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Sensitivity analysis of SWMM model parameters for urban runoff estimation in semi-arid area

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Abstract

Modelling of urban runoff is important for flood prevention and storm water management. For urban runoff modelling, estimate and collection of input parameters (measured and inferred) is very important, but accuracy of the results depend to the precision of the input data and calibration of the model that need to the highly detailed input data. Sensitivity analysis should indicate the parameters with greater effect on the results. In this study, sensitivity analysis of SWMM model parameters was done for urban runoff estimation in a semi-arid area located in the Northwest of Iran (Zanjan city watershed). According to results, depth of depression storage, percent of impervious area and Manning's roughness coefficient of impervious area were the most sensitive parameters of SWMM that affect peak and volume of the runoff. The properties related to the previous surfaces such as curve number, Manning's roughness coefficient and depth of depression storage have not a significantly effect on model outputs. The results of the goodness-of-fit test show the accuracy of the model outputs, consequently, SWMM souled propose for simulating the urban drainage systems in semi-arid area. NOF and NSC criteria indicate that the prediction errors are also well balanced. We can conclude that validated model can use for rainfall-runoff simulation in the area located in the semi-arid area.

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Introduction

By 2030, the urban population will reach to 5 billion or 60 percent of the world's population that will live in the urban area (UN, 2006). Urbanization increase flood risk in the urban areas via local change in the hydrological cycle and hydro-meteorological conditions (Huong and Pathirana, 2013; Ahilan *et al.*, 2016; Lee *et al.*, 2016). Due to variation and complexity of land use, population and socio-economic activities in urban area, storm water management is a complex task (Choi and Ball, 2002; Hoang *et al.*, 2016). Due to this complexity, urban drainage systems would be planned, designed and analyzed using modeling approach (Choi and Ball, 2002). For urban runoff modeling, physical data such as catchment areas, pipe diameters and depth or intensity of rainfall should measure via survey measurements, while inferred data should determine via model application. Different approaches such as parameter optimization, operational management, design space exploration, sensitivity analysis and uncertainty analysis should increase the improvement of the model prediction (Jakeman *et al.*, 2006; Razavi *et al.*, 2012; Wu and Liu, 2012; Nan *et al.*, 2011; Song *et al.*, 2011). Model calibration is the process of achieving a correspondence between model estimates and field data (Cibin *et al*, 2010). Model calibration use to assess and adjust the model parameters for obtain a satisfactory agreement between the predicted and the monitored data (Choi and Ball, 2002). As a large number of parameters participate in the model simulation (Rosso, 1994; Sorooshian and Gupta, 1995), most sensitive parameters must use for model calibration (Zaghloul and Abu Kiefa, 2001). Sensitivity analysis is a helpful tools to determine and rank parameters which have significant effect on model results (Saltelli *et al*, 2000). Sensitivity analysis have an important roles in model parameterization, calibration, optimization and uncertainty quantification (Xiaomeng *et al.*, 2105). Sensitivity is the rate of change in one factor with respect to change in another factor (McCuen, 1972). SWMM is a mathematical models that originally developed for urban runoff quantity and quality simulation in storm and combined sewer systems, for single or continuous events of runoff (Rossman, 2009; Beling *et al*, 2011). SWMM was used to evaluate the impact of urbanization on rainfall-runoff processes in various area of the world with different urbanized scenarios, model performance evaluation show a good agreement between simulated and measured data (Zongxue and Zhao, 2016; Chow *et al.*, 2012; Nestor *et al.*, 2014; Moafi Rabori, 2012; Choi and Ball, 2002). Li *et al.* (2016) indicated that the depth of depression storage on impervious area and conduit roughness are the most important parameters that influence the results of the SWMM in an urban area. Li *et al.* (2014) indicate that sub catchment area, Manning's roughness coefficient for impervious and pervious area are strongly positively correlated with the total runoff volume. Whereas, Manning's N for the conduit, sub catchment width, minimum rate on the Horton infiltration curve and sub catchment slope are strongly negatively correlated to the peak discharge and total runoff volume. Beling *et al.* (2011) showed that the percentage of impervious areas, the sub basins width, Manning's roughness coefficient and the infiltration parameters were the most sensitive parameters for SWMM model calibration. Ahmadian *et al.* (2013) concluded that Manning's roughness coefficient of impervious areas, width, slope and percentage of impervious areas were more effective in changing the peak flow in SWMM model. Rostami Khalaj *et al.* (2012) and Shahbazi *et al.* (2014) found that percent of impervious areas and Manning's roughness coefficient for the conduit and impervious area were the most effective parameter on peak discharge. Barco *et al.* (2008) indicate that imperviousness and depression storage are the most sensitive parameters affecting total runoff and peak flow. Moafi Rabori (2012) revealed that depression storage in impervious area, percent of impervious area with no depression storage, Manning's roughness coefficient for impervious area are the most sensitive parameter affecting peak runoff. The main aim of this study was to conduct a detailed sensitivity analysis of SWMM model parameters for urban runoff estimation in a semi-arid area, to assess the main sensitive parameters of the SWMM which affect rainfall-runoff process simulation and finally to calibrate and validate SWMM model based on the results of the sensitivity analysis.

Materials and methods

Study Site

The study urban area was performed in the Zanjan city watershed (latitude 36° 38′ 26″ and 36°42′ 20″N, longitude 48°26′ 29″ and 48°35′ 02″E) located in the Zanjan province, Northwest of Iran. The area of study watershed is about 39 Km^2 (Fig. 1). Mean annual precipitation in the region is 290mm and the maximum recorded daily precipitation was 50.6mm in 1968. The main part of rainfall in the study area was occurred in the autumn and spring.

Altitude of the study area ranging from 1590m above mean sea level in the southern plain to 1773m in the northern mountain. Zanjan city experienced a rapid development and population expansion during 1956-2012. The total impervious area of the study area was about 75% in the form of buildings, roads, footpaths and sports facilities. The morphology of the study city is generally foothills and piedmont plain. The study watershed was drained by a separate sewage drainage system and the storm runoff water flowed via 16 canals to the outlet (Fig. 2). Flow direction of the artificial canals is from north to south and end to Zanjanrood River. Gavazaang earth dam has been built at the north of the city, so upstream surface water and floods cannot arrive into the city.

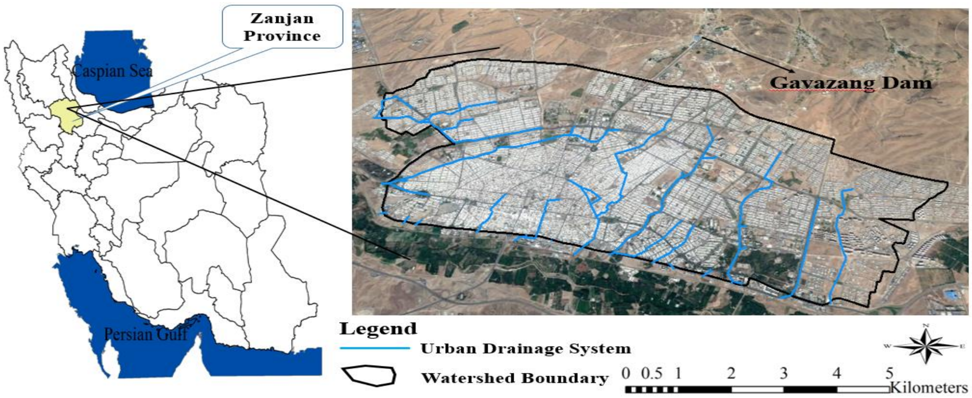

Fig. 1. Locations of the Zanjan City Watershed.

Storm Water Management Model

Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas that developed under the support of the US Environmental Protection Agency (Huber and Dickinson, 1992). In this study, SWMM (Version 5) was applied for simulation the storm drainage system in Zanjan city watershed.

The study area was divided to 16 sub watershed. Each sub watershed considers a junction. According to routing portion of SWMM, sub watershed runoffs transport to the outlets through a system of pipes, channels, storage/treatment devices, pumps and regulators (Gironas *et al.*, 2009).

Urban drainage system

Urban drainage system of the study area was identified using thematic layers of land use and topographic maps (1/2000), digital elevation model (DEM), building blocks and flow direction in curbs, gutter and main canals. Canal-network and link-node, flow direction in all curbs, gutter and main canals were controlled via land survey. Junctions were determined where quick changes in a conduit characteristic was occurred (change in depth, width, bed slope, roughness coefficient and shape) or when tributary canal was connected to the main canals. The properties of the urban drainage network (surface and bottom elevation, maximum water depth of junctions, length, shape, diameter and slope of the storm drainage conduits) were extracted via related maps and direct survey measurement.

The basic data of each sub watershed (such as average slope, perimeter, area and width) were calculated for each sub watershed. Sub watershed map was shown in Fig. 2.

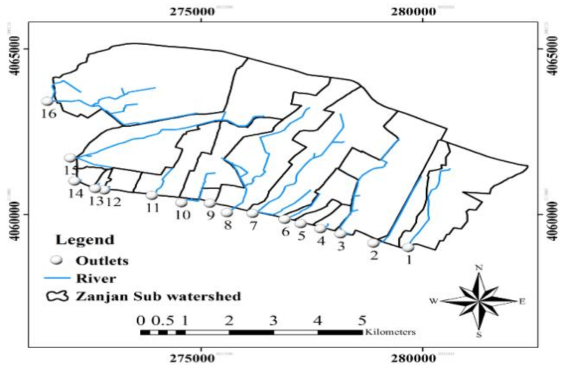

Fig. 2. Urban drainage network, sub watersheds and Outlets location of Zanjan City Watershed.

Determination of model parameters

Surface area, average of sub watershed width, impervious and pervious area, average width of overland flow path, average slope, Manning roughness coefficient, infiltration and depth of depression storage on impervious and pervious area were determined based on the properties of the studied area, related formulas, supplementary tables and recommendations presented by SWMM model. Manning roughness coefficient was obtained from Mc Cuen *et al* (1996) and ASCE (1982) manuals. Depth of depression storage on impervious and pervious area parameters has been extracted from the values suggested by ASCE, (1992). SCS Curve Number method was used for computing infiltration loss on the pervious areas of each sub watershed. Land use map was prepared via processing of the Thematic Mapper (TM) images in the IDRISI Selva and Arc GIS 9.3 software. Based on the land use map, five class of land use include residential area, green space, main roads, dense rangeland and degraded rangeland or urban flatted land was determined. Soil texture achieved from soil surveys of deserts atlas in 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 was estimated based on the land use map. The surface area occupied by urban areas, main roads, green space, dense and destroyed rangeland was 82.9, 5.5, 3, 0.4 and 8.2 percent respectively.

Digital elevation model (DEM) was generated from topographic map and the data imported into Arc View. Average surface slope has been achieved from DEM using ArcGIS 9.3 software. Average width of overland flow path calculated via equation 1.

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

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

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

Where P is perimeter of the sub watershed (km). The design hyetographs, as a main input of SWMM, were constructed based on reformatted rainfall intensity-duration-frequency (IDF) curves developed for the study area. It is supposed that when rainfall duration is equal to the time of concentration, maximum flood should occur. So, rainfall hyetographs which rainfall duration equal to time of concentration were created for each sub watershed. In this study, time of concentration for all sub watershed was computed via TR-55 model suggested by natural resources conservation service (2009). Rainfall hyetographs has extracted based on Ghahreman and Abkhezr method (2004). Equation 3 indicate the relationship between rainfall IDF curves parameters in Iran.

$$R_t^T = At^B[\alpha_1+\alpha_2\ln(T-\alpha_3)]R_{60}^{10} \qquad (3)$$

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 hourly rainfall with 10-year return period. R_{60}^{10} calculated via equation (4)

$$R_{60}^{10} = e^{0.291}(R_{1440}^{2})^{0.694} \quad (4)$$

R_{1440}^{2} (the average of the maximum daily rainfall) was calculated based on the maximum of daily rainfall from 1969-2015 in Zanjan station (where located in latitude 36°41′ N, longitude 48°29′ E and altitude 1620m). To perform the sensitivity analysis, design hyetograph with a 20 year return period were prepared using alternative block method. In this study, partial sensitivity analysis (absolute) was used for evaluating the sensitivity of SWMM model variables. For this purpose, the initial value of 10 parameters of the model has been changed (±15-30% in regard to the given range of the allowable change).

For assessing the effect of variable parameters on the results and determining the most effective parameters, flood peak discharge and input parameters (Table 1) were selected as the objective function and independent variables respectively. The most effective parameters were determined based on the results of SWMM (estimated runoff peak and volume) related to increase or decrease of each parameter.

Table 1. Initial values and allowable range of SWMM model variables.

Variables		Initial values	Allowable range	Reference
Percent of impervious area (%)		-	±30	Temprano *et al* (2006)
Average surface slope		-	±30	Temprano *et al* (2006)
Width of overland flow path(m)		-	±30	Temprano *et al* (2006)
SCS curve number		40-100	±30	Mahdavi (2007)
Manning's roughness coefficient	Channels	0.011 - 0.020	±30	ASCE (1982)
	impervious area	0.013	0.011- 0.033	Huber and Dickinson (1992)
	pervious area	0.05	0.02- 0.8	Huber and Dickinson(1992) Temprano *et al* (2006)
Depth of depression storage(mm)	impervious area	1.778	0.3- 2.5	Huber and Dickinson(1992)
	pervious area	3.81	2.5- 5.1	Tsihrintzis and Hamid (1998)
Percent of impervious area with no depression storage (%)		16	5- 20	Huber and Dickinson (1992)

Source: (Rostami Khalaj *et al*., 2012).

Model calibration

Model calibration is the process of running a model using a set of input data and comparing the model results to actual measurements of the system. For model calibration, rainfall and runoff properties (depth, discharge and velocity) were measured for four specific rainfall events in the study area. The measured rainfall and runoff data were analyzed for calibration and verification. For model validation, long-term continuous SWMM simulation results were compared to the observed runoff properties (Chen and Adams, 2005).

Goodness-of-fit test

When important input parameters have been identified in the sensitivity analysis, SWMM was calibrated and validated for runoff quantity simulation. The reliability of calibration and validation results was evaluated using root mean square error (Equation 5), normalized objective function (Equation 6) and Nash-Sutcliffe coefficient (Equation 7).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}[Q_0(i)-Q_s(i)]^2}{n}} (5) \quad \mathrm{NOF} = \frac{\mathrm{RMSE}}{\overline{Q_s}} \quad (6)$$

Where n is the number of observations in the time series and Qs (i) and Qo (i) are the simulated and observed discharges respectively and $\overline{Q_s}$ is the mean of observed values.

The ideal value for NOF is 0 but values between 0.0 and 1.0 are acceptable when site specific data are available for calibration (Kornecki *et al.*, 1999). The Nash-Sutcliffe coefficient is a goodness of fit criterion recommended by ASCE Task Committee (1993). It used to assess the predictive power of hydrological models

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \quad (7)$$

Where Q_o is observed discharge and Q_m is estimated discharge. Q_o^t is observed discharge at time t. Nash-Sutcliffe efficiencies can range from -∞ to 1. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, an efficiency of 1 (E = 1) corresponds to a perfect match of estimated discharge to the observed data. Whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model estimation (Nash and Sutcliffe, 1970; Chaube *et al.*, 2011). The optimal statistical value occurs when the NSC is close to 1. General performance ratings for recommended statistics is given in Table 2.

Table 2. General performance ratings for NSE methods.

Performance rating	NSE
Very good	0.75 ≤ NSE ≤ 1.00
Good	0.65 ≤ NSE ≤ 0.75
Satisfactory	0.50 ≤ NSE ≤ 0.65
unsatisfactory	NSE≤ 0.50

Sources: (Moriasi *et al.*, 2007).

Results and discussion

Sensitivity analysis results

The sensitivity analysis indicates that how improbability in the output of a model can be qualified to different sources of uncertainty in the model input. For sensitivity analysis, at the first stage, the model was run using the initial parameter of the model. Then sensitivity analysis was performed by changing each parameter either side of their standard values while all others parameter were constant. The results of the sensitivity analysis were illustrated in Fig. 3 to Fig. 4.

The results of the sensitivity analysis indicated that depth of depression storage for impervious area, Manning's roughness coefficient for impervious area, width of overland flow path, percent of impervious area, average surface slope, channel roughness coefficient, percent of impervious area with no depression storage were the most important parameters that influence estimation of the peak runoff via SWMM model in the study area (Fig. 3). According to results, curve number, Manning's roughness coefficient and depth of depression storage for pervious area have not effects on peak runoff estimation.

Percent of impervious area, depth of depression storage for impervious area, percent of impervious area with no depression storage, width of overland flow path, Manning's roughness coefficient for impervious area, average surface slope and channel roughness coefficient are the most important influencing parameters on runoff volume estimated via SWMM (Fig. 4). Curve number, Manning's roughness coefficient for pervious area and depth of depression storage for pervious area have not effect on runoff volume estimated by SWMM.

Model calibration and validation

In order to enhance the accuracy of the model calibration and validation, three calibration data namely; link flow velocity, link flow depth and link flow rate were registered. Observed and simulated graphs of four rainfall-runoff events related to canal number 25, located at the end of sub watershed number 3 were shown in Fig. 5. The area of sub watershed number 3 is 4.6 km² while upstream drainage area of canal number 25 is 2.98km². This canal selected for data measurements because length and shape of this sub watershed can indicate the average condition of the studied watershed. The parameters of SWMM model are calibrated by three measurement data on 02/05/2016, 03/05/2016 and 10/05/2016. Rainfall-runoff event at 10/04/2016 is selected for model validation. The reliability of calibration and validation results was evaluated using the goodness-of-fit tests Nash-Sutcliffe coefficient (NSC) and Root mean square error (RMSE) for normalized objective function (NOF). The results of goodness-of-fit tests for calibration and validation model indicated in Table 3.

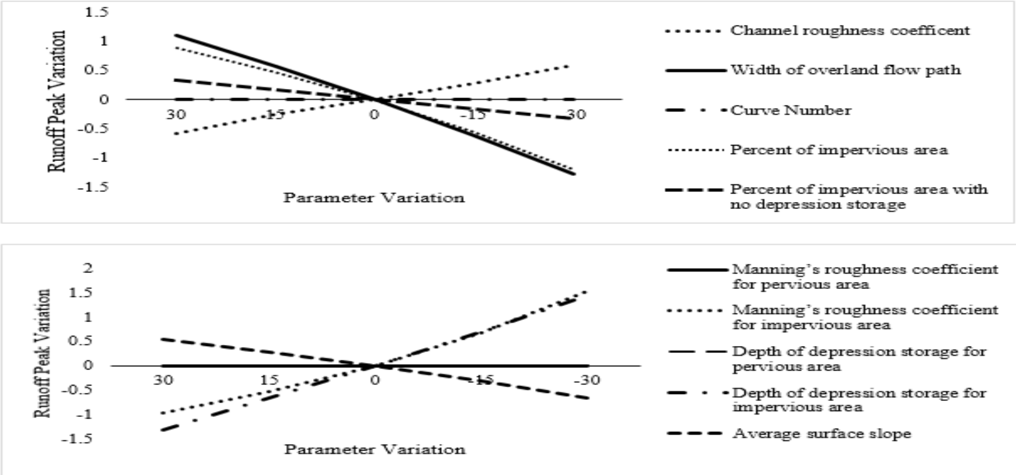

Fig. 3. The effect of SWMM model parameters change on the peak runoff.

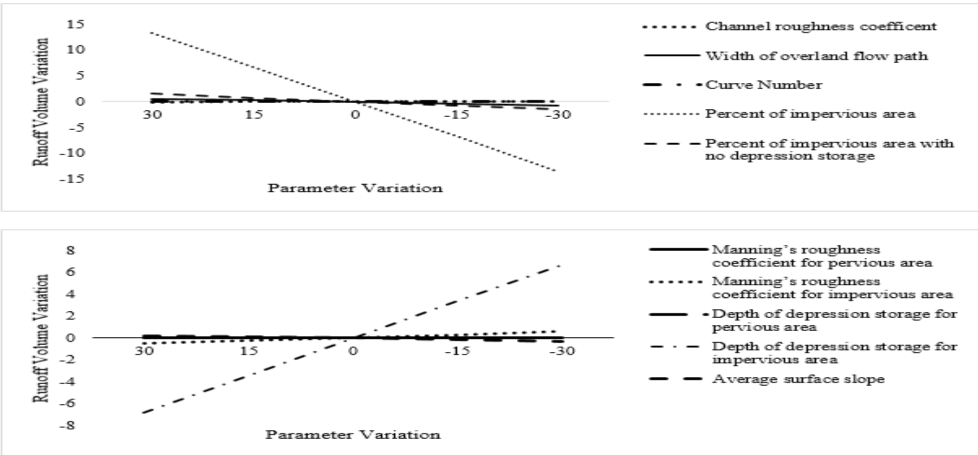

Fig. 4. The effect of SWMM model parameters change on the runoff volume.

Table 3. Goodness-of-fit test results for assessing the reliability of calibration results.

Rainfall – Runoff Events	Goodness of fit test parameters					
	NOF			NSE		
	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	Depth (m)	Velocity (m/s)	Discharge (m^3/s)
02.05.2016	0.322	0.092	0.338	0.911	0.987	0.960
03.05.2016	0.425	0.080	0.185	0.756	0.981	0.976
10.05.2016	0.308	0.055	0.129	0.855	0.992	0.987
10.04.2016	0.320	0.008	0.179	0.921	1.00	0.986

Although ideal value for NOF is 0, but values between 0.0 and 1.0 are acceptable when site specific data are available for calibration and validation. So, in this study, the calibration and validation of SWMM are acceptable (NOF<1.0). The optimal statistical value for Nash-Sutcliffe coefficient occurs when the NSC is close to 1, calibration and validation of the SWMM for storm event was also acceptable (Table 3). NOF and NSC criteria also imply for indicate that the prediction errors are well balanced. This results indicate that model has an acceptable accuracy for rainfall-runoff simulation in Zanjan City Watershed. Fig. 5 indicate the results of the calibration and validation outfall hydrographs of 4 measured events. Three rainfall runoff events (02/05/2016, 03/05/2016 and 10/05/2016) were used for calibration (Fig. 5 A, B and C), while Rainfall-runoff event at 10/04/2016 was used for model validation (Fig. 5 D).

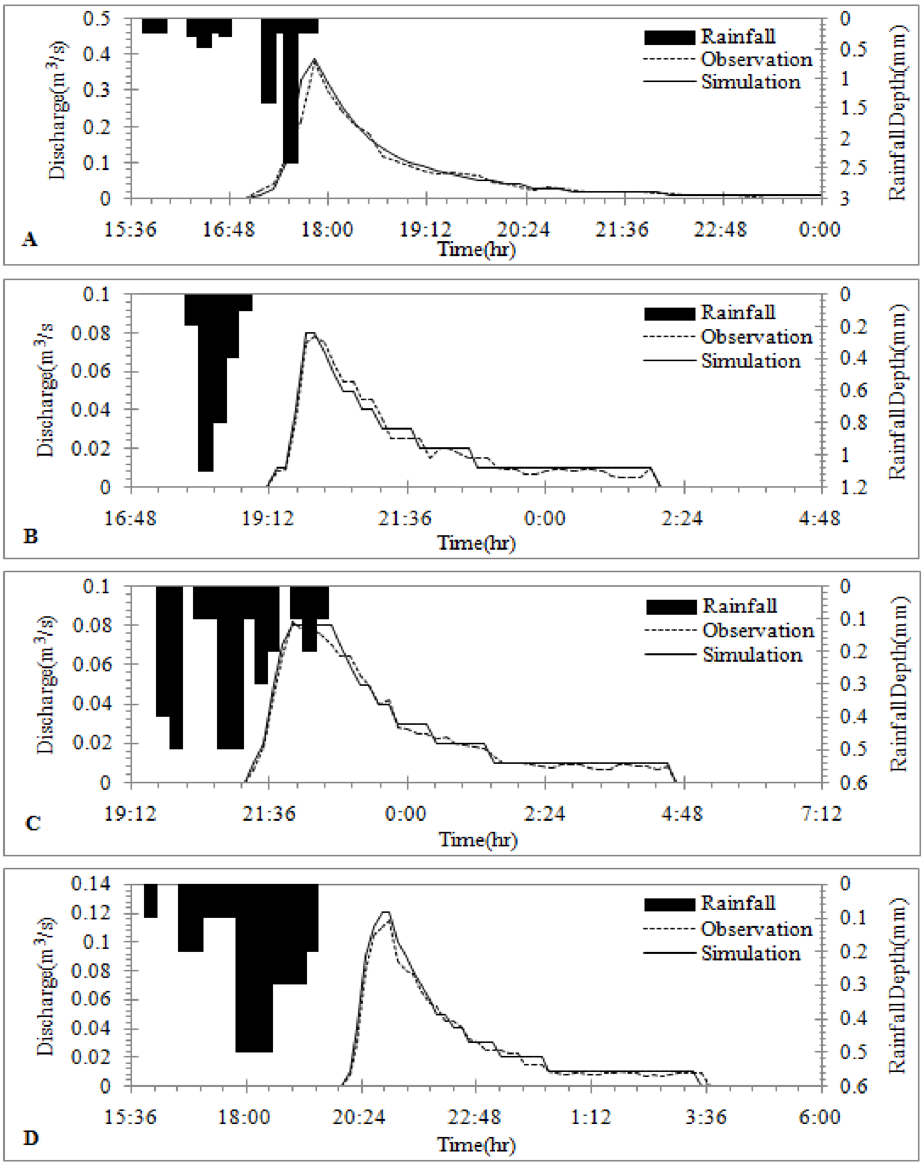

Fig. 5. Calibration and validation outfall hydrographs. A) event at May 02rd 2016, B) event at May 03rd 2016, C) event at May 10rd 2016, D) event at April 10rd 2016.

Conclusion

SWMM is a semi-distribute rainfall-runoff model which is widely used for planning, analysis and design related to drainage systems in urban areas. Sensitivity analysis, calibration and validation are three crucial steps for the proper application of a model. The significance of sensitivity analysis and calibration indexes to quantify reliability of model simulations is being recognized for various region of the world. This paper focused on the sensitivity analysis, calibration and validation of SWMM model in Zanjan city watershed located in a semi-arid environment. Four SWMM parameters include depression storage, imperviousness, width of overland flow path and Manning's coefficient were used for calibration. Performed sensitivity analysis showed that imperviousness and depression storage are the most sensitive parameters affecting runoff peak and volume. The sensitivity analysis results are relatively compared to findings by Li *et al.* (2016), Barco *et al.* (2008), Moafi Rabori (2012) that indicates depression storage of impervious area is the most important parameter that should affect runoff peak and volume. The results are also similar to findings of Beling *et al.* (2011), Rostami Khalaj *et al.* (2012), Barco *et al.* (2008) and Shahbazi *et al.* (2014) that indicate the percent of impervious area is one of the most influential parameter on runoff properties. The results of sensitive analysis in this search confirm that in the semi-arid area, runoff peak and volume simulated by SWMM are most sensitive to change in the properties related to the imperviousness in particularly depth of depression storage, percent of impervious area and Manning's roughness coefficient. The results of performance evaluation criteria show that SWMM model have a good accuracy for the simulation of rainfall-runoff process in the semi-arid area. Other researchers has been also indicated that SWMM model had suitable accuracy for rainfall-runoff process simulation in various climate condition (Zongxue and Zhao, 2016; Chow *et al*, 2012; Nestor *et al*, 2014 and Moafi Rabori, 2012). Selection of model output variables significantly influence the importance of the parameters. It is important to consider more than one model output for evaluating sensitivities over the variety of possible model responses. The sensitivity analysis revealed that a few key input variables should significantly contribute to the model outputs. The results of this study confirm the important of the selection of the input variable for the accuracy and sensitivity analysis of the SWMM.

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