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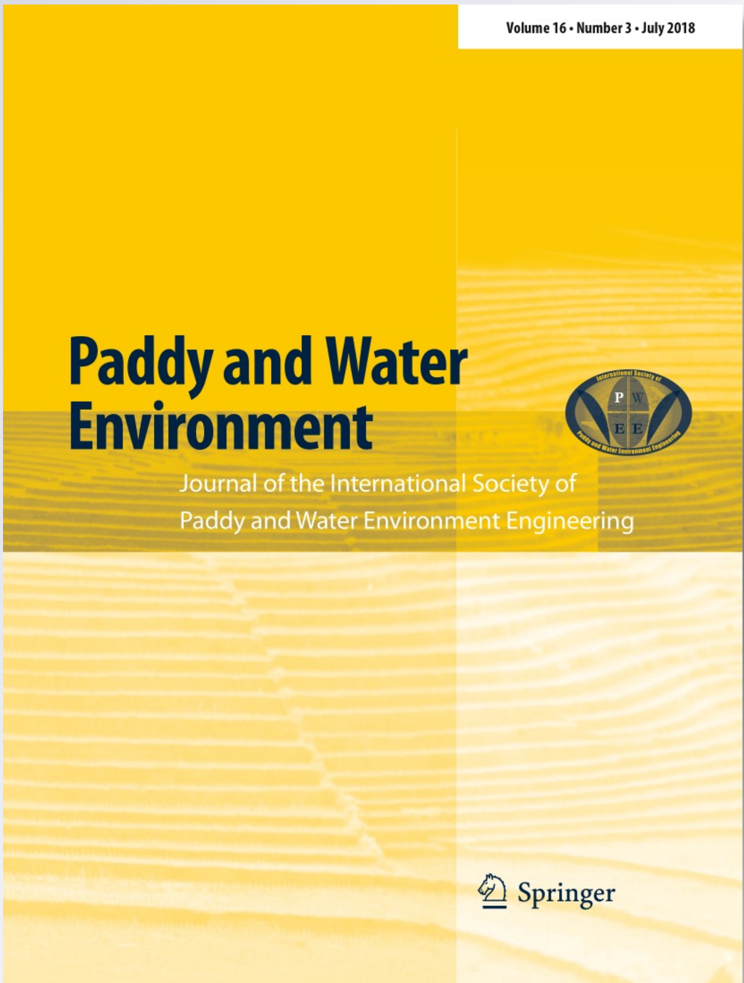

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ARTICLE

Comparative effectiveness of different infiltration models in estimation of watershed flood hydrograph

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Abstract

The present study aims to evaluate performance of different infiltration models, namely initial and constant rate, soil conservation service (SCS) curve number and Green–Ampt in simulation of flood hydrographs for the small-sized Amameh Watershed, Iran. To achieve the study purpose, the infiltration rates were measured using rainfall simulator in work units acquired through overlaying topography, land use, drainage network and soil hydrologic group maps. All parameters of the study infiltration models were determined with the help of the Infilt. software package. The performances of the models in simulation of the observed output hydrographs from the entire watershed were ultimately evaluated for 28 rainfall–runoff events in the HEC-HMS environment. The different components of the observed and estimated hydrographs including time to peak, runoff volume, peak discharge, discharge values and peak time deviation were compared using relative error (RE), coefficient of determination (R^2), peak-weighted root mean square error (PWRMSE) and Nash–Sutcliffe (NS) criteria. The general performance of estimations was also qualitatively assessed using scatter plot and distribution of study variables around standard lines of 1:1 slope. The results revealed that the SCS infiltration model with PWRMSE = 0.61 $m^3\ s^{-1}$ and NS = 0.53 performed better than initial and constant rate model with PWRMSE = 1.1 $m^3\ s^{-1}$ and NS = 0.54, and Green Ampt model with PWRMSE = 1.35 $m^3\ s^{-1}$ and NS = 0.29 in estimation of flood hydrograph for the Amameh Watershed.

Keywords HEC-HMS software · Flood · Rainfall–runoff model · Muskingum routing · Infiltration models

Introduction

Flood hydrograph is an important variable for the design of hydraulic structures like dams and bridges, soil conservation planning, water quality and water resource management schemes (Jain and Kumar 2006). However, the development of flood hydrographs for entire storm events of a watershed needs a large amount of accuracy, expenses and equipment. Furthermore, lack of hydrometric stations and difficulties in field measurement of flow discharge at the outlet of the small watersheds causes inevitable use of the rainfall–runoff models for the estimation of flood hydrograph (Sadeghi et al. 2005). Accordingly, rainfall–runoff models are appropriate tools to study hydrologic processes and water resources assessment (Perrin et al. 2007; Bahremand and De Smedt 2008; Sadeghi and Singh 2010; Noor et al. 2014a, b; Pechlivanidis et al. 2015; Đukić and Radić 2016; Liu et al. 2016; Machado et al. 2016). Therefore, an accurate infiltration model from a variety of methods is needed for the development of precised hydrographs (Chahinian et al. 2005; Ghorbani Dashtaki et al. 2009).

Many factors including soil texture and structure, vegetation, slope and dispersion capability of surface particles influence soil infiltration (Maidment 1992), which drastically vary in time and space and result in differences in infiltration (Parchami-Araghi et al. 2013). On the other hand, rainfall intensity is another effective factor for infiltration rate, which has a major influence on the output hydrograph (Quan 2006). The field experiments are also necessary for the measurement of infiltration for identifying and parameterizing an area-specific model (Crescimanno et al. 2007).

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Many studies have worked on the importance of modeling infiltration process under different conditions applying various models. In this regard, Chahinian et al. (2005) tested four different models, namely Philip (1957), Morel-Seytoux (1978), Horton (1933) and Mockus (1972) for mid-sized plots with an area of 1200 m^2. The results showed that Morel–Seytoux's model performed better than the other three models and the SCS gave the worst results. Unucka et al. (2010) also applied semi-distributed models of HEC-HMS (Feldman 2000), HYDROG (Starý 1998) and distributed models of MIKE SHE (Beven 2002), SIMWE (Mitas and Mitasova 1998) for the analysis of the forest cover impact on the runoff conditions in the Ostravice Basin. They reported that the semi-distributed models such as HEC-HMS and HYDROG together with use of the worldwide standard methods (Mockus 1972; Green and Ampt 1911; Horton 1933) were very suitable for the calibration of particular soil and vegetation parameters within the study watersheds. On the other hand, the complicated distributed model, i.e., MIKE SHE, was suitable for analyzing temporal and spatial variability of key hydrologic parameters of vegetation, soil and groundwater environment.

Kumar and Bhattacharjya (2011) carried out rainfall–runoff modeling using HEC-HMS hydrologic model in the Ranganadi River Basin, Northeastern India. The SCS unit hydrograph transform method, the SCS curve number loss method and the constant monthly method were used to compute direct surface runoff hydrographs, runoff volumes and base flow separation, respectively (Feldman 2000). They also found that the HEC-HMS model reliably estimated infiltration parameters. A similar approach was successfully applied by Bhatt et al. (2012) for estimating infiltration parameters in the Bhagirathi Watershed through formulating an inverse model using the HEC-HMS applied to the historically recorded rainfall and runoff data.

Sardoii et al. (2012) also compared three loss methods, namely the initial and constant, Green and Ampt and SCS curve number to simulate surface runoff in the Amirkabir Dam Watershed. The results revealed the better performance of the Green and Ampt method. In the same context, two transform as well as two loss methods were employed by Halwatura and Najim (2013) to simulate streamflow in HEC-HMS model in the Attanagalu Oya Watershed. The results verified that the transform Snyder unit hydrograph method and the loss deficit and constant method, respectively, performed more reliably than the Clark unit hydrograph and SCS Curve Number methods. Choudhari et al. (2014) simulated rainfall–runoff process in the Balijore Nala Watershed of Odisha, India, using the HEC-HMS model. They successfully applied the SCS curve number, SCS unit hydrograph, exponential recession and the Muskingum routing methods for computing runoff volume, peak runoff rate, base flow and flow routing, respectively.

Considering the importance of input variables on the performance of hydrologic modeling, the use of the proper infiltration model is therefore coherent. The current study makes use different infiltration models in simulating the precise hydrographs for a watershed. Besides that, the entire parameterization and calibration of the models have been made based on data directly obtained through adequate field measurements, which distinctly differs the present study from others already reported in the literature.

Materials and methods

Study area

The Amameh Watershed, one of the subwatersheds of the Jajrood Watershed, is located about 40 km from Tehran, Iran, and bounded by latitudes of 35°51′00″ and 35°75′00″N and longitudes of 51°32′30″ and 51°38′30″E. The watershed covers around 3712 ha (Fig. 1). More than 80% of the Amameh Watershed is covered by mountainous rangelands (Sadeghi and Singh 2010).

Characteristics of the study events

The hyetographs and hydrographs of isolated and bell-shaped flood events with distinct corresponding rainfall (not resulting from snowmelt) occurred in spring, autumn and summer and ultimately were selected for the study. A least 5-day interval was also considered for the recorded storms to minimize effects of antecedent soil moisture condition on model performance. Overall, 28 events with 15-min time resolution were selected from a time span of 43 years at the Amameh climatic station and Kamarkhani hydrometric station situated at the center and main outlet of the watershed. Some 70 and 30% of study storms were randomly assigned for calibration and validation stages, respectively.

Delineation of work units

Based on the drainage network, soil hydrologic groups, land use, topographic condition in Arc-Hydro sector of ArcGIS environment and field surveys, the watershed was divided into 60 work units (Fig. 2). The infiltration was then measured in each specified work unit.

Simulation of rainfall

To properly simulate the rainfall characteristics, the entire data recorded for the Amameh climatic station, located almost at the center of the watershed, were collected for the period of 1969–2012. According to intensity–duration–frequency (IDF) curve, average rainfall intensity with a 10-year

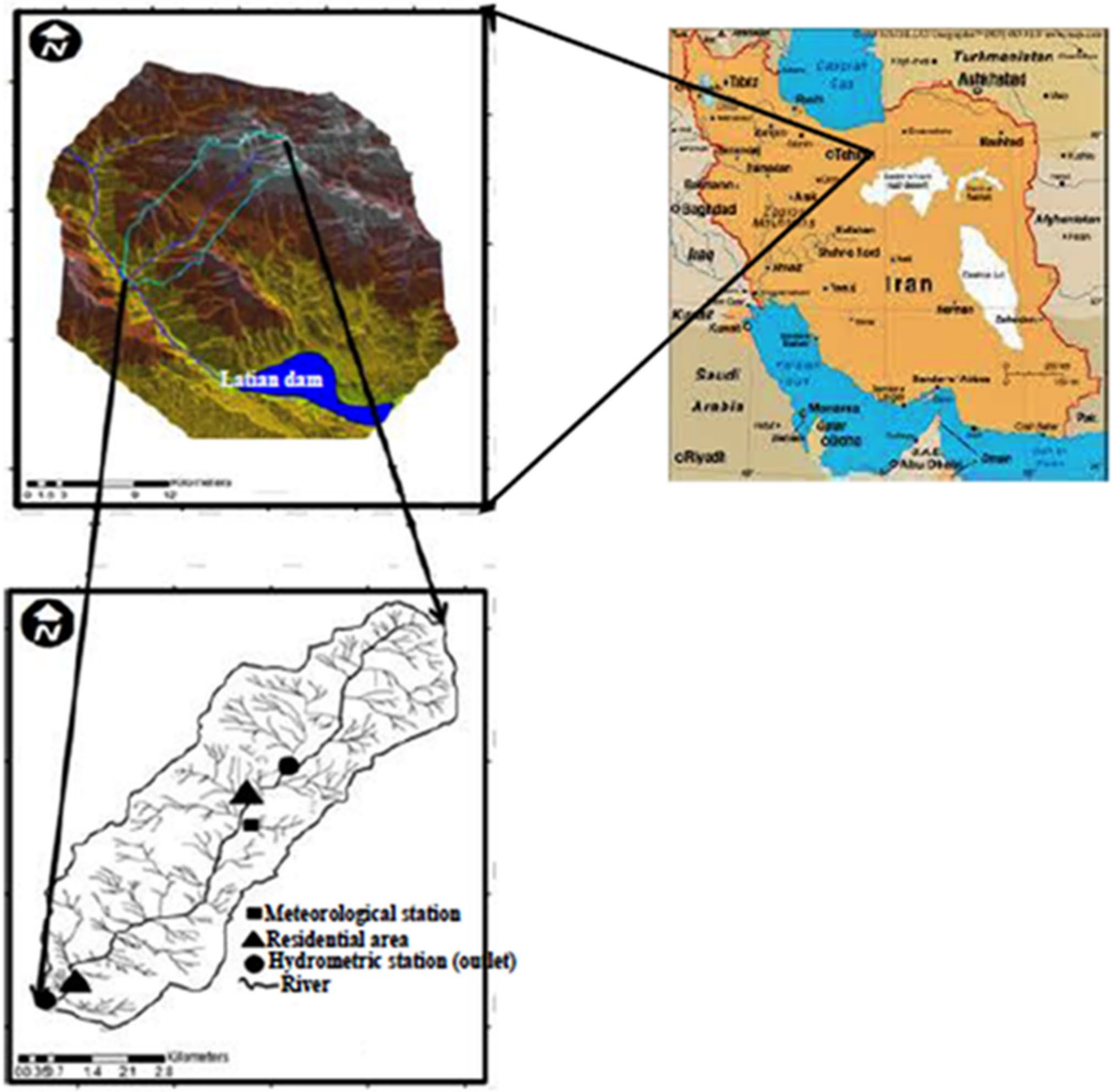

Fig. 1 General location of the study area in Latian Dam Watershed and Iran

return period was identified as 60 mm h^{-1}. The Kamphorst rainfall simulator (Kamphorst 1987) was calibrated based on the study rainfall intensity. The infiltration rate was then measured in 60 sampling points within 12 work units considering all land uses (Fig. 2). The infiltration measurements were continued about 90 min until the steady infiltration rate was obtained. The runoff volume was measured from rainfall simulator plot by scaled cylinder in regular interval in sequences as: 5 measurements with 1-min intervals, 5 measurements in 5-min intervals and 6 measurements in 10-min intervals, and the infiltration rates were consequently calculated.

Measurement of soil properties

The upper 30 cm soil properties such as initial water content, particle size properties and gravel contents were determined in all 60 sampling points using gravimetric method, hydrometer method (Gee and Bauder 1986) and volumetric method, respectively.

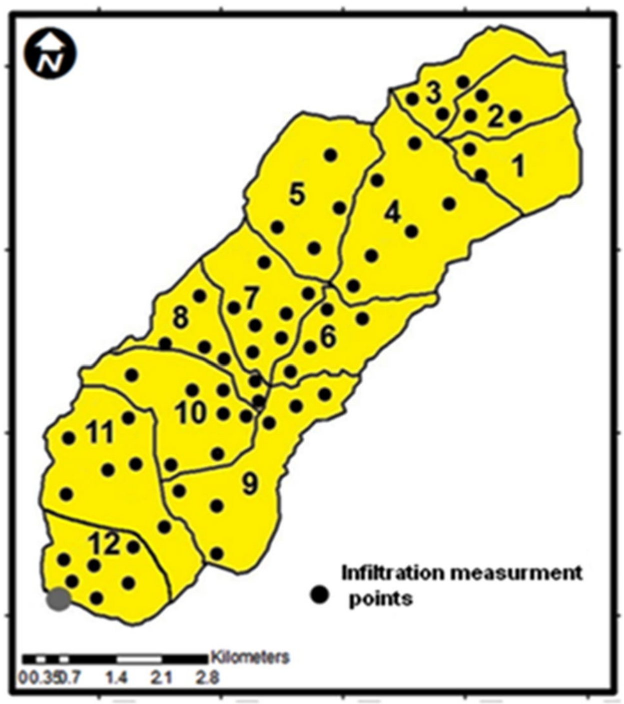

Fig. 2 Distribution of infiltration measurement points in the Amameh Watershed

Application of the models to the Amameh Watershed

In order to apply the HEC-HMS model to the studied watershed, the loss method was applied, since rainfall–runoff modeling was done on the basis of events. To conduct the loss method, three approaches, i.e., initial and constant rate, the SCS curve number method and Green and Ampt method, were considered. The infiltration rate and cumulative infiltration data obtained from 60 sampling points over the study area were fitted to these three infiltration models. The optimal parameters in three infiltration models were determined by the least square technique using Infilt. package based on particle size properties and infiltration measurement rate (Ghorbani Dashtaki et al. 2009). The method suggests that, for the best fits, the sum of the squares of differences between the observed and the corresponding estimated values should be minimum (Parhi et al. 2007). The following objective function was used to determine the parameters:

$$\text{Min } O(p) = \sum_{j=1}^{n} \left(I(m)_j - I(p)_j \right)^2 \tag{1}$$

where $I(m)_j$ is the measured cumulative infiltration for soil (j) and $I(p)_j$ is the predicted cumulative infiltration for soil(j), where $j = 1, 2, \ldots, n$, with n the total number of j determinations for each soil j. Subscript j indicates the number of times which cumulative infiltration was measured or estimated. Infiltration parameters of land uses were then computed on the basis of infiltration parameters in 60 sampling points. Finally, infiltration parameters of subbasins were computed on the basis of infiltration parameters in land uses using a weighted arithmetic mean.

The area of the subbasin which is impervious (%) needs to be specified as a portion of total area. No loss calculations are carried out on the impervious areas where all the precipitation on such portions become excess precipitation and subjected to direct runoff (Halwatura and Najim 2013). A total of four different baseflow methods are provided by the model. In this study, graphical baseflow separation technique by constant slope method was used out of the model. So, the model is proposed without baseflow in all events. The transformation of surface runoff to channel flow was also made through applying SCS curve number method (Tramblay et al. 2010). The Muskingum method was ultimately used to rout flood in the study reach as shown in Fig. 3 and with the help of available information (Sadeghi and Singh 2010) on weighting factor (x) and travel time (k) parameters and summarized in Table 1. Selecting a canopy and a surface flow method is optional and generally only used for continuous simulation (Feldman 2000). Since the simulation of rainfall–runoff used in the study is event-based, a canopy and a surface flow method were not selected.

Calibration of the model

The calibration of the model was made based on optimization method using the Nelder and Mead method in order to simulate the measured hydrograph as closely as possible and minimizes the RMSE. The peak-weighted root mean square error (PWRMSE) function was used in this study:

$$\text{PWRMSE} = \left\{ \frac{1}{n} \left[\sum_{i=1}^{n} \left(q_0(t) - q_s(t) \right)^2 \left(\frac{q_0(t) + q_0(\text{mean})}{2q_0(\text{mean})} \right) \right] \right\}^{\frac{1}{2}} \tag{2}$$

where $q_0(t)$ and $q_s(t)$ are the observed and simulated discharge at time step t, respectively, $q_0(\text{mean})$ is the mean observed discharge, and n is the number of observed data.

Performance evaluation of the models

Five different types of standard statistical criteria (relative error (RE), coefficient of determination (R^2), peak-weighted RMSE, Nash–Sutcliffe efficiency coefficient (NS) and the difference between the 45-degree line) were considered as statistical performance evaluation. Five performance evaluation

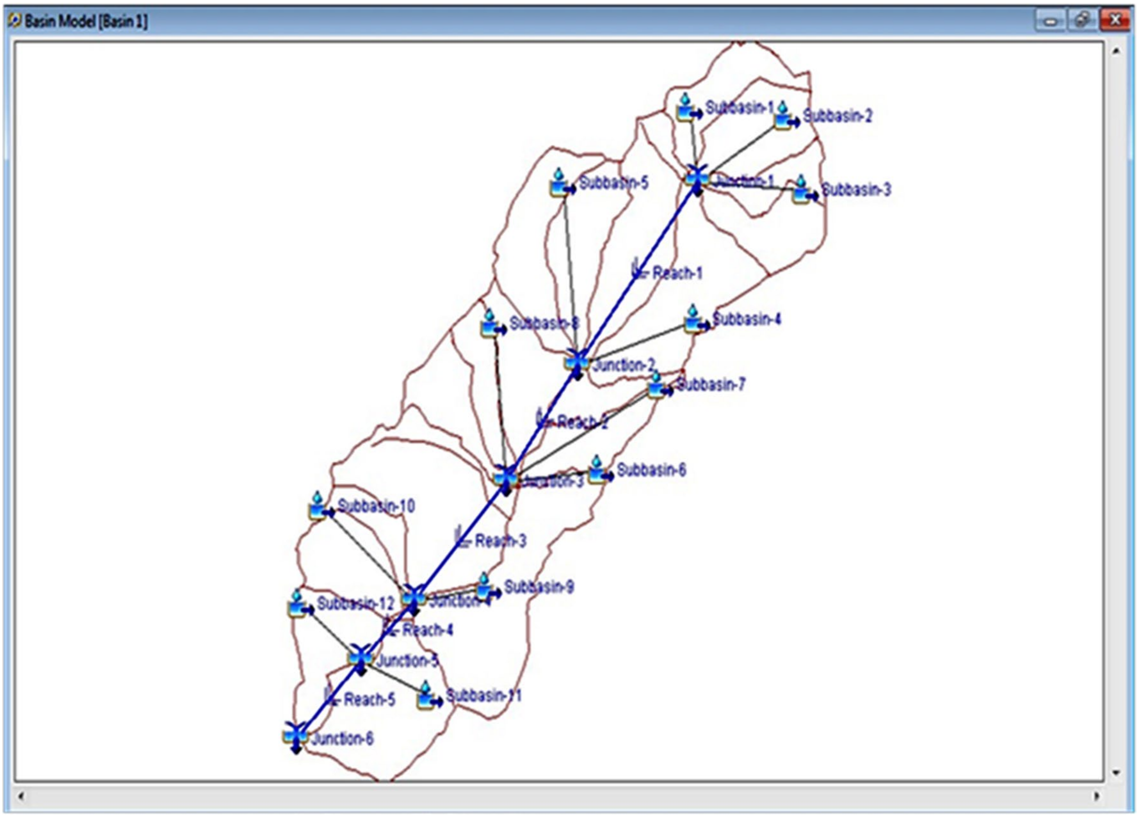

Fig. 3 The study reaches in the Amameh main river extracted from HEC-HMS model

Table 1 The Muskingum X and K parameters in the Amameh river reaches

Reach ID	Muskingum parameters		Travel time (h)
	X	K	l
1	0.443	0.222	0.222
2	0.411	0.234	0.234
3	0.378	0.486	0.486
4	0.388	0.355	0.355
5	0.437	0.072	0.072

criteria used in this study can be calculated utilizing the following equations.

The relative error among the observed and estimated peak discharge, observed and estimated runoff and observed and estimated time to peak was calculated based on the below equation.

$$\mathrm{RE} = \frac{1}{N}\sum_{j=1}^{n}\left(\frac{\left|I_{P_j} - I_{O_j}\right|}{I_{O_j}}\right) \quad (3)$$

It ranges between 0 and 100 (100 inclusive), with RE = 0 being the optimal value.

The coefficient of determination (R^2) describes the degree of collinearity between simulated and measured data. It ranges from 0 to 1, with higher values indicating less error variance (Green and Stephenson 1986).

$$R^2 = \left[\frac{\sum_{j=1}^{n}(I(P)_j(\overline{I(P)_j})(I(o)_j - \overline{I(o)_j})}{\sqrt{\sum_{j=1}^{n}(I(P)_j - \overline{I(P)_j})^2 \sum_{j=1}^{n}(I(o)_j - \overline{I(o)_j})^2}}\right]^2 \quad (4)$$

The Nash–Sutcliffe efficiency (NS) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe 1970). It indicates how well the plot of observed versus simulated data fits the 1:1 line. It ranges between $-\infty$ and 1.0 (1 inclusive), with NS = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values < 0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Green and Stephenson 1986).

$$\mathrm{NS} = 1 - \frac{\sum_{j=1}^{n}(I(P)_j - I(o)_j)^2}{\sum_{j=1}^{n}(I(P)_j - \overline{I(P)_j})^2} \quad (5)$$

where $I(P)_j$ is the simulated discharge at $t = j$, I_o is the observed discharge at $t = j$, and n is the number of observed data.

The performance of the model was also assessed qualitatively using the scattering of the data cloud around the 1:1 sloped line. The difference between the 45-degree line shows the scatter plot of simulated values according to observed values.

$$(A) = a\left(I_0\right) \rightarrow a = \frac{\left(I_P\right)}{\left(I_o\right)} \quad (6)$$

Results and discussion

The descriptive statistics of soil variables, viz. particle size properties, showed that soils of the study area soil are classified sandy clay loam, loam and sandy loam.

Parameterization of the infiltration models

The parameters of initial and constant rate, SCS curve number method and Green and Ampt method were computed for all land uses within Amameh Watershed using Infilt. package (Table 2).

The infiltration parameters of subbasins then were computed on the basis of infiltration parameters in all land uses (Table 2) and area of each land use (Table 3) using a weighted arithmetic mean (Tables 4, 5).

Calibration of the models

The values of the calibrated parameters of the three models for each subbasin within HEC-HMS were calculated using the Nelder and Mead method and are presented in Tables 4 and 5.

The results of calibration of the initial and constant rate, SCS and Green and Ampt are shown in Tables 6, 7 and 8. Thereafter, the models were validated for eight other event data sets whose corresponding results are shown in the same tables and depicted in Fig. 5. The average values of parameters obtained from calibration were used for validation.

As it is implied from Table 6, the RE criterion of runoff volume and peak discharge reported significantly more than the RE criterion of time to peak in validation stage. On the other hand, the R^2 criterion of time to peak reported significantly more than the R^2 criterion of runoff volume and peak

Table 2 Results of mean parameters values for all models in each land use

Land use	Initial and constant rate		SCS	Green and Ampt			
	Initial loss (mm)	Constant loss rate (mm h^{-1})	CN	Initial loss (mm)	Moisture deficit	Wetting front suction (mm)	Hydraulic conductivity (mm h^{-1})
Rangeland	7	0.92	82	0.47	0.92	38	0.5
Farming land	15	2.3	45	1.4	1.03	263	4.87
Orchard	11	1.5	52	0.9	1	186	3.52
Barren land	6	0.3	88	0.1	0.7	32	0.89

Table 3 Area of each land use within each subbasin

Subbasin ID	Rangeland (%)	Farmland (%)	Orchard (%)	Barren land (%)	Area (ha)
1	100	–	–	–	216.08
2	100	–	–	–	333.46
3	100	–	–	–	54.99
4	70	–	10	20	517.04
5	65	–	20	15	411.86
6	20	25	30	25	78.69
7	15	30	45	10	309.77
8	10	30	50	10	332.26
9	55	5	30	10	529.54
10	60	–	25	15	186.18
11	65	5	25	5	715.62
12	5	40	45	10	37.5

Table 4 Results of weighted mean and calibrated parameters values for initial and constant rate and SCS models in each subbasin

Subbasin ID	Initial and constant rate				SCS	
	Initial loss (mm)		Constant loss rate (mm h^{-1})		CN	
	Weighted mean value	Calibrated value	Weighted mean value	Calibrated value	Weighted mean value	Calibrated value
1	16.53	16.19	0.068	0.06	88	87.85
2	16.55	15.73	0.085	0.075	92	91.84
3	15	14.7	0.25	0.222	94	93.84
4	13	12.74	0.085	0.075	85	84.86
5	17.67	171.31	0.085	0.075	93	92.84
6	57	55.86	0.6	0.53	50	49.91
7	66	64.68	0.65	0.578	55	54.90
8	75	73.5	0.85	0.756	47	46.92
9	12	11.76	0.45	0.4	45	44.92
10	10.06	9.85	0.075	0.066	81	80.86
11	16.5	16.19	0.055	0.048	88	87.85
12	70	68.6	0.5	0.445	52	51.91

Table 5 Results of weighted mean and calibrated parameters values for Green and Ampt model in each subbasin

Subbasin ID	Initial loss (mm)		Moisture deficit		Wetting front suction (mm)		Hydraulic conductivity (mm h^{-1})	
	Weighted mean value	Calibrated value	Weighted mean value	Calibrated value	Weighted mean value	Calibrated value	Weighted mean value	Calibrated value
1	0.1	0.14	0.079	0.13	150	250	1.1	0.95
2	0.1	0.14	0.15	0.25	139	232	0.3	0.26
3	0.1	0.14	0.16	0.27	40	66	1.17	1.017
4	0.15	0.21	0.21	0.36	51	85	1.8	1.83
5	0.15	0.21	0.12	0.2	72	120	1.28	1.11
6	0.33	0.46	0.27	0.46	88	146	5.56	4.83
7	0.37	0.51	0.26	0.44	287	479	3.7	3.21
8	0.37	0.51	0.21	0.36	245	409	2.8	2.43
9	0.15	0.21	0.21	0.36	128	213	1.7	1.47
10	0.14	0.21	0.11	0.36	120	213	0.52	1.47
11	0.15	0.21	0.099	0.17	160	267	0.56	0.48
12	0.36	0.5	0.23	0.39	151	252	6.21	5.4

discharge in validation stage. In addition, the "A" criterion of runoff volume and time to peak reported the maximum underestimation and the closest estimation in validation stage, respectively. As can be seen from Tables 7 and 9, the RE, R^2 and "A" criterions of runoff volume, peak discharge and time to peak were found the same in validation stage. As can be seen from Table 8, the RE criterion of time to peak is small, whereas it is significant for peak discharge and runoff volume.

As disclosed in Tables 6, 7 and 8, mean RE criterion for peak discharge in three loss methods ranges between 11 and 27%, for runoff volume between 12 and 28% and for time to peak between 10 and 15%. By studying RE peak discharge and runoff volume, SCS curve number method produced the smallest value and initial and constant rate and Green and Ampt methods produced the same and the highest values. In general, no significant differences were found among models for time to peak simulation. The RMSE analysis of discharge suggests that there are large differences among models. The SCS curve number method produced the smallest value with 0.57 $m^3 s^{-1}$ and Green and Ampt method produced the highest value with 0.87 $m^3 s^{-1}$, whereas initial and constant rate performed almost as well as Green and Ampt method with 0.78 $m^3 s^{-1}$.

Table 6 Results of initial and constant rate method

ID	Phase	Date	Peak discharge	Runoff volume	Time to peak	Discharge		DPOT
			RE (%)	RE (%)	RE (%)	PWRMSE ($m^3 s^{-1}$)	NS	*h*
1	Calibration	14/08/2010	48	41	2	0.66	0.43	3
2		02/05/1978	31	44	23	0.77	0.44	2
3		11/09/1980	39	49	18	0.78	0.55	2.2
4		16/07/1993	24	31	24	0.91	0.59	2
5		06/04/2009	26	12	19	0.84	0.74	1
6		05/06/1992	11	18	17	0.79	0.91	0
7		03/05/1994	18	19	1	0.67	0.92	0
8		19/09/1977	16	12	8	0.72	0.88	0.5
9		05/05/1970	24	19	7	0.7	0.66	1
10		24/04/1970	29	22	1	0.86	0.69	2
11		30/05/1983	26	24	1	0.92	0.74	0
12		02/10/1988	33	28	13	0.7	0.78	1
13		30/10/1985	28	22	8	0.79	0.81	0.75
14		03/11/1979	33	21	14	0.75	0.68	0.5
15		16/06/1997	4	2	13	0.87	0.67	1
16		23/10/2006	18	26	12	0.79	0.72	2
17		07/06/1976	21	3	9	0.74	0.74	1.7
18		30/04/1983	26	21	11	0.81	0.76	0
19		16/11/2009	28	22	1	0.69	0.69	0.5
20		28/09/1994	2	25	1	0.8	0.68	0.25
Max.			48	49	24	0.92	0.92	3
Min.			2	2	1	0.66	0.43	0
Mean			24	23	10	0.78	0.7	1.07
21	Validation	23/05/1998	58	58	48	2.5	0.32	2
22		19/04/1973	25	4	23	1.8	0.4	1
23		20/11/2011	37	46	3	1.2	0.75	0
24		03/12/2001	21	36	17	0.97	0.55	2.5
25		29/09/2000	11	27	1	0.88	0.44	1.5
26		15/05/2009	28	49	2	0.69	0.77	1
27		05/05/2003	35	52	22	0.79	0.56	2
28		24/06/1990	3	43	19	0.75	0.54	3
Max.			58	58	48	2.5	0.77	3
Min.			3	4	1	0.69	0.32	0
Mean			27	39	17	1.1	0.54	1.62

DPOT deviation of peak time of observed and calculated hydrographs

Models performance

As it is understood from Tables 6, 7 and 8, there was a clear difference among the models in validation phase. Studying the RE in peak discharge estimation showed that the SCS curve number method produced the least values of 20% ranged from 3 to 34% so that it varied from less than 20% for 20 events (16 events from calibration phase and 4 events from validation phase) to 20% < RE < 50% for other 8 events (4 events from calibration phase and 4 events from validation phase). In addition, Green and Ampt method produced the highest value with 54% ranged from 7 to 94%. The RE in peak discharge estimation varied from less than 20% for 7 events (6 events from calibration phase and 1 event from validation phase), 20% < RE < 50% for 16 events (14 events from calibration phase and 2 events from validation phase) and to more than 50% for the other five events from validation phase, whereas initial and constant rate performed almost as well as Green and Ampt method with 27% ranged between 3 and 58%. The RE in peak discharge estimation varied from less than 20% for 8 events (6 events from calibration phase and 2 events from validation phase), 20% < RE < 50% for 19 events (14 events from calibration phase and 5 events

Table 7 Results of SCS curve number method

ID	Phase	Date	Peak discharge	Runoff volume	Time to peak	Discharge		DPOT
			RE (%)	RE (%)	RE (%)	PWRMSE (m^3 s^{-1})	NS	*h*
1	Calibration	14/08/2010	45	29	26	1.3	0.62	0
2		02/05/1978	35	22	2	1	0.71	0
3		11/09/1980	13	19	17	0.78	0.76	0
4		16/07/1993	12	19	16	0.65	0.77	2
5		06/04/2009	16	2	18	0.56	0.79	2
6		05/06/1992	8	1	12	0.59	0.93	0
7		03/05/1994	1	11	11	0.39	0.88	1
8		19/09/1977	7	1	1	0.35	0.93	0
9		05/05/1970	5	8	1	0.51	0.85	1
10		24/04/1970	1	1	11	0.26	0.94	0
11		30/05/1983	9	1	12	0.28	0.79	0
12		02/10/1988	22	17	18	0.59	0.81	0
13		30/10/1985	1	13	22	0.62	0.92	0
14		03/11/1979	2	19	19	1.1	0.86	1
15		16/06/1997	9	12	19	0.47	0.95	1
16		23/10/2006	7	14	17	0.42	0.96	0
17		07/06/1976	1	16	21	0.55	0.87	0
18		30/04/1983	21	18	22	0.49	0.83	1
19		16/11/2009	9	1	13	0.16	0.91	1
20		28/09/1994	1	12	15	0.38	0.89	0
Max.			45	29	26	1.3	0.96	2
Min.			1	1	1	0.16	0.62	0
Mean			114	12	15	0.57	0.84	0.5
21	Validation	23/05/1998	28	28	19	0.68	0.49	0
22		19/04/1973	18	24	25	0.62	0.51	1
23		20/11/2011	34	31	18	0.8	0.42	0
24		03/12/2001	22	26	27	0.63	0.43	1
25		29/09/2000	26	25	24	0.66	0.5	1
26		15/05/2009	3	28	16	0.84	0.41	0.5
27		05/05/2003	11	13	8	0.28	0.88	0
28		24/06/1990	14	16	14	0.44	0.65	1
Max.			34	31	27	0.84	0.88	1
Min.			3	13	8	0.28	0.41	0
Mean			20	24	19	0.61	0.53	0.56

DPOT deviation of peak time of observed and calculated hydrographs

from validation phase) to more than 50% for another event from validation phase. In this context, as stated by Van Mullem (1991), the Green–Ampt model only considers upper layer of the soil and had no provision for completely filling the soil profile. Though watershed characteristics (i.e., topography, soil and land cover) vary in the watershed and there are complex relationships among soil infiltration rate, watershed characteristics. In fact, many loss models assume soil hydraulic properties homogeneous in area of 100–1000 km^2, whereas these characteristics have spatial variability within watershed scale (Chahinian et al. 2005). Accordingly, these methods need to calibrate using existing data. This is in agreement with the findings of Chahinian et al. (2005), Vich (2013) and Van den Putte et al. (2013) who showed the positive impact of calibration on Green–Ampt model for estimating peak discharge. Generally in the methods which ignore initial loss, peak discharge is overestimated (Hill et al. 1998; Kumar and Bhattacharjya 2011; Unucka et al. 2010). Whereas our study showed that the Green–Ampt model estimated negligible initial loss, the analysis of "A" peak discharge criterion showed that this model estimated the least peak discharge compared to those of other two models. This result shows that region condition is an essential parameter on loss.

Table 8 Results of Green and Ampt method

ID	Phase	Date	Peak discharge	Runoff volume	Time to peak	Discharge		DPOT
			RE (%)	RE (%)	RE (%)	PWRMSE ($m^3\ s^{-1}$)	NS	*h*
1	Calibration	14/08/2010	11	2	13	1.48	0.24	1
2		02/05/1978	33	28	1	0.54	0.43	0
3		11/09/1980	39	39	22	0.62	0.62	3
4		16/07/1993	31	45	26	1.1	0.48	3.8
5		06/04/2009	29	43	12	0.82	0.67	1
6		05/06/1992	24	11	9	0.54	0.34	0
7		03/05/1994	44	19	13	1.24	0.56	1
8		19/09/1977	46	26	19	0.48	0.61	2.2
9		05/05/1970	12	36	17	0.77	0.62	1
10		24/04/1970	18	3	22	0.69	0.41	4.2
11		30/05/1983	27	15	25	0.79	0.78	4
12		02/10/1988	5	28	29	0.76	0.87	5
13		30/10/1985	25	25	16	0.87	0.69	2
14		03/11/1979	33	39	11	0.84	0.83	1
15		16/06/1997	38	47	1	0.79	0.4	0
16		23/10/2006	19	55	13	0.88	0.55	1
17		07/06/1976	12	28	2	0.82	0.76	3
18		30/04/1983	34	29	15	0.92	0.55	2
19		16/11/2009	27	17	19	1.6	0.73	5.2
20		28/09/1994	29	19	11	0.8	0.39	5
Max.			46	55	29	1.6	0.87	5
Min.			5	2	1	0.48	0.24	0
Mean			27	28	15	0.87	0.58	1.91
21	Validation	23/05/1998	45	66	32	1.35	0.32	2.7
22		19/04/1973	58	58	3	0.9	0.41	2
23		20/11/2011	68	52	24	1.73	0.15	5
24		03/12/2001	7	16	2	1.4	0.3	3
25		29/09/2000	23	37	29	0.7	0.56	1
26		15/05/2009	94	39	18	1.25	0.33	0.75
27		05/05/2003	52	44	14	1.4	0.19	3
28		24/06/1990	88	49	25	2.1	0.1	1.5
Max.			94	66	32	2.1	0.56	5
Min.			7	16	2	0.7	0.1	0.75
Mean			54	45	18	1.35	0.29	2.36

DPOT deviation of peak time of observed and calculated hydrographs

Table 9 R^2 and *A* statistics of three infiltration methods

Infiltration method	Stage	Peak discharge		Runoff volume		Time to peak	
		R^2	***A***	R^2	***A***	R^2	***A***
Initial and constant rate	Calibration	0.9	0.91	0.89	0.75	0.88	0.89
	Validation	0.74	0.79	0.70	0.69	0.90	0.92
SCS curve number	Calibration	0.96	0.99	0.95	0.89	0.96	1
	Validation	0.94	0.93	0.88	0.85	0.95	0.97
Green and Ampt	Calibration	0.73	0.70	0.90	0.81	0.94	0.83
	Validation	0.56	0.65	0.76	0.77	0.75	0.75

When we analyzed the performance in terms of RE runoff volume, SCS curve number method produced the least error for runoff volume estimation. It varies from less than 20% for 20 events (18 events from calibration phase and 2 events from validation phase) to 20% < RE < 50% for other 8 events (2 events from calibration phase and 6 events from validation phase). It varies less than 20% for 8 event (7 events from calibration phase and one event from validation phase), 20% < RE < 50% for 19 events (13 events from calibration phase and 6 events from validation phase) to more than 50% for another event from validation phase in initial and constant rate. It also varies from less than 20% for 7 events (6 events from calibration phase and one event from validation phase), 20% < RE < 50% for 17 events (13 events from calibration phase and 4 events from validation phase) to more than 50% for the other five events (one from calibration phase and 3 events from validation phase) in Green and Ampt method. Therefore, initial and constant rate and Green and Ampt method are ranked in second and third rank in runoff volume estimation, respectively. Based on "A" criterion of runoff volume, all models are underestimation (Fig. 4). This is mainly due to the problems inherent to determine the soil moisture conditions before and during flood events as all three models do not take into account soil moisture redistribution, and soil moisture values are considered constant over the whole duration of the flood event (Chahinian et al. 2005).

Studying the performance of infiltration models for time to peak prediction shows that all flood hydrographs were well simulated. The results of PWRMSE show that SCS curve number method produced the best precision with $0.61\ m^3\ s^{-1}$ and initial and constant rate and Green and Ampt method produced almost the same with 1.10 and $1.35\ m^3\ s^{-1}$, respectively. Elucidating NS criterion shows that flood hydrographs were well simulated by the SCS curve number method for 8 events (one event from calibration phase and 7 event from validation phase) with 0.30 < NS < 0.70 and for the other 20 events (19 events from calibration phase and one event from validation phase) with NS > 70%. Likewise, the initial and constant rates were successfully simulated for 16 events (10 event from calibration phase and 6 event from validation phase) with 0.30 < NS < 0.70 and for the other 12 events (10 events from calibration phase and 2 events from validation phase) with NS > 70%, whereas the unsatisfactory performance of the Green and Ampt method was proved for 4 events (one event from calibration phase and 3 events from validation phase) with NS < 0.30. Although these results differ from some published studies (Chahinian et al. 2005; Vich 2013) due to different spatial scale, they are consistent with those of Bhatt et al. (2012) who observed a good performance of the SCS curve number method at the watershed ($3796\ km^2$) scale. The estimated and observed hydrographs are given for validation stage in Fig. 5.

Conclusions

The present study was carried out to compare the performance of three infiltration models, namely initial and constant rate, SCS curve number and Green and Ampt in estimation of flood hydrographs in the Amameh Watershed, Iran, with an area of 3712 ha with the help of the HEC-HMS

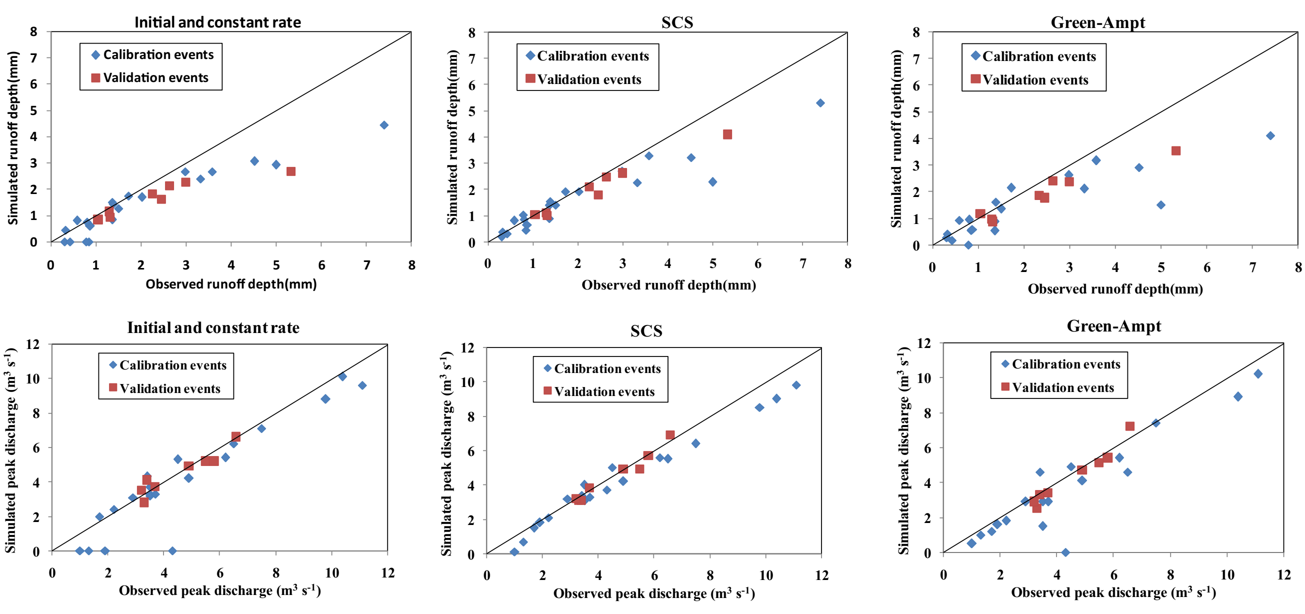

Fig. 4 Comparison of observed and simulated runoff depth and peak discharge for three models for both calibration and validation events

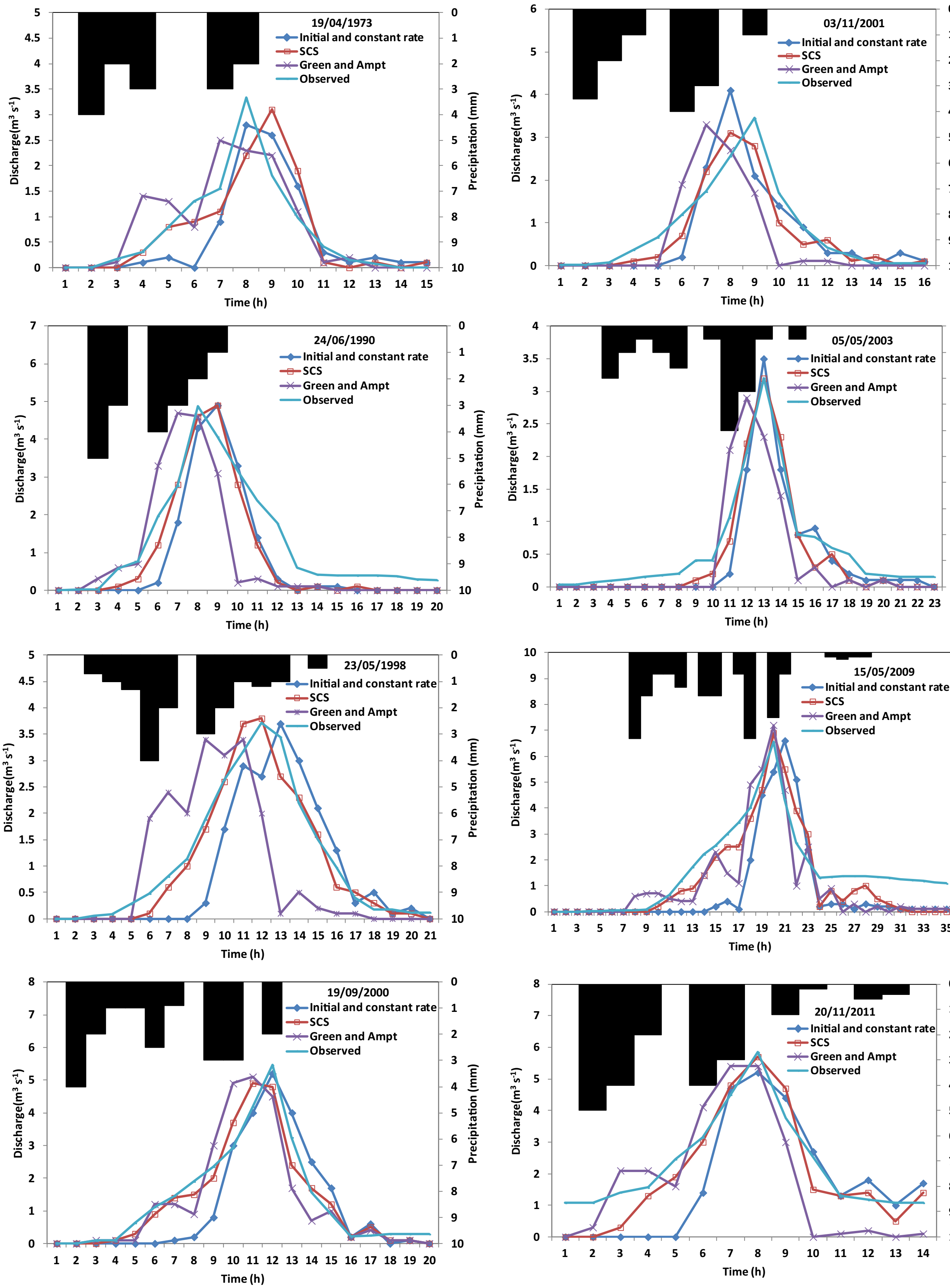

Fig. 5 Validation graphs of initial and constant rate, SCS and Green and Ampt models

software package. To this end, the infiltration rates were measured in 60 points distributed across 12 subwatersheds. From the results of the study, it can be concluded that the SCS curve number and initial and constant rate methods performed better than Green and Ampt to estimate peak discharge. In addition, the SCS curve number method performed satisfactorily in prediction of runoff volume with the least value of estimation error, while the model based on initial and constant rates of the infiltration and the Green and Ampt model was, respectively, prioritized in second and third order. Interestingly, all three study models performed similarly well in simulation of time to peak of the hydrographs. The PWRMSE and NS criteria also verified that the SCS curve number method simulated the entire ordinates of the flood hydrographs superior to other two models of the initial and constant rate and the Green and Ampt. Since the performance of the model is mainly controlled by the comprehensiveness of variables used for the model formulation, the SCS model due to considering more watershed characteristics could perform better in simulation of storm-wise hydrographs in the Amameh Watershed in Iran. However, more insightful studies incorporating different hydrologic and infiltration models should be conducted under different circumstances to enable a more comprehensive conclusion.

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