area.

LID controls in SWMM are presented as a combination of several vertical layers such as surface, soil, storage and drain with specific characteristics for each layer like berm height, vegetation volume, surface roughness and slope, thickness, soil porosity and conductivity. LID controls in SWMM are applicable on an area basis. Moisture balance can track the amount of moisture moving and storing between layers and within each LID control element (Rossman 2010).

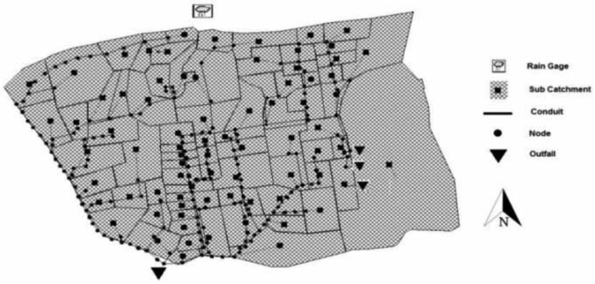

Figure 3 | SWMM model of the study area.

In this study green roof, permeable pavement and bio-retention cells were used as three types of LID source control components in combination with each other in the sub-catchments during land cover conversion scenarios. Some of the design characteristics such as berm height, vegetation fraction and layer thickness are according to the recommended values in SWMM user's manual (Rossman 2010) and relevant literature for the model (Zhang & Guo 2015; Kong *et al.* 2017). Other parameters related to the soil and storage layers like porosity, seepage rate, etc., belong to the available materials at the site for LID applications. Figure 4 shows the figurative structure of these three LID elements and Table 2 shows some of the structural parameters of them in the SWMM model.

LID implementation scenarios

The mainly considered issues in LID design are their type, surface area and location of implementations (Martin-Mikle *et al.* 2015). In this study, three types of LID source control elements including green roof, permeable pavement and bio-retention cell were considered for implementation in the study area under four different land cover conversion ratios. The implementation ratios are 5, 10, 15 and 20% which will be replaced with the existing impervious areas of the catchment. Each LID element is supposed to occupy a specific percentage of total replacement ratio according to the available space and the applicability within each sub-catchment. Additionally, it is attempted to give priority in assigning an area for LID

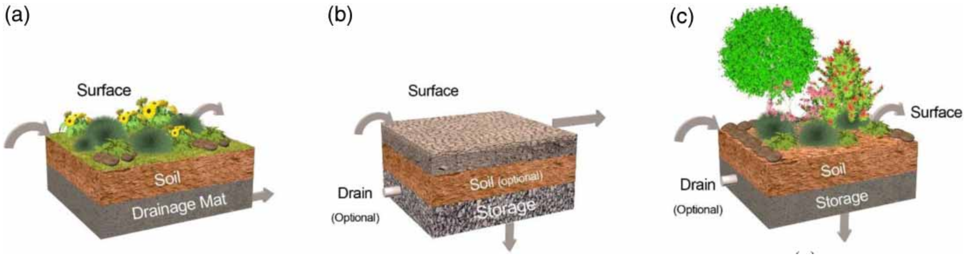

Figure 4 | Structural scheme of: (a) green roof; (b) permeable pavement; (c) bio-retention cell.

Table 2 | Structural parameters of LID components

	Bio-Ret cell			**Permeable pavement**				**Green roof**		
Parameter	**Surface**	**Soil**	**Storage**	**Surface**	**Pavement**	**Soil**	**Storage**	**Surface**	**Soil**	**Drainage mat**
Berm height (mm)	200	–	–	–	–	–	–	–	–	–
Vegetation (Fraction)	0.2	–	–	–	–	–	–	0.2	–	–
Roughness (Manning's N)	0	–	–	0.04	–	–	–	0.4	–	0.1
Thickness (mm)	–	800	450	–	100	450	450	–	150	25.4
Porosity	–	0.45	–	–	–	0.45	–	–	0.45	–
Field capacity	–	0.19	–	–	–	0.19	–	–	0.19	–
Wilting point	–	0.085	–	–	–	0.085	–	–	0.085	–
Void ratio	–	–	0.75	–	0.15	–	0.75	–	–	0.5
Seepage rate (mm/hr)	–	–	0.508	–	–	–	0.508	–	–	–

applications based on the ratio of imperviousness in current condition of each sub-catchment. Thus the higher impervious ratio of a sub-catchment means the higher assigned area for surface replacement.

For green roofs, buildings with large and flat rooftops were selected for implementations. Two types of green roof units with 3 and 2 m^2 surface area were modelled in SWMM and then applied to the roof tops until the total occupied area was considered for green roofs inside each sub-catchment in each scenario. Permeable pavement units were generally implemented in parking lots and areas where cars and vehicles move slowly. Each permeable pavement unit was designed to fill the total area of each parking lot located inside each sub-catchment. Finally, bio-retention cells were implemented in relatively small sub-catchments and generally the ones which are not suitable for green roof and permeable pavement implementations. Similar to permeable pavement, each bio-retention cell unit was designed to occupy the total assigned area inside each sub-catchment. This process continued by adding new LID units to create higher land cover replacement ratios.

The existing and current condition of the study area without any LID implementations is considered as the reference condition for the LID impact comparisons. The area and percentage of each type of LIDs that was used through land cover conversion scenarios are presented in Table 3.

Figure 5 shows the sub-catchments scheme of the study area with the corresponding LID types implemented within each land cover conversion scenario. The identified sub-catchments only imply the location of each LID type and do not indicate the occupied area by LID.

Design storm events

Five synthetic storm events were designed based on IDF (Intensity-Duration-Frequency) curves for the 'Sariyer' district of Istanbul, where the study area is located. The hyetographs of designed storm events were computed by

Table 3 | Area and percentage of each LID type in corresponding land cover conversion scenario

	Green roof		**Permeable pavement**		**Bio-retention cell**		**Total**	
	Area (m^2)	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**
S1	5,510	1.13	17,748	3.64	1,121	0.23	24,379	5
S2	21,113	4.33	26,233	5.38	1,414	0.29	48,760	10
S3	30,475	6.25	40,860	8.38	1,804	0.37	73,139	15
S4	44,176	9.06	50,223	10.3	3,120	0.64	97,519	20

Note: S1, S2, S3 and S4 = LID implementation ratios respectively equal to 5, 10, 15 and 20%.

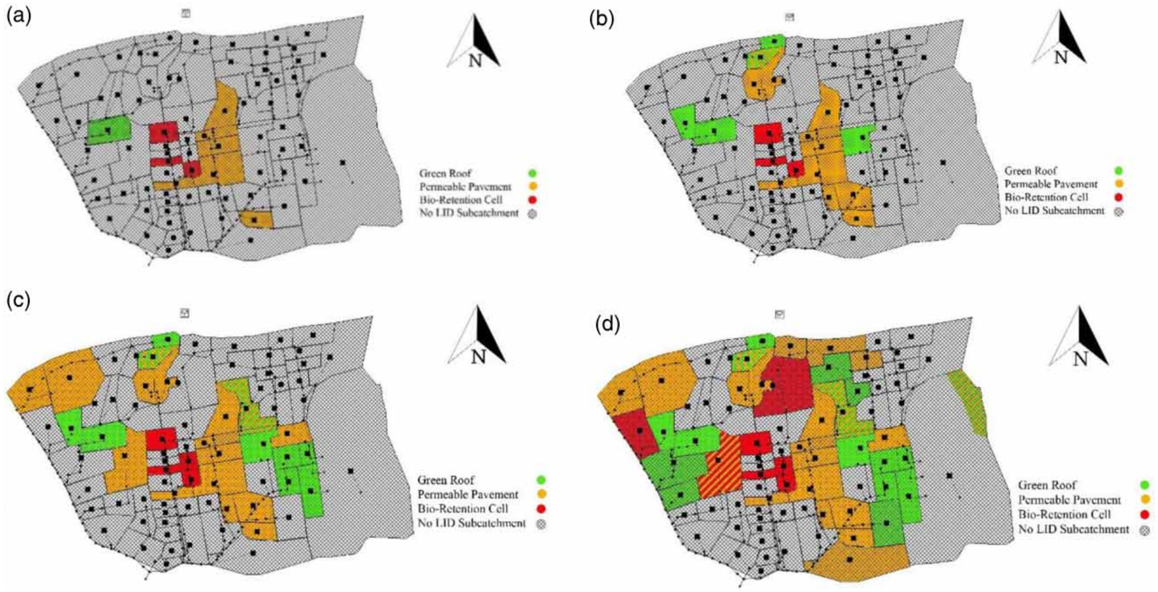

Figure 5 | LID implementation locations within each sub-catchment: (a) 5% LID implementation; (b) 10% LID implementation; (c) 15% LID implementation; (d) 20% LID implementation.

using the IDF curves for storms with return periods of 2, 5, 10, 25 and 50 years with a duration of 2 hours and according to the Chicago storm profile (Keifer & Chu 1957). Time to peak ratio in these storm events was assumed as 0.5.

These storm events were designed and applied to the model to compare the hydrologic response of the altered study area after implementing different LID replacement ratios with each other and with the original condition of the study area.

Figure 6 presents the hyetographs of storm events which were designed for inputting to the model as rainfall data.

Model calibration and validation

To test the accuracy of the results, model calibration and validation was carried out based on field measurements and a series of simulations. A rainfall event with a duration of 5 hours (10:45–15:45) was used for model calibration. The precipitation was recorded at 15 minute intervals with a rain gauge at the study area. Simultaneously, the water depth of the main manhole in the south of the study area was measured at the same time intervals. For the mentioned rainfall event, the accumulated precipitation was recorded as 3.15 mm. The same rainfall event then was input to the SWMM model and after running the model, the water depth for that specific manhole was obtained at 15 minute intervals. For comparing the measured and simulated values of water depth in the manhole, the root mean square error (RMSE) method was used. Furthermore, for quantitatively testing the model accuracy in reproducing the time-related water depth in the manhole, the Nash–Sutcliffe Efficiency index (NSE)

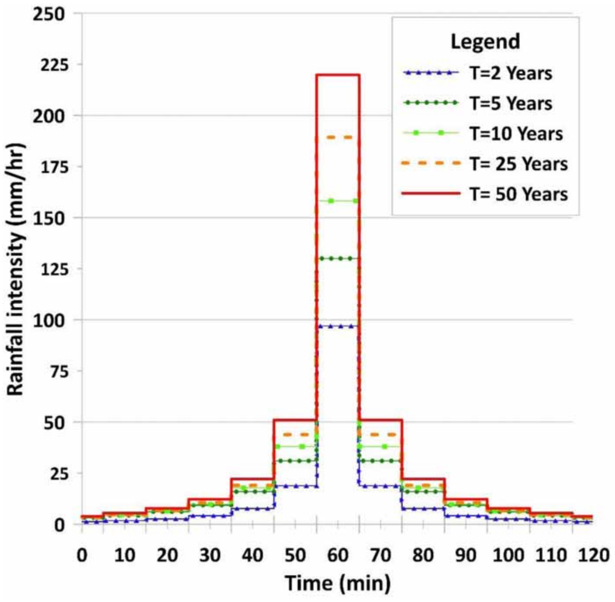

Figure 6 | Designed storms hyetographs based on the Chicago method.

was evaluated (Nash & Sutcliffe 1970). The NSE index is widely used and well accepted in hydrology because of its flexibility in application in various types of mathematical models (McCuen *et al.* 2006; Gupta & Kling 2011):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (Vi - Wi)^2}{n}}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Vi - Wi)^2}{\sum_{i=1}^{n} (Vi - \overline{Vi})^2}$$

where V_i and $\overline{Vi}$ are measured and average measured values for the water depth in the manhole respectively, W_i is the simulated value for water depth in the manhole at time ? and n is the number of measured time steps. By altering some of the soil and surface main parameters and series of simulations, it is attempted to reduce the RMSE value for the model. Table 4 shows some of the calibrated values of the soil and surface parameters.

The RMSE value for the measured and simulated water depth in the manhole after the calibration process was obtained as 10.35 mm. A normalized RMSE value was also obtained as 0.14, which shows there is a good agreement between the measured and simulated values. The NSE value for the calibration process was obtained as 0.97, which indicates that the model is capable of reproducing acceptable values for the water depth in the manhole (Ritter & Muñoz-Carpena 2013).

Table 4 | Calibrated values of soil and surface parameters

Parameters	Soil	Surface
Hydraulic conductivity (K) (mm/h)	0.5	–
Suction head (Su) (mm)	240	–
Porosity (fraction)	0.43	–
Manning's roughness coefficient for impervious surfaces (concrete, asphalt)	–	0.012
Manning's roughness coefficient for pervious areas (lawn)	–	0.2
Manning's roughness coefficient for pervious areas (wooded)	–	0.3–0.6
Depression storage for impervious surfaces (mm)	–	1.2–2
Depression storage for pervious surfaces (mm)	–	6–10

Another rainfall event with a duration of 3 hours (13:15–16:15) and accumulated precipitation equal to 4.5 mm was used for model validation. Precipitation at the study area and water depth at the same manhole was measured and recorded at 15 minute intervals. The observed rainfall event was then simulated in the SWMM model of the study area and water depths of the same manhole obtained at 15 minute intervals. The RMSE and NRMSE values for the validation process were obtained as 27.33 and 0.22 mm respectively. Also, the NSE value for the validation process was obtained as 0.71 which guarantees the validity of the model results. By calculating the flow rates based on the manhole section dimensions and water depths at the manhole, relative errors of flow rates were obtained ranging from 4 to 22% and the relative error of peak flow was obtained as 17%.

Figure 7 shows the values of measured rainfall (mm/hr), measured water depth at the manhole (mm) and simulated water depth for the same manhole in the calibration (a) and validation (b) process of the SWMM model.

RESULTS AND DISCUSSION

The SWMM model simulation results are based on obtaining outflow hydrographs of the study area after LID

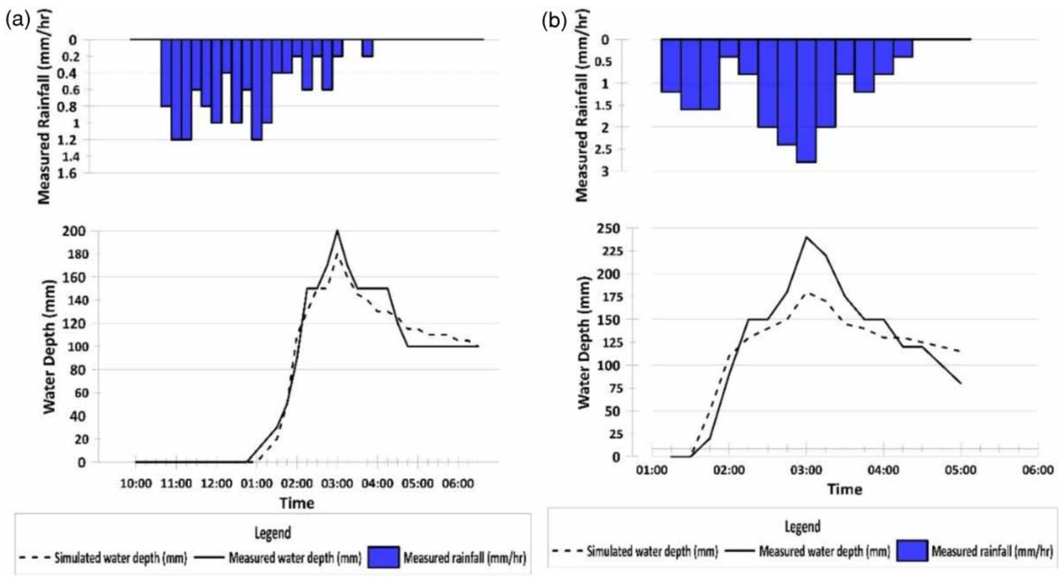

Figure 7 | Measured rainfall (mm/hr), measured water depth at the manhole (mm) and simulated water depth at the manhole (mm) in the SWMM model in the calibration (a) and validation (b) process.

implementation scenarios and for each designed storm event. The obtained outflow hydrographs are then compared with the base case condition of the study area without any LID to evaluate the change rate in runoff characteristics such as peak flow and total volume. The research results imply that the base case condition of the study area has the highest values of runoff peak flow and runoff volume compared to the other land cover conversion scenarios with LID. According to the results, in simulation of the base case condition for the designed storm events with $T = 2$, $T = 5$, $T = 10$, $T = 25$ and $T = 50$ years, runoff peak flow was obtained respectively as 13.14, 16.56, 25.51, 31.73 and 38.26 m^3/s and runoff volume obtained as 18,309, 31,834, 42,613, 51,462 and 61,851 m^3. However, after the application of LIDs in the model, significant reductions were observed in runoff peak flow and volume.

Figure 8 shows the hydrologic response of the catchment for each designed storm event and each applied LID ratio.

As shown in Figure 8, in simulation with a particular storm event, increasing the LID implementation percentage will cause obvious changes in order to diminish the runoff characteristics such as peak flow and runoff volume in the study area. Particularly in the initial portion of the hydrographs, the rising limb tends to have a more gentle slope compared to the base case condition. Additionally, peak flow rate and runoff volume are both decreased after an increase in the LID implementation percentages.

Table 5 presents the reduction percentages in peak runoff and Table 6 shows the reduction percentages in runoff volume after each LID implementing scenario and for each storm event, compared to the base case.

According to the reduction rates that are presented in Tables 5 and 6, by replacing the existing impervious surface of the study area with a combination of LID elements such as green roof, permeable pavement and bio-retention cell, there will be a noticeable amount of reduction both in peak runoff and runoff volume, especially in storm events with shorter return periods. This reduction rate will increase by implementing higher percentages of LIDs at the catchment. For example, in simulation with storm events corresponding to a two-year return period, the peak runoff reduction rate will increase from 6.77 to 24.73% and the runoff volume reduction rate will increase from 5.05 to 16.97% as LID implementation ratios increase from 5 to 20%.

The obtained results also indicated that the reduction percentages of runoff peak flow and runoff volume are linearly correlated with an increase in LID implementation ratio for each designed storm event. The linear relationship between hydrologic performance of the catchment and

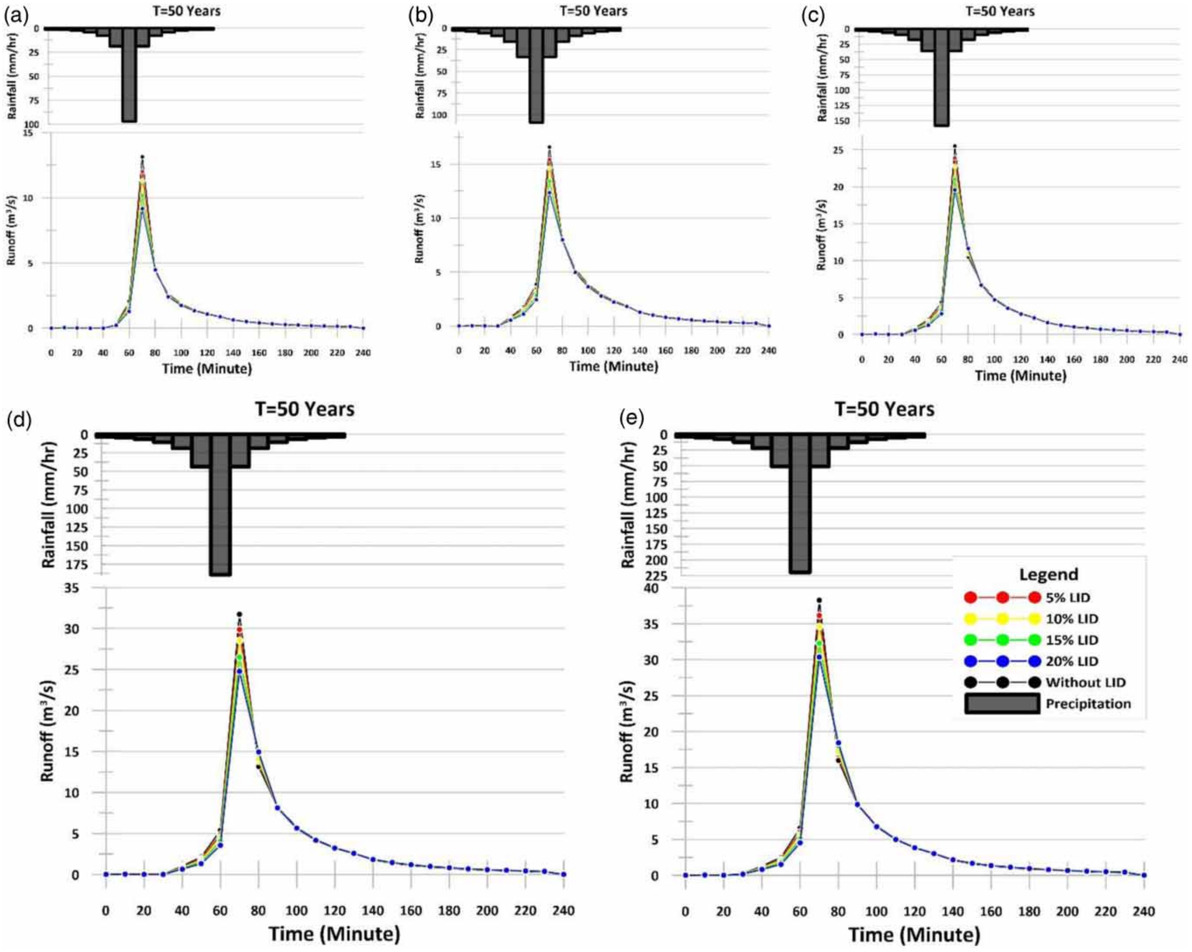

Figure 8 | Hydrologic response of the catchment under land cover conversion scenarios and for each storm event. T = 2 years (a), T = 5 years (b), T = 10 years (c), T = 25 years (d), and T = 50 years (e).

Table 5 | Reduction percentages of peak runoff for each LID implementation scenarios and for each storm event (T = 2, 5, 10, 25 and 50 years)

	Runoff peak reduction			
	5% LID	**10% LID**	**15% LID**	**20% LID**
T = 2 years	6.77	11.79	18.49	24.73
T = 5 years	5.22	9.40	15.29	20.67
T = 10 years	4.22	7.82	12.13	16.24
T = 25 years	3.40	6.68	10.24	13.96
T = 50 years	2.74	5.64	8.60	11.97

Table 6 | Reduction percentages of runoff volume for each LID implementation scenarios and for each storm event (T = 2, 5, 10, 25 and 50 years)

	Runoff volume reduction			
	5% LID	**10% LID**	**15% LID**	**20% LID**
T = 2 years	5.05	7.86	12.52	16.97
T = 5 years	4.10	6.40	10.22	13.72
T = 10 years	3.57	5.55	8.80	11.70
T = 25 years	3.19	4.96	7.84	10.39
T = 50 years	2.89	4.50	7.04	9.32

increase in LID implementation ratio or increase in pervious surface ratio is consistent with previous studies (Kleidorfer *et al.* 2014; Palla & Gnecco 2015). However, this study's results have shown generally higher reduction rates for each specific implementation ratio. Additional to differences in structural design, this can also be a result of site dependent and distributed application of different LID types within the catchment.

Compared to the runoff volume reduction, reduction in peak runoff is more affected by the LID implementation ratio. This is because the reduction rates in runoff peak flow and runoff volume are respectively related to the detention and retention characteristics of the implemented LID types. Dependency of LIDs performance to their physical structure, like effective storage capacity, void ratio etc., is also confirmed by Qin *et al.* (2013).

To investigate the effects of rainfall characteristics on the performance of LIDs in the catchment's hydrologic response, model simulation results were achieved for five different designed storm events corresponding to the return periods of 2, 5, 10, 25 and 50 years. As demonstrated in Tables 5 and 6 by simulating a storm event with a longer return period and higher intensity, the efficiency of LID practices in runoff peak flow and volume reduction will decrease. For instance, the peak runoff reduction rate will decrease from 24.73 to 11.97% and also the runoff volume reduction rate will reduce from 16.97 to 9.32% in the case of 20% LID implementation for the storm events corresponding to the return periods of 2 and 50 years, respectively. This is mainly because of the limited retention capacity of LIDs which cause early saturation when receiving high amounts of rainfall and accompanied by overflow from the LID units. Similar reductions in LID performance against an increase in rainfall event return period was observed by Miao *et al.* (2019).

In drainage system assessments of the study area it was also observed that in peak runoff moment of the simulations for the storm events with $T = 25$ and $T = 50$ there will be inundation and pressurized flow in manholes and conduits of the study area in the base case condition without LID implementations. However, after LID implementation, the number of inundated manholes and conduits with both ends full reduced with a minimum reduction rate of 5% in LID implementation ratio equal to 5% and a maximum of 18% in LID implementation ratio equal to 20% in simulation with storm event corresponding to $T = 25$ years. For a storm event with $T = 50$ years, these reduction rates were obtained as a minimum of 3% in LID implementation ratio equal to 5% and maximum of 11% in LID implementation ratio equal to 20%.

Although the observed results do not imply complete prevention in flooding occurrence, they do show a reduction in the number of flooded manholes and an increase in functionality of the conveyance system at the catchment. Further investigations are needed to reach higher reduction rates in runoff characteristics or flooding by using LID practices in urban areas.

These results also indicate that LID implementations will assist the infrastructure system of an urbanized catchment in order to reach the expected safety, resiliency and sustainability, which are defined as the infrastructure system's service stability in its designed life time in the case of standard loading conditions, exceptional loading conditions and for long-term duration (Butler *et al.* 2014, 2017; Sweetapple *et al.* 2018).

CONCLUSIONS

In this study the hydrological response of a traditionally developed catchment on a city catchment scale was investigated by considering four different land cover conversion scenarios based on implementing LID practices and five designed storm events. For this purpose, Istanbul Technical University main campus with an area of 106 ha was divided into 77 sub-catchments and was modeled in an SWMM program. The conceptual approach of this study is based on obtaining and comparing the outflow hydrographs of the catchment after implementing a combination of three types of LIDs including green roof, permeable pavement and bio-retention cell in the study area with the base case condition without LID implementations.

The main strategy for implementations was through conversion of 5, 10, 15 and 20% of the impervious surfaces according to the applicability conditions and priority, inside each sub-catchment. Each LID implementation scenario was simulated under five designed storm events corresponding to the return periods of 2, 5, 10, 25 and 50 years.

The main results of this analysis are summarized below:

- Maximum runoff reduction was observed in simulations with a storm event corresponding to $T = 2$ years. By increasing the LID implementation ratio from 5 to 20% the reduction rates of runoff peak flow and runoff volume will increase from 6.77 to 24.73% and from 5.05 to 16.97% respectively.

- Maximum reduction rates in peak runoff and runoff volume were observed in the 20% LID implementation scenario. Increasing the storm event's return period from 2 to 50 years results in a decay of the peak runoff reduction rate from 24.73 to 11.97% and runoff volume reduction rate from 16.97 to 9.32%.
- Runoff peak flow and runoff volume reduction trends indicated that for each storm event, hydrologic resiliency of the catchment increases according to a linear relationship with an increase in LID implementation ratio.
- With an LID implementation ratio of 5–20% the number of inundated manholes and both end full conduits was reduced with a minimum of 5% (for 5% LID) and maximum of 18% (for 20% LID) in simulation with T = 25 and with a minimum of 3% (for 5% LID) and maximum of 11% (for 20% LID) in simulation with T = 50 years.

The simulation results of this SWMM model confirmed that implementing a combination of LIDs in the urban areas by considering the proper LID types and distributed implementations will lead to a noticeable decrease in runoff characteristics, especially in storm events with shorter return periods, and will facilitate the runoff mitigation in urban areas and reduce the need for drainage system expansion or renewal operations.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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