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Developing a Distributed Hydrological Balance Model for Predicting Runoff in Urban Areas in Tehran, the Capital of Iran

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ABSTRACT

Aims: The conversion of orchards and agricultural lands in urban areas to residential and commercial areas has caused various hydrological changes in urban watersheds. This research aims to provide an Urban Distributed Hydrological Balance Model (UDHBM) to investigate the urban runoff in some parts of Tehran, including Tajrish and Elahiye.
Materials & Methods: To reach this goal, we first broke down the runoff amount of upstream mountain and urban areas from measured values. The HEC-HMS Model has been used to determine the volume of net runoff and flood produced in metropolitan areas. The annual water balance model, considering rainfall, evaporation, and other necessary inputs, has been made after defining the amount of flood in metropolitan areas. In the next step, a sensitivity analysis was carried out on the main factors affecting the model to better understand the model's behavior by changing these factors.
Findings: This sensitivity analysis showed that this model is most sensitive to the rain factor and soil hydraulic conductivity. Comparing estimated values and urban runoff observations shows a minimum root-mean-square error and a maximum correlation coefficient of 89%, with a significance level of 5%.
Conclusion: The UDHBM model can calculate the runoff volume based on the water balance for each land use, including residential houses and buildings, streets, parks, and urban green spaces.

Keywords: Hydrological Distribution Model; Urban Runoff; UDHBM Model; Water Balance.

CITATION LINKS

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Introduction

Floods are one of the most destructive and complex natural events that threaten human life, property, and economic and social conditions of communities, mainly in urban areas like Golabdare, as in the case of the Tehran flood in 1987. Knowing how much and how each part of the city, such as buildings, avenues, parks, and urban green spaces, are involved in producing a specific volume of runoff can help plan to reduce urban flooding. According to several floods in Tehran and the rate of rainfall that occurred, it is shown that the risk of flooding in Tehran with a threshold of 35- 40 mm is possible [1]. Although there is low rainfall in many parts of Iran, more than half of the annual rainfall may happen in one or two days in many regions due to specific weather conditions. This will cause problems in many urban areas, especially in the hillsides of Alborz and Zagros mountains (such as Tehran) [1]. Nowadays, there are different research studies in distributed hydrological models and, in general, models that are used in urban hydrology. A few articles have investigated urbanization's hydrological effects based on field data [2,7]. These articles showed that validating the physically based distributed hydrological ECOMAG model has positive and hopeful results for spatial observations. By combining a semi-urbanized runoff flow model with GIS and comparing it with the conventional and acceptable models in urban hydrology [8,9], the model provides valuable simulation results and has better progress in urban model performance. Surface runoff in urban watersheds and the determination of morphological hydrograph units according to the urban data bank showed that unit hydrographs for the City (URBS-UHs) are similar in terms of shape and size with rainfall-runoff hydrographs resulting from measurements [10]. Berthier et al. [11] showed that soil has a vital role in making runoff in small-scale like urban areas, and its average share is 14% of the total runoff volume in each rainfall. Vaes G et al. used two one-dimensional hydrodynamic Infoworks CS and MOUSE models for modeling floods in drainage systems in Belgium for two cases of one and two collection routes for each street. It was concluded that in both cases, flood peak discharges do not have a huge difference, but the duration of floods on street surfaces has a significant difference. Cristiano et al. [13] used a new ecohydrological streamflow model to estimate runoff in urban areas. The model was calibrated and validated within two densely urbanized sub-basins in Charlotte (U.S.). A Monte Carlo procedure is used to investigate the efficiency of random sets of 8 model parameters. Results show the high model performance (NSE = 0.72). Synthetic experiments show that increasing urbanization triggers a linear decrease in evapotranspiration and aquifer recharge while it increases the fast runoff. Research conducted in two urban sub-watersheds in the City of Nantes, France, for the development and application of distributed hydrological models for urban areas (URBS-MO) showed how water balance develops in an urban watershed, according to a series of modeling related to the water cycle in the soil water balance develops in an urban watershed. Also, more mapping of hydrological floods in urban areas, such as soil water storage capacity, is essential [14]. By combining water routes in permeable areas in urban hydrological models, Hamouda and Lahbassi [15] showed that in developed models, the hydrological functioning of permeable zones in urban hydrological models is subject to conditions such as continuous flow, wastewater evaporation, sweating, and various other streams. They also showed that the structure of the model is to know the saturation state of soil in each step. In this study, the Nash–Sutcliffe index in flood simulation for two events in 2003 and 2005 were 0.917 and 0.73, respectively, and the RMSE for

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these events were 0.76 and 0.48, respectively. Research by Kidmose et al. [16] showed that in the investigated urban area (City of Silkeborg, Western Denmark), a quarter (24%) of water entering the runoff system of flood comes from groundwater resources. They coupled a distributed hydrological model and a runoff stormwater model and illustrated that there is a high potential for water exchange between urban water cycle compartments that most often are disconnected and not considered in urban runoff modeling. Yu et al. [17], by evaluating the significance of hydrological parameters of catchment areas for modeling surface water flow in a simple hydro-flood model, showed that the model is sensitive to hydraulic conductivity, a crucial hydrological parameter. Miller and Hess [18], also investigating the impact of urbanization on storm runoff, indicated that spatial measures of urbanization can explain differences in the hydrological response between rural and urban catchments.

According to the research, estimating flooding components from rainwater in an urban area in a given storm and determining this in the future is essential to obtain acceptable results for use in urban planning for structural and transportation purposes. On the other hand, an efficient planned model will inevitably be created to prevent flooding of the city and streets and provide a reliable base for adequately implementing the principles of urban watershed management and sustainable development in the metropolis of Tehran. The primary purpose of this research is to provide an Urban Distributed Hydrological Balance Model (UDHBM) in a section of Tehran based on the existing urban information, the test model performance, and the validation of the model in this region.

Materials & Methods

Study Area

The study area is 39.16 km2 and contains two sections: the upstream section of the natural mountain watershed and the downstream urban residential sector. The mountainous watershed of 32.4 square kilometers includes Darband and Golabdare catchments in Tehran (Figure 1). The average slope is around 20 %, and annual precipitation equals 220 $mm.y^{-1}$ based on the recent 30 years of data. Because this watershed is located upstream of the metropolitan area, studies are restricted to hydrograph simulation of input floodwater to this area by the HEC-HMS model. To implement the HEC-HMS model, the mountain section has been divided into four sub-watersheds (Figure 2). The metropolitan area includes parts of one region of Tehran (Tajrish and Elahiye) with an area of 6.76 square kilometers. This region is the main study area in this research.

Methodology

In this research, at first, basic statistics and information were extracted from meteorological and hydrological information, including rainfall information, floodwater hydrographs, daily evaporation, event time information, information about physiographic and morphological sub-watershed and urban areas such as concentration time and lag time, curve number, the percentage of impervious areas, permeability, sub-watersheds areas, the area of each type of land use, canopy in urban areas from banks Ministry of Energy, Tehran regional Water, forest, rangeland, watershed Management, and also the use of remote sensing technology and GIS and conducted field visits and sampling. Then, the gathered data was used in the model. Maghsood-Beyk is the only active hydrometric station in the study area, with information from 2006. Because of the need for more information about simultaneous input hydrographs and output ones for the studied metropolitan area, the HEC-HMS model was used to stimulate hydrographic inputs and calculate floodwater in urban areas. After implementing the HEC-

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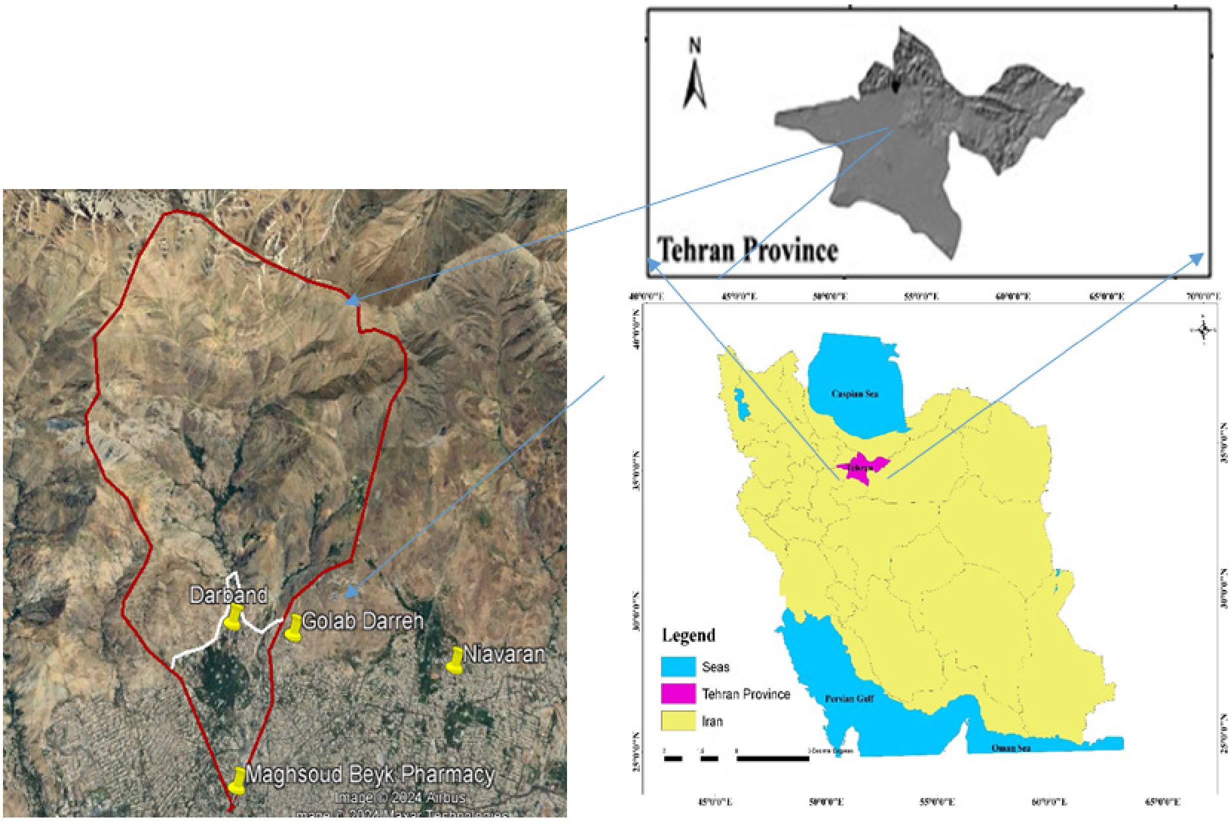

Figure 1) Location of the study area in the Province and City of Tehran, Iran.

Table 1) Physical characteristics of sub-watersheds.

Sub-watershed	Area (km^2)	Curve No.	Concentration time (min)	Lag time (min)	Initial abstraction (mm)	Impervious areas (%)
1	9.62	86.35	32.81	19.69	8.03	4
2	8.71	86.52	36.26	21.76	7.91	18
3	6.84	86.65	27.59	16.55	8.51	2
4	7.23	85.55	75.25	45.15	8.85	3
5	6.76	96.5	57.23	34.34	1.84	70

HMS model, sensitivity analysis was done on curve number, initial abstraction, and lag time, where the last parameter directly relates to Concentration time (Table 1). For model sensitivity analysis, each of the above parameters had a 20% increase and a decrease with 5% steps. Then, the model was implemented for each step.

Eq. (1) has been used to determine the difference in results.

$$D = \left(\left(V_S - V_{Obs}\right)/V_{Obs}\right) \times 100 \qquad \text{Eq. (1)}$$

where D is the percent of the difference, VS is simulated hydrographic volume, and V_{Obs} is hydrograph volume observations.

The introduced model in this research (UDHBM) can be considered a hydrological distribution model. The basic idea of this model is from the [13]. Modeling of rainfall-runoff processes in this research generally had three

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horizontal levels and two vertical sections. The horizontal levels are in terms of land use, including residential houses (hou), streets (str) and urban parks and green spaces (nat), and vertical sections are above-ground processes (including rainwater interception by trees, stem flow and evaporation from surfaces of trees) and on-ground processes (including surface runoff, evaporation from ground surface, and water infiltration into the soil that due to the lack of preparation of the necessary information, it is restricted to information about penetration into zero to 30 cm layers of soil. The horizontal levels and vertical sections for modeling are shown in (Figure 3)

In this study, we tried to provide the model with maximum accuracy and simplicity according to available data and facilities in Iran. The modeling process and model parts are shown in (Figure 4) All the values are calculated volumetrically, and the total runoff volume is calculated.

UDHBM Model Assumptions

1. The depression storage is 0.2 S, which equals 1.84 mm. If multiplied by the street's areas, the value becomes 1619.2 cubic meters.

2. According to the field visits and difficulty in the census of houses, the water collected on the roofs of all residential houses and

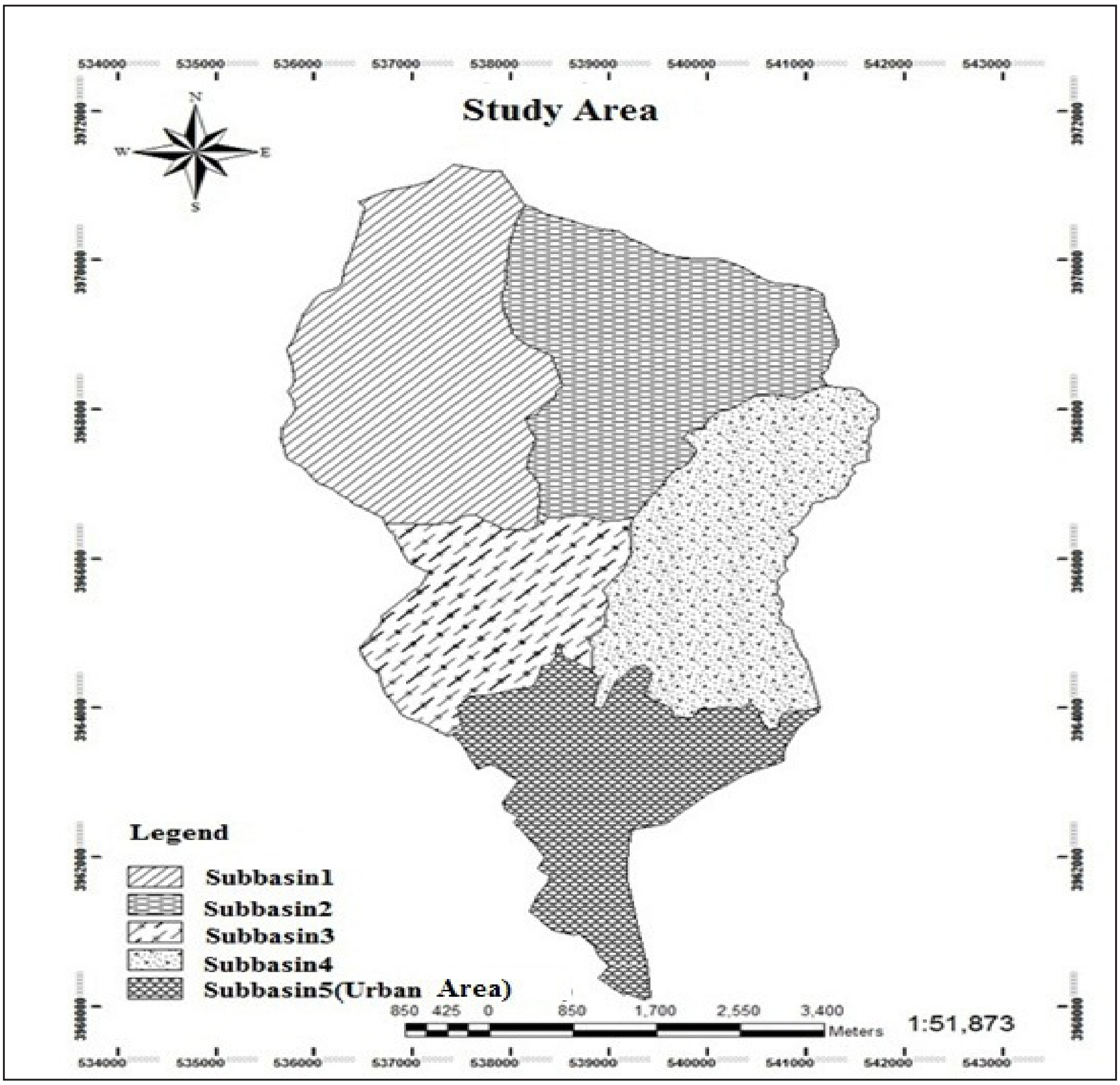

Figure 2) The study area (Darband and Golabdare catchments including one to four sub-watersheds and urban areas including Tajrish and Elahiye in Tehran).

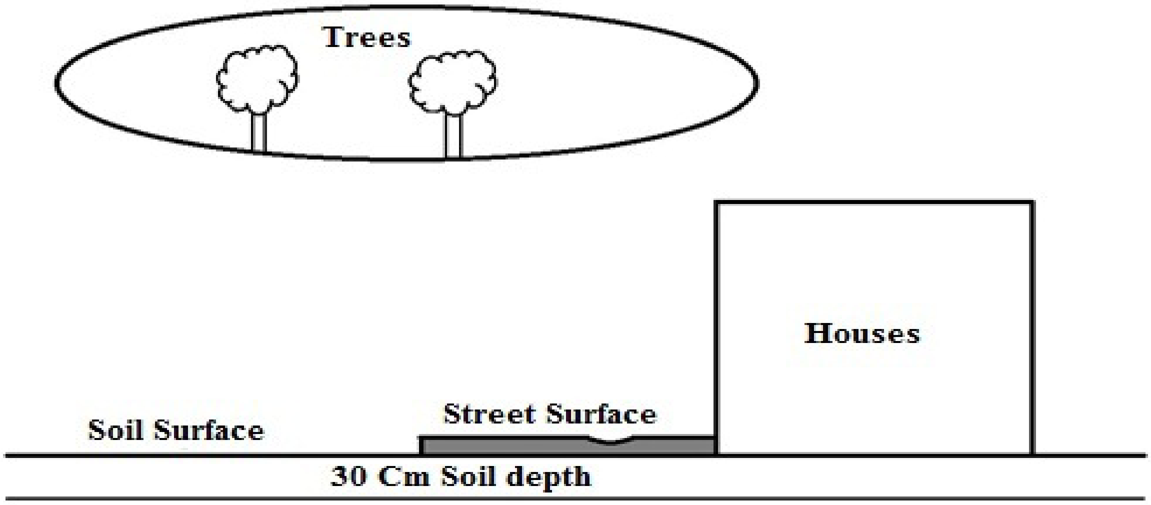

Figure 3) Horizontal levels and vertical sections used in modeling.

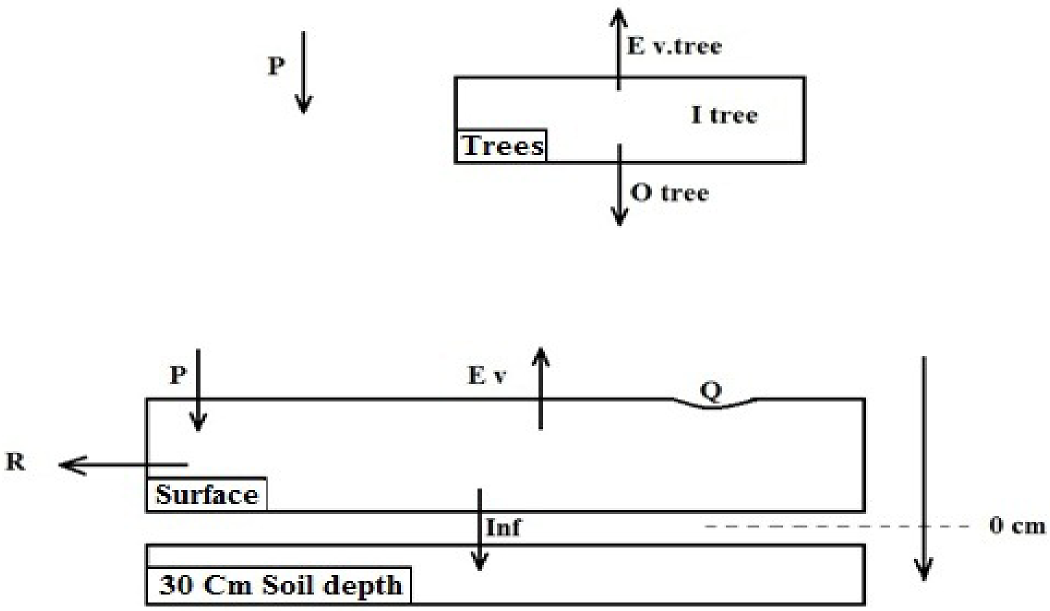

Figure 4) Modeling process and model parts.

buildings is assumed to flow to the street.

3. According to the field visits, most of the vegetation in the city is plane trees, so it is assumed that all the trees in the study area are the type of plane.

4. Fixed infiltration during the rainfall is assumed.

Modeling Over Ground Processes

This study considers rainwater interception by trees in the streets and natural levels necessary. *Asaadi's* results [19] have been used for calculating plant interception and stem flow. Leaves of trees represent a simplified tank model that is rain-fed and then evacuated by evaporation and drainage [13]. Due to the dominance of plane tree coverage in the study area, coefficients of plane trees have been used in the proposed model. Equations of over-ground processes are as follows:

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Eqs. (2) and (3) show the volumes of rainfall on crowns of trees on the streets, parks, and urban green spaces.

$$P_{tree.str} = P.A_{tree.str}.10^3 \quad \text{Eq. (2)}$$

$$P_{tree.nat} = P.A_{tree.nat}.10^3 \quad \text{Eq. (3)}$$

where $P_{tree.str}$ and $P_{tree.nat}$ are the volumes of rainfall on the trees in the street and park trees and urban green spaces in m^3, respectively. $A_{tree.str}$ and $A_{tree.nat}$ are the crown areas covering trees in the street and park trees and urban green spaces in m^2, respectively. P is the cumulative rainfall height of an event or daily rainfall in mm. Coefficients have been used in order to convert units.

The volume of stem flow from trees in the streets, parks, and urban green spaces is as follows:

$$O_{tree.str} = P_{tree.str}.S_f \quad \text{Eq. (4)}$$

$$O_{tree.nat} = P_{tree.nat}.S_f \quad \text{Eq. (5)}$$

where $O_{tree.str}$ and $O_{tree.nat}$ are volumes of stem flow from rainfall on trees in the street and parks and urban green spaces in m^3, respectively. S_f represents the percentage of rainfall that turns to stem flow for plane trees and equals 0.8% [19].

Eqs. (6) and (7) can calculate the volume of plant interception for crown coverage of trees in the streets, parks, and urban green spaces, respectively.

$$I_{tree.str} = P_{tree.str}.I_f \quad \text{Eq. (6)}$$

$$I_{tree.nat} = P_{tree.nat}.I_f \quad \text{Eq. (7)}$$

where $I_{tree.str}$ and $I_{tree.nat}$ are the volumes of plant interception from trees in the street and parks and urban green spaces in m^3, respectively. The plant interception percentage of plane trees equals 9.87% [19].

Eq. (8) shows the amount of evaporation volume for any use of the street trees, park trees, urban green spaces, roofs of houses and buildings, surface of the streets, and natural soil, including parks and urban green spaces.

$$E_{v.i} = E.A_i.10^3 \; i: tree.str, tree.nat, hou, str, nat \quad \text{Eq. (8)}$$

Where E.V.i is the volumetric evaporation of each land use in m^3, E is the daily average evaporation in mm, and A_1 is the area of each land use in km^2. *Tree. str* shows the street trees, *tree nat* shows park trees and urban green spaces, *hou* shows residential houses and buildings, *str* shows the street surface, and *nat* shows the surface of parks and green urban spaces. Coefficients were also used to convert units. Note that daily evaporation was obtained from the Meteorological Organization of Iran.

The volume of water stored on the leaves of the park trees and urban green spaces is as follows:

$$S_{tree.nat} = I_{tree.str} - Ev._{tree.str} \quad \text{Eq. (9)}$$

If $S_{tree\ str} < 0$, then $S_{tree.str} = 0$.

where $S_{tree.str}$ and $S_{tree.nat}$ are the volumes of storage water on the leaves of street trees, park trees, and urban green spaces in m^3, respectively.

Modeling Processes on the Ground Surface

Ground surface processes include surface runoff, evaporation from the surface, and soil infiltration. The amount of soil infiltration was unavailable because digging deep profiles in the neighborhoods was not feasible. Therefore, the infiltration rate in the soil layer was inevitably considered 0 to 30 centimeters.

The hydrological effects of this layer of soil and evaporation of water from the surface of urban spaces must be considered so that a definite

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process, like evaporation, transpiration [20], and soil water drainage through the sewerage network, is proven as a significant component of the urban water balance.

Equation 10 shows the infiltration for natural soil and Permeable zones.

$$Inf = In.A_{nat}.10^3 \quad \text{Eq. (10)}$$

where is volumetric infiltration for the permeable zone in m^3, is infiltration in mm, and is parks' areas and urban green spaces in km^2. According to the fourth assumption in our model assumptions, In is:

$$In = K_s.\Delta t.10 \quad \text{Eq. (11)}$$

$$\Delta t = (t_2 - t_1)/24 \quad \text{Eq. (12)}$$

where In is infiltration during rainfall in mm, K_s is saturated hydraulic soil conductivity in cm / day, and Δt is the rainfall duration in days, t_1 and t_2 are the beginning and end of rain, respectively.

For calculating the hydraulic conductivity of saturated soil, parks, and urban green spaces were divided into three homogeneous units according to vegetation and slope. Sampling has been done on virgin and non-vigent soil groups in every homogenous unit. The samples have been taken to the Laboratory of Soil Science, Faculty of Natural Resources, Tehran University. Experiments on soil density have been done, such as determining the texture by wet sieving and hydrometry methods. Due to the higher accuracy of hygrometry, the results from this model are used. Finally, using RETC software, the hydraulic conductivity coefficient of saturated soil coefficient for each unit is determined [20]. Saturated hydraulic conductivity was calculated using the weighted average for the entire watershed.

The volume of surface runoff from streets is calculated as below:

$$R_{str} = \left[\left(P.A_{str}.10^3\right) + O_{tree.str} - \left(S_{tree.str} + Q + E_{v.str}\right)\right].r_{str} \quad \text{Eq.(13)}$$

where R_{str} is is the volume of surface runoff from streets in m^3, Q is the storage volume of potholes in m^3, $E_{V.str}$ is the volumetric evaporation from the surface of streets in m^3, *and* r_{str} is the runoff coefficient of asphalt and equals 0.9 .

Eq. (14) shows surface runoff from parks and urban green spaces[21].

$$R_{nat} = \left[\left(P.A_{nat}.10^3\right) + O_{tree.nat} - \left(S_{tree.nat} + Inf + E_{v.nat}\right)\right].r_{nat} \quad \text{Eq. (14)}$$

If $\mathrm{R}_{nat} < 0$, then $\mathrm{R}_{nat} = 0$.

where R_{nat} is the volume of surface runoff from parks and urban green spaces in m^3 $E_{V.str}$ is the volumetric evaporation from the surface of parks and urban green places in m^3, and r_{nat} is the runoff coefficient of parks and urban green spaces and equals 0.1.

The volume of runoff from residential houses and buildings can be calculated as below:

$$R_{hou} = \left[\left(P.A_{hou}.10^3\right) - E_{v.hou}\right].r_{hou} \quad \text{Eq. (15)}$$

where R_{hou} is the volume of runoff from residential houses and buildings in m^3, $\mathrm{E}_{V.hou}$ is the volumetric evaporation from roofs in m^3 *and* r_{hou} is the runoff coefficient of roofs, equal to 0.9.

Finally, the total runoff volume in the metropolitan area's water balance is the sum of surface runoff caused by each land use type, based on Eq. (16).

$$R_{total} = R_{str} + R_{nat} + R_{hou} \quad \text{Eq. (16)}$$

R_{total} is the total runoff volume in the water balance of the metropolitan area in m^3.

This model also needs morphological and hydrological parameters. Morphology parameters are listed in (Table 2) and cover an area of three main uses in the model (houses, buildings, streets, and parks and urban green spaces), area

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of street trees canopy and tree canopy in urban green spaces. Hydrological parameters used in the model are also listed in (Table 3).

In the first phase, soil density was determined by the hydrometer method using undisturbed soil samples and soil texture. The results are listed in (Table 4). Sample numbers 1 and 2 are from urban green space regions, and sample number 3 is from the natural soil region with no considerable area. Despite our expectations, sample number 2 had a low specific volume due to high humus volume. In the next phase, these values were used in RETC software. The results are shown in (Table 5).

After determining the saturated hydraulic conductivity coefficient of soil for each specified homogenous unit, the saturated hydraulic conductivity coefficient of soil for the entire region of parks and urban green spaces was determined using the mean weighted method. It was equal to 47.40 centimeters per day.

Results and Discussion

Sensitivity Analysis of HEC-HMS Model

The sensitivity analysis showed that the model has the highest sensitivity to the curve number parameter and considerable sensitivity to the initial loss parameter. Model sensitivity to latency could be higher and should be addressed. Figure 5 shows the results of the sensitivity analysis of the model. There is some consideration about Figure 5. In the curvature number parameter, due to the excessive increase of the curve number parameter, there are no results for the 15% and 20% steps, so consequently, there is an error in the execution of the model. It should be noted that the maximum value of the curve number is 98. Eq. (1) determines the rate of difference in the results.

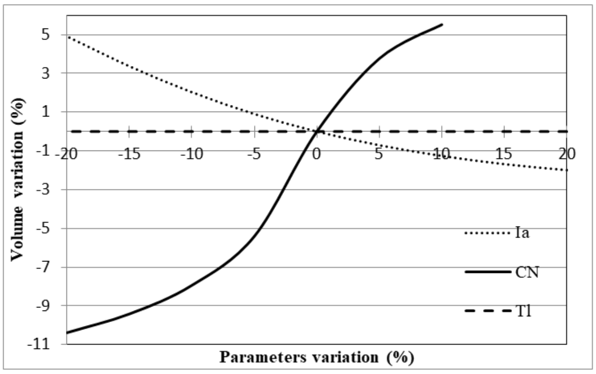

Figure 5) Sensitivity analysis results of HEC-HMS model.

The HEC-HMS model is optimized according to runoff volume, and the suggested water balance model in this study is prepared for flood volume estimation. Three of six available events are selected to validate the model in the optimization phase. (Table 6) shows the optimized curvature number and initial loss for each of the sub-watersheds.

Table 2) Morphology parameters of the metropolitan area.

Symbol	Unit	Description	Value
A_{str}	Km^2	Streets area	0.88
A_{nat}	Km^2	Parks and urban green spaces area	1.51
A_{hou}	Km^2	Residential houses and buildings area	4.38
$A_{tree.str}$	Km^2	Area of street trees canopy	0.25
$A_{tree.nat}$	Km^2	Tree canopy in urban green spaces	1.12
A_{total}	Km^2	Total urban area (sum of areas of three uses)	6.76

Table 3) Hydrological parameters of the model.

Parameter	Unit	Description	Value
P	mm	Cumulative rainfall height of an event or daily rainfall	-
$P_{tree.str}$	m^3	The volume of the rain on the street trees	-
$P_{tree.nat}$	m^3	The volume of rain on trees in urban parks and green spaces	-
$O_{tree.str}$	m^3	The volume of stem flow from the street trees	-
$O_{tree.nat}$	m^3	The volume of stem flow from urban parks and green spaces	-
$I_{tree.str}$	m^3	The volume of vegetal interception of street trees	-
$I_{tree.nat}$	m^3	The volume of vegetal interception of trees in parks and urban green spaces	-
S_f	%	Stem flow of plane tree	0.008
I_f	%	Vegetal Interception of plane tree	0.0978
E	mm	Average daily evaporation	-
$E_{V.tree.str}$	m^3	Evaporation volume from the street trees	-
$E_{V.tree.nat}$	m^3	Evaporation volume from park trees and urban green spaces	-
$E_{V.str}$	m^3	Evaporation volume from the surface of streets	-
$E_{V.nat}$	m^3	Evaporation volume from park and urban green spaces surfaces	-
$E_{V.hou}$	m^3	Evaporation volume from roofs	-
$S_{tree.str}$	m^3	The volume of water stored on the leaves of street trees	-
$S_{tree.nat}$	m^3	The volume of water stored on the leaves of park trees and urban green spaces	-
K_s	$cm.d^{-1}$	Saturated soil conductivity	47.40
In	mm	Infiltration during rainfall	
Inf	m^3	Volumetric infiltration during rainfall	
Q	m^3	Volume of potholes saving on the street surface	1619.2
r_{str}	-	Runoff coefficient of asphalt	0.9
r_{nat}	-	Runoff coefficient of parks and urban green spaces	0.1
r_{hou}	-	Runoff coefficient of roofs	0.9
R_{str}	m^3	Flow rate from streets	-
R_{nat}	m^3	Flow rate from parks and urban green spaces	
R_{hou}	m^3	Flow rate from residential houses and buildings	
R_{total}	m^3	Total runoff volume	

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Table 4) Soil Parameters in the study area.

Parameter	Sample No.1	Sample No.2	Sample No.3
Fine gravel %	38.4	50.6	30.4
Clay %	31.8	27.8	41.98
Silt %	29.8	21.6	27.62
Soil texture	clay loamy	Sandy clay loamy	Clay
Soil bulk density	1.31	1.1	1.22

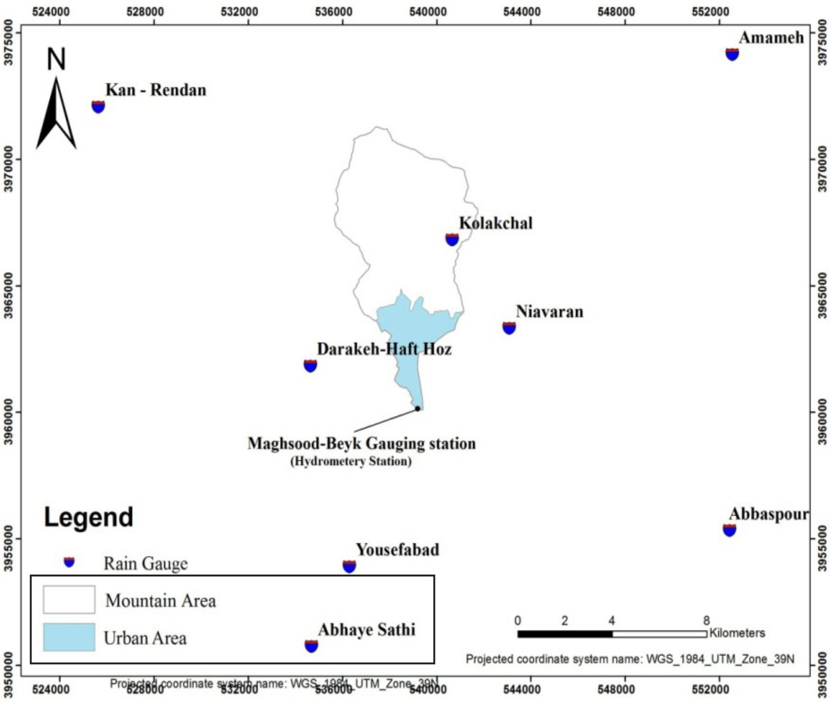

Figure 6) Distribution of stations in the surroundings of the study area.

After determining optimized values, these values were used in the model, and the results were obtained. (Table 7) shows the results for validation.

After the HEC-HMS model validation, the model simulates flood entrances in metropolitan areas. Hyetograph data of storms in total upstream mountain watersheds and average rainfall for each sub-watershed event were included in the model, and the model was implemented. It should be noted that the average rainfall for each sub-watershed is obtained through interpolation and Arc GIS software (Arc Map-Inverse Distance Weighted method). In this phase, the statistics of rain gauge for Kalchal, Niavaran, Yousef Abad, Amame, Surface water, Kan (Rendan), Darake (Hafthoz), and Power and Water University of Technology stations are used to calculate the average rainfall of each sub-watershed more precisely. Figure 6 shows the distribution of stations in the study area.

Urban hydrographs are simulated using the HEC-HMS model. The results are shown in (Figure 7). The volume of simulated flood in mountain regions was obtained from the HEC-HMS model and is deducted from the observed volume of flood hydrographs. These values are listed in (Table 8).

Implementation of the UDHBM Model

First, all the equations were written as code

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Table 5) Results from RETC software.

Parameter	Sample No.1	Sample No.2	Sample No.3
θ_r	0.083	0.0814	0.0967
θ_s	0.4607	0.5144	0.5075
$K_s\left(cm/d\right)$	16.64	61.68	30.82
α	0.0131	0.0164	0.0162
n	1.4368	1.4214	1.3719
I	0.5	0.5	0.5

Table 6) Optimized parameter values for each of the sub-watersheds.

Sub-watershed number	CN	Ia (mm)
1	86.90	7.13
2	86.38	6.39
3	86.13	8.62
4	86.10	8.11
5	96.46	1.67

Table 7) HEC-HMS model validation results.

Event	Observed Flood Volume (1000 m^3)	Simulated Flood Volume (1000 m^3)	The Difference in Percent
April 02, 2007	114.27	118.96	4.4
February 11, 2009	225.15	210.55	-6.48
April 13, 2009	55.36	57.29	3.49

in the MATLAB software to implement this phase, and all the required morphology and hydrology parameters were entered into the model. The model was implemented for each event. In (Table 9) the runoff volume of each type of land use is listed.

As seen in (Table 9), the value of runoff volume from parks and urban green spaces in all the events is zero. The reason is that the total amount of evaporation and infiltration is more remarkable than the rain volume. On the other hand, lawn areas and their high potential in surface absorption and low slopes of parks and urban green spaces have considerable effects.

Streets, buildings, and urban green spaces comprise 13%, 64.8%, and 22.2% of the study area. On average, the share of streets and buildings in runoff is 14.11% and 85.87%, respectively. 77.8% of the study areas, which include impermeable surfaces, affect runoff. With these explanations, increasing parks and urban green spaces has a considerable effect on decreasing runoff.

Model Sensitivity Analysis

The essential input parameters of this model

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Table 8) Volume of flood from urban area according to event date.

Event date	The Observed Volume of the Hydrograph (1000 m^3)	Mountain Region Flood Volume (1000 m^3)	Urban Area Flood Volume (1000 m^3)	Mountain Region Runoff Height (mm)	Urban Area Runoff Height (mm)
December 23, 2005	89.28	24.48	64.80	7.56	95.85
March 23, 2007	114.27	44.84	69.43	13.48	102.70
February 1, 2009	59.23	19.86	39.37	6.13	58.24
February 11, 2009	225.15	87.01	138.14	26.86	204.34
April 13, 2009	55.36	20.78	34.58	6.41	51.16
April 30, 2009	138.82	57.82	81.00	17.85	119.82

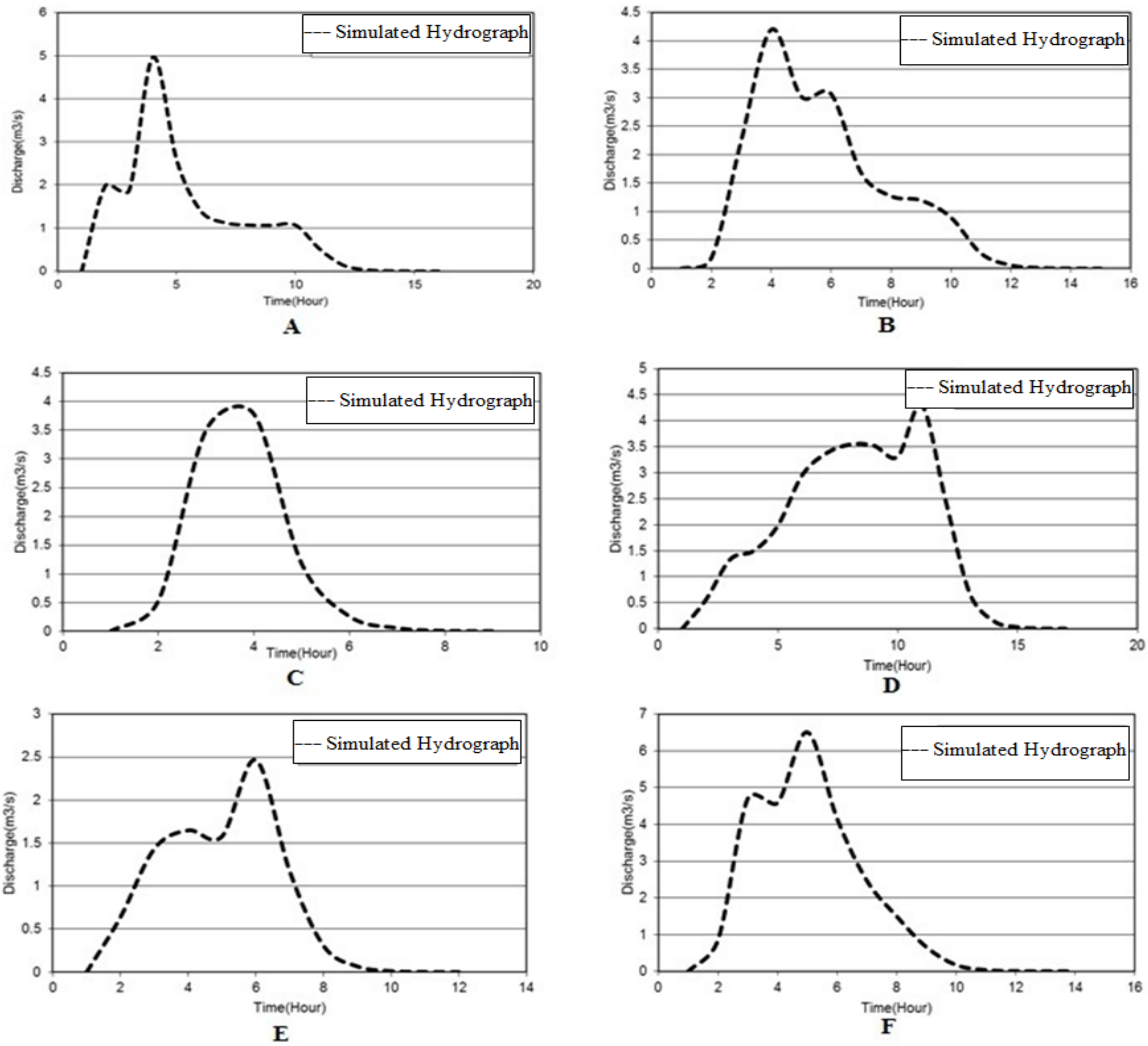

Figure 7) Simulated Hydrographs using the HEC-HMS model. A: simulated hydrographs in an urban area on December 23, 2005. B: simulated hydrographs in an urban area on March 23, 2007. C: simulated hydrographs in an urban area on February 1, 2009. D: simulated hydrographs in an urban area on February 11, 2009. E: simulated hydrographs in an urban area on April 13, 2009. F: simulated hydrographs in an urban area on April 30, 2009.

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Table 9) Runoff volume of each type of land according to event date.

Event date	R_{str} (m^3)	R_{hou} (m^3)	R_{nat} (m^3)	R_{total} (m^3)
December 23, 2005	7262.4	43244	0	50506.4
March 23, 2007	6795	41115	0	47910
February 1, 2009	3382.3	23999	0	27381.3
February 11, 2009	2076	109670	0	129746
April 13, 2009	4186.3	27988	0	32174.3
April 30, 2009	17743	97919	0	115662

include rainfall, evaporation, and saturated hydraulic conductivity. Since the model is based on the estimation of the runoff volume and acts according to the study area, it is evident that minor changes in rainfall (p) have a profound impact on the volume of floods. Usually, the value of this parameter for each event is determined and cannot be changed. As said earlier, the model is sensitive to high rainfall, and the relation between rainfall and estimated volume is direct and linear, as shown in Figure 8. The saturated hydraulic conductivity parameter (k_s) directly related to infiltration is also evaluated. As seen in Figure 8, the saturated hydraulic conductivity parameter has an inverse linear relationship to flood volume, and it can affect the model results only if the amount of rainfall in an event has a greater value than the sum of evaporation and infiltration volumes. According to the sensitivity analysis results, evaporation is an effective parameter in the model, but the effect is less than that of rainfall parameters and saturated hydraulic conductivity. The main reason is the lower value of this parameter compared to the rainfall and saturated hydraulic conductivity parameters during rainfall. The pothole save parameter (q) does not significantly influence results. The relation between pothole saving and total runoff volume is linear and reverse. Eq. (1) is used to determine the variation in the result.

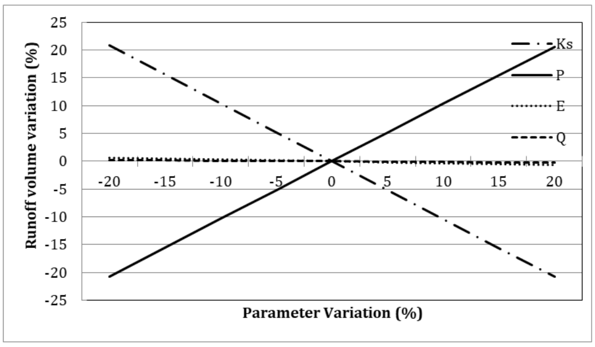

Figure 8) Sensitivity analysis of the water balance model.

Model Validation

For model validation, the Root Mean Square Error (RMSE) for all of the events was determined, and finally, the correlation coefficient between data was evaluated. The RMSE for flood volume is 18657 cubic meters, and the runoff height was 2.7 millimeters. The coefficient of determination data was equal to 0.79. Figure 9 shows the results of model validation. Nash–Sutcliffe model efficiency coefficient is another tool for calculating the relative difference between the observed data and the simulation.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}[OBS_i - SIM_i]^2}{\sum_{i=1}^{n}\left[OBS_i - \overline{OBS}\right]^2} \qquad \text{Eq. (17)}$$

Nash-Sutcliffe coefficient varies between one and negative infinity. The optimal value of this coefficient is one. It should be

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Table 10) Regression analysis for estimated flood volume and the results of the HEC-HMS model.

Source Changes	Degree of Freedom	Sum of Squares	Average of Squares	F	P-value
Regression	1	$10^9 \times 7.751$	$10^9 \times 7.751$	15.715	0.017
Deviation from regression	4	$10^9 \times 1.973$	$10^9 \times 4.932$		

noted that often, when the Nash-Sutcliffe coefficient is more than 0.75, the model is perfect, and if it is between 0.36 and 0.75, the model is satisfactory, and if it is under 0.36, it is acceptable [23].

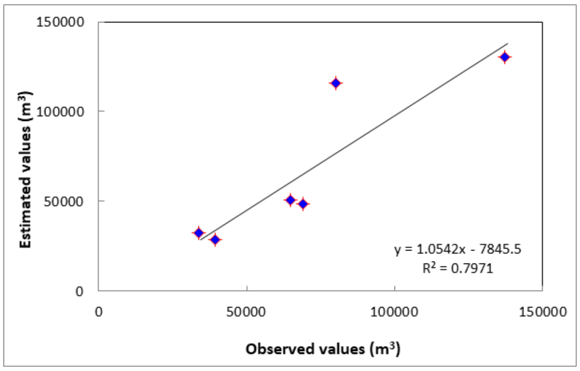

Figure 9) The correlation between the estimated values and those obtained from the HEC-HMS model.

The results of the statistical analysis are shown in (Table 10). According to the obtained results, it can be stated with 95% confidence that the variation of estimated runoff volume for urban areas matches approximately 89% with the variation of flood observations (obtained from the HEC-HMS model). This result is acceptable, given the need for a complete city data bank to determine the urban runoff volume for management and structural purposes. This relationship is statistically significant at the 5% level.

Conclusion

In this study, streets, buildings, and urban green spaces were 13%, 64.8%, and 22.2% of the total study area, respectively. On average, the share of streets and buildings in runoff is 14.11% and 85.87%, respectively. 77.8% of the study area is an impermeable surface, which has a role in total runoff. Therefore, increasing parks and urban green spaces considerably reduces runoff volume (with a 22.2% reduction). Due to the lack of required data, the model was run using six flood events, simultaneous precipitation, and evaporation. The value of RMSE, for flood volume estimated in all events, equals 18657 m3, and for the mean height of runoff in the watershed area is 2.77 mm, which is a significant amount if we limit it to streets. The Nash-Sutcliffe coefficient in determining the runoff volume was 0.70, which shows acceptable UDHBM model results and good compliance with *Hamoda and Lahbasi* results [13].

Sensitivity analysis results showed that the model has the highest sensitivity to rainfall and soil-saturated hydraulic conductivity. Saturated hydraulic conductivity can affect the model only if rainfall on parks and urban green spaces surfaces is more significant than the summation of evaporation volume and infiltration, which agrees with *results* from Yu et al. [15]. The model sensitivity to evaporation rate is less than the other two mentioned parameters. The runoff value has a direct and linear relationship with the amount of rainfall, and the soil-saturated hydraulic conductivity and the evaporation have linear and inverse relations, which is another reason the model is functioning correctly.

The results of the data analysis of regression volume of flood estimation and observations

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(obtained from the HEC-HMS model) for considered metropolitan areas showed that the model estimation of flood volume has a significance level of 5% and with 95% in 89% matches the observed volume. The model can calculate runoff volume based on the water balance for each land use, including residential houses and buildings, streets and parks, and urban green spaces. Thus, this model can be considered a hydrological distribution model. The model performance is acceptable, like models implemented in research cited in the introduction.

This model can have an acceptable estimation of flood volume caused by specific precipitation considering evaporation rate and impermeable and permeable surfaces. Despite its simplicity, it has acceptable accuracy. Generally, the model's base multiplies rainfall, evaporation, and infiltration to the area covered by each parameter. It finally estimates the runoff volume for the metropolitan area regarding the water balance formula. For further studies, the model can be used for other urban watersheds and determining the validity of it.

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