JUEE

Journal of Urban and Environmental Engineering, v.5, n.1, p.1-14

ISSN 1982-3932
doi: 10.4090/juee.2011.v5n1.001014

Journal of Urban and Environmental Engineering

www.journal-uee.org

TOPMODEL CAPABILITY FOR RAINFALL-RUNOFF MODELING OF THE AMMAMEH WATERSHED AT DIFFERENT TIME SCALES USING DIFFERENT TERRAIN ALGORITHMS

Vahid Nourani[1*], Arash Roughani[2] and Mekonnen Gebremichael[3]

[1] *Faculty of Civil Eng., Univ. of Tabriz, Iran; and Dept. of Civil Eng., Univ. of Minnesota, USA*

[2] *Department of Water Resour. Eng., Faculty of Civil Eng., Univ. of Tabriz, Iran*

[3] *Department of Civil and Environmental Eng., Univ. of Connecticut, Storrs, CT, USA.*

Received 05 March 2011; received in revised form 25 May 2011; accepted 28 May 2011

Abstract: In this study, the rainfall-runoff response of the Ammameh watershed located in Tehran, Iran, was studied using TOPMODEL which is a semi-distributed and geomorphologic model that simulates runoff at the watershed's outlet on the basis of saturation excess runoff and subsurface flow concepts. Topographic index as an indicator of the spatial distribution of excess runoff generation in the catchment was calculated using the flow direction, output from two different methods, i.e. Dinf and D8. The analysis was done at three time scales: event, daily, and monthly. The modeling performance of TOPMODEL in simulating runoff process for each of three types of time series was analyzed and compared visually and statistically. Also, the effects of D8 and Dinf methods on rainfall-runoff modeling were compared and it was realized that modeling result of Dinf algorithm, especially in event-based rainfall-runoff modeling was more accurate than the D8 algorithm; whereas, the difference between the results were not notable in the daily modeling. Although the obtained results demonstrate the capability of the TOPMODEL in both event-based and daily simulations, the model could lead to the more reliable results in daily modeling because of considering the watershed soil moisture conditions.

Keywords: TOPMODEL; rainfall-runoff modeling; topographic index; Ammameh watershed.

© 2011 Journal of Urban and Environmental Engineering (JUEE). All rights reserved.

[*] Correspondence to: Vahid Nourani. E-mail: vnourani@yahoo.com

INTRODUCTION

Within the past few years, the analysis of factors affecting the hydrological processes within basins has been one of the most significant areas of research in the field of hydrologic modeling. One of the most important prerequisites of developing the map of watersheds and knowing their hydrologic characteristics is the knowledge of rainfall-runoff simulating at the basin or sub-basins outlets which is one of the most significant challenges of hydrologists, specially in the least developed countries such as Iran that suffer from the lack of adequate data required for the hydrologic modeling. To this point, some models have been employed to overcome this problem (Guzha & Hardy, 2010).

Hydrologic models have been generally classified into two categories: lumped and distributed models. Lumped models act as a black-box model and estimate runoff only at the catchment outlet. These models can not provide any information about the distribution of saturated areas within the basin; therefore, they are unable to describe how saturated areas distributed within the basin and what their role in evapotranspiration and runoff production is. In addition, parameters in such models do not have a clear physical interpretation and estimation of the parameters need to have long-term rainfall-runoff time-series of the watersheds. Distinct from lumped models, distributed models account the heterogeneity and spatial variability by considering variations in water characteristics across the entire area of the watershed. However, such models include many parameters, which though have clear physical meanings, they are very difficult to be calculated. However, increasing the computer power, Geographic Information System (GIS) packages, and spatially distributed data have made distributed modeling possible.

TOPMODEL is a topographically based semi-distributed hydrological model which provides the compromise between the complexity of fully distributed process models and the relative simplicity of lumped models (Robson *et al.,* 1993). In short, TOPMODEL represents a set of modeling tools that combines the computational and parametric efficiency of a lumped modeling approach with the link to physical theory (Beven *et al.,* 1995). In TOPMODEL, rainfall-runoff modeling at the catchment outlet is made based on the theory of hydrological similarity of points in a catchment, with the topographic index used as an index of hydrological similarity (Xiong & Guo, 2004). The concept of topographic index was firstly presented by Beven & Kirkby (1979). Topographic index can quantify the control of topography on rainfall-runoff process and indicates the spatial distribution of soil moisture and surface saturation. Because of the structural simplicity, explicit interpretation of the assumed physical concepts, incorporation of geomorphological effects, a few number of model parameters, and its role of bridging the gap between the conceptual and the physically-based distributed rainfall-runoff models, TOPMODEL has become a widely used hydrologic model in different regions of the world among the hydrologists (Krauth, 1999).

One of the reasons for the TOPMODEL popularity is its capability to application in a wide range of basins. Nourani & Mano (2007) used TOPMODEL for rainfall-runoff modeling in the Karoon River basin in western Iran. This model also has been used successfully by Takeuchi *et al.* (2008), for rainfall-runoff modeling in Mekong basin. TOPMODEL has been successfully used in humid temperate (Beven & Wood 1983; Hornberger *et al.,* 1985; Beven 1993; Robson *et al.,* 1993; Lamb *et al.,* 1998; Guntner *et al.,* 1999) and drier Mediterranean regimes (Durand *et al.,* 1992; Pinol *et al.,* 1997). TOPMODEL has also been applied in two small humid tropical catchments: The Buro-borotu catchment (1.36 km^2), in Ivory Coast (Quinn *et al.,* 1991) and a forested headwater catchment (1.5 ha) of the river Sinamary in French Guiana (Molicova *et al.,* 1997). Also, Bruneau *et al.*, (1995) investigated the interaction of hourly time step and spatial resolution in the modeling framework.

Every hydrologic model, because of its special structure and basic assumptions, is developed for specific time and spatial scales. For example, HEC-HMS (Hydrologic Engineering Center, 2006) and unit hydrograph method are event-based models and cannot be appropriately applied for long-term rainfall-runoff modeling (Nourani *et al.,* 2009). The reason is that because these models are not able to estimate exactly the amount of water content in the soil column, especially before and after long periods.

In the present study, TOPMODEL is used for rainfall-runoff modeling at the Ammameh catchment outlet in central Iran. Three types of rainfall-runoff time-series with different time scales are utilized for rainfall-runoff modeling: storm events, daily and monthly data sets. Also, two different flow direction calculating algorithms, D8 and Dinf, are implemented for obtaining the topographic index as a key component in TOPMODEL. Finally, the effects of time scale and the flow direction calculating algorithms on the rainfall-runoff modeling are evaluated and discussed.

HYDROLOGICAL MODEL AND METHODOLOGY

TOPMODEL is a physically based, semi-distributed catchment model of runoff generation that uses topographic information in the form of an index that describes the tendency of water to accumulate and to be moved down slope by the gravitational force (Beven & Kirkby, 1979). Past studies in the rainfall-runoff modeling of catchments have been dominated by Horton’s theory of infiltration excess overland flow. However, there has been an increased interest on the saturation-excess aspect of overland flow and subsurface runoff generation. The theory behind infiltration excess overland flow states that surface runoff will occur even if the soil beneath the surface is not fully saturated. In contrast, saturation excess generated runoff occurs due to overland flow generated when the soil is fully saturated to the surface. It also occurs when the subsurface flow returns to the surface in saturated areas, such as the bottom of a hill slope. Subsurface flow usually occurs when the top layers of the soil profile have high values of down slope hydraulic conductivity and steep hill slopes.

TOPMODEL, fully described by Beven *et al.*, (1995), uses the distribution of the topographic index, λ, as an index of hydrologic similarity:

$$\lambda_i = \ln\left(\frac{a_i}{\tan\beta_i}\right) \tag{1}$$

where, a_i (m) is the area draining through a grid square of i per unit length of contour and tan β_i is the local surface slope (**Fig. 1**).

The basic model assumptions are (Beven *et al.*, 1995): (1) uniform recharge across the catchment with a quasi steady state condition, (2) local hydraulic gradient can be approximated by the local surface topographic slope, tan β_i, (3) using an exponential decline of transmissivity (or hydraulic conductivity) with depth or deficit.

TOPMODEL represents three layers of the soil column (root, unsaturated and saturated zones) as three interconnected reservoirs (**Fig. 2a**).

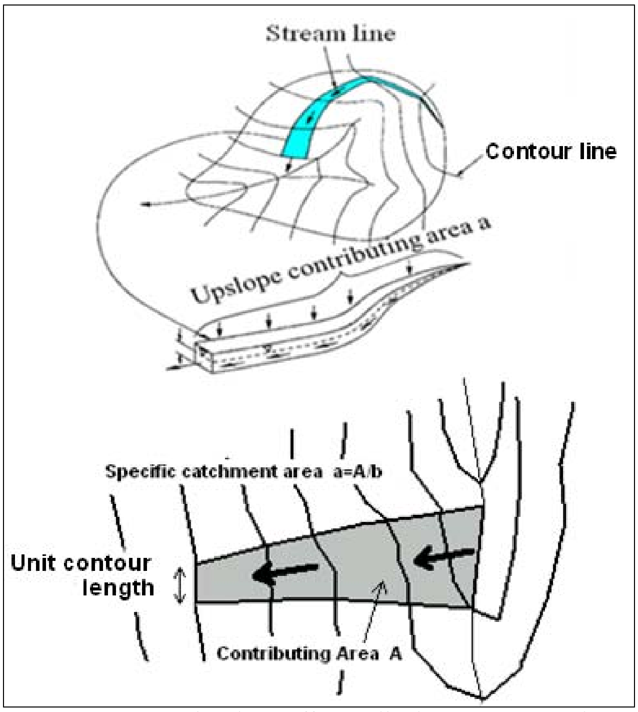

Fig. 1 Accumulated runoff contributing area per unit contour length (Franchini *et al.*, 1996).

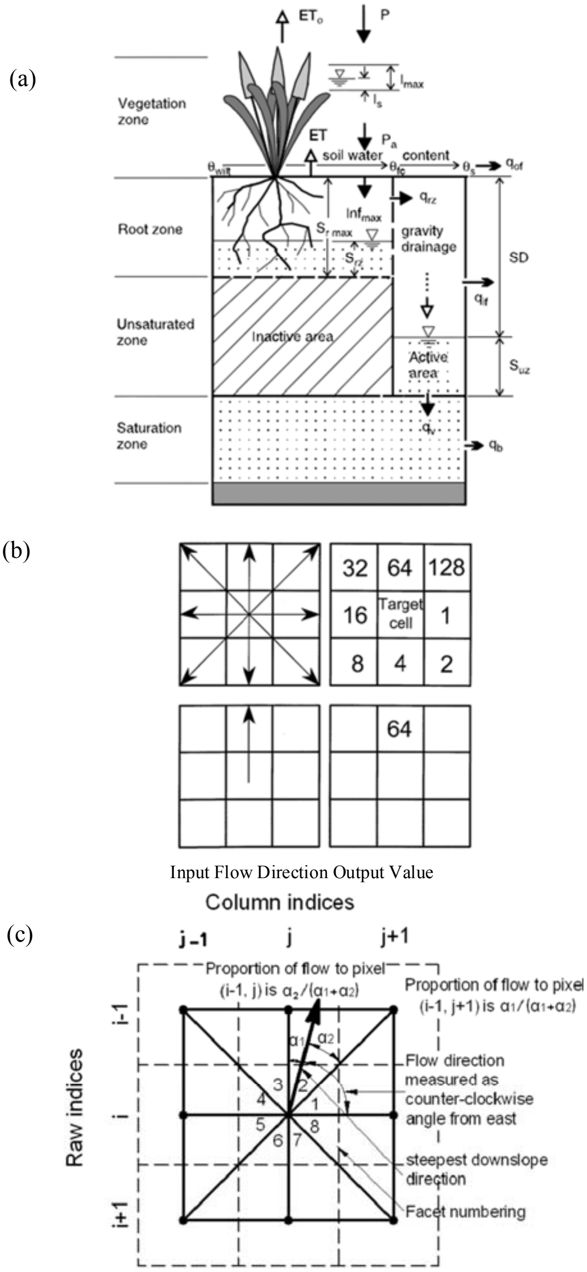

Fig. 2 (a) TOPMODEL concept; flow direction calculation by (b) D8, (c) Dinf (Tarboton, 1997) algorithms.

Evapotranspiration (*ET*) is taken from the root zone storage as actual *ET* (*AET*), which can be computed by the following equation:

$$AET_i = RET \times SRZ_i / SR_{max} \tag{2}$$

where, SRZ_i and SR_{max} are the storage and maximum capacity of the root zone, respectively, *RET* is reference *ET* and the subscript of *i* indicates the location or grid cell; because the potential *ET* denomination is discouraged due to ambiguities in its definition (Irmak & Harman 2003), the *RET* terminology is used in this paper instead. The unsaturated storage is controlled by the saturation deficit of S_i, which is equivalent to the quantity of water required to fill this reservoir. Gravity drainage qv_i to the saturated reservoir is delayed as a function of the unsaturated storage SUZ_i (Franchini *et al.,* 1996):

$$qv_i = SUZ_i / t_d S_i \quad \text{with} \quad qv_i \le SUZ_i \qquad (3)$$

where, t_d is a constant time delay parameter per unit deficit.

According to the third assumption of the model, the following relation can be considered:

$$K_i(Z_i) = k_0 \exp(-fZ_i) \qquad (4)$$

where, Z_i is the depth (Z-axis pointing downwards), k_0 is constant hydraulic conductivity at the ground surface and f is a decay factor of hydraulic conductivity with Z_i. By applying Darcy's law and the second assumption of the model and using water deficit S_i instead of water Table Z_i, local lateral subsurface flow qb_i from the saturated zone can be calculated by the following equation (Franchini *et al.,* 1996):

$$qb_i = T_0 \tan\beta_i \exp(-S_i / m) \qquad (5)$$

where

$$T_0 = k_0 / f \qquad (6)$$

is the transmissivity of the full saturated soil, which, like k_0 and f, is assumed constant over the whole sub-basin and

$$m = \frac{\theta_f - \theta_r}{f} \qquad (7)$$

where, θ_f and θ_r are respectively the field capacity and the residual volumetric water contents of the soil and keep constant with depth. By using the first assumption of the model and **Eq. (5)**, the local saturation deficit can be derived (Beven & Kirkby, 1979):

$$S_i = \bar{S} + m(\bar{\lambda} - \lambda_i) \qquad (8)$$

where, $\bar{S}$ and $\bar{\lambda}$ are the areally averaged values of S_i and λ_i, respectively. Then, subsurface flow contribution Q_b can be obtained by contour integration of q_{bi} (Franchini *et al.,* 1996):

$$Q_b = AT_0 \exp(-\bar{\lambda}) \exp\left(\frac{-\bar{S}}{m}\right) = Q_0 \exp\left(-\frac{\bar{S}}{m}\right) \qquad (9)$$

where, A is the total drainage area of the sub-basin per unit width; for all points with $S_i \le 0$ the saturation condition has been reached and these points generate a sub-basin fraction that is in a saturated condition where rainfall produces direct overland surface runoff. This excess flow plus subsurface flow Q_b at each time step will be the output discharge of sub-basin. According to **Eq. (8)**, all points of the sub-basin with the same topographic index will have the same response in runoff generation. The histogram of topographic index accompanied by meteorological data (precipitation, *ET* and observed discharge) is used as the model input data. The generated runoff is then routed through the main channel which can be controlled by a routing parameter named CHVEL.

The present study has been carried out to determine the effect of time scale on rainfall-runoff modeling using three types of time series with different time scales: storm events, daily and monthly data sets. Also, two different flow direction calculation algorithms, D8 and Dinf, were employed to calculate topographic index as a key component in TOPMODEL. Single flow direction algorithm (D8) is the earliest and simplest method for specifying flow directions which is to assign flow from each pixel to one and only one neighboring pixel which has the lowest elevation (**Fig. 2b**). Multiple flow direction algorithm (Dinf) assumes that flow from the current position could drain into more than one down slope neighboring pixels (**Fig. 2c**) (Tarboton, 1997). In order to compute the local ground surface slope, flow direction and also specific area by D8 and Dinf methods, TauDEM toolbox was employed (Tarboton, 2005).

For the evaluation of the TOPMODEL performance, the Nash & Sutcliffe (1970) index (E) and correlation coefficient between observed data and calculated data (R) have been used. These measures are defined as (Nourani *et al.,* 2009):

$$E = 1 - \frac{\sum_{i=1}^{No} \left(Q_{i,obs} - Q_{i,sim}\right)^2}{\sum_{i=1}^{No} \left(Q_{i,obs} - \bar{Q}_{obs}\right)^2} \qquad (10)$$

$$R = \frac{\sum_{i=1}^{No} \left(\left(Q_{i,obs} - \bar{O}_{obs}\right)\left(Q_{i,sim} - \bar{Q}_{sim}\right)\right)}{\sqrt{\sum_{i=1}^{No} \left(Q_{i,obs} - \bar{O}_{obs}\right)^2 \sum_{i=1}^{No} \left(Q_{i,sim} - \bar{Q}_{sim}\right)^2}} \qquad (11)$$

where, $Q_{i,obs}$ is the observed discharge at $t = i$; $Q_{i,sim}$ is the simulated discharge at $t = i$; *No* is the number of observed data, respectively and the "bar" sign denotes to the average value.

STUDY SITE AND DATA

The Ammameh watershed, one of the sub basins of the Jajrood river basin, upstream of Latyan dam, is located in the southern area of central Alborz, near Tehran (capital of Iran), with an area of 37.39 km^2 and the watershed elevation ranges from 1900 m to 3868 m above sea level. The position of Ammameh watershed and its raster digital elevation model (DEM) with 50 meter resolution are shown in **Fig 3**. Also, geomorphological statistics of the study area which were extracted from DEM are presented in **Table 1**. The geology formation of the watershed is hard volcanic and surface layer is constructed 15 cm approximately thick, dark brown in color with a varying texture of sandy to silt and clay. The vegetation coverage includes gardens and grass, and the remainder has the vegetation coverage of bushes (Nourani *et al.*, 2009).

The slopes in the catchment are rather steep, with a mean value of 11.46 percent. The mean annual precipitation calculated by the Thiessen method and the annual runoff are found to be 848.4 and 504 mm, respectively. Most of the precipitation (almost 73%) falls during the winter and spring seasons (December to May). The months of April and September are the wettest and the driest months during the year, respectively. The annual mean temperature in the area is 8.6°C while the absolute maximum and minimum temperatures are 35 and -24°C, respectively. The least and the highest values of evaporation occur during the months of February and July, respectively.

There are two meteorological stations, Ammameh and Klukan, within the basin and Rahatabad meteorological station out of the basin. There are also two hydrometer stations within Ammameh basin which are operated by Tehran Regional Water Corps since 1990. Baghtangeh station at the upstream of Ammameh meteorological station and Kamarkhani station at the outlet of the catchment. In order to allow the comparison with other studies, the data of nine recorded events which have been already used by the authors in the previous study (Nourani *et al.*, 2009) were employed in this study. The stream flow and precipitation data of six storm events were used for the model calibration and three of storms were used for the verification phase. Also, daily and monthly average rainfall-runoff data sets from five years (2001 to 2006) were utilized for daily and monthly simulations. Three years (2001–2003 and 2004–2005) for calibration phase of TOPMODEL and the rest for the verification purpose.

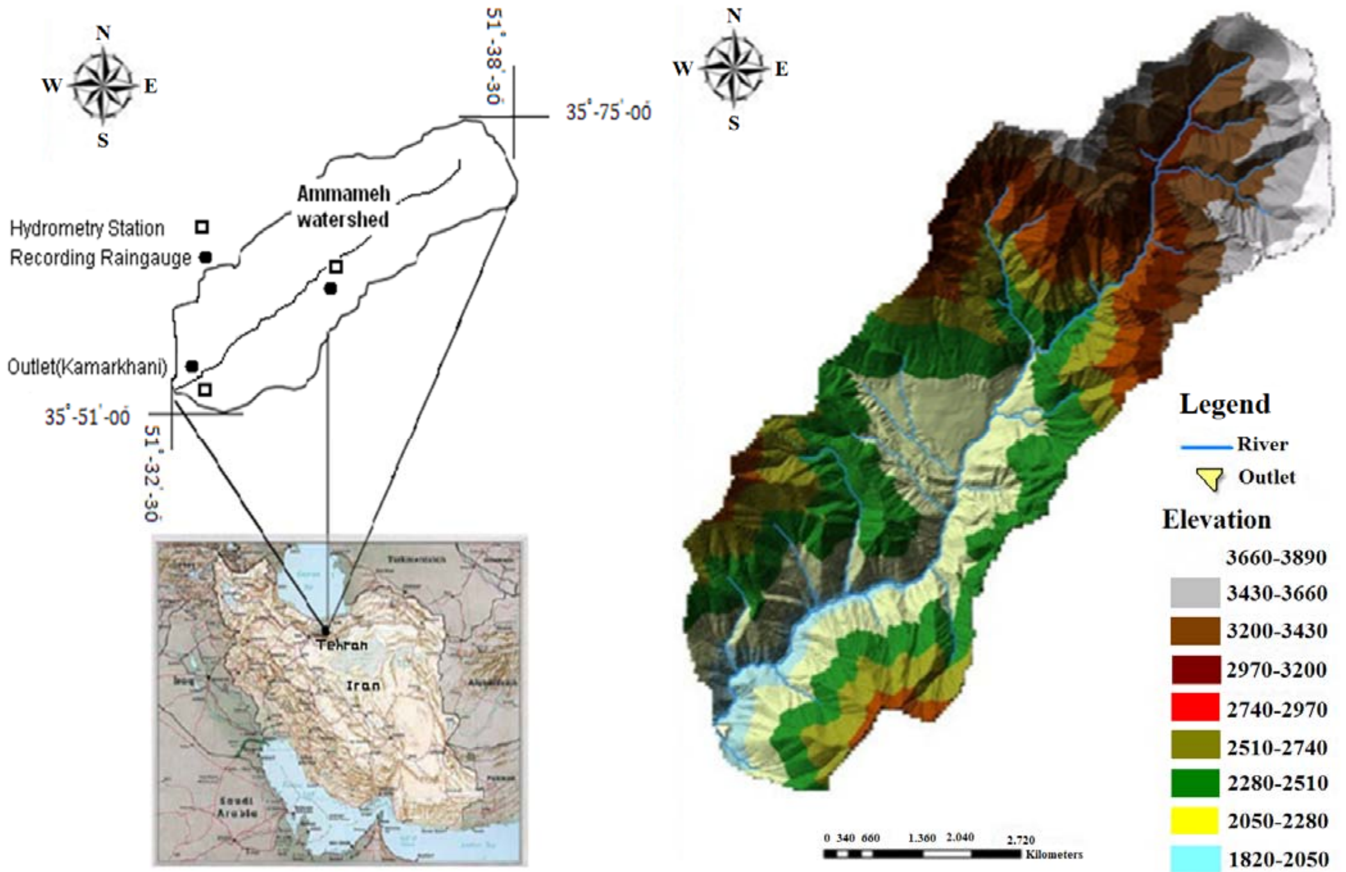

Fig. 3 The position and DEM of study area.

Table 1. Geomorphological statistics of Ammameh watershed

Main Channel Slope (%)	Main Channel Length (m)	Channel Maximum Slope (%)	Longest Channel Length (m)	Catchment Mean Elevation (m)	Perimeter (m)	Area (m^2)
11.46	13228	14.25	14422	2679.30	41594	37.39

RESULTS AND DISCUSSION

As the first step of the modeling, a comparison was done between the computed topographic index by D8 and Dinf methods. **Figure 4** compares the computed spatial distributions of λ derived by both D8 and Dinf algorithms. In accord with this figure, it can be seen that the Min, Max, and Mean values of topographic index, calculated by Dinf method, are higher in comparison with the D8 algorithm.

Event-based rainfall-runoff modeling

The parameters of the model, calibrated in the calibration step for both D8 and Dinf methods have been presented in **Table 2**. The hydrological characteristics obtained in calibration and verification steps have been summarized up in **Tables 3** and **4** for both D8 and Dinf methods, respectively. Also, **Figs 5–6** compare the computed hydrographs of events using D8 and D_{inf} methods in the calibration and verification phases, respectively.

As it is clear in the **Tables 3–4**, there is a reasonable match between the simulated and observed hydrographs, peak points, time to peaks, and total runoff volumes, especially in the Dinf flow direction algorithm results.

From the results of calibration phase (**Table 2**), it can be seen that the there is no difference between SR_{max} values in different events; whereas the values of m, $\ln T_0$, SR_{initi}, and CHVEL differ from an event to the other which is because of the lack of appropriate evapotranspiration data as the inputs to the model. Since SR_{max} is an evapotranspiration process related parameter which is defined as the maximum allowable root zone storage, the lack of appropriate evapotranspiration data set leads to SR_{max} parameter plays no role on the results of TOPMODEL calibration and verification phases.

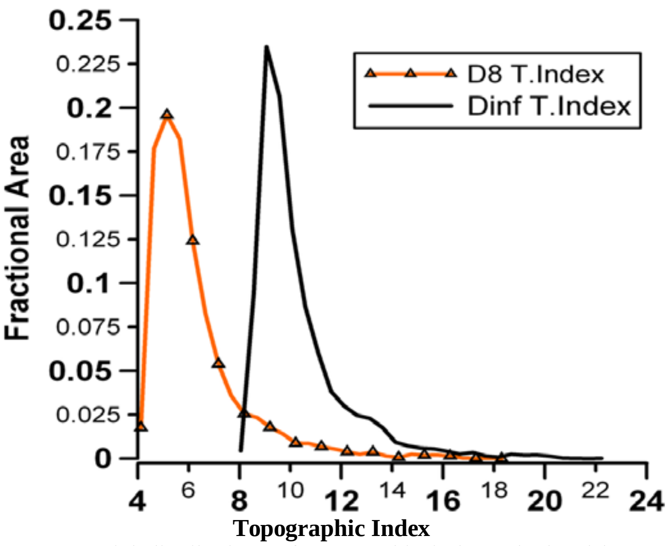

Fig. 4 Spatial distributions of topographic index calculated by D8 and Dinf algorithms.

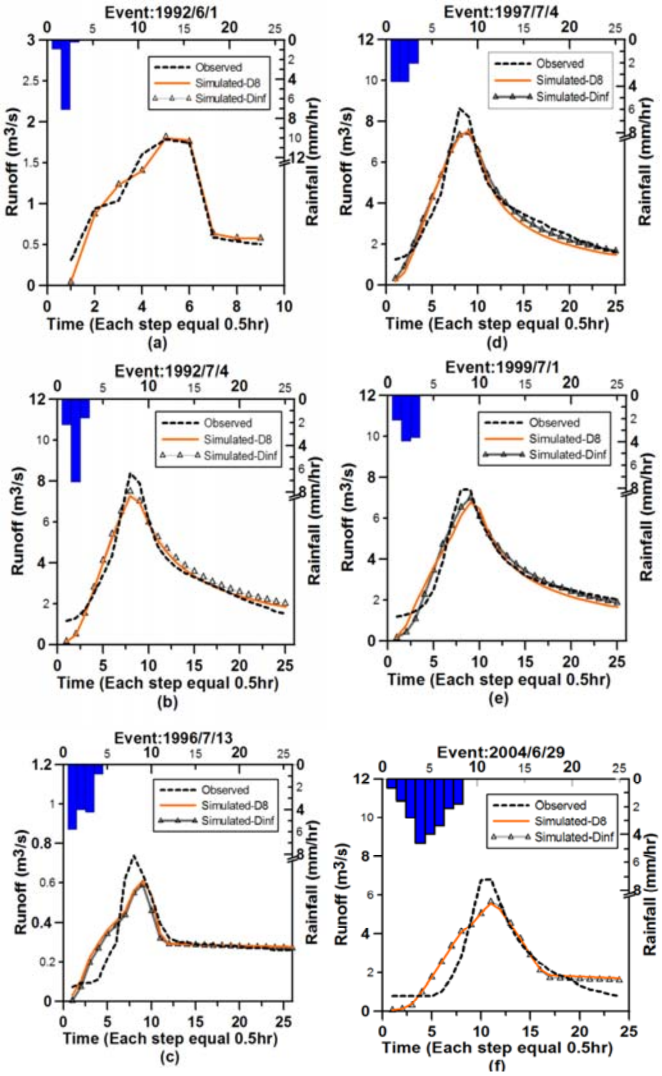

Fig. 5 Observed and simulated hydrographs of events obtained by D8 and Dinf algorithms at calibration step.

As it is interpreted from **Table 2**, the routing parameter (CHVEL) using Dinf algorithm has higher values in comparison with D8 algorithm. A possible explanation for this might be that CHVEL parameter refers to the velocity within a stream segment or within a distance increment and also refers to the velocity that translates the runoff from a location in the catchment to the catchment outlet. Besides, in the calculation of flow direction using Dinf algorithm, the number of cells that water flows into or out of them is more than that of using D8 algorithm. As a result, the length of flow paths and diffusion area of water in Dinf algorithm seems to be higher than that of in D8 algorithm. This can demonstrates the reason of considerable differences between CHVEL parameter values obtained by the Dinf and D8 algorithms.

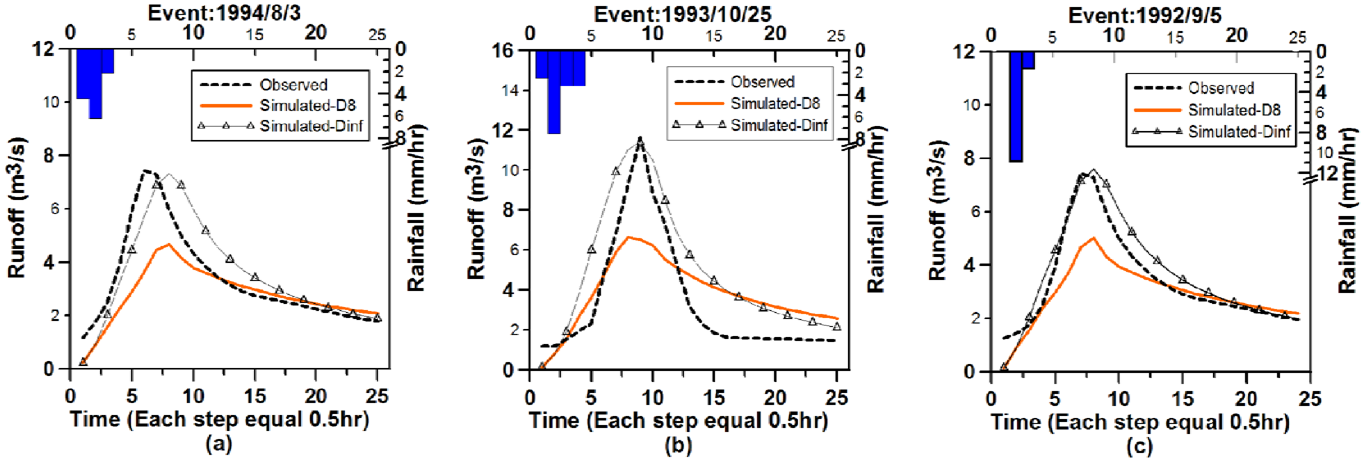

Fig. 6 Observed and simulated hydrographs of events obtained by D8 and Dinf algorithms at verification step.

Table 2. Calibrated parameters by D8 and Dinf algorithms

Event	Soil Transmissivity Decay (m)		lnT_0		Soil Surface Transmissivity T_0 (m²/h)		Maximum Water Storage in Root Zone SR_{max} (m)		Initial Moisture Deficit in Root Zone SR_{init} (m)		Routing Parameter CHVEL (m/h)	
	D8	Dinf	D8	Dinf	D8	Dinf	D8	Dinf	D8	Dinf	D8	Dinf
1992/6/1	0.0072	0.0066	-0.89	3.05	0.41	21.10	0.05	0.05	0.003	0.003	4880	4900
1992/7/4	0.0041	0.0046	0.50	9.50	1.65	13 359.70	0.05	0.05	0.001	0.00	3700	3800
1996/7/13	0.0075	0.0049	1.36	4.95	3.9	141.17	0.05	0.05	0.004	0.006	2830	3010
1997/7/4	0.003	0.0035	3.80	6.00	44.70	403.4	0.05	0.05	0.001	0.00	3400	3210
1999/7/1	0.0035	0.0042	0.50	10.00	1.65	22 026.50	0.05	0.05	0.001	0.00	2900	3770
2004/6/29	0.0155	0.0016	-0.89	3.00	0.41	20.08	0.05	0.05	0.0035	0.0042	2700	2680
Mean*	0.0068	0.0042	1.48	6.08	33.26	5995.33	0.05	0.05	0.002	0.0023	3402	3562

*The mean values of topographic index distributions computed by D8 and Dinf methods are 6 and 10.04, respectively.

Table 3. The results of calibration and verification phases of storm events by D8 algorithm

Phase	Event	TOPMODEL Peak Flow Q_s (m³/s)	Observed Peak Flow Q_o (m³/s)	TOPMODEL Time to Peak T_{po} (h)	Observed Time to Peak T_{ps} (h)	V_{ts} (m³)	V_{to} (m³)	E (%)	R (%)
Calibration	1992/6/1	1.803	1.79	2.00	2.00	16 023.30	16 293	93.80	97.14
	1992/7/4	7.28	8.39	3.50	3.50	152 641	153 402	94.00	96.95
	1996/7/13	0.61	0.74	4.00	3.50	14807	14 486	77.30	89.10
	1997/7/4	7.54	8.64	4.00	3.50	147 489	160 187	91.90	97.00
	1999/7/1	6.78	7.40	4.00	3.50	143 845	150 056	90.10	95.30
	2004/6/29	5.56	6.84	5.00	5.00	110 318	103 576	81.00	90.63
	E(%)	92.50 (for Peak Flow)		83.20 (for Time to Peak)		99.00 (for Total Runoff)		E_{Av} = 88.00	R_{Av} = 94.35
	R(%)	99.60 (for Peak Flow)		96.10 (for Time to Peak)		99.60 (for Total Runoff)			
Verification	1992/9/5	5.03	7.45	3.50	3.00	135 530	156 131	67.60	90.50
	1993/10/25	6.64	11.64	3.50	3.50	191 128	165 776	61.10	84.60
	1994/7/24	4.76	7.45	3.50	3.50	128 111	152 265	46.20	77.40

V_{ts} = TOPMODEL total runoff, V_{to} = Observed total runoff, E (%) = Nash and Sutcliffe efficiency, R (%) = Correlation coefficient.

Table 4. The results of calibration and verification phases of storm events by Dinf algorithm

Phase	Event	TOPMODEL Peak Flow Q_s (m^3/s)	Observed Peak Flow Q_o (m^3/s)	TOPMODEL Time to Peak T_{po} (h)	Observed Time to Peak T_{ps} (h)	V_{ts} (m^3)	V_{to} (m^3)	E (%)	R (%)
Calibration	1992/6/1	1.72	1.79	2.00	2.00	16 075	16 293	93.80	97.12
	1992/7/4	7.49	8.39	3.50	3.50	159 794	152 402	92.60	96.50
	1996/7/13	0.59	0.74	3.50	4.00	14 142	14 486	77.40	89.80
	1997/7/4	7.47	8.64	4.00	3.50	156 705	160 187	94.10	97.07
	1999/7/1	6.99	7.40	4.00	3.50	148 903	150 056	93.20	96.71
	2004/6/29	5.65	6.84	5.00	5.00	109 088	102 776	81.60	90.70
	E(%)	93.70 (for Peak Flow)		84.10 (for Time to Peak)		99.60 (for Total Runoff)		E_{Av}=	$R_{A\ v}$=
	R(%)	99.60 (for Peak Flow)		92.60 (for Time to Peak)		99.80 (for Total Runoff)		88.78	94.65
Verification	1992/9/5	7.61	7.45	3.50	3.00	168 527	156 131	89.70	97.20
	1993/10/25	11.51	11.46	4.00	4.00	238 351	168 776	61.50	93.70
	1994/7/24	7.24	7.45	3.50	2.50	163 219	152 365	71.70	88.10

V_{ts} = TOPMODEL total runoff, V_{to} = Observed total runoff, E(%) = Nash and Sutcliffe efficiency, R(%) = Correlation coefficient.

The graphs plotted in **Fig. 6** indicate that the simulated hydrographs using Dinf algorithm has a much better fit on the observed hydrographs in comparison with D8 algorithm. Also, the results given in **Tables 3** and **4** show that in general, the values of E and R obtained using Dinf are much accurate than those of using the D8 algorithm. Therefore, employing Dinf algorithm for calculating topographic index in event based rainfall-runoff modeling using TOPMODEL has much promising results in comparison with the D8 algorithm.

Considering the presented results in **Table 2**, it can be seen that the discrepancies of the T_0 calibrated by D8 and Dinf algorithms are significant. Whereas, simulated hydrographs and averaged values of efficiencies, E and R, do not have any significant differences in the calibration phase because the calibration process tries to regulate the parameters so that the simulated and observed hydrographs have a good match with together. In simulating process by TOPMODEL, one of the extracted outputs is the spatial distribution map of saturation areas. **Figure 7** shows the distribution of saturated areas at the end of storm (1992/6/1) by D8 and Dinf algorithms. According to the **Fig. 7**, it is concluded that the number of the saturated points obtained by Dinf algorithm **(Fig. 7a**) is less than that of the D8 algorithm (**Fig. 7b**). Referring to **Table 2**, T_0 obtained by the D8 algorithm equals to 0.41; however, the value of T_0 obtained by the Dinf algorithm is almost 21.10. As a result, the low number of saturated areas obtained by Dinf algorithm is well justified. Considering the high amount of infiltration estimated by this method, contrary to expectations, there was not any significant difference between runoff values estimated by two algorithms in this study. This contradiction may be due to the higher number of accumulated cells by Dinf method which water outflows from to other certain cells. Thus, the higher amount of water inflows to the saturated cells by Dinf method is more probable. Although, the number of estimated saturated cells by Dinf algorithm is less, the amount of flow which is entered to these cells is higher. By this way, the above mentioned contradiction can be justified well.

(a) (b)

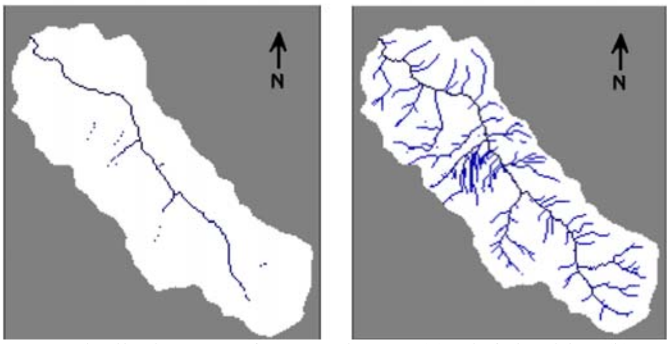

Fig. 7 Distribution map of saturated areas: (a) Dinf algorithm (b) D8 algorithm (event: 1992/6/1).

Also, according to the results given in **Tables 3** and **4**, it can be seen that, simulated runoff amounts applying Dinf flow direction algorithm are higher than that of obtained by D8 algorithm. Because topographic index indicates the amount of moisture in the soil column, overestimating of soil moisture using Dinf algorithm resulted in overestimating the amount of runoff volume.

Sensitivity analysis of parameters was also performed based on the more preferable algorithm, Dinf, and using storm event, 1992/7/4. SR_{max} has no influence on the results of simulation (see **Table 2**); therefore, model sensitivity analysis did not perform on this parameter. **Figure 8a** shows the simulated hydrographs as the value of the m increases from 0.003 to 0.02 m. As the m increases to intermediate values, the peak of the hydrograph begins to fall down to smaller values. With these increased m values, the simulated hydrograph responds slower. Thus, the peak drops and the recession becomes more gradual. As a result, the area under the hydrograph as an indicator of total runoff volume at the outlet of the catchment is reduced. This occurs due to the large values of *m* which indicates a deeper effective soil allowing more rainfall to infiltrate to the soil. The *m* parameter also has a significant impact on the subsurface portion of the runoff. For small values of *m*, the amount of subsurface flow decreases and moves toward the outlet quickly. In fact, it arrives at the outlet almost coincident with the surface flow. This result in large peak flows and very little contribution to base-flow after the rainfall has ended. The ln T_0 denotes to the effective transmissivity of the saturated soil. The simulated hydrograph generated by TOPMODEL is sensitive to changes in the ln T_0 parameter, although not as sensitive as to changes in the *m* parameter. **Figure 8b** shows the simulated hydrographs as the value of ln T_0 increases from 3 to 6. According to the **Fig. 8b**, as the ln T_0 parameter increases to higher values, the peak flow drops to lower values. Because ln T_0 refers to soil surface transmissivity, by increasing the values of ln T_0, the portion of rainfall that reaches to the outlet is increased.

The CHVEL parameter is the effective surface routing velocity for scaling the distance/area routing procedure (Beven & Kirkby, 1979). As can be seen in **Fig. 8c**, the rising side of simulated hydrographs is more sensitive than recession limb to changes in the CHVEL parameter. As the value of CHVEL increases, the amount of peak flow increases slightly. But changes in the values of time to peak are more significant.

In TOPMODEL, the basin response to the rainfall is sensitive to the moisture capacity in the soil column. The moisture in the soil column is controlled by the *m* and ln T_0 parameters, the amount of the previous rainfall event, and the length of time since the previous rainfall event. In fact, it makes sense that as time passes without rainfall, moisture in the soil column decreases via evapotranspiration and water drainage. These decreases in soil moisture affect the hydrologic response during the next rainfall. Even by allowing more space for water to infiltrate the soil thus decreasing the amount of surface runoff.

According to the **Fig. 8d**, as the value of SR_{initi} parameter increases, the amount of total runoff decreases. This means that root zone stores a large amount of rain water and prevents it to flow. Consequently, it can be deduced from the **Figs 8a–d** that the SR_{initi} parameter has an effect on the simulated hydrographs but not as much as the effects of m and ln T_0.

Daily rainfall-runoff modeling

At the second stage, rainfall-runoff modeling was performed using daily data in which the results are shown in **Tables 5–7** and **Figs 9–11** for D8 and Dinf algorithms. A relatively good agreement exists between observed and simulated hydrographs, as can be seen by the obtained results.

As can be seen in **Table 5**, the CHVEL parameter is constant and has no influence on the results of TOPMODEL calibration phase. Channel and routing velocity parameter refers to the velocity that translates the runoff from a location in the catchment to the main catchment outlet. Therefore, CHVEL parameter refers to the temporal characteristics of the catchment that never exceeds from a few hours for a small catchment such as Ammameh basin. Therefore, it is substantially impossible to establish a certain temporal relationship between rainfall and runoff of one day and another day in such a small basin. This also demonstrates the invariability of CHVEL parameter values in TOPMODEL calibration phase.

According to the presented results in **Tables 6–7**, it can be seen that there is a weak fitness between the observed and simulated time to peak values. High values of *E* and *R* between the observed and simulated time to peak values (**Tables 6–7**), represents the high capability of TOPMODEL for estimating the amount of peak flows in daily simulation. Also, total runoff volumes are well estimated particularly by Dinf algorithm.

Dinf flow direction algorithm from the hydrologic point of view is more realistic and accurate than D8 algorithm. There is a similar result in the storm events rainfall-runoff modeling section. It can thus be suggested that employing Dinf algorithm to calculate topographic index is much appropriate.

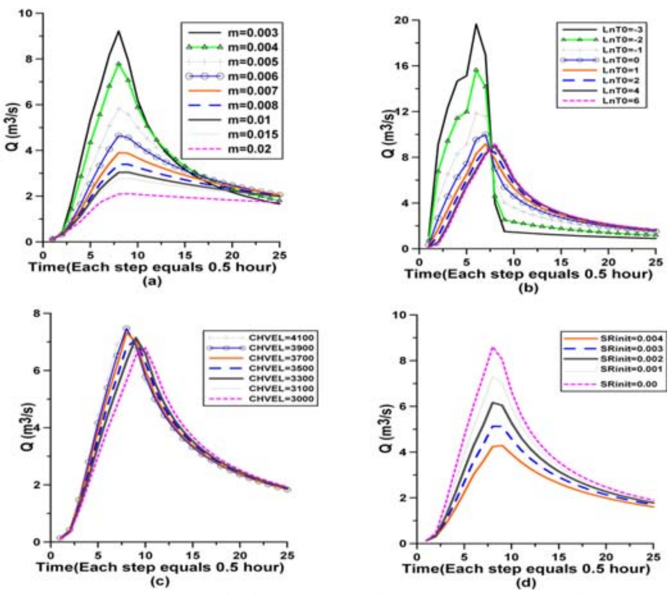

Fig. 8 Sensitivity analysis: (a) *m*, (b) ln T_0, (c) CHVEL, (d) SR_{init}.

Table 5. Calibrated parameters in daily modeling by D8 and Dinf algorithms

Time	Soil Transmissivity Decay m (m)		$\ln T_0$		Soil Surface Transmissivity T_0 (m^2/h)		Maximum Water Storage in Root Zone SR_{max} (m)		Initial Moisture Deficit in Root Zone sr_{init} (m)		Routing Parameter CHVEL (m/h)	
	D8	Dinf	D8	Dinf	D8	Dinf	D8	Dinf	D8	Dinf	D8	Dinf
2001-2002	0.0018	0.0019	-4.10	-0.20	0.017	0.82	0.05	0.05	0.0029	0.0025	4000	4000
2002-2003	0.002	0.0021	-3.80	0.11	0.022	1.12	0.05	0.05	0.0094	0.0097	4000	4000
2004-2005	0.0041	0.0041	-3.00	0.90	0.05	2.46	0.05	0.05	0.0025	0.0029	4000	4000
Mean	0.00 263	0.0027	-3.63	0.27	0.0279	1.47	0.05	0.05	0.00 493	0.00 503	4000	4000

Table 6. The results of calibration and verification phases in daily modeling by D8 algorithm

Phase	Time	TOPMODEL Peak Flow Q_s (m³/s)	Observed Peak Flow Q_o (m³/s)	TOPMODEL Time to Peak T_{po} (h)	Observed Time to Peak T_{ps} (h)	V_{ts} (m^3)	V_{to}	E	R
						(m^3)		(%)	
Calibration	2001–2002	4.075	4.41	223	192	19283818	20168712	86.20	92.93
	2002–2003	9.34	9.76	206	206	24211820	28974874	81.60	91.40
	2004–2005	5.41	5.97	171	171	22658395	21454843	74.00	86.11
	E(%)	93.70 (for Peak Flow)		84.10 (for Time to Peak)		99.60 (for Total Runoff		E_{Av}=	R_{Av}=
	R(%)	99.60 (for Peak Flow)		92.60 (for Time to Peak)		99.80 (for Total Runoff		80.60	90.15
Verification	2003–2004	6.73	8.45	–	–	24140783	24307748	75.90	87.70
	2005-2006	3.00	3.90	–	–	15345909	18063259	70.00	85.60

V_{ts} = TOPMODEL total runoff, V_{to} = Observed total runoff, E(%) = Nash and Sutcliffe efficiency, R(%) = Correlation coefficient.

Table 7. The results of calibration and verification phases in daily modeling by Dinf algorithm

Phase	Time	TOPMODEL Peak Flow Q_s (m^3/s)	Observed Peak Flow Q_o (m^3/s)	TOPMODEL Time to Peak T_{po} (h)	Observed Time to Peak T_{ps} (h)	V_{ts}	V_{to}	E	R
						(m^3)		(%)	
Calibration	2001-2002	4.30	4.41	223	192	19574659	20168712	86.00	92.77
	2002-2003	9.44	9.34	206	206	23936414	24212285	81.70	99.90
	2004-2005	5.68	5.97	171	171	22301837	21454843	73.40	86.19
	E(%)	99.20 (for Peak Flow)		55.00 (for Time to Peak)		86.00 (for Total Runoff)		E_{Av}=	R_{Av}=
	R(%)	99.90 (for Peak Flow)		74.20 (for Time to Peak)		94.00 (for Total Runoff)		80.37	92.95
Verification	2003-2004	7.05	8.15	–	–	23959401	24307748	76.60	93.20
	2005-2006	3.09	3.90	–	–	15162521	18063259	68.50	90.70

V_{ts} = TOPMODEL total runoff, Vto = Observed total runoff, E(%) = Nash and Sutcliffe efficiency, R(%) = Correlation coefficient.

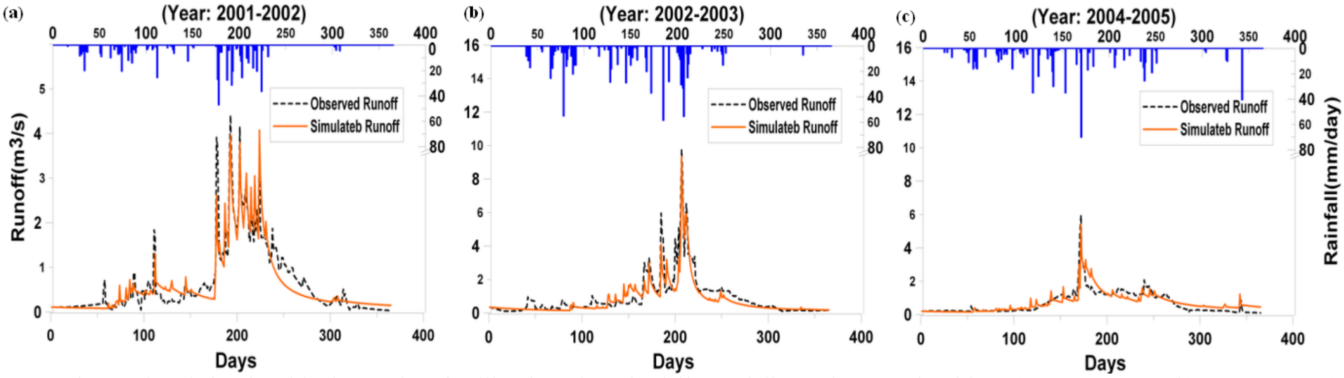

Fig. 9 Observed and simulated hydrographs of calibration phase in daily modeling using D8 algorithm: (a) 2001–2002, (b) 2002–2003, (c) 2004–2005

Table 8. Comparison of flow accumulation statistics, calculated by Dinf and D8 algorithms

Method	D8	Dinf
Min	1	50
Max	14687	740722
Mean	118	5966

According to the statistics presented in **Table 8**, it can be seen that the average, maximum, and minimum number of cells which water flows into them computed by Dinf algorithm are more than D8. As a result, the value of *a* (drainage area at the certain location) is higher in Dinf method. Thus, according to the **Eq. (1)** and considering the same value of tan β for both of the algorithms, the higher average value of topographic index by Dinf method is justified well.

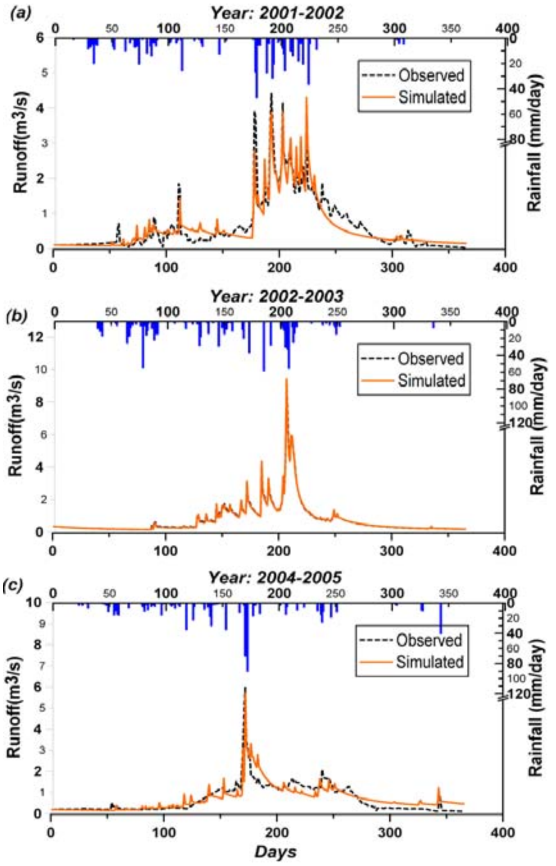

Fig. 10 Observed and simulated hydrographs of the calibration phase in daily modeling using Dinf algorithm: (a) 2001–2002, (b) 2002–2003, (d) 2004–2005.

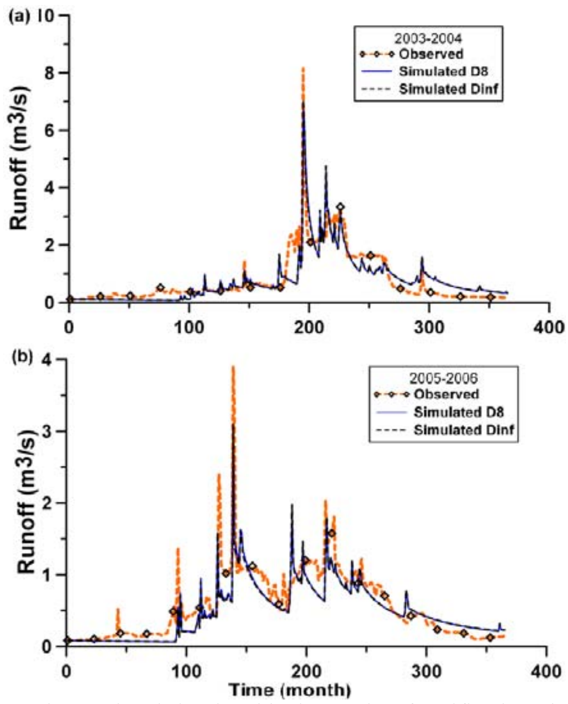

Fig. 11 Observed and simulated hydrographs of verification phase in daily modeling using D8 and Dinf algorithms: (a) 2003–2004, (b) 2005–2006.

Monthly rainfall-runoff modeling

At the final stage, rainfall-runoff modeling of the basin was carried out in the monthly time scale and the results are shown in **Figs 12–13** and **Tables 9–10**.

Plotted graphs in **Figs 12–13** do not show a strong match between simulated and observed hydrographs. Also, considering the results given in **Table 10**, it can be seen that the values of simulated total runoff volume are higher in comparison with observed values. The reason seems to be related to the long monthly time intervals between the values and the size of basin which leads to a short concentration time. In such modeling intervals, TOPMODEL is not capable of estimating the amount of moisture in the soil column accurately. As a result, TOPMODEL underestimates the amount of water that infiltrates to the soil. In other words, soil will actually be drier than TOPMODEL predicts. Thus, TOPMODEL will tend to over predict the runoff hydrograph.

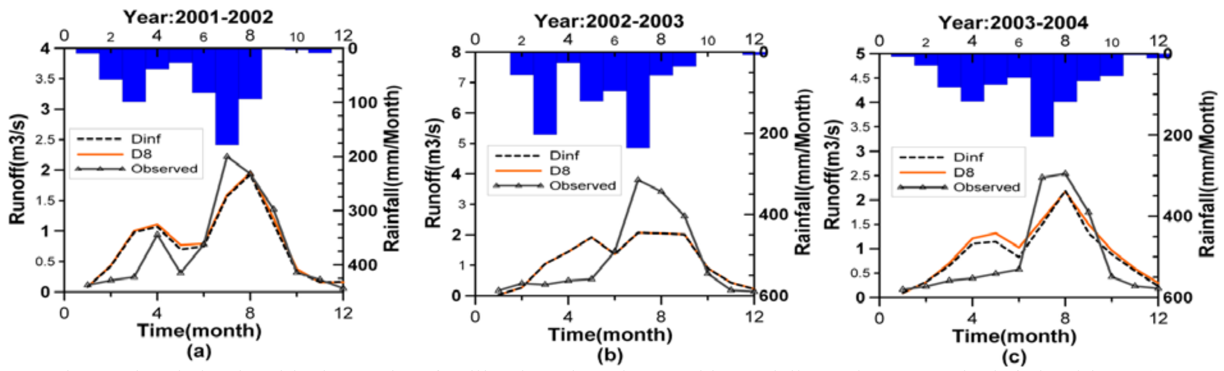

Fig. 12 Observed and simulated hydrographs of calibration phase in monthly modeling using D8 and Dinf algorithms: (a) 2001–2002, (b) 2002–2003, (c) 2003–2004.

Table 9. The results of calibration phase in monthly modeling by Dinf and D8 algorithms

Time	Soil Transmissivity Decay m(m)	$\ln T_0$	Soil Surface Transmissivity T_0 (m^2/h)	Maximum Water Storage in Root Zone SR_{max} (m)	Initial Moisture Deficit in Root Zone SR_{init} (m)	CHVEL (m/h)	E (%)	R (%)
D8 Algorithm								
2001-2002	0.0030	-6.80	0.00110	0.05	0.00	5 400	78.60	89.92
2002-2003	0.003	-7.00	0.00091	0.05	0.00	3 600	55.70	77.03
2004-2005	0.0043	-6.40	0.00170	0.05	0.00	5 300	64.90	84.33
Mean	0.0034	-6.73	0.00124	0.05	0.00	4 633	66.40	83.76
Dinf Algorithm								
2001-2002	0.0010	-2.80	0.0610	0.05	0.00	5 100	79.40	90.13
2002-2003	0.0024	-3.00	0.0498	0.05	0.00	3 600	55.70	77.00
2004-2005	0.0030	-1.95	0.1420	0.05	0.00	5 800	64.90	86.50
Mean	0.0021	-2.85	0.0842	0.05	0.00	4 833	66.70	54.54

CHVEL = Routing parameter, E = Nash and Sutcliffe efficiency, R = Correlation coefficient (%)

Table 10. The results of verification phase in monthly modeling by Dinf and D8 algorithms

Time	TOPMODEL Peak Flow Q_s (m^3/s)	Observed Peak Flow Q_s (m^3/s)	V_{ts} (m^3)	V_{to} (m^3)	E (%)	R (%)
D8 Algorithm						
2004-2005	2.12	1.94	327078851	212646369	29.30	85.32
2005-2006	1.37	1.67	203157412	173554485	25.10	56.77
Dinf Algorithm						
2004-2005	2.13	1.94	325995824	212646369	29.10	84.84
2005-2006	1.57	1.67	219583730	173554485	19.00	58.31

V_{ts} = TOPMODEL total runoff, Vto = Observed total runoff, E = Nash and Sutcliffe efficiency, R = Correlation coefficient.

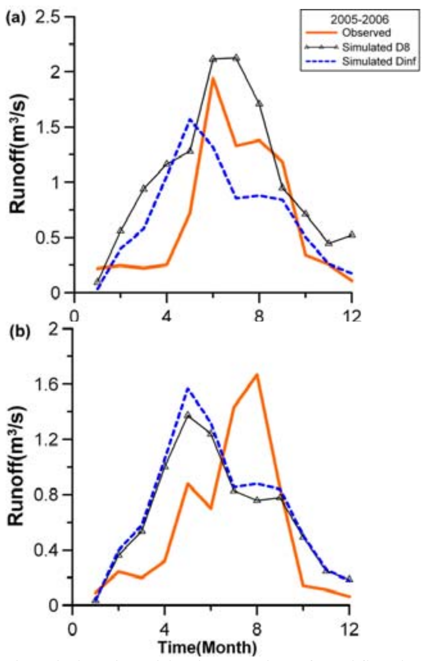

Fig. 13 Observed and simulated hydrographs of verification phase in monthly modeling using D8 and Dinf algorithms: (a) 2004–2005, (b) 2005–2006.

Comparison of the results with other studies

The results of calibration and verification phases of TOPMODEL using D8 and Dinf methods are briefly presented in **Table 11**. In the following section, the results of this study are compared to the results of a previously carried out study in Ammameh basin. Nourani *et al.* (2009) have applied five models namely Nash, SCS (Soil Conservation Service, formerly), GUHD (Geomorphological Unit Hydrograph-Distributed), GUHN (Geomorphological Unit Hydrograph – Nash), and GUHCR Geomorphological Unit Hydrograph - Cascade of linear Reservoirs) for rainfall-runoff modeling in Ammameh basin. The results of the study are given in **Table 12**.

The results shown in **Table 11** indicate that the modeling results of storm events by Dinf algorithm are more appropriate than D8 algorithm. Considering the results given in **Tables 11** and **12** and based on the results of verification phase, it can be seen that modeling results of GUHD, GUHCR, Nash, and Dinf methods respectively have the best average values of efficiency. Also, modeling results of D8 and GUHN methods are acceptable to some extent. But the results of SCS model are not very encouraging in comparison with the other models. From the results, it is apparent that the results of Nourani *et al.* (2009) are more appropriate in comparison with the results of the current study.

Table 11. Comparison of D8 and Dinf algorithms in event, daily and monthly modeling

Time Series	Method	Verification R (%)	Verification E (%)	Calibration R (%)	Calibration E (%)
Events	D8	84.17	58.30	94.35	88
	Dinf	93.00	74.30	94.65	88.78
Daily Data	D8	86.65	72.95	90.15	80.60
	Dinf	91.95	72.55	92.95	80.37
Monthly Data	D8	71.00	27.20	83.76	66.40
	Dinf	71.60	24.05	84.54	66.70

Table 12. Comparison of Nash, SCS, GUHCR, GUHN and GUHDN methods (Nourani *et al.*, 2009)

Method	Verification		Calibration	
	R (%)	E (%)	R (%)	E (%)
Nash	92	76	91	76
SCS	95	43	95	45
GUHCR	90	81	90	81
GUHN	86	65	97	91
GUHD	95	88	94	86

Because GUHN, GUHCR, GUHD, and Nash models are classified as black-box models, their parameters are calibrated uniquely for a basin. While, TOPMODEL is a semi-distributed physically-based model and parameters in this model are physically interpretable which have explicit physical meanings; therefore, the results of physically-based models are more generalized and less accurate in comparison with the black-box models.

CONCLUSIONS

The following conclusions may be drawn from the present study:

1- The results of this study indicate that Dinf flow direction algorithm from the hydrological point of view is more realistic and accurate than D8 algorithm. It can be thus suggested that employing Dinf algorithm to calculate topographic index is much appropriate.

2- Well estimation of peak points by TOPMODEL is indicating the more capability of TOPMODEL to simulate stream peak flows for the Ammameh basin.

3- Modeling results of storm events and especially of daily data sets are much satisfactory.

4- The results of monthly rainfall-runoff modeling are not so satisfactory. The reason seems to be related to the long monthly time intervals between each value to another which cause to underestimating the amount of water that infiltrates the soil by TOPMODEL.

5- The results of sensitivity analysis indicate that *m* and ln T_0 parameters, which refer to the soil moisture condition, have the most effect on the results of rainfall-runoff simulation.

One source of weakness in this study, which could have affected the results, was the lack of appropriate evapotranspiration data set as the input to the model. Therefore, a further study which takes this into account by implementing an evapotranspiration estimation model to produce required data sets will need to be undertaken.

REFERENCES

Beven, K.J. (1993) Prophecy, reality and uncertainty in distributed hydrological modeling. *Adv. Water Resour.* **16**(1), 41–51. doi: 10.1016/0309-1708(93)90028-E.

Beven, K.J. & Kirkby, M.J. (1979) A physically based variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.* **24**(1), 43–69.

Beven, K.J. and Wood, E.F. (1983) Catchment geomorphology and the dynamics of runoff contributing areas. *J. Hydrol.* **65**(2), 139-158. doi: 10.1016/0022-1694(83)90214-7.

Beven, K.J., Lamb, R., Quinn, P., Romanwvic, R. and Freer, J. (1995) TOPMODEL. In *Computer Models of Hydrology*, Singh VP (ed). Water Resour. Publications, Highlands Ranch, CO, p. 627.

Bruneau, P., Gascuel-Odoux, C., Robin, P., Merot, Ph. & Beven, K. J. (1995) The sensitivity to space and time resolution of a hydrological model using digital elevation data, *Hydrol. Process.* **9**(1), 69–81. doi: 10.1002/hyp.3360090107.

Durand, P., Robson, A. & Neal, C. (1992) Modeling the hydrology of sub-Mediterranean mountain catchments (Mont Loz'ere, France), using TOPMODEL: initial results. *J. Hydrol.* **139**(1), 1–14. doi: 10.1016/0022-1694(92)90191-W.

Hornberger, G.M., Beven, K.J., Cosby, B.J. & Sappington, D.E. (1985) Shenandoah watershed study: calibration of a topography-based, variable contributing area hydrological model to a small forested catchment. *Water Resour. Res.* **21**, 1841.

Hydrologic Engineering Center (HEC) (2006). HEC-HMS Hydrologic Modeling System: User's Manual, U.S. Army Corps of Engineers, Davis, CA.

Franchini, M., Wendling, J., Obled, Ch. ,and Todini, E. (1996) Physical interpretation and sensitivity analysis of the TOPMODEL. *J. Hydrol*. 175(2), 293–338. doi: 10.1016/S0022-1694(96)80015-1.

Guntner, A., Uhlenbrook, S., Seibert, J. & Leibundgut, Ch. (1999) Multi-criteria validation of TOPMODEL in a mountainous catchment. *Hydrol. Process.* **13**(11), 1603–1620. doi: 10.1002/(SICI)1099-1085.

Guzha, A.C. & Hardy, T.B. (2010) Application of the Distributed Hydrological Model, TOPNET, to the Big Darby Creek Watershed, Ohio, USA. *Water Resour. Manage*. **24**(5), 979–1003. doi: 10.1007/s11269-009-9482-6.

Irmak, S. & Harman, D.Z. (2003) Evapotranspiration: potential or reference? IFAS Extension, ABE 343, University of Florida.

Krauth, L.G. (1999) Hydrologic Modeling of Floods in an Eastern Kentucky Catchment Using TOPMODEL. M.Sc. Thesis, University of Louisville.

Lamb, R., Beven, K.J. & Mirabo, S. (1998) A generalized topographic soils hydrological index. In Landform Monitoring, Modelling and Analysis, Lane SN, Richards KS, Chandler JH (eds). Wiley: Chichester, UK, p. 263.

Molicova, H., Grimaldi, M., Bonell, M. & Hubert, P. (1997) Using TOPMODEL towards identifying and modeling the hydrological patterns withina headwater, humid, tropical catchment. *Hydrol. Process.* **11**(9), 1169–1196. doi: 10.1002/(SICI)1099-1085(199707).

Nash, J.E. & Sutcliffe, J.V. (1970) River flow forecasting through conceptual models part I – a discussion of principles. *J. Hydrol.* **10**(3), 282–290. doi: 10.1016/0022-1694(70)90255-6.

Nourani, V. & Mano, A. (2007) Semi-distributed flood runoff model at the sub-continental scale for south-western Iran. *Hydrol. Process.* **21**(23), 3173–3180. doi: 10.1002/hyp.6549.

Nourani, V., Singh, V.P. & Delafrouz, H. (2009) Three geomorphological rainfall– runoff models based on the linear reservoir concept. *Catena* **76**(3), 206–214. doi: 10.1016/j.catena.2008.11.008.

Pinol, J., Beven, K.J. & Freer, J. (1997) Modeling the hydrological response of Mediterranean catchments, Prades, Catalonia: the use of distributed models as aids to hypothesis formulation. *Hydrol. Process*. 11(9), 1287–1306. doi: 10.1002/(SICI)1099-1085(199707).

Quinn, P.F., Beven, K.J., Chevallier, P. & Planchon, O. (1991) The prediction of hill slope flow paths for distributed hydrological modeling using digital terrain models. *Hydrol. Process*. **5**(1), 59–79. doi: 10.1002/hyp.3360050106.

Robson, A.J., Whitehead, P.G. & Johnson, R.C. (1993) An application of a physically based semi-distributed model to the Balquhidder catchments. *J. Hydrol.* 145(4), 357–370. doi: 10.1016/0022-1694(93)90063-F.

Takeuchi, K., Hapuarachchi, P., Zhou, M., Ishidaira, H. & Magome, J. (2008) A BTOP model to extend TOPMODEL for distributed hydrological simulation of larg basins. *Hydrol. Process*. **22**(17), 3236–3251. doi: 10.1002/hyp.6910.

Torboton, D.J. (1997) A new method for the determination of flow directions and up slope areas in grid digital elevation models. *Water Resour. Res.* **33**, 309.

Torboton, D.G. (2005) Terrain Analysis Using Digital Elevation Models (TauDEM). Available in: *http://hydrology.neng.usu.edu/taudem*.

Xiong, L. & Guo, Sh. (2004) Effects of the catchment coefficient on the performance of TOPMODEL in rainfall-runoff modelling. *Hydrol. Process*. 18(10), 1823–1836. doi: 10.1002/hyp.1449.