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Full Length Research Paper

Nonlinearity in storage- discharge relationship and its influence on flood hydrograph prediction in mountainous catchments

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The influence of nonlinearity in storage-discharge relationship on flood hydrograph prediction in three catchments in Zagros mountain region in south west of Iran is examined. An event based runoff routing model, watershed bounded network model (WBNM) is applied to assess the response of the selected catchments. Using all available hyetographs and corresponding flood hydrographs, the nonlinear parameter value of m = 0.61 is computed for the three study catchments. The obtained nonlinear parameter is applied to evaluate catchment response along with m = 0.77 (default nonlinear parameter value of WBNM) and m = 1.0 (complete linear response). It is found that there is no unique value of m that can be valid for prediction of all floods. The results showed that there is significant relationship between the antecedent wetness of soil and the response of catchment and hence less nonlinear response or maybe complete linear response can be expected in wet conditions of soil. The value of m = 0.61 is the most appropriate value for dry condition of soil. However, under wet and saturate conditions of soil, the values of m = 0.77 and m = 1.0 can be used accordingly.

Key words: Storage-discharge, runoff routing, hydrograph, watershed bounded network model (WBNM), linear-nonlinear response of catchment.

INTRODUCTION

Rainfall-runoff relationships are among the most complex hydrologic phenomena to comprehend due to the tremendous spatial and temporal variability of watershed characteristics and precipitation pattern as well as number of variables involved in modeling the physical processes. Runoff routing methods have received a great deal of attention by researchers in the last decades and are increasingly used in hydrology (Willing and Partners, 1988; Carroll, 1994; Laurenson and Mein, 1997; Rigby et al., 1999; Boyd et al., 2001; Rahman and Goonetilleke, 2001; Singh and Frevert, 2006; England et al., 2007; Gong et al., 2009; Lu, 2009). A central component of these models is a conceptual storage and storage routing procedure. Indeed, the growing availability of computing power and hydrological data observed at spatial and temporal scales make the application of these methods an attractive option for answering many of questions which are frequently posed to hydrologists. Australian rainfall and runoff (IEA, 2001) recommends to use a nonlinear storage-discharge relationship for estimation of large floods although some investigators have proposed other forms of storage-discharge relationships (Bates and Pilgrim, 1983; Wong, 1989; Bates et al., 1993; Sriwongsitanon et al., 1998; Zhang and Cordery, 1999).

Runoff routing provides an alternative to unit hydrograph (IEA, 1987). It is not restricted to the assumption of linear behavior and in most applications nonlinear response is assumed. The estimation of flood hydrograph by runoff routing methods involves the routing of rainfall

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Table 1. Details of the study catchments.

Catchment	Hydrometeric Station	Area (km^2)	No. of Sub-areas	No. of Storms
Abolabbas	Pole Monjenigh	290	17	9
Rood Zard	Mashin	875	37	10
Allah	Jokanak	2260	49	10

excess through a model representing the watershed storage (IEA, 1987). The output represents the surface or direct runoff hydrograph. Rainfall excess must first be estimated from rainfall before it can be applied to the runoff routing model to compute the surface runoff hydrograph. The differences from normal flood routing are that the input of rainfall excess is distributed spatially over the watershed instead of being concentrated at a single location. Moreover, the mathematical model of storage is more complex as it represents the nature of watershed storage which is also distributed spatially (Boyd et al., 2007).

As with unit hydrograph, runoff routing can be used to estimate floods using simulated storms as input, or to estimate floods resulting from actual storms. Runoff routing is being used increasingly for rural floods estimation and is particularly useful for the design large structures (IEA, 2001). It is applicable to small and medium sized of rural watersheds in cases where the more complex computation are justified. It is particularly useful for determining design hydrographs for detention basins as linear unit hydrograph theory is not really applicable to urban watersheds (Pilgrim, 1986).

Many types of models have been developed and used in runoff routing applications. Among these models, network models are becoming more widely accepted for flood hydrograph estimation and flow forecasting. In these models, the storage are arranged to represent the drainage network of the watershed. The distributed nature of the storage is represented by separate series of concentrated storage for the main stream and for major tributaries. This provides a degree of physical realism. A major advantage of this type of models is that it is relatively easy to realistically model the effects of changes to the watershed such as the construction of a reservoir or retarding basins or the lining of a channel. Watershed Bounded Network Model (WBNM) is one such model. This maintains a good relationship between the hydrological and geomorphologic properties of a watershed and is capable of accurate flood hydrograph estimation.

This paper presents a study to assess the effects of nonlinearity in storage-discharge relationship on flood hydrograph prediction. It is known that the catchment response can be controlled by both rainfall characteristics and soil properties and therefore miss-evaluating of the storage capacity of the catchment leads to large error on the simulated hydrograph. Our hypothesis is that soil wetness can be a significant factor on predicting flood hydrograph. Hence, the main objective of this study is better understanding the influence of antecedent wetness of soil on the hydrologic response of catchment. Moreover, since the runoff generation mechanism is a dominant factor in the response of catchment, studying the influence of this factor on outlet hydrograph is the second objective of this study which is usually neglected in existing runoff routing models.

MATERIALS AND METHODS

Study catchments

Three catchments, Abolaabas, Rood Zard and Allah with different sizes, in the Zagros mountain region in the south west of Iran, were selected for the study. The details of the three study catchments including area, number of sub-areas and number of storms are shown in Table 1. The three catchments are characterized by mixed topography with altitude range between 380 to 3,700 m. Orography plays a decisive role to form strong convective instability situations which their spatial scales are very often lower than the catchment scales. The formation of more than one local rainfall system with different characteristics such as rainfall intensity and duration are consequences of these phenomena. Each catchment was divided into several sub-areas based on the catchment area (Boyd et al., 2007). The digital elevation models (DEMs) of catchments are shown in Figure 1.

To simulate hydrograph at the outlet of each catchment, 30 min recorded hyetographs at 5 rain gauges within and adjacent to the catchments were used (Table 2). The rainfall and discharge data for this study were obtained from the hydrological database of Khuzestan Water and Power Authority, Ahvaz, Iran over the period of 1992 to 2004. Khuzestan Water and Power Authority is the most important organization concerned about water resources in Iran since most of water resources are located in this province. The quality of data is usually very good because of high quality of instruments they used in the stations. Besides, there is a department to control the quality of collected data in this organization. However, the available data were controlled and filtered since we were insisted to use high quality data. The quality of data was good and also there were no missing data. The available data were categorized into three categories based on soil wetness: (1) Storm events and the corresponding discharges which obtained in dry conditions of soil (15 days after the previous rainfall). (2) Storm events and the corresponding discharges which obtained in saturate conditions of soil (less than 24 h after the previous rainfall). (3) Storm events and the corresponding discharges which obtained in wet conditions of soil (1-15 days after the previous rainfall). Then, the data in each category were divided into two groups for calibration and validation randomly. For each storm, base flow was subtracted from the runoff hydrographs using the straight line method. In addition, the initial loss-continuing loss method (IEA, 1987) was applied to subtract excess rainfall from the

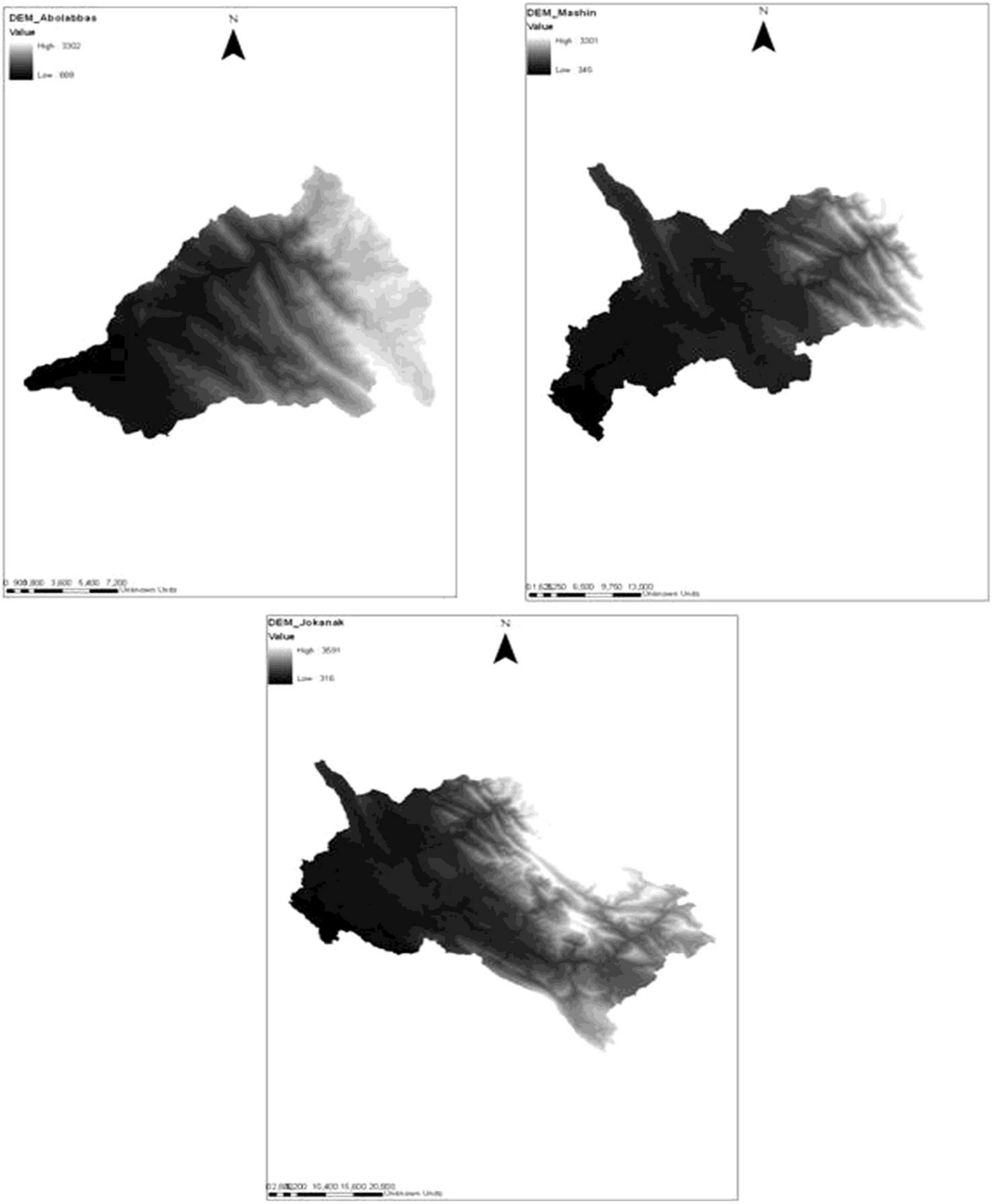

Figure 1. Digital elevation eodel (DEMs) of the Abolabbas (left), Rood Zard (center) and Allah (right) catchments.

Table 2. Details of the rain gauge stations.

Station	Latitude	Longitude	Altitude (m)
Pole Shaloo	31 44	50 08	700
Izeh	31 49	49 51	764
Bagh Malek	31 31	47 54	700
Mashin	31 23	49 43	380
Ramhormoz	31 17	49 36	155

rainfall hyetograph of each storm.

Model description

WBNM was originally developed to be a physically realistic representation of the catchment as it transforms storm rainfall into a flood hydrograph (Boyd et al., 2007). It has built in lag relations, based on catchment geomorphology (Venugopal et al., 1983). WBNM needs a single parameter and realistically represents the catchment structure and flow of water on the catchment surface. The stored volume is related to the outflow discharge as shown below (Boyd et al., 2007):

$$S = 60KQ \tag{1}$$

Where, $Q(m^3/s)$ is the outflow rate at time t, $S(m^3)$ is the volume of water stored on catchment surface at time t and $K(min)$ is the lag time between centroids of inflow and outflow hydrographs. The lag time, K, will depend on the size of the subarea. If it remained constant for this subarea for all size floods, the model would be linear. However, based on recorded rainfall and flood hydrograph data (Askew, 1968, 1970), and also on hydraulic considerations, WBNM allows K decrease as flood discharges increase, and is thus nonlinear. WBNM uses lag relations developed by Askew (1968, 1970):

$$K = C.A^{0.57}.Q^{-0.23} \tag{2}$$

Where, $A(km^2)$ is the area and C is the lag parameter. This equation contains a nonlinearity component (lag decreases as discharges increase), and an area component. WBNM proposes a global value of the lag parameter near 1.6, unless there is good evidence for varying it.

WBNM is using m - 1 as its measure of nonlinearity. It uses the value of m – 1 = -0.23 (m = 0.77) for nonlinearity and recommends it as a global value for all watersheds. However, it allows to be varied if there is strong evidence that it is different than this value. If m - 1 is less than -0.23 (e.g. –0.3) the nonlinearity is greater and lag times decrease even more as discharges increase. If m – 1 = 0 the flood response is linear and lag times remain constant over the range of discharges.

Efficiency criteria

We use Nash-Sutcliffe Efficiency (NSE) as a dimensionless statistic and Percent Bias (PBIAS) as an error index as well as hydrograph graphical comparison.

Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe Efficiency NSE indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007). NSE ranges between $-\infty$ and 1.0. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance (Moriasi et al., 2007). NSE is computed as shown as follows:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(y_i^{obs} - y_i^{sim})^2}{\sum_{i=1}^{n}(y_i^{obs} - y^{min})^2}\right] \tag{3}$$

Where: y_i^{obs} is the ith observation for the constituent being evaluated, y_i^{sim} is the ith simulated for the constituent being evaluated, n is the total number of observations.

Percent Bias (PBIAS)

Percent bias measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. PBIAS is calculated with equation as follows (Moriasi et al., 2007):

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(y_i^{obs} - y_i^{sim})^2 \times 100}{\sum_{i=1}^{n} y_i^{obs}}\right] \tag{4}$$

RESULTS AND DISCUSSION

Estimation of nonlinear parameter for selected catchments

To detect possible evidences that the value of m is different from the default value of the model for the selected catchments, an investigation was carried out. Using all available hyetographs and corresponding flood hydrographs of each catchment, floods lag time were computed and plotted against mean flood discharges for the corresponding catchment to form the scatter plot and then a power function model was fitted as shown in Figure 2. The computed nonlinear parameter value of -0.39 was found for the three catchments comparing to -0.23 for South Creek catchment (base study catchment for WBNM) (Boyd et al., 2007). It is quite evident that the nonlinear parameter used in WBNM is different from those that were found for selected catchments. Since all

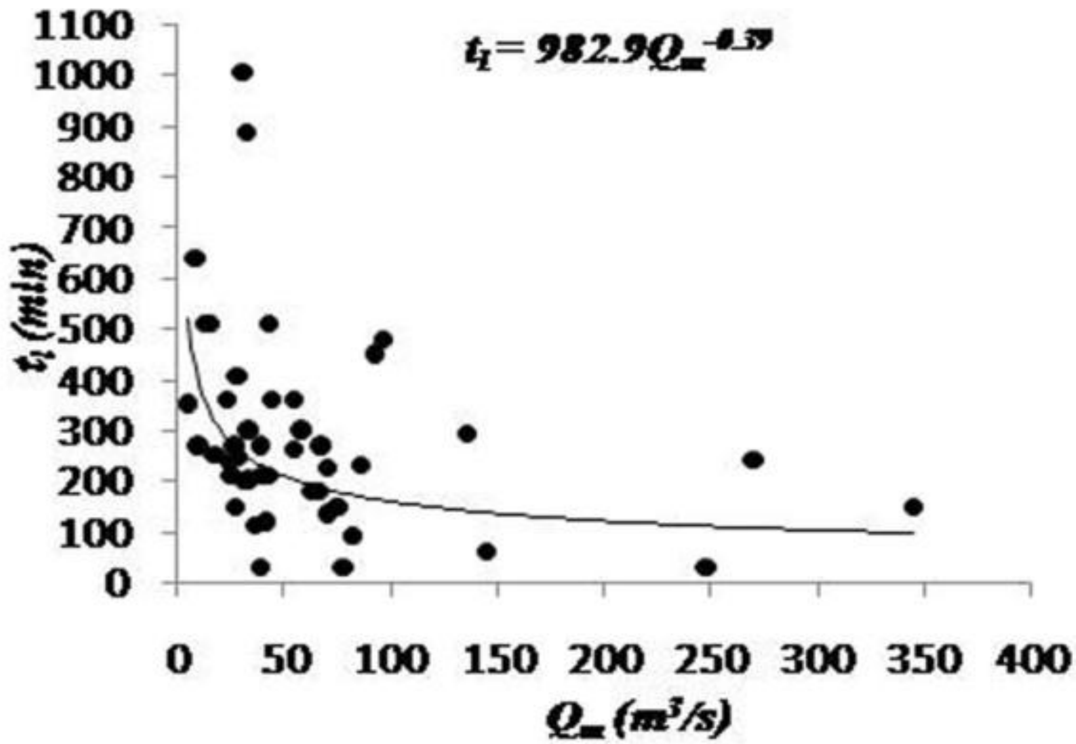

Figure 2. The relationship between lag time and mean flood discharge for the selected catchments.

Table 3. Ranges of lag parameter (c) obtained in the calibration phase for the selected catchments.

Catchment	Lag parameter (c)			
	m = 0.50	m = 0.61	m = 0.77	m = 1.0
Abolabbas	1.48 - 3.00	1.10 - 2.41	0.64 - 1.65	0.31 - 0.92
Rood Zard	1.60 - 4.92	1.24 - 2.95	0.70 - 1.42	0.25 - 0.99
Allah	1.85 - 4.46	1.17 - 3.44	0.54 - 2.60	0.25 - 1.58

the study catchments are located in the same geographical region, the mean value of m – 1 = -0.39 (m = 0.61) can be recommended as a global value for the mountainous catchments in the south west of Iran.

Model calibration and validation

To calibrate the model, rainfall hyetographs at nearest rain gage from catchment were inserted into WBNM assuming the same rainfall pattern over the whole catchment. The runs were implemented with two different nonlinear parameters including m = 0.61 (the new approach) and m = 0.77 (the default value of WBNM) as well as m = 1 (linear response). The parameters were used to calibrate the model were lag parameter and linear or nonlinear parameter. The calibration of WBNM to fit the recorded events followed a straightforward procedure:

(i) The rain before the recorded hydrograph started to rise was treated as initial loss,
(ii) The continuing loss rate was adjusted so that the depth of excess rainfall equaled the recorded surface runoff depth,
(iii) The model's lag parameter was adjusted to match the hydrograph's peak discharge.

The range of lag parameter values obtained for three selected catchments is shown in Table 3. Boyd and Cordery (1989) suggested a mean value of lag parameter (*c* = 1.8) for 36 catchments in the eastern and inland of New South Wales, Australia (size range 0.04 - 1140 km^2). However, it is evident from the Table 3 that the values vary considerably.

Having completed the parameter estimation process, the next step in the model calibration is model validation. Model validation is essential to a river basin in order to document the predictive capabilities and credibly of the

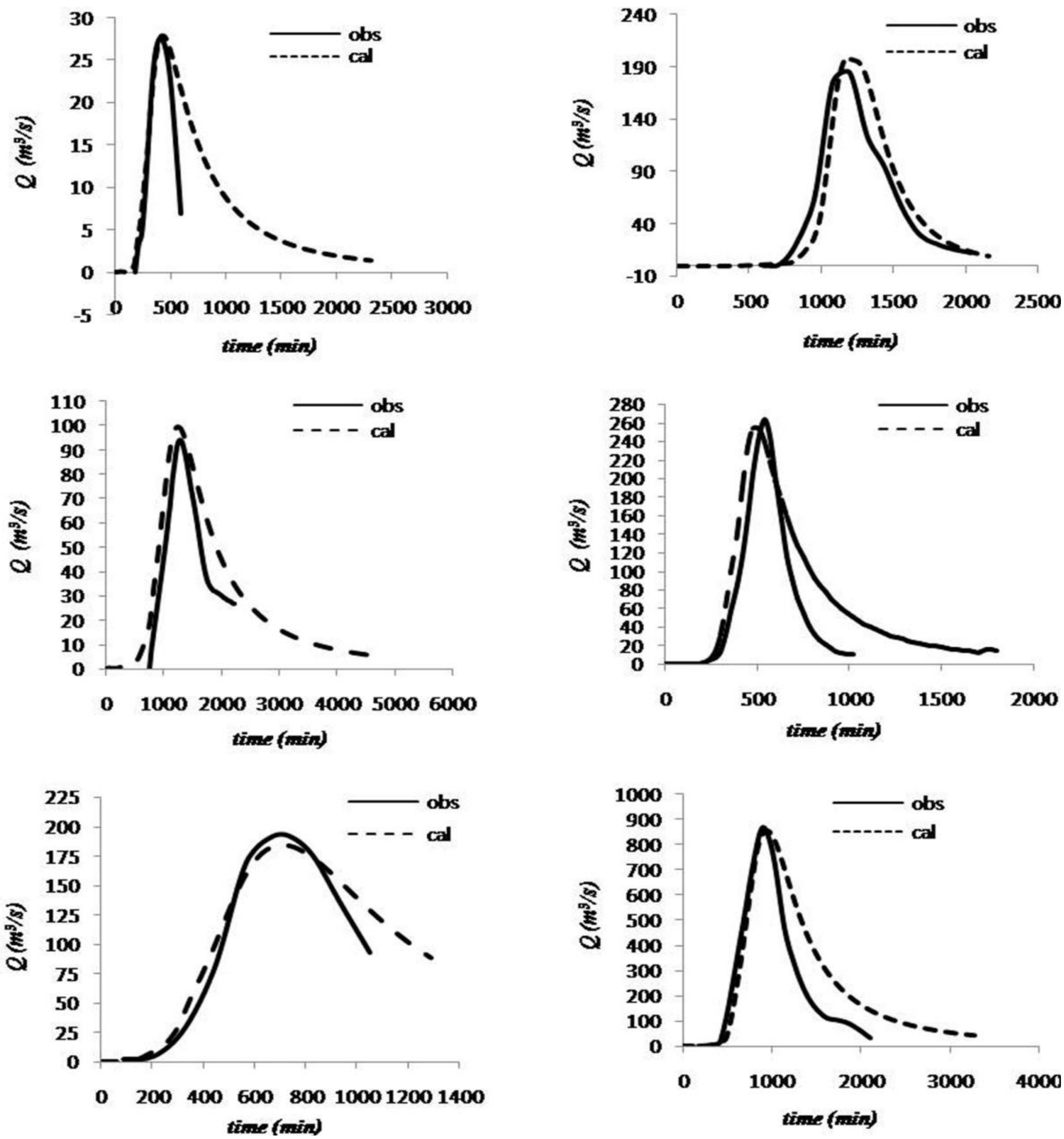

Figure 3. The validation results for six storm events which occurred in the three study catchments.

calibrated model (Madsen, 2007). As part of this study, the model parameters obtained in the calibration phase for three study catchments validated for some independent events that have not been used in the model calibration. A visual comparison of the validation for six storm events that occurred at the selected catchments is presented in Figure 3. It is quite evident that the calibrated parameters matches peak discharges, time to peaks and approximate runoff volumes. The calibration and validation results show the robustness of WBNM for predicting the catchment response.

Influence of antecedent wetness of catchments on outlet hydrographs

Whenever rainfall intensity exceeds the infiltration rate, Hortonian infiltration excess runoff occurs (Nicotina et al., 2008). After ponding, a wetting front propagates downwards and if the duration of the rainfall is large enough, reaches the bottom of the interacting soil layer eventually (Dingman, 1994). At this time, saturation excess runoff starts to occur. The Green and Ampt model provides a simple-physical based description of both

Table 4. Performance statistics for the four storm events that occurred in the Abolabbas catchment.

Event	Performance statistics	m = 0.61	m = 0.77	m = 1.0
25th February 1992	NSE	0.895	0.904	0.877
	PBIAS	8.45	1.55	-4.37
7th January, 2002	NSE	0.766	0.667	0.642
	PBIAS	1.272	-2.978	-8.317
2sd January, 1992	NSE	0.553	0.292	-0.011
	PBIAS	-43.909	-57.2	-69.674
11th March, 1994	NSE	0.829	0.826	0.752
	PBIAS	-13.495	-25.154	-36.589

Table 5. Performance statistics for the four storm events that occurred in the Rood Zard catchment.

Event	Performance Statistics	m = 0.61	m = 0.77	m = 1.0
7th January, 1993	NSE	0.842	0.732	0.619
	PBIAS	-10.105	-20.87	-29.86
7th January, 2002	NSE	0.659	0.737	0.93
	PBIAS	15.955	7.481	-1.849
11th March, 1994	NSE	0.629	0.323	-0.066
	PBIAS	-51.281	-66.072	-80.125
25th November, 1994	NSE	0.84	0.731	0.618
	PBIAS	-7.788	-19.876	-32.835

Table 6. Performance statistics for the four storm events that occurred in the Allah catchment.

Event	Performance Statistics	m = 0.61	m = 0.77	m = 1.0
13th January, 2004	NSE	0.59	0.618	0.436
	PBIAS	13.022	4.26	-3.014
5th March, 1991	NSE	0.402	0.408	0.357
	PBIAS	42.946	40.042	37.962
7th February, 1995	NSE	0.754	0.658	0.538
	PBIAS	-19.25	-29.01	-40.812
11th March, 1994	NSE	0.772	0.591	0.361
	PBIAS	-38.929	-50.931	-58.252

infiltration excess and saturation excess mechanisms (Nicotina et al., 2008), which is crucial for a realistic representation of actual runoff generation processes in catchments where the infiltration opportunity is well enough to allow rainfall to wet the interacting soil layer. Performance statistics for some events considered in the study are shown in Tables 4 to 6. It was found that the degree of improvement in prediction of runoff hydrographs is dependent on the antecedent wetness of soil so that by increasing antecedent wetness, the catchment tends towards more linear response. For instances, for the storm events of 7th January, 1993 and 7th January, 2002 which occurred in dry conditions of soil in the Abolabbas and Rood Zard catchments, respectively, the nonlinear parameter of m = 0.61 produced more accurate results than the other m parameters (Tables 4 and 5). However, for the storm events of 5th March, 1991 and 13th January, 2004 which occurred in saturate conditions of soil in the Allah catchment, due to heavy rains that happened a few hours before the selected events (Table 6), the linear response of the catchment (m = 1.0) was obtained. Moreover, it

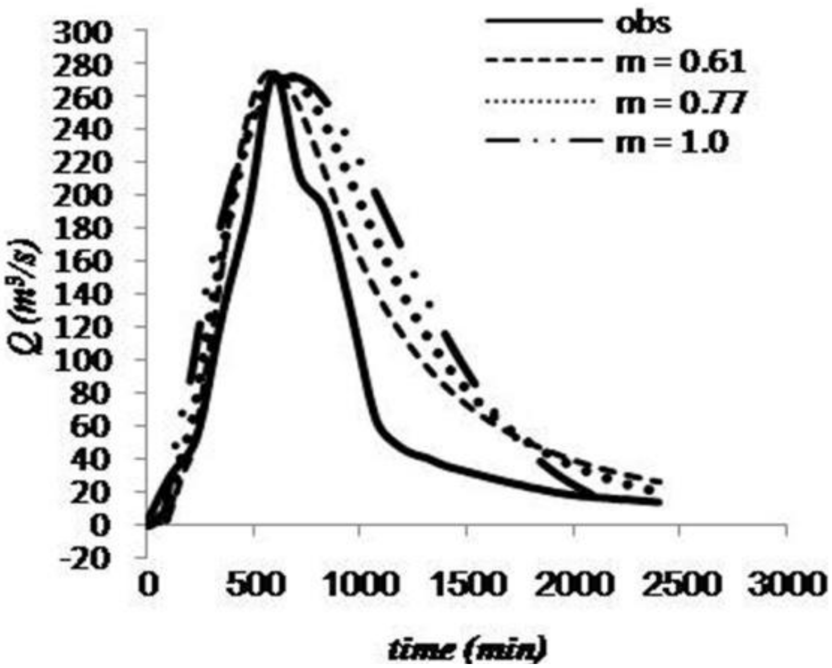

Figure 4. The estimated and observed hydrographs for the storm which occurred on 11th Mar 1994 in the Allah catchment.

can be seen that nonlinear parameter of m = 0.77 produced better results for the 25th February, 1992 storm event that occurred in the Abolabbas catchment because of slight increase of soil wetness due to 8.3 mm precipitation which occurred 24 h before the event. An interpretation can be provided by considering the possible influence of runoff generation mechanism on outlet hydrograph as a function of antecedent wetness of soil.

When soil is in dry condition, infiltration capacity is high enough and important portion of rainfall can thus infiltrate. Under these circumstances, a prescribed fraction of the rainfall contributes to the subsurface flow toward the channel network, leading to reduction of the catchment response and hence more nonlinear response. Consequently, the slope of the falling limb of outlet hydrograph is moderate, and the base time of hydrograph as well as the time to peak increased considerably as shown in Figure 4 indicating that the outlet hydrograph was estimated more accurately using nonlinear parameter of m = 0.61. On the contrary, in catchments with antecedent wetness, less portion of rainfall can infiltrate into the soil since saturation excess mechanism is provoked very soon in comparison with dry soil. Accordingly, the infiltration opportunity is less and the fraction of infiltrated rainfall decreases, causing less nonlinear or maybe complete linear response of catchment. Therefore, much volume of water contributes to surface flow which rapidly joins the streamflow in channel network. This causes the outlet hydrograph to be steeper in rising and falling limbs and the base time of the hydrograph to decrease significantly as shown in Figures 5 and 6 indicating that the outlet hydrographs were predicted more precisely using nonlinear parameter of m = 0.77 and linear parameter of m = 1.0, respectively. Hence, it can be concluded that the higher the antecedent wetness of soil, the higher the shift towards linear performance of catchment.

Conclusion

The analyses performed for three catchments in the Zagros mountain region in the south west of Iran indicate that there is a significant relationship between antecedent wetness of soil and the response of the catchments. Hence, less nonlinear response or maybe complete linear response can be expected in wet conditions of soil. On the basis of using a nonlinear runoff routing model (WBNM), it was found that the value to m = 0.61 is the most appropriate nonlinear parameter for dry conditions of soil in comparison of m = 0.77, the default nonlinear parameter value of WBNM that proposed for Australia by Boyd et al. (1979). However, less nonlinear response of catchment was obtained for wet conditions of soil that causes important changes in the outlet hydrographs, especially, in terms of runoff volumes and time to peaks. Hence, the value of m = 0.61 is proposed for dry conditions of soil in the region. Nevertheless, if the catchment is in wet condition due to previous rainfall, the

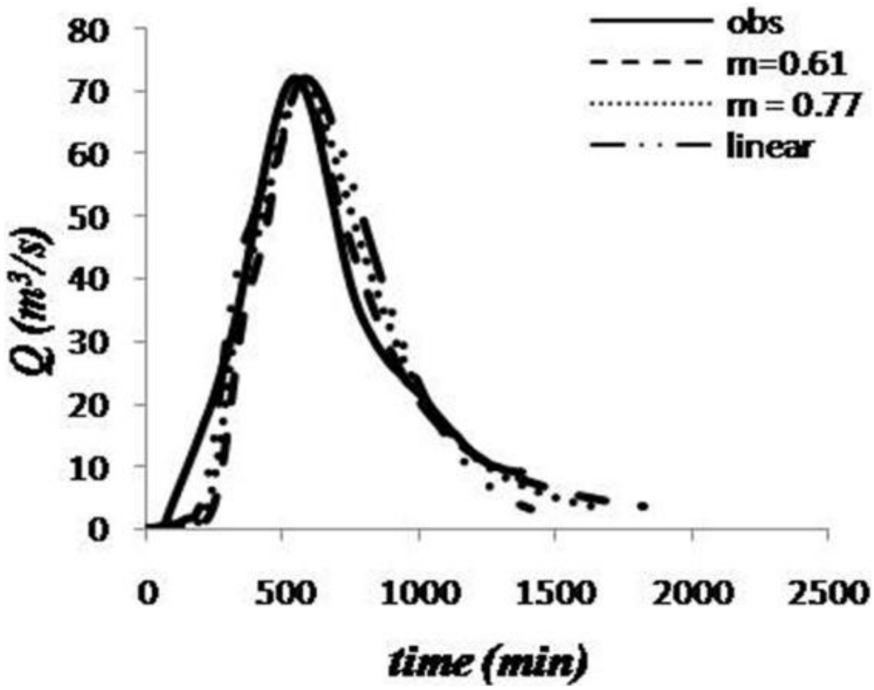

Figure 5. The estimated and observed hydrographs for the storm which occurred on 25th Feb 1992 in the Abolabbas catchment.

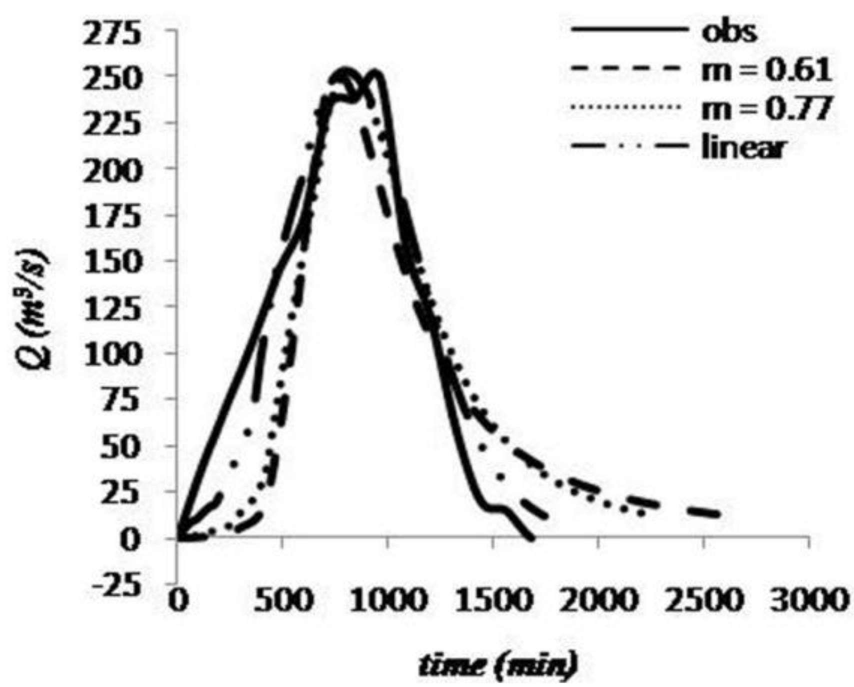

Figure 6. The estimated and observed hydrographs for the storm which occurred on 7th January, 2002 in the Rood Zard catchment.

value of m = 0.77 (default value of the WBNM) can be use satisfactorily. In saturate condition that usually happens just after previous storms, the value of m = 1.0 (linear response) can be applied. Therefore, there is an important relationship between antecedent wetness of soil and flood response and there is no unique m value that can be equally valid for all storms.

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