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Surface runoff and pollutant load response to urbanization, climate variability, and low impact developments – a case study

Mohammad Nazari-Sharabian, Masoud Taheriyoun and Moses Karakouzian

ABSTRACT

Using the Storm Water Management Model (SWMM), this study evaluated the impacts of (a) 20% and 50% urbanization at the mountainous Mahabad Dam watershed in Iran, as probable future land developments, (b) the urbanization location (near the outlet, in the middle, and at the far end of the watershed), (c) climate variability (increase in evaporation and rainfall intensity), and (d) implementing vegetative swales as low impact developments (LIDs), on watershed-generated runoff and pollutant loads (total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP)). Combination of the above-mentioned factors resulted in 17 scenarios, and each scenario was run for a 12-hour simulation in the model. The results indicated that based on land developments, areas with more dominant agricultural land generated more TN and TP, areas with more undeveloped lands generated more TSS, and more urbanized areas generated more runoff. Moreover, the 50% urbanization scenario resulted in more runoff and pollutant loads, compared with the 20% urbanization scenario. Under scenarios with climate variability, runoff and pollutant load peaks occurred earlier in time, due to the higher intensity rainfall events. Furthermore, LIDs decreased pollutant loads up to 25%, indicating their effectiveness in decreasing the impact of urbanization on receiving water bodies.

Key words | climate variability, low impact development (LID), surface runoff, SWMM, vegetative swales

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INTRODUCTION

Due to ongoing climate change, population growth, and high rates of urbanization during the late 20th and early 21st centuries, more cities have become exposed to the occurrence and impacts of pluvial flooding (Kalra *et al.* 2017). Land development is strongly related to imperviousness, which is a critical property for determining surface runoff in an area. Therefore, unplanned urbanization can cause excessive runoff and higher pollutant loads, which can deteriorate water quality in receiving water bodies (Thakali *et al.* 2018). Moreover, climate change will affect the hydrological cycle and change atmospheric and meteorological properties, such as precipitation patterns, atmospheric water vapor, and evaporation (IPCC 2007; Thakali *et al.* 2016). In this situation, cities that lack drainage facilities are more vulnerable to flood inundations, especially from increased rainfall intensities and flash-floods, as a consequence of the change in climatic conditions (IPCC 2012). Understanding how pollutants travel in an environment requires an analysis of the underlying hydrological processes (Nazari-Sharabian *et al.* 2018).

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The Storm Water Management Model (SWMM) is a dynamic model, widely used for single-event to long-term simulations of surface/subsurface hydrological quantities and qualities from primarily urban/suburban areas (Rossman 2010). The literature shows numerous applications of this model at different scales. Zhang and Guo (2015) evaluated the runoff reduction performance of permeable pavement systems using the low impact development (LID) module of the SWMM, through example applications with rainfall data from Atlanta. In another study, employing the SWMM, Jiang *et al.* (2015) simulated the urban flooding of Dongguan City in southern China. The authors observed no flooding under a 1-year return period of precipitation, but for 2-, 5-, 10-, and 20-year return periods of precipitation, the simulations showed that the area would be inundated. Furthermore, in order to provide a solution for the stormwater management problem in a small, urbanized area in West Bengal, India, Bisht *et al.* (2016) used the 1D SWMM and 2D MIKE URBAN models, and designed an efficient drainage system for the study area. Dan-Jumbo *et al.* (2018) assessed the impacts of urbanization on flood risk in the River State region of the Niger Delta. The authors reported that due to planned urban development, urban expansion could increase by 80% by 2060, in which 95% of the conversions to urban land would occur chiefly at the expense of agricultural land, which could amplify flood risk and have other severe implications for the watershed in the future.

In another study, Williams (2018) used the SWMM and studied the effectiveness of conventional and LID management scenarios for reducing runoff depths and peak flows of moderate-magnitude storms in the upper Rocky Branch Watershed in Columbia, South Carolina. The author modeled various configurations and locations of detention ponds and LIDs, to compare the effectiveness of individual strategies, under two levels of initial investment, based on unit storage costs ($/m^3). The simulation results indicated that the individual application of both strategies was only effective when placed upstream in the smaller, highly impervious sub-catchment, and detention ponds were effective in reducing peak discharges at both initial investment levels. Moreover, using the SWMM and HydroDynamic Model-2D (HDM-2D), Kim *et al.* (2018), introduced a simplified urban storm water inundation simulation model for two small and medium-sized cities in South Korea. The authors used the SWMM to calculate the runoff flow and surcharged overflow of the existing urban drainage network; they then coupled HDM-2D with 1-D SWMM to simulate flood propagation.

Furthermore, Hung (2018) examined the degrees of urbanization and climate change in the Rocky Branch Watershed in Columbia, South Carolina. Using the SWMM, the author studied a series of scenarios to compare relative effects of the projected percent impervious area and climate-change scenarios on runoff for the near term (2035) and far term (2060), and reported that climate change generated a greater impact on runoff than did urbanization. In another study, Xiong *et al.* (2018) used the SWMM to investigate the potential changes of extreme rainfall and their impact on the drainage infrastructure in an urban area in Wuhan City, China. The authors concluded that the lack of capability of the current drainage infrastructure in the study area would be aggravated, since rainfall with return periods of 2, 3, 4 and 5 years would increase more significantly than that of 10 and 20 years.

Furthermore, Bai *et al.* (2019) used SWMM to study the effect of four different types of LID scenarios (no LID; LID based on infiltration; LID based on water storage; LID based on the combination of infiltration and water storage) on urban flooding under different rainfall patterns. The simulation results indicated that infiltration facilities had a greater reduction rate of surface runoff, compared with storage facilities.

Tuomela *et al.* (2019) investigated the use of constant source concentrations in modeling pollutant loads. Using the SWMM, and based on the literature, event mean concentrations (EMCs) for different land cover types, and on-site rainfall and discharge data for a residential area in southern Finland, the authors modeled the source area contributions of total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), lead, copper, and zinc. Finally, they reported that large differences were evident in the modeled catchment-scale and land cover specific loads, depending on the EMC data source. Also, they concluded that the widely used storm water quality modeling with constant EMCs is uncertain, even when on-site water quality and rainfall–runoff data from a catchment outlet are available. In another study, Zhou *et al.* (2019) investigated the impacts of urban

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development on runoff and urban flood volumes in the city of Hohhot, located in northern China. Moreover, the authors compared the urbanization impacts with the effects induced by climate change. They reported that urbanization led to an increase in annual surface runoff by 208% to 413%. Through comparing the impacts of urbanization and climate change on urban runoff and flood volumes, they concluded that a re-assessment of current and future urban drainage, in coping with the changing urban floods induced by local and large-scale changes, was important.

The literature review showed that previous studies provided valuable insights into the impacts of climate variability and urbanization on runoff, in watershed scales. Nevertheless, these impacts on quantitative and qualitative aspects of runoff in a mountainous watershed, in particular upstream of a dam reservoir, are still less understood. Through the implementation of the SWMM, this study examined the surface runoff generation and select water quality characteristics in the Mahabad Dam watershed in Iran, under several scenarios based on urbanization, climate variability, and LID. In this study, the scope of water quality analysis was limited to TSS, TN, and TP. Moreover, the applicability of vegetative swales as LID, in reducing pollutant loads, was evaluated. Ultimately, the findings of this study can be used as a guide for urban development in a watershed that is in accordance with environmental quality standards.

CASE STUDY AND DATA

The Mahabad Dam watershed is located in the West Azerbaijan province in northwestern Iran (36°44′N, 45°39′E), and is one of the Urmia Lake basins. This mountainous watershed covers an approximate area of 808 km^2 (199,661 acres), and is mostly covered by agricultural fields and grasslands. The average precipitation in this area is 350 mm/yr. The Kauter and Beytas Rivers originate from the southern heights of the plain and run to the north in parallel. They join and create the Mahabad Dam reservoir, and continue running as the Mahabad River (Figure 1). Based on the data records from hydrometric stations, the average flow rates of the Kauter and Beytas Rivers during 1988–2012 were 6.18 m^3/s and 1.82 m^3/s, respectively (http://www.irimo.ir/eng/).

Tables 1 and 2 present the land use and soil classification of the watershed, respectively.

A digital elevation model (DEM) of the study area with 30 m spatial resolution was downloaded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) database (https://asterweb.jpl.nasa.gov/gdem.asp),

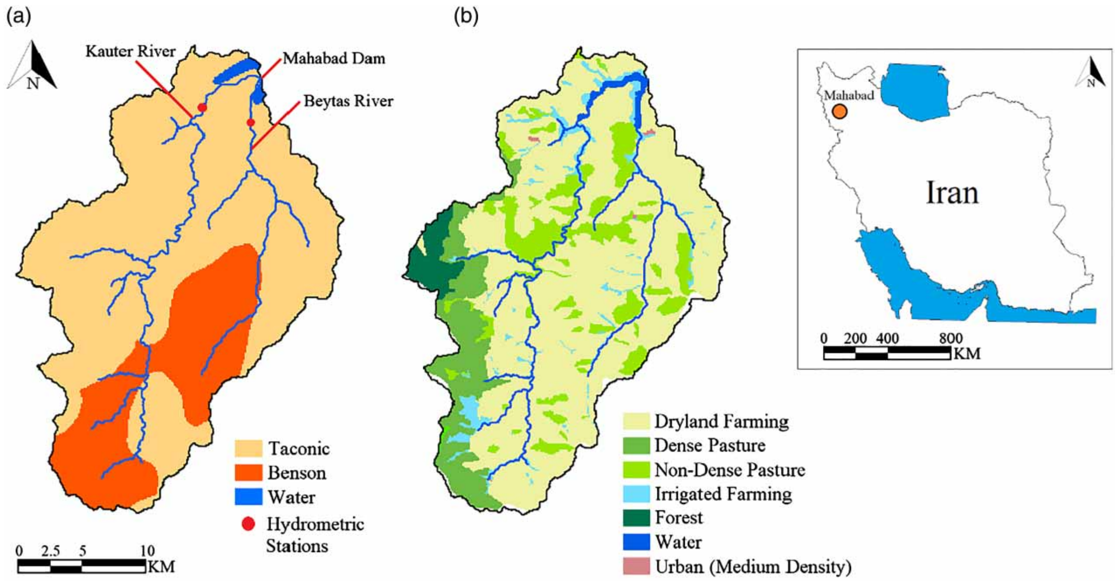

Figure 1 | (a) Land use map and (b) soil map of the Mahabad Dam watershed.

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Table 1 | Land use classification of the Mahabad Dam watershed

Land use type	Watershed area (%)
Dryland farming	66.37
Dense pasture	13.82
Non-dense pasture	11.09
Irrigated farming	4.49
Forest	2.95
Water	1.03
Urban (medium density)	0.13

Table 2 | Soil types in the Mahabad Dam watershed

Soil type	Sand (%)	Silt (%)	Clay (%)	Watershed area (%)
Taconic	43	35	23	72
Benson	35	37	30	28

to delineate the watershed in geographic information system (GIS) and, subsequently, to create the model in the SWMM model. The soil map was retrieved from the Food and Agriculture Organization of the United Nations (FAO) soils portal, using the Harmonized World Soil Database (HWSD) Ver. 1.2 (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/), and the land use map was provided by the Mahab Ghodss Consulting Engineering Company (http://www.mahabghodss.com/).

MATERIALS AND METHODS

Storm Water Management Model

The Storm Water Management Model has been developed by the United States Environmental Protection Agency (US EPA). The hydrology component of this model operates on a collection of sub-catchment areas divided into impervious and pervious portions, with and without depression storage, in order to predict runoff and pollutant loads from precipitation, evaporation, and infiltration losses. The routing, or hydraulics section of the SWMM transports runoff, and its possible associated water quality constituents, through a system of closed pipes, open channels, storage/treatment devices, ponds, storage areas, pumps, orifices, weirs, outlets, outfalls, and other regulators. The SWMM tracks the quantity and quality of the flow generated within each sub-catchment, as well as the flow rate and depth, and the quality of water in each pipe and channel, during a simulation period composed of multiple fixed or variable time steps. The water quality constituents can be simulated from their buildup through wash-off to a hydraulic network in sub-catchments, with optional first-order decay and linked pollutant removal. Moreover, best management practices (BMPs) and LID removal and treatment can be simulated for the selected storage nodes. In this model, the hydrologic network is created by adding visual objects in the graphical user interface. These visual objects include both human artifacts, such as weir gates, pumps, and reservoirs, and natural features such as drainage basins and streams (Rossman 2010).

Conceptual design and layout

The SWMM version 5.1.013 was utilized in this study. There were four types of visual objects that comprised the model of the Mahabad Dam watershed: sub-catchments, conduits, junctions, and the rain gauge. The first step in creating the hydrological network was to determine the number of sub-catchments that comprised the watershed. An elevation map was required to determine the number of sub-catchments. An ArcGIS extension, called ArcSWAT, was used to delineate sub-catchments of the Mahabad Dam watershed based on the DEM. The conversion from a GIS map to the SWMM graphical user interface, which includes junctions and conduits, is shown in Figure 2.

Table 3 shows how the GIS-delineated sub-catchments were grouped, in order to have fewer sub-catchments in the SWMM.

After drawing the SWMM network, the properties of each visual object were input into the model. The following subsections present how these values were obtained.

GIS-defined properties

Using the ArcToolbox in ArcGIS, the area, width, and slope of each sub-catchment were obtained and input as the sub-catchment properties in the SWMM. Moreover,

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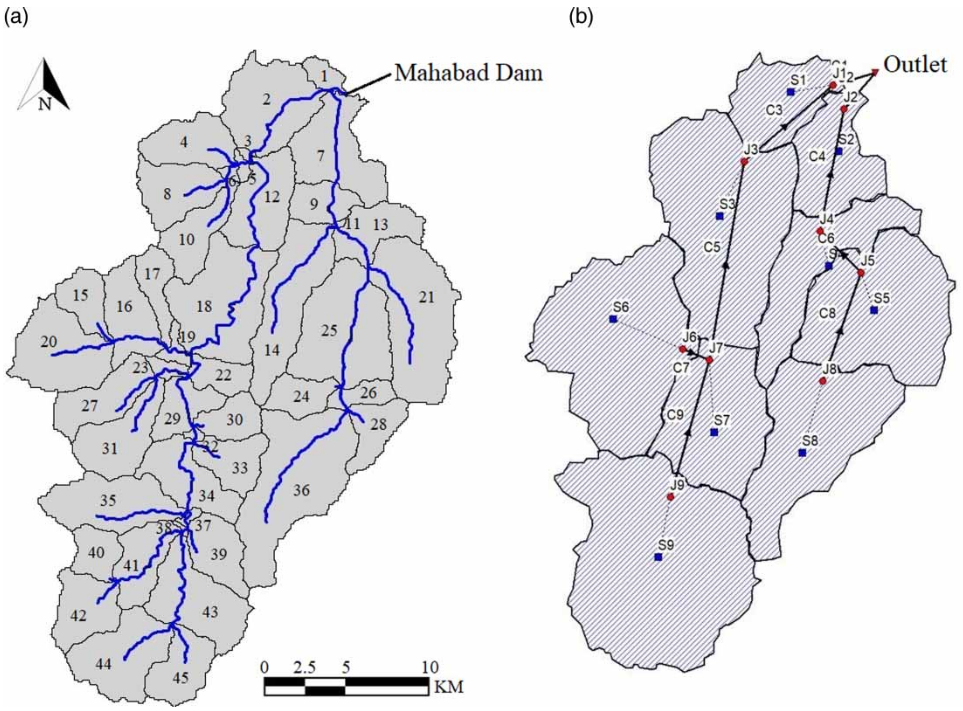

Figure 2 | (a) Delineated watershed in the ArcSWAT model; (b) the watershed configuration in the SWMM.

Table 3 | Sub-catchments in GIS and in the SWMM

GIS-delineated sub-catchments	Grouped sub-catchments in the SWMM
1, 2	1
7, 9	2
3, 4, 5, 6, 8, 10, 12, 18	3
11, 13, 14	4
21, 25	5
15, 16, 17, 19, 20, 21, 27, 31	6
22, 28, 30, 32, 33, 34	7
24, 26, 28, 36	8
35, 37, 38, 39, 40, 41, 42, 43, 44, 45	9

Table 4 | GIS-defined sub-catchment properties

Sub-catchment	Area (acre)	Width (ft)	% Slope	% Impervious
1	9,384	16,400	32	5
2	10,105	16,400	24	5
3	31,169	26,240	32	4
4	13,284	16,400	29	5
5	23,095	26,240	29	5
6	40,916	32,800	36	3.5
7	17,033	19,680	31	5
8	21,462	26,240	30	5
9	41,318	32,800	34	3

the amount of imperviousness was determined based on the percent urbanization in each sub-catchment. A summary of all of the values derived from the GIS-defined sub-catchment properties is presented in Table 4.

Manning's *n* and depth of depression storage

Manning's *n* value describes the resistance of an area to water flowing over it, and depends on the type of land use. Manning's *n* values of 0.2 and 0.1 were assigned to the pervious and impervious portions of the watershed, respectively. These values were obtained by a trial-and-error procedure as part of the calibration process, so the model results matched observed runoff values at the watershed outlet.

For the impervious and pervious portions of the watershed, the depth at which the precipitation can pool is defined as the depth of depression storage. The pooled precipitation, thus, does not become runoff. In this study,

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the depth of depression storage on pervious and impervious areas of the watershed was assumed to be 0.05 in., based on the model's recommendation.

Infiltration

There are several ways to estimate the amount of precipitation that infiltrates into the pervious portions of the sub-catchment. In this study, the SCS Curve Number method was used as the infiltration method. This method only requires a single Curve Number (CN) value to be assigned to each sub-catchment. CN values of 91.3 and 86.14 were assigned to those sub-catchments in the SWMM covering the sub-catchment numbers 11, 13, 14, 21, 24–26, 28, 36, and 15–20, 22, 23, 27, 29–35, 37–45, in the delineated watershed in ArcGIS, respectively. These values were used based on the land use type in each sub-catchment, and were obtained in the model calibration process.

Conduit properties

The lengths of conduits were determined using the ArcGIS ruler tool, by measuring the lengths of the streams from the ArcSWAT-derived stream network. The conduits were sized in a way that no conduit surcharge happened under the most critical scenario. The scenarios used in this study are listed in the 'Scenarios' subsection.

Junction properties

Only the invert elevation, as the junction property, was considered in this study. The invert elevation is simply the elevation at the junction, measured from sea level. This elevation was obtained from the Google Earth software. It was assumed that the maximum depth at the junction was the same as the depth of the connecting stream segment. Initial depth was ignored since the results were centered only on the flow from runoff and not the base flow.

Non-visual objects

Non-visual objects, such as climatology, land uses, pollutants, and LIDs, do not appear in the SWMM graphical user interface, but are, nevertheless, important components of the model. These objects are explained in the following subsections.

Climatology and climate variability

A rainfall time series shows the amount of precipitation that falls within a specified time interval. A single rain gauge was used to provide the rainfall data for the basin, and a 76.2 mm (3 in.) rainfall event, which occurred in May 2012 during 6 hours, was used for model calibration and simulations. Moreover, for comparison purposes and based on the scope of this study, a scenario on climate variability was defined, and it was assumed that the same amount of rainfall precipitates with higher intensity, in a shorter time period of 4 hours (Figure 3). Furthermore, based on the observations in May 2012, the evaporation rate in the area was 80 mm/month (0.1 in./day). It was assumed that the evaporation rate doubles due to the change in climatic conditions.

Land uses and pollutant loads

Each land use must have its properties defined in order to run a water quality simulation in the SWMM. Each land use contains a buildup and wash-off function, whose forms are defined by the user. The SWMM allows users to define any number of pollutants, though in this study only TSS, TN, and TP were analyzed. The antecedent dry days were assumed to be 100 days. Observations in the area showed that agricultural TN and TP rate constants and wash-off EMCs were almost twice the value of those in residential areas. These values are presented in Tables 5 and 6, respectively (Nazari-Sharabian et al. 2019).

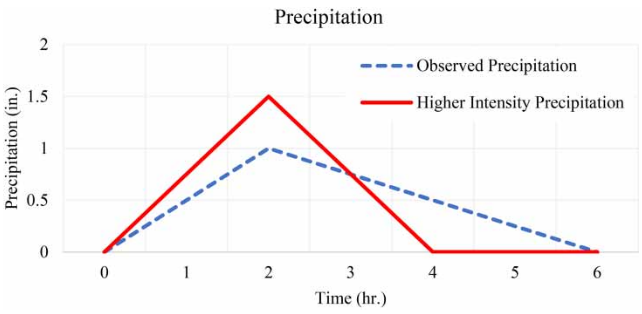

Figure 3 | The observed and higher intensity precipitation for scenario definition.

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Table 5 | Buildups: rate constant (kg/acre.year)

Pollutant	Residential (medium density)	Undeveloped (dense pasture + non-dense pasture)	Agricultural (dryland farming + irrigated farming + forest)
TSS (max. buildup)	0.26 (22.68)	0.118 (11.34)	0.24 (22.68)
TN (max. buildup)	0.0048 (0.45)	0.0024 (0.23)	0.0097 (0.91)
TP (max. buildup)	0.00062 (0.23)	0.00031 (0.11)	0.0012 (0.45)

Table 6 | Wash-off EMCs (mg/L)

Pollutant	Residential (medium density)	Undeveloped	Agricultural
TSS	60	50	60
TN	3	1.7	6
TP	0.3	0.12	0.6

Low impact development (LID)

LID is an approach to land development that works with nature to manage storm water as close to its source as possible. In order to treat storm water as a resource, rather than a waste product, LIDs employ principles such as preserving and recreating natural landscape features to create functional and appealing site drainage (http://www.epa.gov/nps/urban-runoff-low-impact-development).

In this study, vegetative swales were used as the LIDs in the sub-catchments undergoing urbanization. It was assumed that the LID in each sub-catchment covered 10% of the area and treated 50% of the runoff from developed areas, and 50% of the runoff from undeveloped areas. Vegetative swales act as natural biofilters to reduce storm water flows and pollutant loads. They remove sediment and chemicals attached to sediment particles, organic material, trace metals, and nutrients, such as nitrogen and phosphorus (Babaei *et al.* 2019). Table 7 presents the properties of the LID used in this study.

Table 7 | Vegetative swale properties

Berm height (In.)	Vegetation volume fraction	Surface roughness (Manning's *n*)	Surface slope (%)	Swale side slope (run/rise)
1.0	0.0	0.1	1.0	5.0

Table 8 | Scenarios on land development

Scenario description	Scenario #	
	Normal conditions	With climate variability
The baseline scenario (current watershed conditions)	0	9
20% urbanization near the watershed outlet	1	10
50% urbanization near the watershed outlet	2	11
20% urbanization in the middle of the watershed	3	12
50% urbanization in the middle of the watershed	4	13
20% urbanization at the far end of the watershed	5	14
50% urbanization at the far end of the watershed	6	15
20% urbanization in the whole watershed	7	16
50% urbanization in the whole watershed	8	17

Scenarios of urbanization

In order to determine the impact of urbanization and climate variability on runoff and water quality, 17 scenarios were proposed, as are presented in Table 8. For these scenarios, it was assumed that urbanization only changes the percent imperviousness of the sub-catchments, and leaves everything else constant; 20% and 50% urbanizations were proposed as possible future developments in the watershed, and for comparison purposes based on different scenarios in this study.

Table 9 presents the percentages of residential, undeveloped, and agricultural land uses in each sub-catchment,

Table 9 | Land uses before land developments

Sub-catchment #	% Residential	% Undeveloped	% Agricultural
1	5	65	30
2	5	65	30
3	4	86	10
4	5	90	5
5	5	90	5
6	3.5	86.5	10
7	5	85	10
8	5	65	30
9	3	77	20

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before urbanization. In Table 10, the land use percentages are presented based on urbanization near the outlet, in the middle, at the far end, and in the whole watershed.

RESULTS AND DISCUSSION

In this study, considering the rainfall duration, and to let all surface runoff reach the watershed outlet, each scenario was run for a 12-hour simulation. Figure 4 shows the change in runoff, TSS, TN, and TP loads received at the watershed outlet, relative to the baseline scenario. Figure 5 presents the time required for each component to peak at the watershed outlet, under each scenario. Finally, Figure 6 shows how the implementation of LIDs helped to reduce pollutant loads reaching the watershed outlet. According to Figure 4, the highest increase in runoff and pollutant loads was observed under Scenario 8, with 50% urbanization in the whole watershed, and this created the most critical case among all scenarios. Under this scenario, relative to the baseline scenario, runoff, TSS, TN, and TP loads increased by 137%, 158%, 119%, and 232%, respectively. These findings are in agreement with the results obtained by Zhou *et al.* (2019), that reported urbanization led to an increase in annual surface runoff in the city of Hohhot, China. After Scenario 8, the highest increase was observed under Scenario 17 (50% urbanization in the whole watershed with climate variability). The results indicate that urbanization of land, by affecting the imperviousness in sub-catchments, can amplify the flood risk in the region, and have severe implications for the watershed, regarding water quality issues.

On the other hand, the lowest increase was observed in Scenario 1 (20% urbanization near the watershed outlet). Under this scenario, runoff, TSS, TN, and TP loads increased by 15%, 16%, 18%, and 21%, relative to the baseline scenario, respectively. Moreover, under Scenarios 9 (baseline scenario with climate variability), 10 (20% urbanization near the watershed outlet with climate variability), 12 (20% urbanization in the middle of the watershed with climate variability), and 14 (20% urbanization at the far end of the watershed with climate variability), the watershed yields were decreased, relative to the baseline scenario. The decrease can be attributed to increased evaporation under

Table 10 | Land uses after land developments

Sub-catchment #	% Residential	% Undeveloped	% Agricultural
Near the watershed outlet			
1	20 (50)[a]	50 (20)	30
2	20 (50)	50 (20)	30
3	20 (50)	70 (40)	10
4	20 (50)	75 (45)	5
5	5	90	5
6	3.5	86.5	10
7	5	85	10
8	5	65	30
9	3	77	20
In the middle of the watershed			
1	5	65	30
2	5	65	30
3	4	86	10
4	5	90	5
5	20 (50)	75 (45)	5
6	20 (50)	70 (40)	10
7	20 (50)	70 (40)	10
8	5	65	30
9	3	77	20
At the far end of the watershed			
1	5	65	30
2	5	65	30
3	4	86	10
4	5	90	5
5	5	90	5
6	3.5	86.5	10
7	5	85	10
8	20 (50)	50 (20)	30
9	20 (50)	60 (30)	20
In the whole watershed			
1	20 (50)	50 (20)	30
2	20 (50)	50 (20)	30
3	20 (50)	70 (40)	10
4	20 (50)	75 (45)	5
5	20 (50)	75 (45)	5
6	20 (50)	70 (40)	10
7	20 (50)	70 (40)	10
8	20 (50)	50 (20)	30
9	20 (50)	60 (30)	20

[a]The values in parentheses show percentages based on the 50% development scenario in the same sub-catchment.

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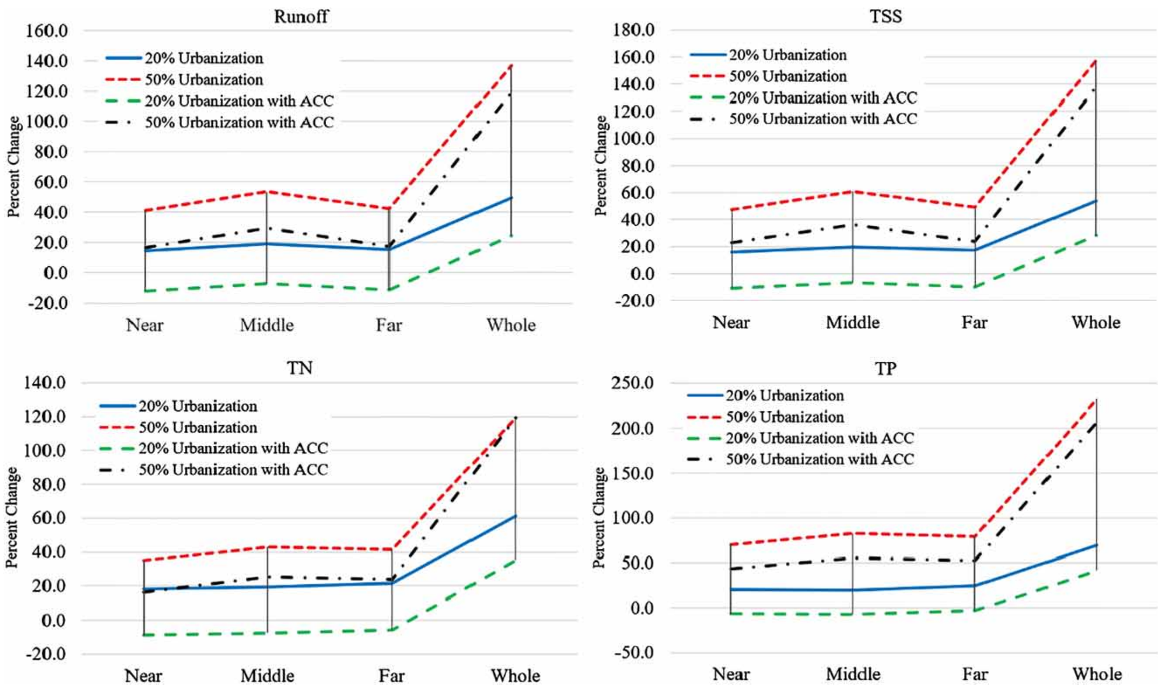

Figure 4 | The change in the runoff, TSS, TN, and TP loads, relative to the baseline scenario, under normal and altered climatic conditions (ACC).

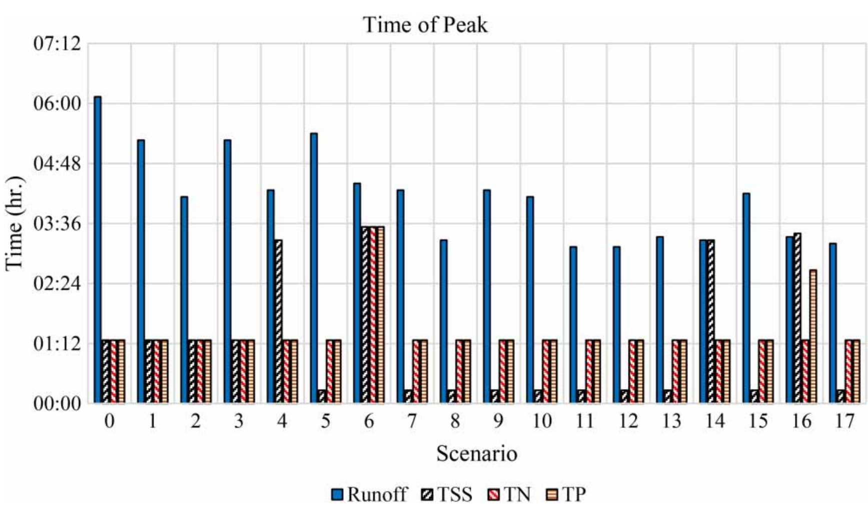

Figure 5 | Time of peak for runoff, TSS, TN, and TP.

climate change conditions. These findings are in accordance with the results obtained by Hung (2018). He reported that although urbanization leads to increased surface runoff due to increased imperviousness of land, climate change can generate a greater impact on runoff than urbanization.

Furthermore, Figure 5 indicates that during the 12-hour simulation, the baseline scenario showed the longest time for a peak in the runoff received at the watershed outlet (6:08). This can be due to the fact that by urbanizing undeveloped lands, surface runoff moves faster on more impervious lands and reaches the watershed outlet earlier. This situation requires drainage facilities that can handle an increased amount of surface runoff in a shorter time, without undergoing any overloading. Similarly, in the study by Xiong et al. (2018), the authors stressed the fact that the incapability of the drainage infrastructure in

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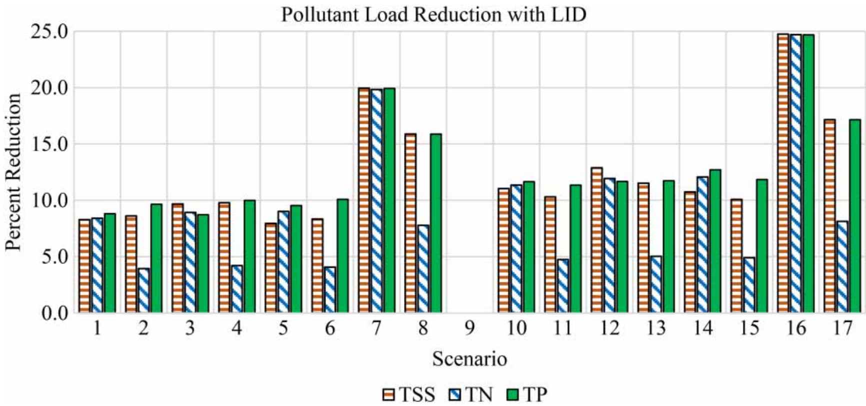

Figure 6 | Pollutant load reductions in the watershed after implementation of the LIDs.

Wuhan City, China, can be aggravated under climate change conditions. Kim *et al.* (2018) also reported similar results. The authors concluded that climate change will increase the rainfall intensity and flash-floods in their study area located in South Korea, resulting in exacerbated flood inundation. Moreover, under the baseline scenario, the time of peaks for TSS, TN, and TP were 1:16. The highest increase in the pollutants' peak times was observed under Scenario 6 (50% urbanization at the far end of the watershed). Under this scenario, since the urbanized area was far from the watershed outlet, and the highest urbanization percentage considered in this study was employed, the pollutant loads and the time of peak increased.

Finally, according to Figure 6, after the implementation of LIDs, the highest reduction in pollutant loads was achieved under Scenario 16 (20% urbanization in the whole watershed with climate variability). This scenario showed a 25% reduction in all pollutant loads. After that, Scenarios 7 (20% urbanization in the whole watershed), 17 (50% urbanization in the whole watershed with climate variability), and 8 (50% urbanization in the whole watershed) showed highest percentages of reduction in pollutant loads. Furthermore, under Scenario 9 (baseline scenario with climate variability), no pollutant load reductions were observed. Bai *et al.* (2019) also reported the effectiveness of LIDs based on infiltration, in reducing pollutant loads in the case study of Sucheng District of Suqian City, Jiangsu Province, China.

In summary, these findings indicate that the location of urbanization affected both the amount and timing of runoff and pollutant loads. As the urbanized area was constructed farther away from the outlet point of the watershed, the peaks occurred later in time. The percentage of urbanization was another factor affecting these values. As the urbanization percentage increased, more runoff and pollutants were generated in the watershed. Furthermore, the change in climatic conditions affected the watershed yields in a way that as the rainfall intensity increased, the peaks at the watershed outlet occurred earlier in time. Moreover, vegetative swales as LIDs were proved to be effective in reducing pollutant loads in the watershed.

CONCLUSIONS AND RECOMMENDATIONS

This study covered 17 scenarios on the impact of urbanization and climate variability, as well as the implementation of vegetative swales as LIDs, on runoff and pollutant loads in the mountainous Mahabad Dam watershed in Iran. The following summarize the main findings of this study:

- Comparing the 20% and 50% urbanization scenarios with the baseline scenario, scenarios containing 50% urbanization showed more severe results for the region: 50% urbanization near the watershed outlet resulted in runoff and pollutant load increases of 23.1% and 27.4%, respectively; 50% urbanization in the middle of the watershed resulted in 28.8% and 35.4% increases of runoff and pollutant load, respectively; and 50% urbanization at the far end of the watershed resulted in runoff and pollutant load increases of 23.1% and 3.9%, respectively. Finally, 50% urbanization of the whole watershed

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resulted in runoff and pollutant load increases of 58.6% and 66.3%, respectively. The change in watershed yields, due to urbanization in different locations, can be attributed to different sub-catchment areas, land uses, and imperviousness.

- The urbanization location affected both the amount of runoff and pollutant loads. Areas that were urbanized farther from the watershed outlet showed delayed peaks in runoff and pollutant loads, compared with urbanized areas near the watershed outlet.
- Under scenarios with climate variability, the peaks occurred earlier in time because of higher intensity and shorter duration rainfall events.
- The LIDs decreased pollutant loads. The highest reductions were observed when LIDs were employed in the following scenarios: 20% urbanization in the whole watershed with climate variability (25% reduction in all pollutant loads); 20% urbanization in the whole watershed (20% reduction in all pollutant loads); and 50% urbanization in the whole watershed with climate variability (17% reduction in TSS and TP loads, and 8% reduction in TN load).

Based on the findings of this study, in order to reduce the pollutant loads entering the streams and the reservoir, the implementation of LIDs in the watershed is encouraged. Moreover, it is recommended to locate critical source areas (CSAs) in the watershed and to avoid urbanizing them, since greater imperviousness will increase the amount of pollutant loads from CSAs, as a result of increased surface runoff. In addition, CSAs should be the priority for the implementation of LIDs.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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