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Watershed-scale surface runoff and water quality response to climate change, urbanization, and implementation of LIDs

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Abstract: The Storm Water Management Model (SWMM) was used to evaluate the impact of urbanization, climate change, and implementation of Low Impact Developments (LIDs) at the Mahabad Dam watershed, Iran. Several scenarios of urbanization, with and without climate change impacts, in different locations were defined, including near outlet, middle, far end, and whole watershed. Climate change was considered to change the intensity of rainfall and increase evaporation. Vegetative swales were implemented as LIDs to evaluate their applicability to reduce pollutant loads. Digital Elevation Model (DEM) of the area was input into ArcGIS, and the watershed was delineated using the ArcSWAT extension to identify topographic features. Water quality properties were defined in the software, and each scenario was run for a twelve-hour simulation. The results indicated that urbanization affects the imperviousness of sub-catchments, and location of urbanization affects the amount and timing of runoff and pollutant yields. Fifty-percent urbanization near the watershed outlet resulted in 23.1% and 27.4% increases in runoff and pollutant loads, respectively. Fifty-percent urbanization in the middle resulted in 28.8% and 35.4% increases in runoff and pollutant loads; and, at the far end, 23.1% and 3.9% increases in runoff and pollutant loads were the result; Fifty-percent urbanizing the whole watershed gave 58.6% and 66.3% increases in runoff and pollutant loads, respectively; Under climate change scenarios (higher intensity, shorter duration rainfall) peaks occurred earlier. Moreover, results showed LIDs decreased pollution loads up to 25%.

Keywords: Urbanization; Climate Change; SWMM; LID; Runoff; Water Quality

1. Introduction

Land development is strongly related to imperviousness, which is a critical property for determining surface runoff in an area. Analyzing how surface runoff may vary depending on changes in the imperviousness of the land can help in making decisions to manage development so that it does not cause excessive runoff and ultimately lead to higher pollutant loads, which damages ecosystems in the receiving water bodies. Moreover, climate change will affect the hydrological cycle and change atmospheric and meteorological properties, such as precipitation patterns, atmospheric water vapor, and evaporation [1–4]. Sediment yield and nutrient losses occur as water pollutants are affected by spatial and temporal alterations in precipitation patterns and precipitation intensity, as well as land-use practices, land management, and population pressure.

Understanding how pollutants travel in an environment requires analyses of the underlying hydrologic processes. The previous work of hydrologists has yielded several mathematical models that can analytically describe some of the processes in this cycle. Based on these mathematical models, a variety of hydrologic computer models have been developed since the Stanford Watershed Model (SWM) was first introduced in 1966. Among these models is the Storm Water Management Model (SWMM). The appropriateness of these models may vary depending on the characteristics of the study area and user objectives.

In 2014, [5] evaluated the runoff reduction performance of permeable pavement systems using the low-impact development (LID) module of the widely used Storm Water Management Model (SWMM) through example applications with rainfall data from Atlanta. The authors found that when the depth of the pavement layer is less than 120 mm and the computational time steps are longer than 30 min, the method of calculating infiltration through the pavement layers of permeable pavement systems in the LID module are inadequate.

Employing the SWMM model, [6] simulated urban flooding of Dongguan City in southern China. They observed no flooding under the 1-year return period precipitation, but for the 2, 5, 10 and 20-year return periods of precipitation, the simulations showed that the area would be inundated.

Moreover, in order to provide a solution to the storm water management problem in a small urbanized area in West Bengal, India, [7] used the 1D SWMM and the 2D MIKE URBAN models to design an efficient drainage system for the study area. The authors also designed a multi-purpose detention pond for groundwater recharge and attenuating the peak of the outflow hydrograph at the downstream end during high-intensity rainfall. This study provided an insight into the importance of 2D models to deal with location-specific flooding problems.

More recently, [8] provided a method to determine pollutant buildup and washoff parameters in a semi-arid Texan urban watershed, using inverse modeling. The authors calibrated hydraulic and pollutant parameters, using Shuffled Complex Evolution – University of Arizona (SCEUA). Additionally, the confidence intervals of pollutant parameters were calculated by GLD (Generalized Lambda Distribution). The modeling results showed that buildup parameters were clustered in narrow numerical ranges, indicating that spatially uniform factors were responsible for pollutant buildup. Washoff parameters did not cluster and were distributed more evenly, indicating the strong influence of local factors, such as topography.

Furthermore, [9] assessed the historical and future land-use/land-cover dynamics in the River State region of the Niger Delta. In order to perform land-use classification and change detection analysis, multi-source (Landsat TM, ETM, polygon map, and hard copy) data of the study area for the years 1986, 1995, and 2003, as well as projected conditions for 2060 were used. The authors concluded that historical urbanization was rapid, and due to planned urban development, urban expansion could increase by 80% in 2060; moreover, 95% of the conversions to urban land occurred chiefly at the expense of agricultural land, which in the future could amplify flood risk and have other severe implications for the watershed.

The Mahabad Dam reservoir in Iran is suffering from year-round eutrophication caused by excess nutrient loadings from the watershed. Moreover, due to land-use changes and the degradation of vegetation in this watershed, the soil has become very erodible, making it vulnerable to high-intensity rainfall events. In this situation, the soil wash can increase sediment yield and nutrient loadings, making the reservoir's eutrophic condition even worse. Over the past decades, meteorological records have shown temperature rises and precipitation declines in the region. Therefore, it is expected that in changing climate conditions, with possible further anthropogenic changes in this area, the water quality of the reservoir will be affected.

Therefore, through implementing the SWMM model, this study intends to examine the surface runoff generation and water quality characteristics in the Mahabad Dam watershed, under several scenarios based on urbanization and climate change. This study, however, will limit the scope of water quality analysis to pollutants, such as total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP), which enter the streams from areas with different land use practices.

Ultimately, the findings of this study can be used as a guide for urban development that is in accordance with environmental quality standards.

2. Materials and Methods

2.1. Case Study and Data

Mahabad Dam watershed is located in West-Azerbaijan province in the northwest of Iran (36°44’N, 45°39’E), and is one of the Urmia Lake basins. The watershed covers an approximate area of 808 km² (199,661 ac) and is mostly covered by agricultural fields and grasslands. 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).

Figure 1. Geographical location of Mahabad Dam.

In the watershed, the soil is mainly composed of Taconic and Benson. The composition of each soil type in detail, and the percent coverage of the watershed area are presented in Table 1.

Table 1. Soil types in the Mahabad Dam watershed.

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

Fortunately, the data for several necessary parameters are freely available in the form of Geographic Information System (GIS) raster data layers derived from satellite imagery. These layers can be processed in GIS so that particular parameter values can be extracted and input to SWMM. In this regard, a digital elevation model (DEM) of this area with 30m spatial resolution, was downloaded from the ASTER database, to delineate the watershed in GIS and, subsequently, to create the model in SWMM.

2.2. The SWMM Model

The Storm Water Management Model (SWMM) [10] is a dynamic model used for single-event to long-term simulation of the surface/subsurface hydrology quantity and quality from primarily urban/suburban areas. The hydrology component of SWMM operates on a collection of sub-catchment areas divided into impervious and pervious areas, with and without depression storage, in order to predict runoff and pollutant loads from precipitation, evaporation, and infiltration losses from each of the sub-catchments. The routing or hydraulics section of the SWMM transports this water and possible associated water quality constituents through a system of closed pipes, open channels, storage/treatment devices, ponds, storages, 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, flow depth, and 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 buildup on the sub-catchments through washoff to a hydraulic network with optional first-order decay and linked pollutant removal. Best management practices (BMPs) and low-impact development (LID) removal and treatment can be simulated at selected storage nodes [11].

2.3. Conceptual Design and Layout

In the SWMM, the hydrologic network is created by adding visual objects in the graphical user interface. These visual objects include both human artifacts, like weir gates, pumps, and reservoirs, and natural features, such as drainage basins and streams. The SWMM version 5.1.013 was utilized in this study. There are four types of visual objects that will comprise the model of the Mahabad Dam watershed: sub-catchments, conduits, junctions, and rain gage. The first step in creating the hydrologic network is to determine the number of sub-catchments that will comprise the watershed. An elevation map is required to determine the number of sub-catchments. Therefore, a digital elevation model (DEM) of the area in a raster data format was downloaded and input into ArcGIS.

An ArcGIS extension called ArcSWAT was then used to delineate all of the sub-catchments of the Mahabad Dam watershed based on the DEM. The following graphics show the conversion from a GIS map to the SWMM graphical user interface, which includes junctions and conduits (Figure 2).

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

Table 2 shows how GIS delineated sub-catchments were grouped in order to have a fewer number of sub-catchments in SWMM.

Table 2. Sub-catchments in GIS and SWMM	
GIS Delineated Sub-Catchments	Grouped Sub-Catchments
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

After drawing the SWMM network, the properties for each visual object has to be input. The processes for determining the values of these properties are presented in the following subsections.

2.4. GIS-Defined Properties

In ArcToolbox, the area of each polygonal feature, i.e., sub-catchments, can be tabulated. These area values can then be easily input as the sub-catchment properties in the SWMM. A summary of all the values derived from the GIS-defined sub-catchment properties is presented in Table 3. The amount of imperviousness was determined based on the approximate percent urbanization in each sub-catchment.

Table 3. GIS-defined sub-catchment properties

Sub-Catchment	Area (ac)	Width (ft)	% Slope	% Impervious
1	9384	16400	32	5
2	10105	16400	24	5
3	31169	26240	32	4
4	13284	16400	29	5
5	23095	26240	29	5
6	40916	32800	36	3.5
7	17033	19680	31	5
8	21462	26240	30	5
9	41318	32800	34	3

2.5. Manning’s n and Depth of Depression Storage

Manning’s n value describes the resistance of an area for water to flow over it, and depends on the type of land use. In this study, pervious portions of the watershed were considered to have n values equal to 0.15, while the impervious portions of the watershed were considered to have Manning’s n values equal to 0.01.

For the impervious and pervious portions of the watershed, the depth for which precipitation can pool is defined as the depth of depression storage. The pooled precipitation, thus, does not become runoff. In this study, the depth of depression storage on pervious and impervious areas was assumed to be 0.05 In.

2.6. 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, developed by the Soil Conservation Service, was used as the infiltration method because of its simplicity. This method only requires a single Curve Number value to be assigned to sub-catchments. Based on the dominant land-use in the region, a Curve Number value of 80 was assigned to each sub-catchment.

2.7. Conduit Properties

The length of conduits was determined using the ArcGIS ruler tool and tracing the length of each of the stream segments from the ArcSWAT derived stream network. The conduits were sized in

a way that no conduit surcharge happens under the most critical scenario. The list of scenarios is presented in Table 7, under the scenarios subsection.

2.8. 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 is 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 base flow.

2.9. Non-Visual Objects

Non-visual objects do not appear in the SWMM graphical user interface, but are nevertheless important components of the model, such as climatology, land-uses, pollutants, and low impact developments (LIDs).

2.9.1. Climatology

A single rain gage was used to provide the rainfall data for every sub-catchment. A rainfall time series shows the amount of precipitation that falls within a specified time interval. In this study, it was assumed that a 3-inch rainfall event occurs in 6 hours. In the climate change scenario, it was assumed that the same amount of rainfall precipitates in a shorter time period of 4 hours and has a higher intensity (Figure 3). Without climate change, the evaporation rate was considered to be 80 mm/month (0.104 in/day), while the amount of evaporation under climate change was considered to be 154 mm/month (0.2 in/day).

Figure 3. Precipitation, with and without climate change.

2.9.2. Land-Uses and Pollutants

Each land-use must have its properties defined in order to run a water quality simulation. Each land-use contains a buildup and washoff 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. The agricultural TN and TP rate constants and washoff EMCs were assumed to be twice the value of those in residential areas. The buildup and washoff EMC values used in this study are presented in Table 4 and 5, respectively [11].

Table 4. Buildups: rate constant (lb/ac.year)

Pollutant	Residential (Medium Density)	Undeveloped	Agricultural
TSS (Max. Build Up)	0.52 (50)	0.26 (25)	0.52 (50)
TN (Max. Build Up)	0.01068 (1)	0.00534 (0.5)	0.02137 (2)
TP (Max. Build Up)	0.00137 (0.5)	0.00068 (0.25)	0.00274 (1)

219 **Table 5.** Washoff 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

220 2.9.3. LIDs

221 LID is an approach to land development that works with nature to manage storm water as close
222 to its source as possible. In order to treat storm water as a resource rather than a waste product, LIDs
223 employ principles such as preserving and recreating natural landscape features to create functional
224 and appealing site drainage [12].

225 In this study, vegetative swales were used as the LIDs in sub-catchments undergoing
226 urbanization. It was assumed that LIDs in each sub-catchment cover 10% of the area and treat 50% of
227 runoff from developed areas and 50% of runoff from undeveloped areas. Table 6 represents the
228 properties of the LIDs used in this study.

229 **Table 6.** Vegetative swale properties

Berm Height (In.)	Vegetation Volume Fraction	The Surface Roughness (Manning's n)	Surface Slope (%)	Swale Side Slope (run/rise)
1.0	0.0	0.1	1.0	5.0

230 2.10. Scenarios

231 In order to determine the impact of urbanization on runoff and water quality, several scenarios
232 were proposed, which are presented in Table 7. For these scenarios, it was assumed that urbanization
233 only changes the percent of imperviousness of the sub-catchment and leaves everything else constant.

234 **Table 7.** Scenarios on land development

Scenario #	Scenario Description
0	The baseline scenario
1	20% urbanization near the outlet
2	50% urbanization near the outlet
3	20% urbanization in the middle of the watershed
4	50% urbanization in the middle of the watershed
5	20% urbanization in the far end of the watershed
6	50% urbanization in the far end of the watershed
7	20% urbanization in the whole watershed
8	50% urbanization in the whole watershed
9	The baseline scenario with climate change
10	20% urbanization near the outlet with climate change
11	50% urbanization near the outlet with climate change

- 1220% urbanization in the middle of the watershed with climate change
- 1350% urbanization in the middle of the watershed with climate change
- 1420% urbanization in the far end of the watershed with climate change
- 1550% urbanization in the far end of the watershed with climate change
- 1620% urbanization in the whole watershed with climate change
- 1750% urbanization in the whole watershed with climate change

Table 8 presents the percentages of residential, undeveloped, and agricultural land-uses in each sub-catchment before urbanization. In Table 9, the land use percentages are presented based on urbanization near the outlet, in the middle, at the far end, and in the whole watershed.

Table 8. Land-uses before development			
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

Table 9. Land-uses after development			
Near the Outlet			
Sub-Catchment #	%Residential	%Undeveloped	%Agricultural
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	5	90	5
6	3.5	86.5	10
7	5	85	10
8	5	65	30
9	3	77	20
Middle			
Sub-Catchment #	%Residential	%Undeveloped	%Agricultural
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

Far End			
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	20 (50)	50 (20)	30
9	20 (50)	60 (30)	20

Whole Watershed			
Subcatchment #	%Residential	%Undeveloped	%Agricultural
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

3. Results

In this study, each simulation was run for twelve hours. The following graphs show the impact of urbanization and climate change on surface runoff generation and select water quality features. Figure 4 shows the change in the runoff, TSS, TN, and TP loads received at the outlet of the watershed, relative to the baseline scenario. Figure 5 represents the time that it took for each component to reach the maximum value under different scenarios. Figure 6 shows how the implementation of LIDs helps to reduce the pollutant loads in the watershed.

Figure 4. The change in the runoff, TSS, TN, and TP loads, relative to the baseline scenario.

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

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

The results indicate that urbanization affects the imperviousness of the sub-catchments. Consequently, as the imperviousness increases, rainfall no longer infiltrates into the ground, and instead runs into streams. Conversions to urban land could amplify flood risk in the future and have other severe implications for the watershed.

According to Figure 4, the highest increase in runoff and pollutant loads was observed under scenario 8, which is 50% urbanization in the whole watershed, which creates 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. After scenario 8, the highest increase was observed under scenario 17 (50% urbanization in the whole watershed with climate change). The results indicate that shorter duration precipitation events, along with increased evaporation rates, decrease the cumulative watershed yields. On the other hand, the lowest increase was observed in scenario 1 (20% urbanization near the 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 scenario 9 (baseline scenario with climate change), 10 (20% urbanization near the outlet with climate change), 12 (20% urbanization in the middle of the watershed with climate change), and 14 (20% urbanization in the far end of the watershed with climate change), the watershed yields were decreased.

Furthermore, Figure 5 indicates that during the twelve-hour simulation, the baseline scenario showed the longest time for a peak in the runoff, received at the outlet of the watershed (6:08). Under the same scenario, the time of peak for TSS, TN, and TP were 1:16. The highest increase in pollutants' peak time can be observed under scenario 6 (50% urbanization in the far end of the watershed). Under this scenario, since the urbanized area is far from the watershed outlet and the highest urbanization percentage considered in this study was employed, the pollutant loads and the time of peak were increased.

These findings indicate that the location of urbanization affects both the amount and timing of runoff and pollutant loads. As an urbanized area is constructed farther away from the outlet point of the watershed, the peaks occur later in time. The percentage of urbanization is another factor affecting these values. As the urbanization percentage increases, more runoff and pollutants are generated. Moreover, climate change also affects the watershed yields. When the rainfall intensity and evaporation rates were increased under climate change conditions, the peaks occurred earlier in time.

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 change). This scenario shows 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 change), and 8 (50% urbanization in the whole watershed) showed highest percentages of reduction in pollutant loads. Furthermore, under scenario 9 (baseline scenario with climate change), no pollutant load reductions were observed.

4. Discussion

In this study, the impact of urbanization, climate change, and implementation of vegetative swales, as LID, on runoff and pollutant loads in the Mahabad Dam watershed in Iran, were evaluated. The watershed was first delineated in ArcGIS and then modeled in SWMM Ver. 5.1.013. This study covered seventeen scenarios on urbanization and climate change in different locations throughout the watershed. The following are the main findings of this study:

- The percentage of urbanization affects the watershed yields. In this study, 50% urbanization created higher runoff and pollutant loads in comparison with 20% urbanization. Comparing the 20% and 50% urbanization scenarios, 50% urbanization near the watershed outlet, resulted in runoff and pollutant loads increase of 23.1% and 27.4%, respectively. Urbanization in the middle of the watershed resulted in runoff and pollutant load increases of 28.8% and 35.4%. At the far

end of the watershed, urbanization resulted in runoff and pollutant load increases of 23.1% and 3.9%. Finally, urbanizing the whole watershed 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 is because of different sub-catchment areas, land uses, and imperviousness.

- The location of urbanization affects the amount of runoff, as well as pollutant loads. Areas urbanized farther away from the watershed outlet have delayed peaks in runoff and pollutant loads compared to urbanized areas near the outlet.
- Under climate change scenarios, the peaks occurred earlier in time because of the higher intensity and shorter duration rainfall events.
- LIDs decreased the pollutant loads. The highest reductions were observed when LIDs were employed in the following scenarios: 20% urbanization in the whole watershed with climate change (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 change (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 reservoir, the implementation of LIDs in this watershed is encouraged. Moreover, it is recommended to find critical source areas in this watershed and to avoid urbanization in these areas, since more imperviousness will increase the amount of pollutant loads from these areas as a result of increased surface runoff. In addition, critical source areas should be the priority for the implementation of LIDs. Ultimately, the findings of this study can be used as a guide for urban development that is in accordance with environmental quality standards.

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