Regional Analysis Using the Geomorphologic Instantaneous Unit Hydrograph (GIUH) Method

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Abstract

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The construction of design flood hydrographs for ungauged drainage areas has traditionally been approached by regionalization, i.e. the transfer of information from the gauged to the ungauged catchments in a region. Such approaches invariably depend upon the use of multiple linear regression analysis to relate unit hydrograph parameters to catchment characteristics and generalized rainfall statistics. In the present study, Geomorphologic Instaneous Unit Hydrograph (GIUH) was applied to simulate the rainfall-runoff process and also to determine the shape and dimensions of outlet runoff hydrographs in a 37.1 km^2 area in the Ammameh catchment, located at northern Iran. The first twenty-one equivalent rainfall-runoff events were selected, and a hydrograph of outlet runoff was calculated for each event. An intercomparison was made for the three applied approaches in order to propose a suitable model approach that is the overall objective of this study. Hence, the time to peak and peak flow of outlet runoff in the models were then compared, and the model that most efficiently estimated hydrograph of outlet flow for similar regions was determined. Statistical analyses of the models demonstrated that the GIUH model had the smallest main relative and square error. The results obtained from the study confirmed the high efficiency of the GIUH and its ability to increase simulation accuracy for runoff and hydrographs. The modified GIUH approach as described is therefore recommended for further investigation and intercomparison with regression-based regionalization methods.

Keywords: Ammameh catchment; geomorphologic and geomorphoclimatic instantaneous unit hydrographs; rainfall-runoff model; regionalization

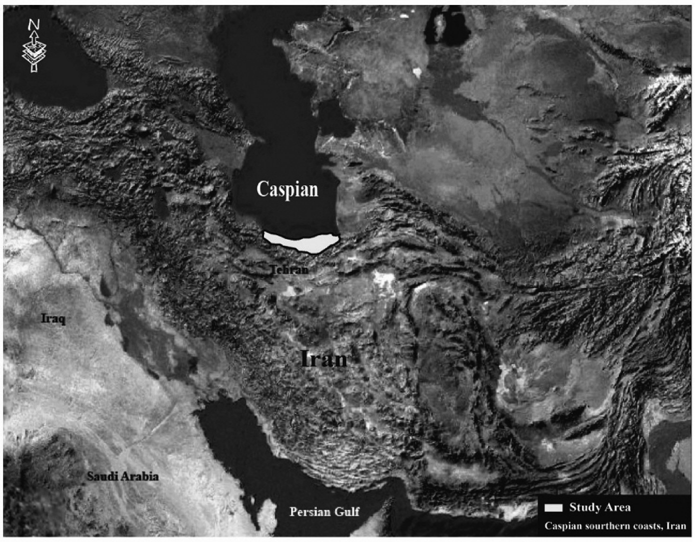
Lack of flood data is a basic problem for hydrological studies and hydrologic modelling in Iran. In fact, many past floods have not been recorded by hydrometric stations, and many catchment areas lacked stations (Khaleghi *et al*. 2011). In catchment planning and flood management, estimating the maximum flood discharge is necessary for predicting catchment hydrological behaviour. Flood management in a catchment will not be successful unless the hydrological behaviours of the catchment are predicted (Bhadra *et al*. 2008). Unfortunately, many streams are ungauged and do not have flow records. Even when stream gauges are in place, the record is often too short to accurately predict extreme events (Ajward 1996). Major problems concerning hydrological predictions include lack or low accuracy of rainfall data, high cost, lack of information about catchments, and the length of time required to obtain study results (Maheepala *et al*. 2001; Vaes *et al.* 2001; Lopez *et al.* 2005; Vahabi & Ghafouri 2009). The hydrological response of a river catchment is based on the relationship between the catchment geomorphology (catchment area, shape of catchment, topography, channel slope, stream density, and channel storage) and its hydrology (Loukas *et al*. 1996; Shamseldin & Nash 1998; Ajward & Muzik 2000; Hall *et al*. 2001; Jain & Sinha 2003; Agirre *et al*. 2005; Nourani *et al*. 2009). Rasool *et al*. (2011) evaluated the morphometric characteristics (such as the ratios of bifurcation, length, and area) of the Upper Subarnarekha Watershed drainage and concluded that the morphometric parameters evaluated using GIS software helped us understand various terrain parameters such as nature of the bedrock, infiltration capacity, runoff, etc. Stream networks and catchment basins are characterized by numerous fractal dimensions. These fractal dimensions are related to the values of the bifurcation ratio, the stream length ratio, and the stream area ratio (Beer & Borgas 1993). Many studies have been carried out on the efficiency of artificial unit hydrographs and instantaneous unit hydrographs (IUHs) in Iran and around the world (Wang & Chen 1996; Jeng & Coon 2003). The concept of the GIUH was first introduced by Rodriguez-Iturbe and Valdes (1979) and later generalized by Gupta *et al.* (1980). Their quantitative understanding opened a new dimension in the hydrological analysis, especially for the ungauged river basin. In this approach, excess rainfall is assumed to follow different probabilistic flow paths in the channel and on overland areas to reach the catchment outlet (Bhadra *et al.* 2008). Cudennec *et al.* (2004) investigated the geomorphologic aspect of the unit hydrograph concept and concluded that the use of geomorphologic parameters explained the unit hydrograph and geomorphologic unit hydrograph theories. Jain *et al.* (2000) investigated rainfall-runoff modelling using GIUH in the Gambhiri catchment in western India. The results indicated that peak characteristics of the design flood are more sensitive to various storm patterns.

The current study has been conducted to determine the most appropriate method of creating flood hydrographs in the Ammameh catchment. In other words, it has been conducted to develop a spatially distributed unit hydrograph model suitable for ungauged basins based on the spatial analysis functions in a raster GIS. A selection of storm events was analyzed for the Ammameh catchment in order to determine whether comparable levels of goodness-of-fit can be obtained, thereby demonstrating the utility of the GIUH catchment and channel characteristics as a possible basis for the regionalization of the catchment response.

MATERIAL AND METHODS

The Ammameh catchment encompasses an area of about 37.1 km² and is located at northern Iran within the limits of eastern longitude 51°32'38''to 51°38'20''and northern latitude 35°51'20'' to 35°57' in the southern part of Tehran province (Figure 1). The climate of the area is semi-humid and cold, with an average annual precipitation of 791 mm and average temperature of 11°C. A hydrometric station is located at the outlet of the catchment (Jajrud Station), and a rain recorder station (Ammameh Station) is located upstream of the station. This study was conducted from the winter of 2007 (October) to the winter of 2009 (January).

In the present study, an attempt has been made to compare the performance of the GIUH method with other methods and to validate the model with recorded data from the catchment. Twenty-one single rainfall-runoff events (which were collected among other data, including snowmelt, which had no effect on the obtained flood) were selected for the GIUH creation. In this study, precipitation (the most essential process for the generation of runoff at a catchment scale) is considered in the form of rain only. Hence, data and information on equivalent rainfall-runoff events, in which snow did not melt, were collected from graphs. After separating the base flow and calculating curve areas from each event, the



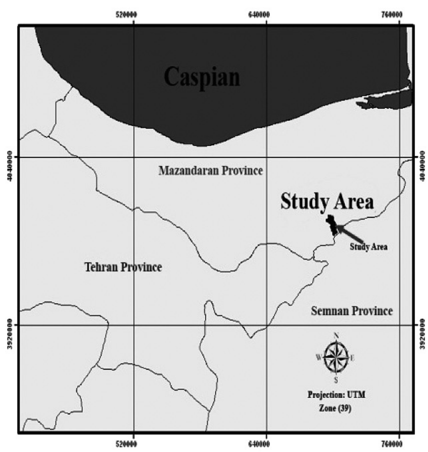


Figure 1. Location of the study area (Ammameh catchment)

Table 1. Morphometric parameters (after Horton 1945)

Parameter	Definition	Relationships	Range of parameter variation	Value of constants	Authors
Bifurcation ratio (R_B)	ratio of number of streams	$R_B = N_{u-1}/N_u$ N_u = No. of streams of order u	$3 < R_B < 5$	4.02	Horton (1945)
Length ratio (R_L)	ratio of average length of streams	$R_L = L_u/L_{u-1}$ R_L = Avg. length of streams of order u	$1/5 < R_L < 3/5$	2.3	Horton (1945)
Area ratio (R_A)	ratio of average area of streams	$R_A = A_{ū}/A_{ū-1}$ $A_{ū}$ = Avg. basin area of streams of order u	$3 < R_A < 6$	5.2	Schumm (1956)

Table 2. Geomorphologic characteristics of the Ammameh catchment

Order	No. of streams	Average length (km)	Average area (km^2)
1	595	0.31	0.21897
2	148	0.45	1.1298
3	34	1.05	4.4640
4	12	1.4	6.3501
5	3	0.89	24.7790
6	1	8.56	37.1

direct runoff was obtained by dividing the value by the total area of the catchment. The excess rainfall of the rainfall event was determined. After the base flow was removed from the total runoff hydrograph, the direct runoff hydrograph remained (Annex). The total runoff volume was determined by integrating the direct runoff hydrograph. Geomorphologic analysis involved the computation of stream number, average stream length, and average stream area of the Ammameh catchment following Strahler's (1956) ordering scheme. Arcview GIS software was extensively used to prepare model input data, such as the area, slope, and length of the main river catchment, and geomorphologic characteristics, such as R_A (area ratio), R_B (bifurcation ratio), and R_L (length ratio). Detailed morphometric and geomorphologic factors of the catchment listed in Tables 1 and 2 were calculated by applying a Digital Elevation Model (DEM) using a 20-m resolution raster elevation data set (Figure 2). The study catchment was discovered to be a sixth-order catchment. For the studied catchment, the bifurcation, length, and area ratios, which are non-dimensional characteristics, are 4.2, 2.03, and 3.9, respectively (Figure 3). These parameters were used to determine the Horton's ratio. Flow velocity was obtained through calibrating historical data.

To evaluate the suitability of the method for the studied catchment, two criteria were chosen to analyze the degree of goodness of fit. These criteria are Mean Relative Error (*RME*) and Mean Square Error (*MSE*), which are based on the following equations:

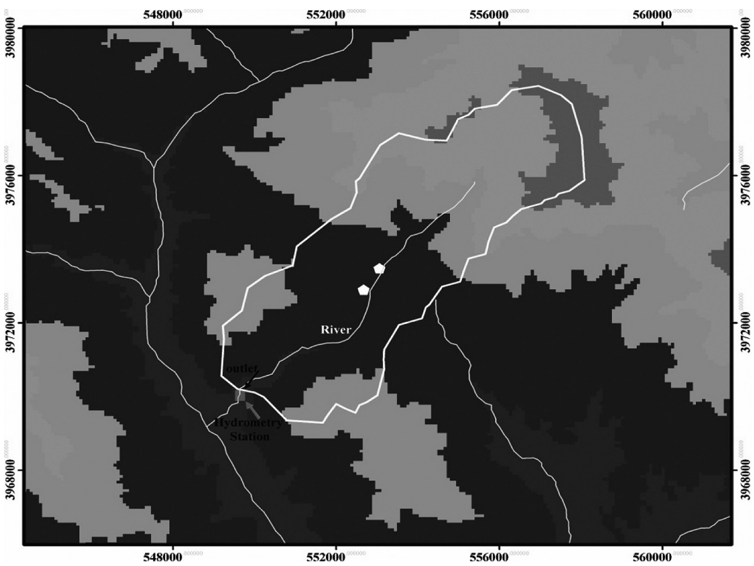


Figure 2. The Ammameh catchment Digital Elevation Model (DEM)

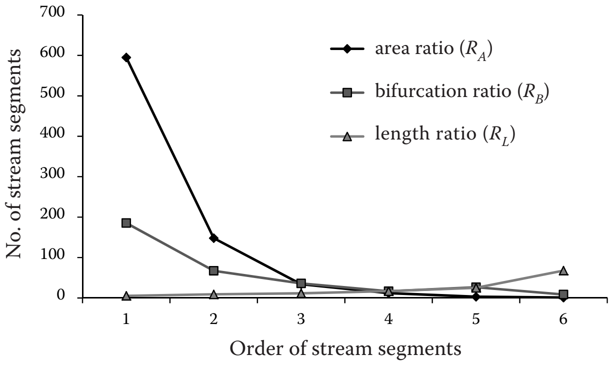


Figure 3. Law of stream numbers, lengths, and areas, Ammameh drainage basin

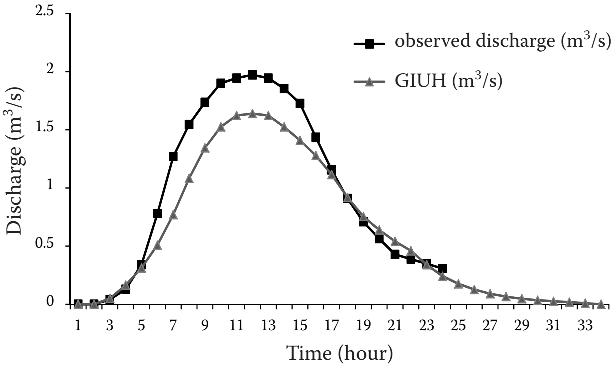


Figure 4. Simulated hydrograph in comparison to observed hydrograph in 1-hour time durations

$$R_{Ei} = \frac{O-P}{O} \times 100 \quad (1)$$

$$RME = \frac{1}{n}\sum_{i=1}^{n} R_{Ei} \quad (2)$$

$$S_{Ei} = \left[\left(Q_{oi} - Q_{ci}\right)/Q_{oi}\right]^2 \quad (3)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n} S_{Ei} \quad (4)$$

where:

n – number of estimations

R_{Ei} – percentage of relative error in each estimation of the related parameter (here, 4 parameters have been considered: time to peak, base time, total volume, and flood discharge)

O – observed values

P – calculated values

S_{Ei} – sum of squares of errors between observed and calculated hydrographs in each time interval

Q_{oi} – dimension of the observed hydrograph

Q_{ci} – dimension of calculated hydrographs

RESULTS AND DISCUSSION

Simulated hydrographs were compared to observed hydrographs in 1-hour time durations using different methods (Figure 4). Figure 5 shows the GIUH at different values of average channel velocity. The stage-velocity curve shows variation in average channel velocity from 1 m/s (during lean period) to 4 m/s (during peak discharge time). Thus, in order to analyze the effect of average channel velocity on the GIUH, four graphs were generated for the velocity of 1, 2, 3, and 5 m/s, while the geomorphic parameters were kept fixed (Figure 5). Lower velocity values are corresponding to low stage indicating the lean period. Higher velocity values indicate higher stage period. Variation in the GIUH parameters with respect to velocity reflects the dynamic behaviour of hydrological response of the Ammameh river basin in different periods. Figure 5 shows that an increase in average channel velocity causes a significant increase in the peak of hydrograph (Q_p) with less time to peak (T_p). Thus, the general form of the GIUH is expressed by average channel velocity at peak discharge. Table 3 shows the rates of excess rainfall and their duration for selective floods in the Ammameh catchment. Table 3 shows the values of *MSE* and *RME* for each method. The results illustrate the efficiency of extracted hydrographs using different methods through these two indices (the *MSE* and *RME*). The *MSE* and *RME* values for the Geomorphologic Model in the studied catchment are 0.215 and 8.524%, respectively. Also, statistical parameters obtained during validation run are shown in Table 3. It is seen that Coefficient of Residual Mass (*CRM*) value is positive in the case of the GIUH method, which indicates under-prediction of observed hydrograph ordinates. Modelling Efficiency (*ME*) and *CRM* values for the GIUH method are rea-

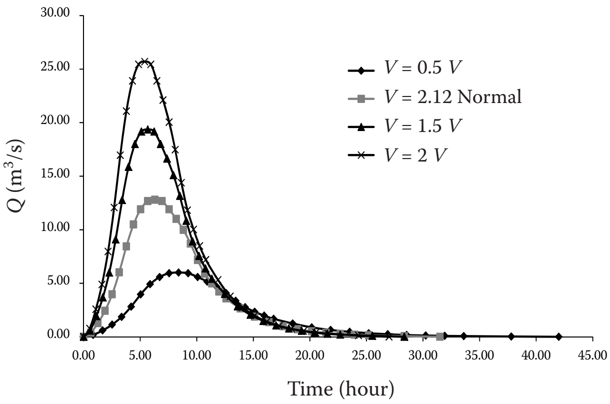


Figure 5. Relationship between flow discharge and flow velocity in different variations of flow velocity

Table 3. Mean Square Error (*MSE*), Mean Relative Error (*RME*), a systematic deviation from the true value (Bias), *Z* test (*Z*) and R^2 values for the Ammameh catchment

Row	Date	GIUH						Z
		Q_p		T_p		V		
		Bias	R^2	Bias	R^2	Bias	R^2	
1	1991/05/12	0.69	0.99	1.05	0.96	1.08	0.99	0.06
2	1994/03/27	0.47	0.997	1.05	0.96	1.17	0.98	0.11
3	1994/07/22	0.62	0.808	1.24	–3.5	1.59	0.69	0.29
4	1996/07/02	1.21	0.941	1.23	–11	1.66	0.89	0.32
5	1996/07/12	0.74	0.999	1.12	–34	1.03	1.00	0.14
6	1999/05/10	0.81	0.999	1.08	–0.4	1.23	0.99	0.14
7	2002/08/20	0.76	0.997	0.91	0.94	1.03	1.00	0.15
8	2003/07/07	0.42	0.997	0.95	–304	0.80	0.99	0.20
9	2004/06/20	0.58	0.996	0.90	0.87	0.86	0.60	0.12
10	2005/04/30	0.68	0.999	1.09	0.29	1.11	0.97	0.08
11	2005/07/12	0.71	0.959	1.10	0.55	1.21	0.77	0.13
12	2005/09/21	0.71	1.000	1.14	–75	1.12	1.00	0.13
13	2006/08/05	0.5	0.998	1.11	–0.2	1.04	1.00	0.12
14	2007/08/08	0.63	0.995	0.92	–34	0.94	0.94	0.09
15	2007/09/02	0.381	0.995	1.10	–0.3	0.98	1.00	0.16
RME		9.1		11.2		17		
MSE		0.25		0.55		89.91		
ME		0.92		0.65		0.98		

GIUH – Geomorphologic Instaneous Unit Hydrograph

sonably good. The *MSE* and *RME* values indicated that the GIUH method could best predict the peak flow rate and time to peak rate. The GIUH method has the highest R^2 value for more storm events. According to the R^2 statistics, the GIUH could best predict the hydrograph shape.

CONCLUSION

After applying the GIUH, a general conclusion is that the GIUH models showed a good behaviour for hydrograph generation. When the number of events increases, the estimation accuracy and the efficiency and precision of excess water estimation increase. Also, for short storms where the phi-index line seems to accurately predict the pattern of rainfall excess, the unit hydrograph predictions are generally good. Given that the proposed method is simple and a low design risk is desired, it seems that the proposed method is the best one to be applied for catchments that lack data. Compared to traditional methods, the proposed method can be used for a precise investigation of morphogenetic characteristics and their effects on catchment hydrology. Using very limited data makes this model very useful for an ungauged catchment aiming at event prediction. In other words, the GIUH is recommended to predict the discharge of the Ammameh catchment in event mode. Using Horton's morphometric parameters derived from DEM in specific software environment (Arcview) and estimated velocity of stream, the model is easy-to-use. In this model, the Curve Number (CN) value was kept constant (no calibration). It should be further investigated what affects this factor so that the calibrated parameter would be representative. From these results, it can be stated that using the proposed method, the contributions of different tributaries to flood hazards in the river catchment can be well understood. The effects of individual morphogenetic parameters on flood discharge could also be provided by the proposed method. Some of the errors in the model predictions are a result of the errors in determining the time distribution of the rainfall excess (Kilgore 1997). In this study, we found that errors existed in previous datasets due to the lack of skilled experts. This drainage network analysis and application of the GIUH can provide a significant contribution towards flood management program. Thus, the present model could be applied to simulate flood hydrographs for the catchments that have not been studied yet.

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