A Rainfall-Runoff model for highly urbanized areas: A case study at Istanbul Technical University main campus

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ABSTRACT: Rapid urbanization and increasing impervious surfaces at the urban areas leads to serious reduction in infiltration rate of the surface and this causes several environmental problems and critical challenges in stormwater management. This research work dedicated to develop a Rainfall-Runoff and inundation model for a highly urbanized area using EPA SWMM (Storm Water Management Model). For this purpose, Istanbul Technical University main campus selected to model development and simulations under a rain storm event with 25-year return period and duration of 2 hours. This model developed based on the GIS data and infrastructure map of the study area. The peak runoff value and its occurring time have calculated through the model. Also, the number and location of flooded nodes of the study area’s drainage system at the peak runoff moment have determined in this study. According to the model results at the peak runoff moment there will be several flooded nodes in the study area. For reducing the number of flooded nodes and peak runoff value it is proposed to use LID (Low Impact Development) strategies at the university campus.

KEYWORDS: Storm Water Management, Urbanized Area, Inundation Model, Rainfall-Runoff Model, EPA SWMM, Istanbul Technical University.

1. Introduction:
Rapid urbanization is a critical phenomenon all over the world and unfortunately this may cause land surface modifications and increase impervious surfaces (Leopold, 1968) which in turn might cause several environmental problems regarding changing the natural flow regime of ground (Poff, 1997). In recent years flood management became one of the most challenging issues for the human societies (Sundermann et al., 2014). So there is a raising need for developing exact and accurate hydrological rainfall-runoff models in urban areas for flood forecasting and water resources administrations for sustainable urban development (Zhang and Pan, 2014). Wu et al. (2018) developed a hydrodynamic inundation model by coupling SWMM and IFMS-Urban and investigated inundation depth, runoff volume and peak runoff in case of simulating different rain storm events in Guangming New District of Shenzhen, China. Qin et al. (2013) considered an urbanizing catchment located in china for developing a rainfall-runoff model by using EPA SWMM and calibrated by using RMSD method. They investigated the changes in peak runoff, runoff volume and time to peak in case of change in rain storm characteristics such as: amount, duration and peak location of storm. For this purpose they used events with return
periods of 1 to 100 years and duration of 24 hours. Gülbaz & Kazezyılmaz-Alhan (2013) investigated the effects of urbanization on Sazlıdere watershed in Istanbul, Turkey, modeled and calibrated by EPA SWMM and noticed that there will be 64% and 126% increase in flooding amount due to the respectively 60% and 100% extreme urbanization in 2035. Hassan et al. (2017) developed a model by using EPA SWMM for evaluating the function of storm drainage system which subjected to illegal sewage connections and also climate change effects in an urban catchment in Karbala city, Iraq. They used a rain storm event with duration of 1 hour and return period of 2 years in this simulation. They found out that, by connecting extra sewage entries to the system and also occurring intense storm events due to the climate change the current system will be insufficient for storm water managements and there is an increasing flooding risk at the region.

The present study focuses on developing a rainfall-runoff model for Istanbul Technical University main campus as a small urban catchment by using EPA SWMM program. The study area’s hydraulic response to a storm event with duration of 2 hours and return period of 25-year was investigated through this simulation. The performance of campus drainage system measured with simulating the peak runoff discharge and number of flooded nodes belonging to the drainage system after the storm event.

2. Materials and methods:
A high resolution land cover map of the study area created by considering the GIS data and based on ITU main campus Auto CAD file. For this purpose Arc GIS program was used. Also a DEM file of the study area with resolution of Δx = Δy = 5 m, was used for elevation evaluations and sub catchment delineation. The infrastructure data belonging to the drainage system of the study area were also obtained from the Auto CAD file of the campus. Further field investigations were done for locating the missing nodes of the drainage system and also for validating the accuracy of the infrastructure data.

The rainfall data which used in this model obtained from “Sariyer” meteorology station located at the same district of the study area and fed into to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function and with 10 minutes intervals.

By preparing the initial information and data in Arc GIS program, Rainfall-Runoff model for the study area developed by using, EPA SWMM program. This SWMM model of the study area which has 1.08 km² area, consists of: 77 sub catchments, 196 junction nodes, 197 conduits and 4 outfall points in total. Figure 1 below, shows the location of rain gage, sub catchments, conduits, nodes and outfall points in the SWMM model of the study area.

![Figure 1: Position plan of different objects in the SWMM model of study area.](image-url)
This model employs nonlinear reservoir model to calculate the surface runoff due to the precipitation and correspond to each sub catchment. From conservation of mass in each sub catchment SWMM calculates the change in depth per unit of time with the formula below. All the equations have taken from the SWMM manual (Rossman 2015).

\[
\frac{\partial d}{\partial t} = i - e - f - q
\]  

(1)

Where: \(i\) is the Rainfall or snowmelt rate (mm/s), \(e\) is the Evaporation rate (mm/s), \(f\) is the Infiltration to the subsoil rate (mm/s) and \(q\) is the Runoff rate (mm/s). All the parameters are per unit area.

Assuming that each sub catchment has a width of “W” and slope of “S” and a height of “d” SWMM uses Manning equation for obtaining volumetric flow rate for each sub catchment:

\[
Q = \frac{1}{n} S^{1/2} A x R_x^{2/3}
\]  

(2)

Where: \(Q\) is the Volumetric flow rate (m³/s), \(n\) is the Surface roughness coefficient, \(S\) is the Average slope of sub catchment, \(A_x\) is the Area across the sub catchment’s width (m²) and \(R_x\) is the Hydraulic radius associated with the area (m).

Also this model uses dynamic wave routing method for flow routing in pipes which applies the complete one-dimensional “Saint Venant” flow equations, consist of continuity and momentum equations in conduits and volume continuity equations at the nodes and therefore provides the most real and accurate results relatively to other methods like: steady flow routing and kinematic wave routing.

- Momentum equation:

\[
\frac{\partial q}{\partial t} = g A \frac{\partial h}{\partial x} + g A S f + \frac{\partial (Q^2)}{\partial x}
\]  

(3)

- Continuity equation at a node:

\[
H_{t+} = H_t + \sum g A \frac{\partial h}{\partial x} 
\]  

(4)

In this method it is possible to model the pressurized flow and calculate the backwater effect in conduits and nodes. In pipes with fully pressurized flow and with circular force main cross-section this SWMM model instead of Manning equation uses Hazen-Williams formula.

Hazen-Williams formula (SI):

\[
h_f = 10.7 \times \left(\frac{Q}{C}\right)^{1.852} \times \frac{L}{D^{5/8}}
\]  

(5)

where: \(h_f\) is the Friction head loss (m), \(Q\) is the Discharge rate of the pipe (m³/s), \(C\) is the Hazen-Williams coefficient, \(L\) is the Pipe length (m) and \(D\) is the Pipe diameter (m).

Hazen-Williams coefficient \(C\), supplied as one of the cross section parameters and changes inversely with surface roughness. Furthermore in this model “Modified Green-Ampt” method used for infiltration losses calculations. The integrated form of Green-Ampt equation is given below:

\[
F = K_s + \psi_s \theta_d \ln \left(1 + \frac{F}{\psi_s \theta_d}\right)
\]  

(6)

Where: \(F\) is the Cumulative infiltration (mm), \(K_s\) is the Saturated hydraulic conductivity (mm/hr), \(\psi_s\) is the Capillary suction head along the wetting front (mm) and \(\theta_d\) is the Initial moisture deficit.

Dynamic wave routing and modified Green-Ampt methods were used for obtaining results with higher accuracy in simulations.

3. Model calibration:

For model calibration a rainfall event at the study area with duration of 8 hours and 30 minutes starting at 10:00, April 18 considered for measurements with 15 minutes intervals.
For this rainfall event measured cumulative rainfall obtained 3.15 mm at the field. At the same time the water depth at one main manhole measured with intervals of 15 minutes. At the end, same rainfall event simulated at SWMM model of the study area. The corresponding depths which obtained from SWMM model for the same manhole compared with the measured ones.

Figure 2 shows the values of simulated water depth at the manhole by SWMM before calibration and measured values for the water depth at the manhole according to the time.

![Figure 2: Values of simulated water depth before calibration and measured water depth in (mm).](image)

Root Mean Square Deviation (RMSD) method which is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed, was used for comparison process in this study.

RMSD formula is given below:

\[
RMSD = \left( \frac{1}{n} \sum_{i=1}^{n} (V_i - W_i)^2 \right)^{1/2}
\]

Where: \(V_i\) and \(W_i\) are the measured and simulated values for the water depth at the manhole at the time \(i\) and \(n\) is the number of measured time intervals.

By modifying some of soil properties and Manning’s roughness coefficient of the surfaces, it is tried to reduce the RMSD value from 14.14 mm to the 10.35 mm in manhole water depth comparisons.

Table 1 below shows the values for the soil characteristics of the study area before and after the calibration. The calibrated parameters inputted to the model for Rainfall-Runoff model development.

|                      | Before calibration | After calibration |
|----------------------|--------------------|------------------|
| Hydraulic Conductivity (K) (mm/h) | 1.01               | 0.5              |
| Suction Head (Su) (mm)         | 270                | 240              |
| Porosity ( fraction )          | 0.471              | 0.43             |

Figure 3 below shows the values of simulated water depth at the manhole by SWMM after using calibrated parameters and measured values for the water depth at the manhole according to time.
4. Results and discussions:
A rain storm with duration of 2 hours and return period of 25-year simulated in this model and the response of the campus area investigated for this rain storm event. This rain storm was inputted to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function.

From the model results peak runoff of the simulated model occurs 70 minutes after the rain storm begins and the value of peak runoff obtained 1.30 (m³/s). Lag time of the precipitation hyetograph and peak runoff in this simulation obtained 10 minutes. Figure 4.a) shows the precipitation data (mm/hr.) inputted to the model while Figure 4.b) shows the system runoff (m³/s) at the outlet point of the study area.

To illustrate the inundation condition of the study area at the peak runoff moment of the simulation, Figure 5 was prepared according to the model results and presented below.
Figure 5: Inundation condition of the study area at the peak flow moment of the simulation.

According to the results of simulation and as it is obvious from the Figure 5, there are 4 nodes which identified with red color and located at the central parts of the study area, they are completely inundated because water depth reached over 2 m in them and this is while their maximum available depth is 2 m. Additionally there are 12 nodes which identified with yellow and green colors again located at the central parts of the study area which are close to be flooded because of their limited available depths.

It is obvious from the model results that in case of a storm event with duration of 2 hours and return period of 25-year there will be flooding specially in central parts of the study area.

5. Conclusion:
This research aims to simulate the hydraulic response of the ITU main campus as a small urban catchment under a storm event with duration of 2 hours and return period of 25-year by using EPA SWMM program. During this simulation the study area divided to 77 sub catchments and then the drainage system of university campus which consisted of 196 junction nodes, 197 conduits and 4 outfall points modeled in the SWMM by using GIS and infrastructure data.

For model calibration field measurements were compared with the simulated values. Some of the soil characteristics of the study area were modified in calibration process. The RMSD value after calibration obtained 10.35 mm which shows the SWMM model has a good representation of the storm runoff process in this simulation.

The model results in this research show that there will be peak runoff at the university campus with the value of 1.3 (m³/s) after 70 minutes since rain storm begins. This means that the lag time between hyetograph and hydrograph equals to 10 minutes.

Furthermore it seems that the central parts of the study area have more critical situation during heavy storms. The model results show that there will be absolutely flooding in 4 nodes and partly flooding in 12 nodes all located at the central parts of the university campus in the try with a rain storm with 2 hours duration and 25-year return period.

Design and implementation of low impact development strategies, especially at central parts of the study area highly recommended for increasing the permeability of the surface and decreasing the risk of flooding.
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