Effects of geomorphologic characteristics on the hydrological response of Varband river basin, South of Iran

Marzieh Moghali[1] and Mojtaba Khalilizadeh[2]

[1]*Department of GeographyLarestan Branch, Islamic Azad University Larestan, Iran*
Email:mmoghali@yahoo.com
Tel:+98-781-2249840,Fax:+98-781-2249845

[2]*Department of Watershed ManagementScience and Research Branch*
Islamic Azad University, Tehran
Iran
Email: mkhz57@gmail.com
Tel.:+98-21-44817170-4, Fax.:+98-21-44817175

***Corresponding author:** mmoghali@yahoo.com

Abstract: Water resource management in a basin depends upon the hydrological response of upstream basin area. Upstream basin area may produce different amounts of run-off for a given rainfall based on its hydrologic response. Present communications show the importance of geomorphologic characteristics in understanding the hydrologic response of a basin. This study is carried out through Geomorphologic Instantaneous Unit Hydrograph (GIUH) analysis, wherein Horton's morphometric ratios were used to define the drainage network in comparison with Snyder, SCS and Triangle unit hydrographs for determination of shape and dimensions of the outlet runoff hydrograph in the Varband river basin located in Fars province in Iran. Comparison of calculated and observed hydrographs showed that GIUH had the most direct agreement in two parameters of peak time and peak flow of direct runoff. Also, GIUH indicated the least amount of main relative and square error. Results also showed the efficiency of GIUH ratio for Snyder, SCS and Triangle hydrographs in the basin are 91.06, 99.11 and 88.64, respectively. The study shows the length ratio (*R*L) significantly influences the hydrologic response of the river basin. Hence, computation of this parameter should be included in the flood analysis of any rivers.

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INTRODUCTION

Water resource management is one of the main challenges in the social-economic development of the countries located in Southeast Asia. Introduction of mechanized equipment, artificial fertilizers, herbicides, pesticides and new cultivars has led to an increase in productivity of between 400 and 500% (Hafner, 2003; Bakker et al., 2005a).Hence, in the last decade, there has been a great concern about severe effects of land use changes, and forest and farming destruction on water resources and occurrence of hydrologic hazards (Thanapakpawin,et al.2006). Runoff production is an important process in land degradation causing soil erosion and influencing the soil water balance and hydrology of catchments. (Descheemaeker, et al.,2006).

However, they are not the only factors producing such hazards. Geomorphologic factors can also influence on the hydrologic regime changes of river basins. Since it is possible to quantify geomorphic variables in a basin with regard to the present facilities such as remote sensing data, which can be extracted through aerial photos and satellite images, it is necessary to use calculating methods and prepare instant unit hydrograph to overcome the difficulty of the assessment of runoffs with varied return periods. Unless we use such methods, there is no possibility of an accurate assessment of floods for reducing probable losses, nor designing hydrologic formations.

Lack or low accuracy of rainfall data, high cost, lack ofinformation of catchments and long waiting time in obtaining results are the major problems in hydrological predictions (Maheepala et al., 2001; Vaes et al., 2001; Lopez et al., 2005 Bhadra et al., 2008. Vahabi and Ghafouri, 2009). Hydrological response of a river basin is defined by the production of run-offs against a given rainfall, which in turn is characterized by soil characteristics and basin geomorphology. Soil characteristics control infiltration loss, whereas the distribution of remaining 'rainfall excess' is governed by basin geomorphology. Hydrological response of a river basin is a function of relationship between basin geomorphology (catchment's area, shape of basin, topography, channel slope, stream density and channel storage) and its hydrology (Snyder, 1938; Loukas et al., 1996; Shamseldin and Nash, 1998; Ajward et al., 2000; Hall et al., 2001; Jain and Sinha, 2003; Nourani et al., 2008).

A major emphasis in geomorphology over the past six decades has been on the development of quantitative physiographic methods to describe the evolution and behavior of surface-drainage networks (Horton, 1945; Leopold and Maddock, 1953, Leopold and Wolman, 1957; Abrahams, 1984). These parameters have been used in various studies of geomorphology and surface-water hydrology, such as flood characteristics, sediment yields, and evolution of basin morphology (Jolly, 1982; Ogunkoya et al., 1984; Aryadike and Phil-Eze, 1989; Jenson, 1991; Breinlinger et al., 1993).

Geomorphologic factors play an important role in the assessment of pedology, geology, lithology, land structure, ground aquifers, and many other cases pertinent to hydrology. In this study, we have greatly emphasized on the role of landforms and other related factors and finally the environmental conditions of the region while paying attention to the following cases:

- assessment of the basin with an emphasis on morphometric features
- analysis of waterway networks in the eroded parts of the basin
- quantitative features of waterway networks
- flow features of the main river and its tributaries and the way of producing sediments in the basin

Waterways constitute a small area of a basin while they provide one of the most important and basic Geomorphologic and hydrologic issues especially since Robert Horton (1945) carried out several studies on this ground and published his results. Quantitative explanations offered by him are significant guidelines for the study of a comprehensive geomorphic system. Hence, the method offered by him and then by Strahler (1957) was developed and completed. Of course, some scholars such as Abraham (1984), Gardiner and Park (1978), and Smart (1972) have also performed the same studies.

Cudennec et al (2004) investigated the geomorphologic explanation of the unit hydrograph concept and concluded the use of geomorphologic parameters provides deterministic explanation of the assumption of the unit hydrograph and geomorphologic unit hydrograph theories. Sorman (1995) applied the GIUH model to estimate the peak discharges resulting from various rainfall events for basins in Saudi Arabia and concluded that the length ratio (R_L) significantly influenced on the hydrologic response of a river basin and it must be considered for flood-forecasting studies of any rivers. Hall et al (2001) did regional analysis using the GCIUH (Geomorphoclimatic Instantaneous Unit Hydrograph) in the southwest of England. In this study, rainfall excess duration was divided into several time increments, with separate IUHs being generated for each interval. Results showed fine time interval captures the shape of the runoff hydrographs. Jain et al (2000) worked on a rainfall-runoff modeling using GIUH in Gambhiri catchment in western India. Results showed the peak characteristics of the design flood are more sensitive to various storm patterns.

When the active power of water is adequate to remove bed materials, first-grade waterways appear. The amount of runoff able to remove sediments is considered as a function of climatic and geomorphologic characteristics. Analysis of the results and experiences indicates that the soil appearing in the region is due to soft stones with low penetrability, which produces much runoff compared to soils with coarse gravels. This feature is more evident in a semiarid climate.

Iran is the second largest country in the Middle East and almost 87% of the land area is located in arid and semiarid regions (Rangavar, 2004). Recent studies represent the total volume of annual precipitation is almost 430 billion m^3, out of which about 20% is lost in the form of flash floods (Foltz, et. al. 2008).

In this article, we have focused on logical relationships between geomorphologic parameters and the hydrologic response of Varband river basin at the southern part of Iran. Finally, using these relations and instant Unit Hydrograph theory, we could estimate the hydrograph of floods due to rainfalls on the surface of the basin.

METHODS AND MATERIALS

Studyarea

Varband River basin is located in the south of Fars province, Iran. It comprises 925.5 km^2 distributed within 14 sub-basins and extends between 27˚34′ to 27˚49′ N latitude and 53˚56′ to 54˚34′ E longitude (Fig. 1). The highest point in the basin is 2190 m above sea level, and its lowest point is 870 m above sea level. Mean annual rainfall is around 244 mm, mostly concentrated in the rainy season from December to February.

Geomorphologic Instantaneous Unit Hydrograph

The concept of Geomorphologic Instantaneous Unit Hydrograph (GIUH) is essentially based on this fundamental idea and has provided the first analytically developed model to calculate river hydrograph from Horton’s morphometric parameters. In the GIUH model, uniform distribution and instantaneous imposition of unit ‘rainfall excess’ over the basin is assumed. Thus, GIUH is independent of rainfall characteristics and loss parameters. Further assumption is made that the incoming discharge due to this rainfall excess is filling a bucket at the outlet and the rate of filling of a bucket at the outlet of a basin will give the hydrograph. The GIUH is defined as the probability density function for the time of arrival of a randomly chosen drop to the trapping state (bucket). The bucket at the outlet will start to empty and will reach a final volume equal to the total volume of rainfall excess over the basin. The total volume yielded as output up to a certain time t will be given by, volume [$V_{(t)} = q_{(t)}d_t$]. The derivative of the observed $V_{(t)}$ gives the hydrograph of discharge $q_{(t)}$ resulting from the rainfall input. This hydrograph $q_{(t)}$ is the IUH of the river. General equations of GIUH are a function of Horton's numbers, i.e. bifurcation ratio (R_B), area ratio (R_A), length ratio (R_L), length of highest-order stream (L_{Ω}) and mean velocity of stream flow (v). Therefore, it provides a theoretical link between hydrology and geomorphology, and can be used to analyze the geomorphic control on basin hydrology. Basic hydrologic and geomorphologic data of Varband river basin are listed in Table 1.

Hydrograph yielded by rainfall falling instantly and steadily on the whole surface of the basin and the area under its curve equals to the unit depth of the runoff (Rudriguez-Iturb and Valdès, 1979). In the instant unit hydrograph, the duration of rainfall is divided into very short intervals and the rainfall-runoff relation is calculated momentarily.

Therefore, the hydrograph extracted by this method has no limitation of consistency. Since, geomorphologic parameters of the basin were constant and it was possible to measure them on topographic maps and aerial pictures quickly and accurately, we could offer an artificial unit hydrograph theory.

With different methods of extracting artificial hydrograph, we can determine artificial unit hydrograph features based on geomorphologic characteristics of the basin (Mays and Taur, 1980). In this research, using this method and calculating artificial unit hydrograph, we compared geomorphologic instant unit hydrograph, and Shneider, SCS, and triangular methods with observational hydrograph. The most important advantage of the above theory compared to the experimental methods was the lack of changes in intensity and duration of rainfalls so that we could achieve the hydrologic reaction function of the basin in a particular shower with less error (Gupta & Wimer (1983), Zelazinskey (1986), Vandertake and Bras (1990), Jin (1993), Shennel & Sivapallan (1994), and Kilgur (1997)).

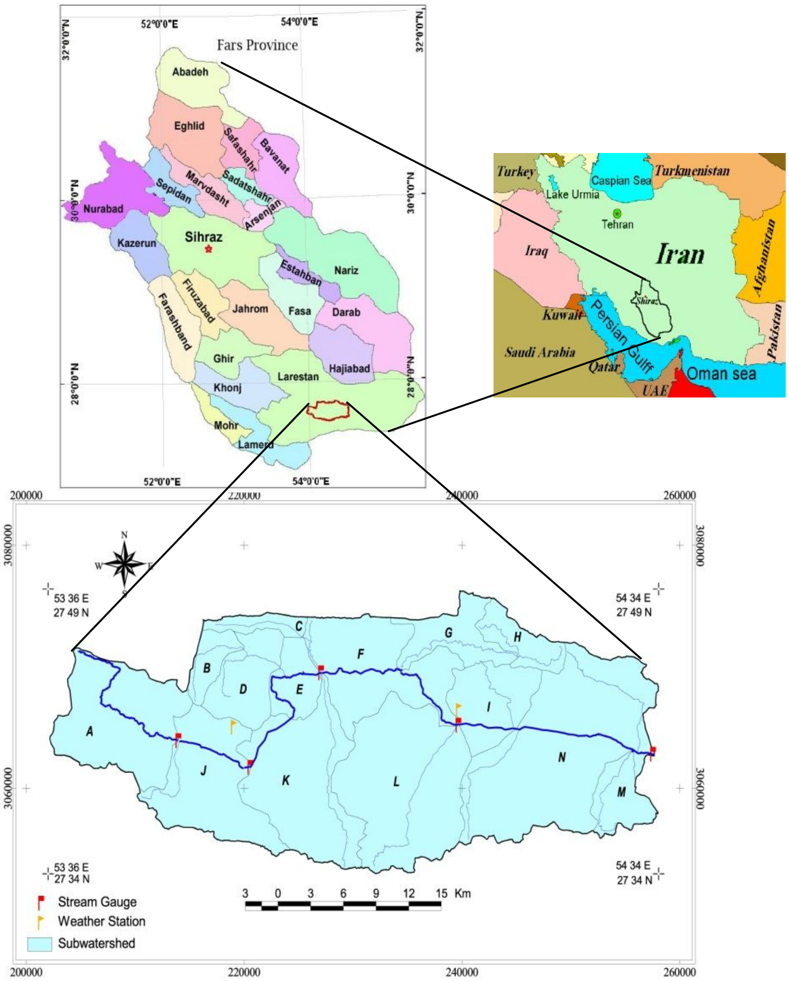

Fig. 1. Study location and Varband river system with its main tributaries.

Table 1. Hydrologic and geomorphologic characteristics of Varband river basin

Parameter	Value	Parameter	Value
Basin area	925.5	Mean slope	16.5%
Average infiltration rate	0.3cm/h	Mean annual rainfall	244mm
Input parameters for GIUH	**Definition**		
Bifurcation ratio (*R*B)	RB = *Nu*–1/*Nu*; *Nu* = No. of streams of order *u*		4.02
Length ratio (*R*L)	*R*L = *Lu*/*Lu*–1; *Lu* = Length of streams of order *u*		1.3
Area ratio (*R*A)	*R*A = *Au*/*Au*–1; *Au* = Area of streams of order *u*		3.9
Length of main channel (*L*□)	Length of the highest order stream		42.5km
Average stream velocity			1.05m/s

Model performance measures

To evaluate the suitability of the method for the basin of interest, three criteria were chosen to analyze the degree of goodness of fit. These criteria are Mean Relative Error (*MRE*) and Mean Square Error (*MSE*) based on the following equations:

$$R_{Ei} = \frac{O-P}{O} \times 100$$

(1)

$$RME = \frac{1}{n}\sum_{i=1}^{n} R_{Ei}$$

(2)

$$S_{Ei} = \left[\frac{(Q_{oi} - Q_{ci})}{Q_{oi}}\right]^2$$

(3)

$$MSE = \frac{1}{n}\sum_{i=1}^{n} S_{Ei}$$

(4)

where, *MRE* is mean relative error percentage, n is number of estimation, R_{Ei} is the percentage of relative error in each estimation of the related parameter (here four parameters of peak time, base time, peak volume and discharge rate of flood have been considered). *O* is the observed values, *P* is the calculated values, *MSE* is mean of power 2 error, S_{Ei} is sum of squares of errors between observed and calculated hydrographs in each time interval, Q_{oi} is dimension of observed hydrograph and Q_{ci} is dimension of calculated hydrographs.

To determine percentage of superiority of the models in estimating outlet hydrograph dimensions, the mean of power 2 of error of efficiency of each model with respect to other models has been used based on the following equation:

(MSE_2/MSE_1) ×100 = Ratio of estimating 1 percentage efficiency of estimating 2

Sensitivity Analysis

Further work is continuing to analyze the influence of individual morphometric parameters on flood characteristics. In order to assess the GIUH model's sensitivity to different parameters, a series of sensitivity analyses were performed. Performing sensitivity analyses is a method to identify the input parameters that have the biggest impact on model predictions. As each variable was allowed to vary, all others were held constant. As each parameter was evaluated, the impacts on the peak flow rate, the time to peak and the overall hydrograph shape were examined. The channel flow velocities and geomorphologic ratios were investigated by multiplying the base value by 0.5, 1.0, 1.5, and 2.0 in order to evaluate how the peak flow rate, time to peak and general hydrograph shape were affected by the changes in these parameters. In order to test the GIUH model's responsiveness to different excess rainfall intensities, unit hydrographs were developed for 0.03 cm/hr, 0.05 cm/hr, 0.1 cm/hr, and 0.15 cm/hr.

RESULTS AND DISCUSSION

Dimensions of calculated outlet hydrographs by different methods were compared with observed hydrograph for 1hr time durations (see Fig. 2).

Performance of the model was also checked with respect to the peak discharge (Qp) and the time to peak (tp) of different storm events. It was found that the study basin is a sixth order basin. Also, it is observed that the bifurcation ratio, length ratio and area ratio, which are non-dimensional characteristics, are 4.2, 1.03 and 3.9, respectively, for the study basin. These values are within the limits, which have already been reported in the literature. Table 2 gives hydrograph dimensions in SCS, Snyder and Triangle methods in the study basin. It demonstrates that a comparable level of performance was achieved for all methods. Also, agreement between hydrographs with respect to the peak discharge has negligible errors while with regards to peak arrival time, it shows more differences. This may be because of the peak flow dependence on excess rainfall intensity. The amounts of *MSE* and *MRE* of each method for the study basin are observed inTable 3. Results show the efficiency of extracted hydrographs in different methods by two indices of *MRE* and *MSE*. As we can see, performance of the methods on the largest events is better. Amounts of MSE for geomorphologic, Snyder, SCS and Triangle models in the study basin are 0.215, 19.634, 21.37 and 19.11 percent, respectively. Amounts of *RME* for geomorphologic, Snyder, SCS and Triangle models in the study basin are 8.524, 72.04, 77.64 and 73.63 percent, respectively. The result shows the efficiency of extracted hydrographs in different methods by two indices of *MRE* and *MSE*.

Table 4 presents relative efficiency of methods in estimating dimensions of outflow in the study basin. For this purpose, *MSE* of each model was used. Results show the efficiency of GIUH method ratio to other models. Comparison of the estimated hydrographs of the studied models with observed hydrographs showed the efficiency of geomorphologic model ratio to Snyder, SCS, and Triangle in the study basin are 91.06, 99.11, 88.642 and 48.195,respectively. Compared with other models (based on this study) in the study basin, the geomorphologic model is the most efficient model to estimate flood discharge. Also, Results showed a high agreement of GIUH, SCS, Snyder and Triangular methods with the observed hydrograph in the parameter of outlet runoff. Generally, comparison of obtained results of the methods under study shows that GIUH method is more efficient than other methods. Thus, the GIUH model can be adapted as a standard tool for modeling rainfall-runoff transformation process in basins with no data.

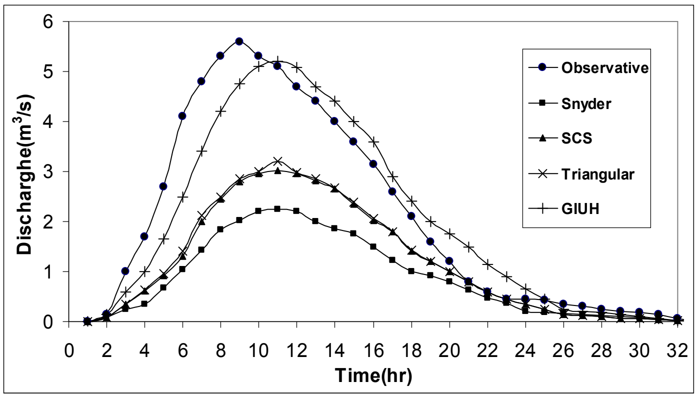

Fig. 2. Comparison of observed and calculated hydrographs of different models.

Channel velocity estimate is an important variable in estimating the time-area curve and the resulting runoff hydrograph. While keeping geomorphic parameters fixed, the channel velocity was varied from 50% to 200% of the base channel velocities calculated in Table 3. Despite large changes in the channel velocities, the peak flow rate varied less than 30% (see Fig. 3a). Changes in the channel velocity did have an impact on the hydrograph timing. As the channel velocity increased, the hydrograph shifted to the left and occurred earlier. As the channel velocity increased, the time to the peak discharge decreased from 2.75 hours to 2 hours. Lower velocity values are corresponding to low stage indicating the lean period. Higher velocity values indicate higher stage periods.As shown in Figure 3a, increase in average channel velocity causes a significant increase in the peak of hydrograph (Q_P) with less time to peak (t_P). This finding is in good agreement with that obtained by Kilgore (1997) and Jain et al. (2003).

Because there is a good deal of uncertainty in the estimate of the rainfall excess intensity, the effects of different rainfall excess intensities were investigated by allowing the intensity to vary from 0.03 cm/hr to 0.15 cm/hr. As the intensity of rainfall excess increased, the resulting hydrographs showed less attenuation and a higher, faster peak flow rate (see Fig. 3b).

Table 2. Hydrograph dimensions in SCS, Snyder and Triangle methods in Varband river basin

Date	Methods							
	Flood		SCS		Snyder		Triangle	
	$Qp(m^3/s)$	*tp(hr)*	$Qp(m^3/s)$	*tp(hr)*	$Qp(m^3/s)$	*tp(hr)*	$Qp(m^3/s)$	*tp(hr)*
1991/05/12	12.10	8.30	18.33	5.69	17.33	9.67	17.83	5.69
1992/06/20	12.55	8.10	3.35	3.14	2.35	5.17	2.85	3.14
1993/06/04	11.70	6.50	6.35	3.49	2.35	5.17	5.85	3.49
1994/03/27	2.12	8.20	19.13	5.32	1.81	8.92	18.63	5.32
1994/07/22	3.89	5.70	17.49	4.13	2.04	7.05	21.00	4.13
1995/08/27	5.81	5.84	3.35	3.71	2.35	5.17	2.85	3.71
1996/07/02	2.85	5.90	3.47	4.50	1.94	7.79	4.97	4.50
1996/07/12	1.75	6.11	5.21	3.34	2.32	5.36	6.71	3.34
1999/05/10	1.90	6.23	8.91	4.64	2.19	6.11	9.41	4.65
2001/09/26	11.50	4.65	3.35	2.94	2.35	5.17	2.85	2.95
2002/08/20	1.86	4.53	5.22	4.60	2.22	5.92	6.72	4.60
2003/07/07	1.38	6.24	23.22	4.77	2.22	5.92	22.72	4.77
2004/06/20	3.30	8.88	16.03	4.94	2.10	6.67	21.53	4.94
2004/09/20	3.66	5.94	3.33	2.64	2.33	5.28	2.83	2.64
2005/04/30	13.05	6.87	5.35	3.35	2.35	5.17	4.85	3.35
2005/07/12	10.68	5.47	14.00	4.75	1.90	8.17	19.50	4.75
2005/09/21	1.68	6.31	6.66	7.44	1.66	10.42	6.15	7.44
2006/07/02	1.90	5.21	3.43	4.10	2.43	4.79	2.93	4.10
2006/08/05	2.20	5.70	3.22	4.28	2.22	5.92	3.72	4.28
2007/08/08	8.30	6.13	3.43	3.14	2.43	4.76	2.93	3.14
2007/09/02	2.04	5.76	18.00	4.63	1.90	8.17	19.50	4.63

Table 3. Amounts of (*MSE*) and (*MRE*) for Varband river basin

Event	Geomorphologic	Snyder	SCS	Triangular
1991/05/12	0.08	27.35	38.81	32.83
1992/06/20	0.01	0.45	2.80	1.38
1993/06/04	0.06	10.97	18.60	7.91
1994/03/27	0.02	31.13	43.28	36.95
1994/07/22	0.31	33.52	33.52	39.56
1995/08/27	0.53	0.24	0.255	3.04
1996/07/02	0.04	5.54	1.83	8.15
1996/07/12	0.73	5.38	1.74	7.95
1999/05/10	0.44	9.65	9.65	13.01
2001/09/26	0.02	0.36	2.57	1.22
2002/08/20	0.01	6.59	2.45	9.40
2003/07/07	1.19	115.07	137.52	52.23
2004/06/20	0.95	18.99	28.71	78.47
2004/09/20	0.01	0.19	2.058	0.87
2005/04/30	0.02	4.64	9.96	7.05
2005/07/12	0.030	22.14	32.5	27.09
2005/09/21	0.03	5.57	11.28	8.17
2006/07/02	0.05	0.28	2.33	1.05
2006/08/05	0.07	3.39	3.39	5.48
2007/08/08	0.04	0.33	2.48	1.15
2007/09/02	0.06	35.46	24.55	41.67
RME	8.52	72.04	77.64	73.63
MSE	0.21	19.63	21.37	19.11

Table 4. Relative efficiency of estimator (1) to estimator (2) in estimating runoff in Varband river basin

Estimator(2) Estimator(1)	Geomorphologic	Snyder	SCS	Triangular
Geomorphologic	1	0.01	0.01	0.01
Syder	91.06	1	0.91	1.02
SCS	99.11	1.08	1	1.11
Triangular	88.64	0.97	0.89	1

As the rainfall excess intensity increased, the time to peak decreased from 2.5 hours to 1.5 hours. This finding is in agreement with that obtained by Kilgore (1997).

Effects of different rainfall excess durations were investigated by allowing the duration to vary from 2 to 8 hours. As the duration of rainfall excess increased, the resulting hydrographs showed a higher, faster peak flow rate (see Fig. 3c). As the rainfall excess duration increased, the time to peak decreased from 2.5 hours to 1.8 hours.

Effects of different geomorphologic ratios (R_L, $R_A$and R_B) were investigated by allowing the geomorphologic ratios to vary from 1.5 to 6. Our preliminary results suggest that out of the three Horton morphometric ratios, $R_L$influences $Q_P$and $t_P$most significantly. Our analysis predicts higher $Q_P$for higher R_L. This demonstrates the influence of particular morphologic parameters on flooding behavior of individual basins. As the length ratios (R_L) increased, the resulting hydrographs showed a higher, faster peak flow rate (see Figs 3d, e, f). As the length ratioincreased, the timeto peak decreased from 2.5 hours to 2.1 hours. This finding is in agreement with that obtained by Sorman (1995) and Jain et al. (2003). Also, as the area ratio and the bifurcation ratio increased, the time to peak increased from 2.5 to 2.8 hours.

CONCLUSIONS

In case of outlet runoff values, all the tested methods have high agreement with the observed hydrograph. When the number of events increases, the estimation accuracy, and the efficiency and precision of excess water estimation increase. Our results are validated by comparison with the result of flood frequency analysis based on observed data. Due to simplicity of the proposed method in comparison with other methods in flood estimation and since lower design risk is desired, it can be used for a basin with no data.Compared with synthetic unit hydrographs, this method (GIUH) has better estimation of time to peak and peak discharge. Hence, the prediction performance of the developed GIUH was evaluated by comprising the peak discharge (*Qp*) and time to peak (*tp*).Compared to traditional methods, the proposed method can be used for precise investigation of morphogenetic characteristics and their effects on basin hydrology.Using the proposed method, contributions and participations of different tributaries to flood hazard in the river basin can be well understood. The effect of individual morphogenetic parameters on flood discharge can be provided by the proposed method.In order to identify the input parameters that had the biggest impact on the GIUH model, a series of sensitivity analyses were performed.

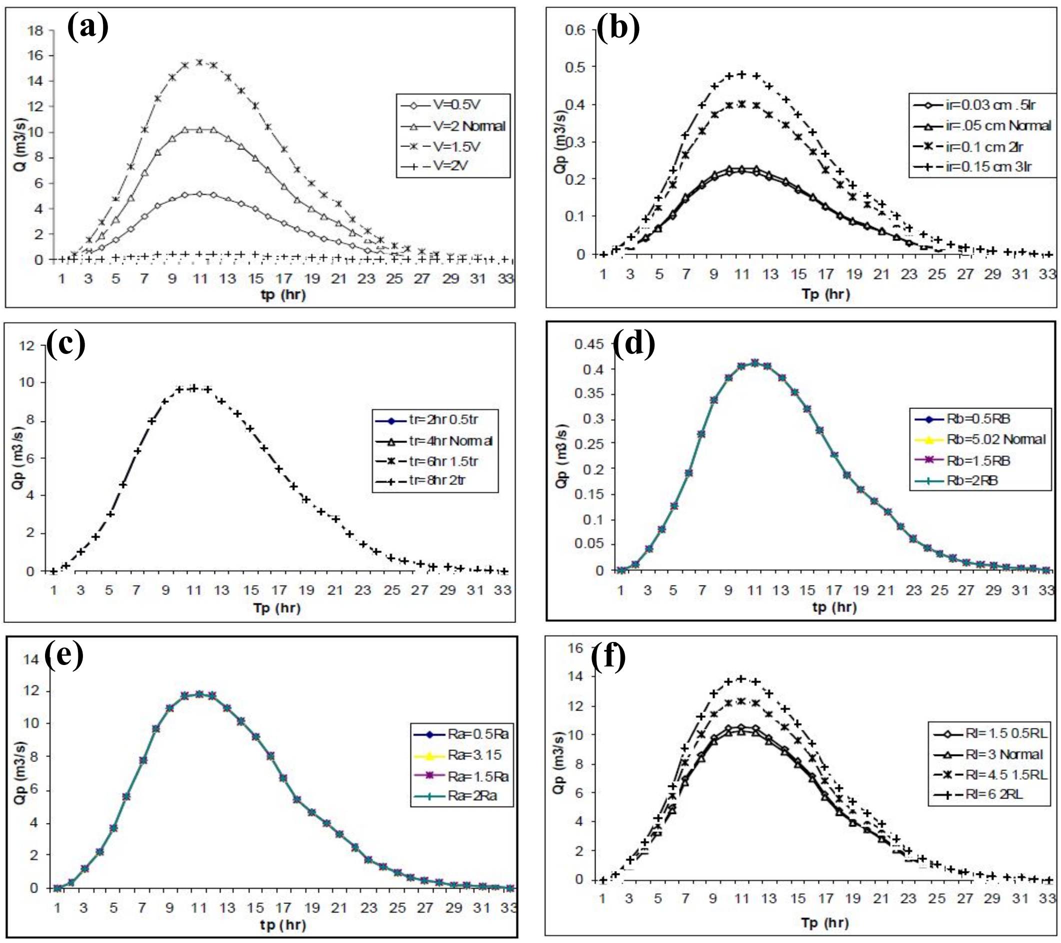

Fig. 3. Sensitivity of model response to variations.

The channel velocity and rainfall excess intensity had the biggest influence on the peak flow rate. Also the channel velocity and rainfall excess intensity had the greatest effect on the time to peak prediction. When a sensitivity analysis was performed, the channel velocity had the most influence over the time to peak. It appeared that changes in channel velocity affected the time to peak to a much greater extent than the peak flow rate. The higher the channel velocity, the lower the cumulative travel time and eventually the lower the time to peak. On the other hand, changes in the overland flow velocity had more impact on the peak flow rate than on the time to peak. Hence, it is worth mentioning that the geomorphologic unit hydrograph is not linear because its main characteristics, *Qp* and *tp* vary with the velocity *V* of the main river course. The effect of velocity on GIUH reflects the dynamics of hydrological response of basin.

Excess rainfall intensity was found to have a big impact on both the time to peak flow rate and the peak flow rate. Increasing the excess rainfall intensity caused an earlier and larger peak flow rate. The rainfall excess intensity is an important parameter for estimating the peak flow rate and the time to peak. Care should be taken when selecting a technique to estimate the rainfall excess.

Length ratio (R_L) is an important parameter for estimating the peak flow rate and the time to peak in the GIUH model. The length ratio significantly influenced the hydrologic response of the study basin. Area ratio (R_A) and bifurcation ratio (R_B) are important parameters only for estimating the time to peak in the GIUH model. Variations in GIUH parameters with respect to velocity reflect the dynamic behavior of the hydrological response of Varband river basin in different periods.The developed model when applied to predict storm runoff on Varband river basin, performed well as it yielded the model estimated values in reasonably close agreement to the corresponding observed values.

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