

The effects of rainfall intensity-duration-frequency curves reformation on urban flood characteristics in semi-arid environment

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Abstract

A design storm is a theoretical storm event based on rainfall intensities associated with frequency of occurrence and having a set duration. Estimating design storm via rainfall intensity–duration–frequency (IDF) curves is important for hydrological planning of urban areas. The main aim of this study was to estimate impacts of rainfall IDF curves change in flood properties of an urban area using Storm water Management Model (SWMM). IDF curves of Zanjan city located in the north-west of Iran were generated by Sherman method and Ghahreman and Abkhezh method. Sherman empirical equation was determined in 1995, but due to climate change, Ghahreman and Abkhezh (2004) show that rainfall IDF curves has changed significantly in the recent years. They presented a new equation to indicate the relationship between rainfall IDF curve parameters in Iran. The accuracy of model simulations was confirmed based on the results of calibration. According to results, estimated rainfall depth for different return periods was decreased in the recent years except for 2-year return period, consequently runoff peak was decreased. Decrease of runoff peak was 30, 39, 41 and 42 percent for 5-10-20 and 50-year return periods respectively.

Key words: Design storm, Drainage system, Flood, Rainfall IDF curve, Stormwater, SWMM, Urban, Zanjan city

25 **Introduction**

Due to variation and complexity of land use, population and social economic activities in urban area, storm water runoff management is a complex task in such area (Choi and Ball, 2002; Hoang et al., 2016). This issue will become more complex due to urban development. By 2030, the urban population will reach 5 billion or 60 percent of the world's population (UN, 2006). In many countries, less than 5 percent of land occupied via urban area, consequently, concentration of human activities, shortages and unavailability of resources intensifies local competition for all types of resources, with water amongst the most vital (Zoppou, 2001). Due to local change in hydrological cycle and hydro-meteorological conditions in urban areas, urbanization should increase flood risk (Huong and Pathirana, 2013; Ahilan et al., 2016; Eunsek et al., 2016). Modeling is important for facilitating the development of urban drainage infrastructure design and planning (Choi and Ball, 2002). Estimate and collection of input parameters (measured and inferred) is very important in the catchment modelling. Rainfall intensity-duration-frequency (IDF) curves are important parameters in hydrological modelling. Today, due to urban development, urban flooding increased in terms of intensity and frequency.

Various tools such as structures or non- structures used for urban flooding management and control. Estimating the design storm has an important role in designing and operations of structural hard-engineered solutions for urban runoff management. Use of rainfall IDF curves is a critical method for estimating the design storm. Modeling the impacts of urbanization and climate change on flood properties shows that increase in rainfall intensity and impervious surfaces should cause flashier runoff periods, greater peak flows and heightened risk of flooding (Semadeni-Davies et al., 2008). Several studies indicate that rainfall condition changed due to climate change (Watt et al., 2003; Ghahreman and Abkhezr, 2004). These changes should lead to change in rainfall IDF curves (Ghahreman and Abkhezr, 2004). The impact of the current and future climate change on the rainfall IDF curves and urban design storms in Quebec was estimated using SWMM model (Desramaut, 2008). For developing rainfall intensity-duration-frequency curves in scarce data region, in North-West of Angola, an index flood procedure was used for generate the theoretical regional distribution equation (Ayman et al., 2011).

In order to design the drainage structures, Ibrahim (2012) conducted a study for developing rainfall IDF relationship for two regions in Saudi Arabia. Using improved IDF relations in Khorasan region of Iran, a study was performed to determine the spatial distribution of storms (Akbari et al., 2014).

50 During the last century, the concentration of greenhouse gases has increased due to urban development and increasing of industrial activities (Prodanovic and Simonovic, 2007). This change can lead to changes in temperature and precipitation characteristics, consequently urban flood characteristics should change. In this study, rainfall IDF curves were prepared based on two methods: Sherman method using rainfall data of 1972-1993; Ghahreman and Abkhezr method using long term rainfall data (1972-2004). Then the effects of rainfall intensity-duration-frequency curves reformation on urban flood
55 characteristics investigated using SWMM model. Finally the effects of rainfall IDF curves updating on peak and volume of flood was examined.

Study area

The study area is located in the center of Zanjan province, north-west of Iran (latitude 36° 38' 26" and 36° 42' 20"N, longitude 48° 26' 29" and 48° 35' 02" E). Altitude of the study area range from 1590 m above mean sea level in the southern
60 plain to 1773m in the northern mountain (Fig.1). Total area of the study urban watershed is about 39 km² and the mean annual rainfall is 290 mm. The main part of rainfall in the study area occurred in the autumn and spring. Urban runoff drain into Zanjanrood River via several artificial canals. Flow direction of this canals is from north to south of urban area. Gavazaang earth dam has been built at the north of the city. This dam limit upstream surface water and floods. The study area includes central business district of Zanjan city, public parks, green space, residences and streets. This city experienced
65 rapid development and population expansion during 1956-2012.

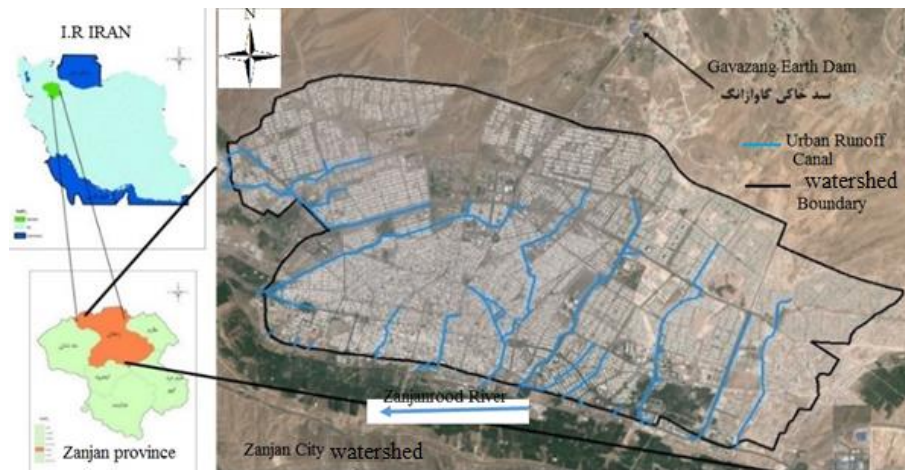


Fig. 1. Locations of the Zanjan City Watershed

Material and Methods

70 Flooding in urban areas can occurred via river floods, coastal floods or flash floods, but there is also a specific flood type that is called urban flooding. Urban flooding is specific in the fact that the cause is a lack of drainage in an urban area. In this study, this kind of flood was investigated using IDF curves and SWMM model.

Model description

75 The EPA Storm Water Management Model (SWMM) developed under the support of the US Environmental Protection Agency (Huber and Dickinson, 1992). SWMM is a dynamic rainfall-runoff simulation model that computes runoff quantity from primarily urban areas. SWMM widely used throughout the world for planning, analysis, and designing related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban and non-urban areas. The runoff component of SWMM operates on a collection of sub catchment areas that receives precipitation and generates runoff and
80 pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps and regulators. SWMM tracks the quantity of runoff generated within each sub catchment and the flow

rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Gironas et al., 2009).

85 **Model implementation**

The primary objective of this study was to evaluate the hydrologic and hydraulic response of an urban watershed to the rainfall IDF curves updating based on increasing of the statistical period length of the rainfall data.

IDF curves of the study area were prepared based on Sherman method using rainfall data of 1972-1993. At the first step, design hyetographs of the study area was prepared via this method. This hyetographs was used as the input of SWMM
90 model for estimating peak and volume of runoff.

In 2004, rainfall IDF curves were updated by Ghahreman and Abkheyr (2004), using long term rainfall data (1972-2004). A new general relationship for rainfall IDF curves was introduced. According to Ghahreman and Abkheyr method, previous relationship is not useful for estimating 10-year hourly rainfall.

At the second step of this study, design hyetographs of the study area was prepared via IDF curve generated via Ghahreman
95 and Abkheyr method. This hyetographs was also used as the input of SWMM model for estimating peak and volume of runoff.

The implementation of SWMM model necessitates several steps include; (1) identification of sub watersheds (2) representation of the channel network and (3) identification of the model parameters (Camorani et al., 2005).

100 **Identification of sub watershed**

Sub watershed was identified based on urban drainage system. Basin boundary and sub watershed borders determined using land use maps, topographic map (1/2000), building blocks, direction of flow in canals and land survey. 16 sub watershed were determined (Fig. 2 and Table 1).

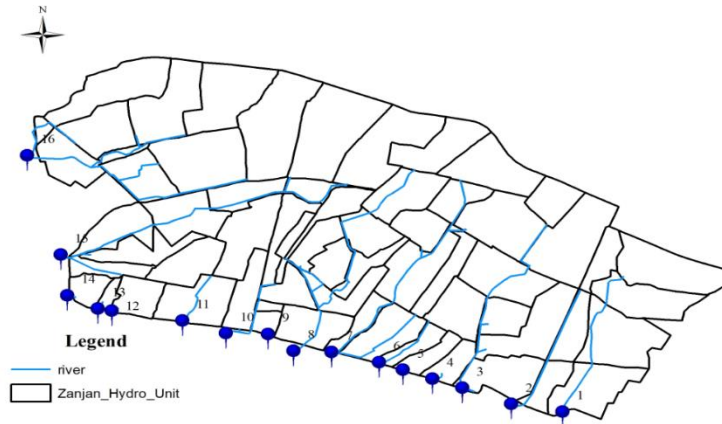


Fig. 2. Urban drainage network, sub watershed and location of the watershed outlets of the study city

Table 1. Canals name, length and corresponding sub watershed area

Canal name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Main Canal length (km)	2.9	2.4	3.6	0.2	0.2	1.1	4.3	4	0.03	1.5	1.0	0.2	0.2	0.1	5.1	2.8
Sub watershed area(km ²)	3.7	1.1	4.6	0.3	0.3	0.9	4.9	4.5	0.2	1.5	1.6	0.4	0.1	0.3	6.1	7.9

Urban drainage system representation

The canal-network as a link-node system were entered into the model. Additional nodes (junctions) inserted where links (conduits) characteristic changed (e.g. depth, width, bed slope, roughness coefficient and shape), or when tributary canals is connected to the main canal. The network geometry (canal profile and cross-sections) has been derived from the topographical map and land survey.

Model parameters

Surface area, Manning roughness coefficient of canals, impervious and pervious area, average width of overland path, average surface slope, percent of impervious area, depth of depression storage on impervious and pervious area, percent of impervious area with no depression storage and infiltration parameters are prepared for implementation in SWMM.

Average surface slope has been achieved from the digital elevation model (DEM) using ArcGIS 9.3 software. Characteristic width of the overland flow path calculated via equation 1.

$$(1) \quad L = \frac{C\sqrt{A}}{1.128} \left[1 - \sqrt{1 - \left(\frac{1.128}{C} \right)^2} \right]$$

Where L is the width parameter (m), A is the area of sub watershed (km²) and C is the compactness coefficient. Compactness coefficient calculated via equation 2 for sub watersheds with compactness coefficient greater than 1.128. Otherwise, based on the user manual of SWMM, an initial estimate of the characteristic width is given by the sub watershed area divided by the average maximum overland flow length.

$$(2) \quad C = 0.282 \frac{P}{\sqrt{A}}$$

Where P is the perimeter of sub watershed (km). Depth of depression storage on impervious and pervious area parameters has been extracted from the values suggested by ASCE (1992). Manning roughness coefficient was obtained from McCuen et al (1996) and ASCE (1982) manuals. Curve number method was selected for modelling the infiltration process. Land use map of the study area was prepared via processing the Thematic Mapper(TM) images in the IDRISI Selva and ArcGIS 9.3 software. Five class of land use was investigated (residential area, green space, main roads, dense rangeland and degraded rangeland or urban flatted land). Soil texture of the study watershed achieved from soil surveys deserts atlas of Iran and controlled with soil studies of Agriculture and Natural Resources Research and Education Center of Zanjan. Soil hydrological group map was determined based on NRCS Hydrologic Soil Group Definitions in user manual of SWMM (Rossman, 2009). Percent of the impervious area calculated based on the land use map of 2012 (Fig. 3). Based on the land use map, urban areas, main roads, green space, dense and destroyed rangeland were occupied 82.9, 5.5, 3, 0.4 and 8.2 percent of the city area respectively.



Fig. 3. Land use map of the study area

Rainfall hyetograph generation

Rainfall is the primary driving force in a SWMM simulation that entered to the model in the form of hyetograph. Maximum flood occur when rainfall duration is equal to the time of concentration. In this study, time of concentration for all sub watersheds was computed via TR-55 model suggested by natural resources conservation service (2009). Rainfall hyetographs were prepared using alternating block method. The alternating block method is a simple way for developing a design storm from an IDF curve. The design storm produced by this method specifies the rainfall depth occurring in "n" successive time intervals of duration (Δt) over a total duration ($T_d = n * \Delta t$). Based on the design return period, the rainfall intensity extracted from the IDF curve/relation for each of the durations (Butler and John, 2011). This hyetograph represent a rainfall with distinct return period and a rainfall duration equal or less than T_d . Also when rainfall duration is less than T_d , the central part of the main hyetograph with rainfall duration of T_d will be used (Behbahani, 2009).

Rainfall hyetograph of Zanjan city based on Sherman equation

155 The rainfall IDF curves was derived for all rain gauges stations using an empirical equations. This equation represent a relationship between maximum rainfall intensity as dependent variable and other parameters such as rainfall duration and frequency as independent variables (Le et al 2006). In this study, Sherman equation was used for Zanjan City (Equation 3)

$$(3) \qquad i = \frac{a}{(d+b)^e}$$

160 Where i is the rainfall intensity (mm/hour); d is the duration (minutes); a, b and e are constant parameters related to the metrological conditions. These empirical equations show rainfall intensity decreases with rainfall duration for a given return period. At Zanjan station, the parameters of Sherman empirical equation were determined in 1995(Meteorological Organization of I.R IRAN), (Table 2).

Table 2. Constant parameter with Sherman empirical equation at the Zanjan City watershed in different return period

Return periods T(year)	A	b	e
2	2654.628	164.735	1.093
5	1977.214	87.108	1.017
10	2111.948	69.215	1.007
20	2473.737	60.915	1.016
50	2884.057	53.450	1.021

165 The rainfall IDF curves for the Zanjan station constructed using Sherman equation (Fig. 4). Rrainfall hyetographs of all studied sub-watersheds in different return periods were prepared in time intervals of 10 minute using rainfall IDF curves of the year 1995.

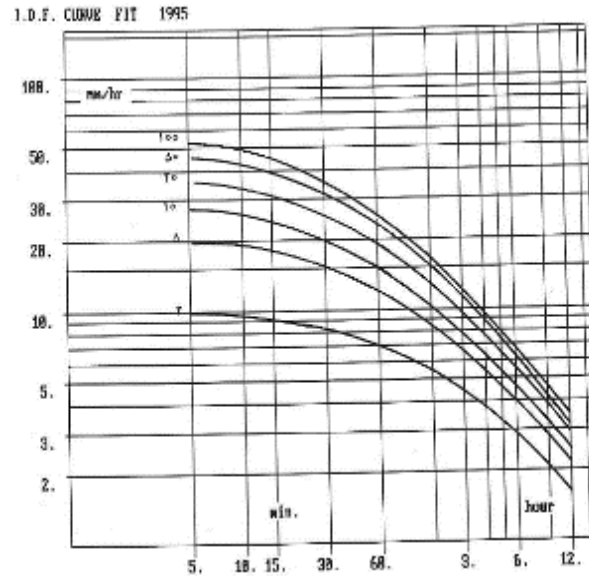


Fig. 4. Rainfall intensity–duration–frequency curves of Zanjan station for 1995(Meteorological Organization of I.R IRAN, 1955)

Rainfall hyetograph of Zanjan city based on Ghahreman and Abkhezr equation

Due to climate change, Ghahreman and Abkhezr (2004) show that in the recent years, rainfall IDF curves changed significantly. They presented a new equation for indicating relationship between rainfall IDF curves parameters in Iran (Equation 4)

$$(4) \quad R_t^T = At^B[\alpha_1 + \alpha_2 \ln(T - \alpha_3)]R_{60}^{10}$$

Where R_t^T is rainfall depth (mm) with time increment of "t" and return period of T. A and B are the coefficients of rainfall duration (for rainfall less or equal to an hours are 0.1299 and 0.4952 respectively). α_1 , α_2 and α_3 are coefficients of rainfall duration (for rainfall less or equal to two hours are 0.4608, 0.2349 and 0.62 respectively). R_{60}^{10} is the hourly rainfall with 10-year return period. R_{60}^{10} calculated via equation (5)

$$(5) \quad R_{60}^{10} = e^{0.291}(R_{1440}^2)^{0.694}$$

Where R_{1440}^2 is the average of the maximum daily rainfall that calculated based on the maximum of daily rainfall from 1969- 2015 in Zanzan station. Rainfall hyetographs of all sub watersheds were prepared for different return periods and rainfall duration with 10 minute interval using equation (4) and (5).

185 Urban study watershed has 16 sub-basin (Table 1). Hyetograph of each hydrological unit was prepared separately (16 hyetograph based on Sherman method and 16 hyetograph based on Ghahreman and Abkhezr) and presented to model. For each outlet, a separated hydrograph were created via SWMM model.

Model Calibration

190 Calibration of the SWMM model was proceeded by comparing real field measured hydrographs with simulated flow hydrographs (Zaghloul and Abu Kiefa, 2000). Model calibration is the process of achieving a correspondence between model estimates and field data. For SWMM model calibration, the goal of calibration was to achieve agreement between measured and simulated peak flow rates. The evaluation criteria of root mean square error (RMSE) was used to compare the simulated model output with the observed data. Root mean square error (RMSE) for discharge is based on equation 6.

195 (6)
$$RMSE = \sqrt{\frac{\sum_{i=1}^n [Q_o(i) - Q_s(i)]^2}{n}}$$

Where $Q_s(i)$ and $Q_o(i)$ are the simulated and observed discharges, respectively, and, n is number of observations in the time series.

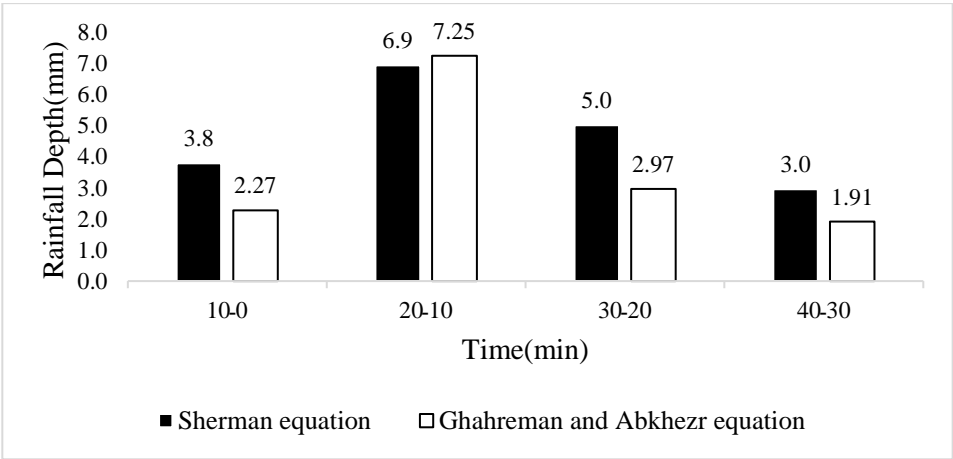
In this study, for model calibration, rainfall and runoff measured in 10 minute interval for three events in one sub basin. The area of this sub basin was 4.6 km². As all sub-watershed have same rainfall and land use condition, the calibrated model was used for the study watershed. Furthermore, calibration files normally contain measurements of only a single parameter at one locations that compared with simulated values in Time Series Plots. At this research, in order to enhance the accuracy of the model calibration, we register three calibration data (Link flow velocity, link flow depth and link flow rate). So, flow rate in any measured runoff event, flow velocity and flow depth were compared with simulated runoff velocity and depth.

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Results and discussion

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Based on both Sherman and Ghahreman and Abkhezzr methods, for all 16 sub-watershed, design rainfall hyetograph developed in 10-minute growths for different return periods. As the same results obtained for all study sub watershed, the results obtained for sub watershed 16 (the biggest sub watershed) was presented in this section. Figure 5 indicates design rainfall hyetograph created via alternative block method based on Sherman equation, and Ghahreman and Abkhezzr equations for sub watershed number 16 (Fig. 5)



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Fig. 5. A design rainfall hyetograph created for sub watershed number 16 via alternative block method based on Sherman equation, and Ghahreman and Abkhezzr equations

220

Based on Sherman, and Ghahreman and Abkhezzr equations, design rainfall hyetograph was developed in 10-minute increments for different return periods for all 16 sub watershed using alternative block method. Table 3 indicates design rainfall hyetograph of sub watershed 16.

225 **Table 3.** Design rainfall hyetograph developed in 10-minute increments for different return periods using Sherman and Ghahreman and Abkhezzr equations (sub watershed 16)

Method	Return Period(year)		Time(min)				Cumulative Rainfall Depth(mm)
			0-10	10-20	20-30	30-40	
Sherman	2	Rainfall Incremental Depth(mm)	1.2	1.6	1.4	1.1	5.3
	5		2.1	3.1	2.5	1.8	9.6
	10		2.7	4.3	3.3	2.2	12.5
	20		3.2	5.4	4.1	2.5	15.2
	50		3.8	6.9	5.0	3.0	18.7
Ghahreman and Abkhezzr	2	Rainfall Incremental Depth(mm)	0.9	2.8	1.2	0.7	5.6
	5		1.3	4.3	1.7	1.1	8.5
	10		1.6	5.2	2.1	1.4	10.3
	20		1.9	6.1	2.5	1.6	12.1
	50		2.3	7.3	3.0	1.9	14.5

230 According to results, the rainfall depths increased with increasing of return period, whereas rainfall amount decreased with increasing rainfall duration in all return periods. The results obtained from the two methods have a good uniformity. Based on design hyetographs in different return periods, rainfall depth calculated via Sherman method are greater than rainfall depth calculated via Ghahreman and Abkhezzr method except for 2-year return period. As recent data was used in Ghahreman and Abkhezzr equation, we can conclude that rainfall depth decreased in the recent decade (Table 3). Same results was observed for all sub watershed in the study area.

Based on the results, peak of the hyetograph created via Ghahreman and Abkhezh method is greater than Sherman method (Fig. 5). Design hyetographs for 50-year return period indicate that 57.22 percent of rainfall depth has been occurred in the first twenty minutes for both Sherman and Ghahreman and Abkhezh methods, whereas the percent of rainfall depth that happened after hyetograph peak was 42.88 percent in the Sherman method and 33.79 percent in Ghahreman and Abkhezh method (Table 3). This results indicate that estimated hyetograph peak in Ghahreman and Abkhezh method is greater than Sherman method while the depth of rainfall in Sherman method is greater than Ghahreman and Abkhezh. The results of calibration model based on measured three rainfall runoff events in one sub basin has been shown in Table 4.

Table 4. Calibration of the model results with peak flow

Rainfall- runoff events	Observed peak flow (m ³ /sec)	Simulated peak flow (m ³ /sec)	RMSE
02 May 2016	0.088	0.09	0.005
03 May 2016	0.018	0.02	0.003
10 May 2016	0.022	0.02	0.001

According to calibration of model results, RMSE criteria imply that the prediction errors are well balanced and simulated hydrograph looks rather reasonable. Comparison has been made between simulated and measured hydrographs (Fig.s 6a, b and c). The results of calibration confirmed the accuracy of model simulation. Based on entered hyetographs characteristics, change in flood properties were simulated via SWMM model for all sub watershed. Maximum runoff has been calculated via SWMM model in different return period for different watershed outlets. The results of outlet 16 indicated in Fig. 7.

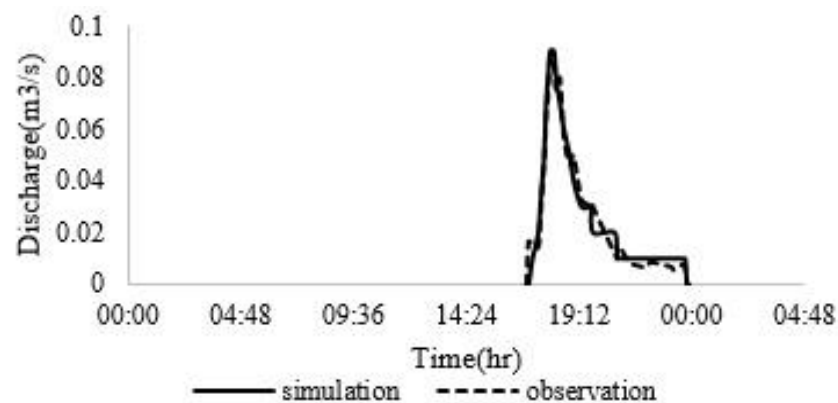


Fig 6a. Calibration outfall hydrograph for rainfall- runoff event at 02 May 2016

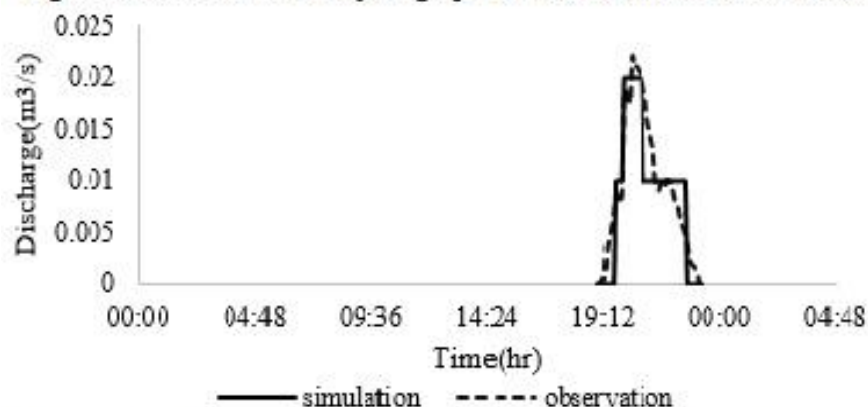


Fig 6b. Calibration outfall hydrograph for rainfall- runoff event at 03 May 2016

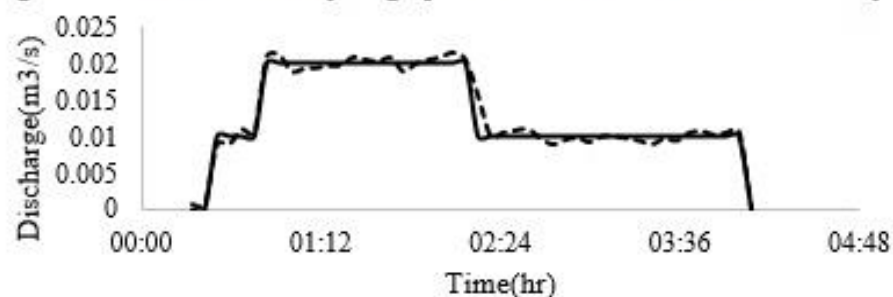
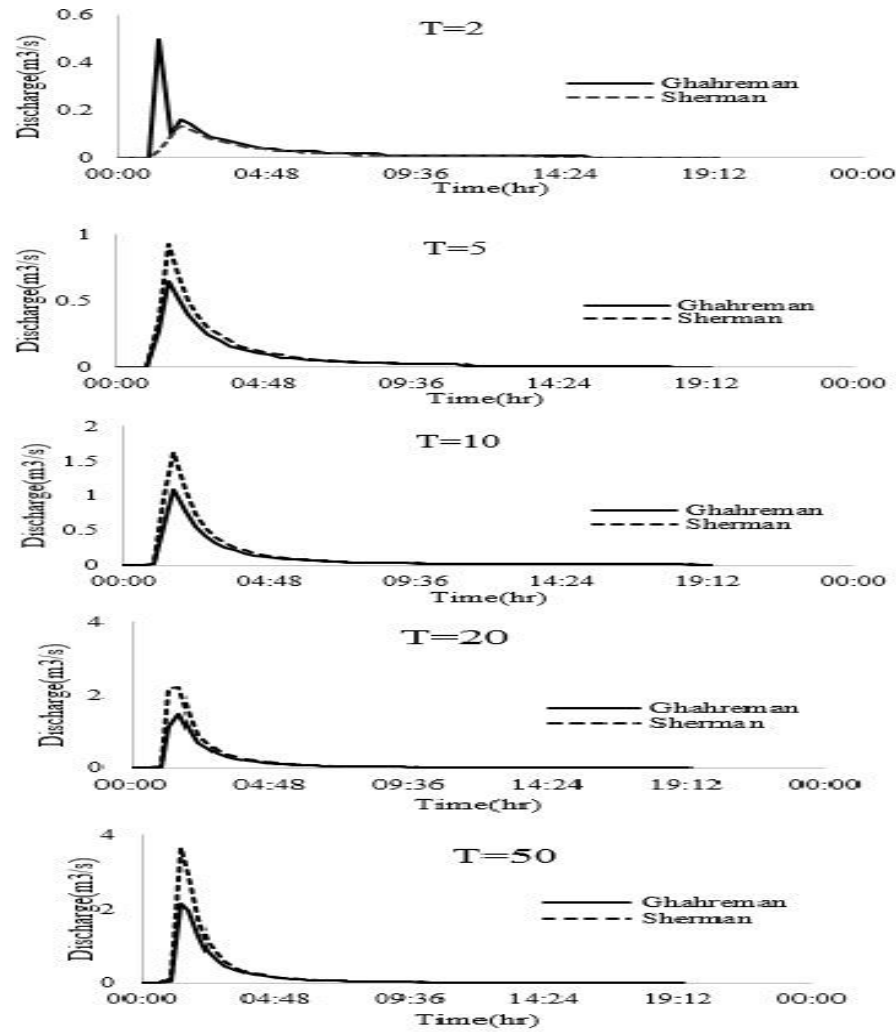


Fig 6c. Calibration outfall hydrograph for rainfall- runoff event at 10 May 2016

Fig. 6. Calibration outfall hydrographs



255 **Fig. 7.** The estimated maximum runoff based on two made hyetograph in different return period for sub watershed 16.

Maximum flow (peak runoff) and maximum runoff volume for urban watershed was calculated using sum of the sub-basins outlet. Table 5 indicate the estimated maximum runoff of urban drainage system based on two made hyetograph in different return period for total of the urban watershed drainage system (sum of the 16 sub basin)

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Table 5. The estimated maximum runoff of urban drainage system based on two made hyetograph in different return period

Return period	2	5	10	20	50
Sherman method	0.44	3.08	6.31	9.95	15.39
Ghahreman and Abkhezr method(m^3/s)	0.53	2.17	3.85	5.85	8.97
Difference between two method(m^3/s)	20	-30	-39	-41	-42

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According to results, for 2-year return period, estimated peak runoff has increased by 20 percent using Ghahreman and Abkhezr hyetographs compare to Sherman method. While for 5, 10, 20 and 50-year return periods, the peak runoff has been decreased by 30, 39, 41 and 42 percent respectively in the Ghahreman and Abkhezr method compare to Sherman method. Table (6) indicate estimated total runoff volume for urban drainage system of Zanjan city watershed.

Table 6. The estimated total runoff volume of urban drainage system based on two made hyetograph in different return period

Return period	2	5	10	20	50
Sherman method(m^3/s)	6.9	30.5	47.7	63.3	83.4
Ghahreman and Abkhezr method(10^6 Liter)	8.5	24.2	35.2	45.6	59.5
Difference between two method(10^6 Liter)	23	-21	-26	-28	-29

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The results show that runoff volume decreased using prepared hyetographs of Ghahreman and Abkhezr method compare to Sherman method except for 2-year return period. Decreasing of total runoff volume for 5, 10, 20 and 50 year return periods using prepared hyetographs of Ghahreman and Abkhezr method was 21, 26, 28 and 29 percent respectively. While for 2-year return period, evaluated runoff volume increased by 23 percent.

Based on the results, for peak runoff evaluated in 50-year return period using Sherman and Ghahreman and Abkhezr hyetograph, percent of flood that occurred before of peak runoff were 27 and 22 percent respectively (Fig. 7).

275 According to the results of Sherman method, time to peak is 30 minute and base time of runoff hydrograph is 17 hour and 40 minute for Sherman hyetograph. Same time to peak was observed for Ghahreman and Abkhezi method, while base time of hydrograph decreased by 20 minute. Time to peak is very important for establishment of flood warning systems and prepare the condition for property protect of humans life and increase the safe lives. In generally, we can conclude that peak and volume of runoff estimation need to update for urban runoff modelling.

280 **Conclusions**

Urbanization and climate change affected local rainfall intensity. As rainfall characteristics are often used to design urban drainage system, so for watershed modelling and estimate of flood properties, updating and reviewing of rainfall characteristics is necessary.

285 The first step in many hydrological design projects is to determine the maximum rainfall event. IDF curves, which relate the rainfall intensity, duration, and frequency, is the most common method of determining the design storm event. It also provides a summary of the site's rainfall characteristics by relating storm duration and exceedance probability to rainfall intensity which is assumed to be constant over the duration (time of concentration) .The IDF curves of the study area were developed in this study using historical rainfall data available. This study was conducted for analyzing the effect of rainfall IDF curves updating on the flood properties in Zanjan city watershed using SWMM model. Design storm in different return 290 period and rainfall duration determined based on two method (Sherman equation, Ghahreman and Abkhezi method). Ghahreman and Abkhezi (2004) attempting to reform the equations of the rainfall intensity estimating in Iran using larger statistic period length. Prepared hyetographs show that Sherman method gave larger rainfall intensity compared to Ghahreman and Abkhezi method. Estimated peak and total runoff volume follow trend of rainfall intensity.

Rainfall intensity in the IDF Curve is the average rainfall depth that falls per specific time duration. AS Ghahreman and 295 Abkhezi method use longer and newer rainfall data for creating IDF curves, we can conclude that climate change cause change in rainfall characteristics. According to results, more accuracy was observed between simulated and real condition when Ghahreman and Abkhezi method was used. When we used Ghahreman and Abkhezi method, peak of the rainfall hyetograph increased but depth of rainfall decreased, consequently flood volume decreased. This mean that climate change

300 would be affected rainfall pattern of the study area. Desramaut (2008) indicated that change in rainfall characteristics lead to runoff decreasing. Willems (2011) also indicated that changes in flood frequencies of sewer systems and overflow frequencies of storage facilities should be quantified based on the climate scenarios and related changes in rainfall statistics. Due to climate change peak and volume of runoff decreased in the recently decade. According to results of SWMM model, the urban drainage system of Zanzan city watershed has enough transfer capacity against the flood condition. But survey information indicated several inundations in some area of the studied watershed. Poor maintenance of drainage systems, 305 instantaneous heavy rainfall, erosion and sedimentation are some parameters that could lead to such temporal inundation.

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