Comparison between GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models

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Abstract

The estimation of flood hydrographs has a high level of importance in ungauged watersheds.

Methods currently being widely used for the estimation of flood hydrographs utilize historical rainfall-runoff data. For ungauged watersheds, the unit hydrograph may be derived using the geomorphologic instantaneous unit hydrograph (GIUH) and geomorphoclimatic instantaneous unit hydrograph (GcIUH) approaches. This research is aimed at comparing the accuracy of GcIUH-based Clark (GcIUH-Clark) and GIUH-based Nash (GIUH-Nash) models. For this purpose, the Clark-IUH model option of the HEC-HMS package and the Nash-IUH model were employed with and without the use of historical rainfall-runoff data, respectively, to determine shape, peak discharge, and time to peak of direct surface run-off (DSRO) hydrographs. The case study in this study was the Kasilian watershed, located in Mazandaran Province of Iran, with an area of 67.5 km^2. The results obtained from these models were compared with observed DSRO hydrographs based on 3 performance criteria, namely EFF, PEP, and PETP.

The results clearly revealed the accuracy and applicability of these 2 models (the GcIUH-Clark model and the GIUH-Nash model) for derivation of DSRO hydrographs.

Key Words: GcIUH-Clark model, GIUH-Nash model, Kasilian watershed, instantaneous unit hydrograph

Introduction

Estimation of flood hydrographs for ungauged watersheds is a key step in the planning, development, and operation of various water resources projects. Watershed research priorities of hydrologists for ungauged or

partially gauged watersheds were renewed with the introduction of geomorphologic instantaneous unit hydrographs (GIUH) by Rodriguez-Iturbe and Valdes (1979). They conceptualized that river watersheds follow Horton's geomorphologic laws and that the instantaneous unit hydrograph of a watershed may be interpreted as the probability density function (PDF) of travel time in the watershed.

Along the same line of investigation, Rodriguez-Iturbe et al. (1982a, 1982b) proposed what they called a geomorphoclimatic instantaneous unit hydrograph (GcIUH) as a link between climate, geomorphologic structure, and the hydrologic response of a watershed. The resultant GcIUH is a function of the excess rainfall intensity.

Sorman (1995) applied the GIUH model to estimate the peak discharges resulting from various rainfall events for watersheds in Saudi Arabia. A hydraulic approach was used to estimate both kinematic and dynamic wave velocities.

Yen and Lee (1997) derived a GIUH using the kinematic wave theory, based on the travel times for overland and channel flows in a stream ordering subwatershed system for the Kee-lung River watershed in Taiwan.

Rinaldo and Rodriguez-Iturbe (1996) and Rodriguez-Iturbe and Rinaldo (1997) expressed the PDF of travel times as a function of the watershed forms characterized by the stream networks and other landscape features. They, however, stated that a triangular IUH would, in some cases, provide a satisfactory approximation.

Al-Turbak (1996) developed a geomorphoclimatic peak discharge model with a physically based infiltration component. The model calculated the peak discharge and time to peak, which were then incorporated into an infiltration model for calculating the ponding time and effective rainfall intensity and its duration.

Bhaskar et al. (1997) related GIUH to the parameters of the Nash-IUH model. This study showed that the GIUH-based Nash model can be used for the estimation of floods in ungauged watersheds with a reasonable degree of accuracy.

Jain et al. (2000) derived the peak discharge of runoff and time to peak using the GIUH formulas for rivers in western India. The morphologic parameters required by the formulas were prepared and were used to develop the complete shape of the IUHs by use of the Clark model (Clark, 1945) through a nonlinear optimization procedure.

Hall et al. (2001) did a regional analysis using GcIUH in the southwest of England. In that study, the rainfall excess duration was divided into several time increments, with separate IUHs generated for each interval. The results showed that a fine time interval captured the shape of the runoff hydrographs.

Zhang and Govindaraju (2003) developed geomorphology-based artificial neural networks (GANNs) for the estimation of runoff hydrographs from several storms over 2 Indiana watersheds. The study revealed GANNs to be promising tools for estimating direct runoff.

Sahoo et al. (2006) applied GIUH-based Nash and Clark models for flood estimation to the Ajay river watershed in northern India. The results demonstrated that these can be successfully used for runoff prediction in ungauged watersheds or scantly gauged watersheds.

Kumar and Kumar (2008) concluded that direct runoff from an ungauged hilly watershed can be predicted fairly accurately using the GIUH approach based on kinematic wave theory and the geomorphologic parameters of Horton's stream order ratios, without using historical rainfall-runoff data.

The GIUH and GcIUH approaches have many advantages over the regionalization techniques, as they avoid the requirement of rainfall-runoff data and computations for the neighboring gauged watersheds in the region, as well as the updating of the parameters. Another advantage of these approaches is the potential for deriving the geomorphologic parameters using only the information obtainable from topographic maps or remote sensing, possibly linked with geographic information systems (GIS) and digital elevation models (DEM).

The objectives of the present study were as follows:

(i) To evaluate the geomorphologic parameters of the catchments required for derivation of GIUH and GcIUH by employing a geographic information system (GIS).

(ii) To derive the DSRO hydrographs using the GcIUH-Clark and GIUH-Nash models, without using historical rainfall-runoff data; and to compare these hydrographs with those derived by the classical Clark-IUH model option of the HEC-HMS package and the Nash-IUH model.

Case Study

In addition to geomorphologic data, the obtained data from several rainfall-runoff events were recorded in the Kasilian watershed. This watershed is a small part of the Caspian Sea watershed and is considered as 1 of the 6 major watersheds in Iran. The Kasilian watershed is located between 35 ° 58′45¨N and 36 ° 07′45¨N, and 53 ° 10′30¨E and 53 ° 17′30¨E. The Tajor and Bozla river watersheds are located in the north and south of the Kasilian watershed, respectively.

In addition, the Tajan and Talar river watersheds are located in the east and west of the Kasilian watershed, respectively.

The Kasilian watershed has an area of 67.5 km² and is 1100-2900 m above sea level. A hydrometric station was constructed at the end point of the watershed, in Valikben village. In this paper, a 29-year time series of hydrometric data, from October 1970 to October 1999, was employed.

The Kasilian watershed has 3 ordinary rainfall stations. The Sangdeh rainfall station is one of these stations, located in the center of the Kasilian watershed, and, in comparison with the other stations, it has more accurate data. The Kasilian River is the main river of the watershed, with a length of 16.2 km. A map of the Kasilian watershed is shown in Figure 1.

The research methodology

Estimation of geomorphologic parameters: In this study, the geomorphologic characteristics of the Kasilian watershed were evaluated using the procedure described by Kumar et al. (2002) and Arc GIS software. The boundary of the watershed, stream network, and contours were digitized using Institute Survey of Iran topography map sheets on the scale of 1:25,000. The Strahler ordering scheme was followed for the ordering of the river network (Strahler, 1956). The maximum order of the Kasilian watershed is equal to 4. The corresponding length and area of the surface runoff of each channel order was measured. Geomorphologic parameters, namely the average value of the bifurcation ratio (R_B), stream length ratio (R_L), and stream area ratio (R_A), were calculated for the consecutive order channels using Horton's law (see Table 1). The values of R_B, R_L, and R_A were determined to be 3.79, 2.43, and 4.93, respectively.

Nash-IUH model: The Nash model utilizes n series of reservoirs for estimation of runoff from rainfall. Reservoirs of the Nash model are linear, and their storage equation is defined as follows:

$$S = c.Q \qquad (1)$$

where S is the storage of reservoir (MCM), Q is the outflow from reservoir (CMS), and c is a constant known as the lag time of the reservoir.

The equation of a Nash instantaneous unit hydrograph is described as follows:

$$u(t) = \frac{1}{k\Gamma_n} e^{(\frac{-t}{k})} (\frac{t}{k})^{n-1} \tag{2}$$

where $u(t)$ is the value of the Nash-IUH model in time step t, n is the shape parameter denoting the number of reservoirs, and k is the scale parameter showing storage coefficient.
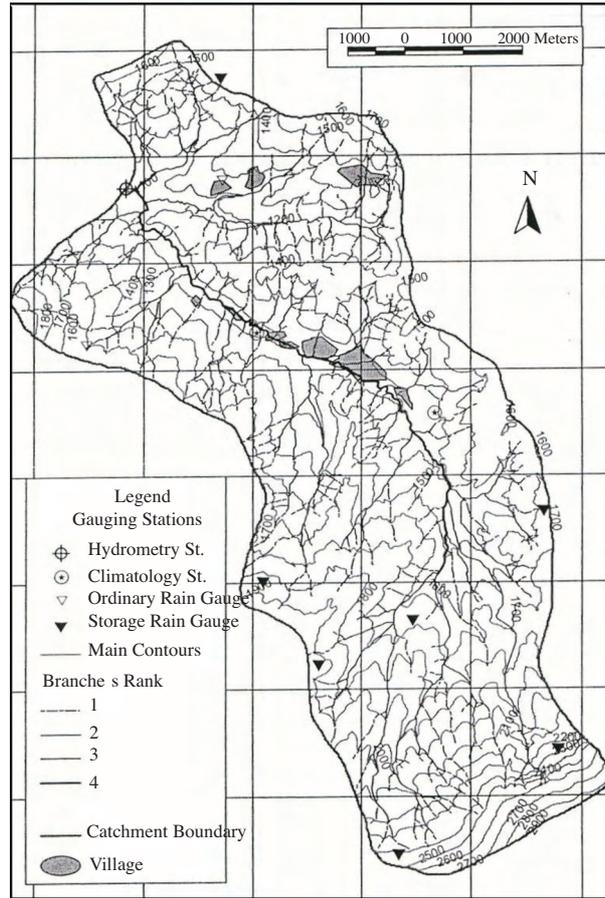
Figure 1. Map of the Kasilian watershed.

Table 1. Details of number, mean length, mean area, and Horton's ratios for streams of various orders for the Kasilian watershed.

Stream order Ω	Total number of streams N_Ω	Mean stream length L_Ω (km)	Mean stream area A_Ω (km^2)	Bifurcation ratio R_B	Stream length ratio R_L	Stream area ratio R_A
1	53	0.7675	0.62	3.12	-	-
2	17	1.6894	2.48	4.25	2.2	4
3	4	5.1182	16.8	4	3.03	6.77
4	1	10.6	67.5	-	2.07	4.01

The Nash-IUH model, along with the parameters n and k, is determined for each of the historical storm (or rainfall-runoff) events.

It can be shown that the first and second moments of the Nash-IUH model about the origin ($t = 0$) are $m_1 = n.k$ and $m_2 = n.(n+1).k^2$, respectively. To calculate the parameters n and k, the above equations can be solved simultaneously. The moments m_1 and m_2 are computed by using the excess rainfall hyetograph and the DSRO hydrograph.

GIUH-Nash: Rodriguez-Iturbe et al. (1979) suggested that it is adequate to assume a triangular form of IUH. This assumption enables us to consider peak discharge and time to peak for a wide range of parameters.

Bhaskar et al. (1997) derived the GIUH from the watershed geomorphologic characteristics and then related it to the parameters of the Nash-IUH model. To develop the complete shape of the GIUH by using the Nash-IUH model, the shape parameter of the Nash-IUH Model, n, is obtained by solving the following equation by the Newton-Raphson nonlinear optimization scheme:

$$\frac{(n-1)}{\Gamma(n)}.e^{-(n-1)}.(n-1)^{n-1} = 0.5746 R_B^{0.55} R_A^{-0.55} R_L^{0.05} \tag{3}$$

The scale parameter can be best determined from:

$$k = \frac{t_p}{(n-1)} = 0.44(\frac{L_\Omega}{V})(\frac{R_B}{R_A})^{0.55} R_L^{-0.38} \frac{1}{(n-1)} \tag{4}$$

where R_B is the bifurcation ratio, R_A is the stream area ratio, R_L is the stream length ratio, L_Ω is the length of the highest order stream (km), V is the peak flow velocity in the watershed outlet (m/s), and t_p is the time to peak (h).

Clark-IUH model: The Clark-IUH model is based on the concept that IUH can be derived by routing unit excess-rainfall in the form of a time-area diagram through a single linear reservoir. For derivation of IUH, the Clark model uses 2 parameters, time of concentration (T_c) in hours and storage coefficient (R) in hours, in addition to the time-area diagram. The governing equation of the Clark-IUH (HEC-HMS) model is expressed as:

$$u_i = (\frac{\Delta t}{R + 0.5\Delta t})I_i + (\frac{R - 0.5\Delta t}{R + 0.5\Delta t})u_{i-1} \tag{5}$$

where u_i is the ith ordinate of the IUH, Δt is the computational time interval (h), and I_i is the ith ordinate of the time-area diagram.

The HEC-HMS package (HEC 2006) employs a synthetic accumulated time-area diagram. The package can optimize the runoff parameters (T_c) and (R) in rainfall-runoff events.

GcIUH-Clark model: The disadvantage of Rodriguez-Iturbe and Valdes' formulation lies in its dependence on the characteristic velocity V.

Rodriguez-Iturbe et al. (1982a, 1982b) proposed an approach for determining the velocity term V by applying kinematic wave assumptions. The peak flow velocity in the watershed outlet (V) is calculated by the following equation in this method:

$$V = 0.665\alpha_\Omega^{0.6}(i_r A_\Omega)^{0.4} \tag{6}$$

where A_Ω is the watershed area (km^2), i_r is the excess rainfall intensity (cm/h), and α_Ω is the kinematic wave parameter for the highest-order channel (s^{-1}.m$^{-1/3}$).

According to Henderson (1963), the peak discharge, Q_P, can be described as follows, using the results of a DSRO hydrograph:

$$Q_p = 2.42\frac{i_r A_\Omega t_r}{\Pi^{0.4}}(1 - \frac{0.218t_r}{\Pi^{0.4}}) \tag{7}$$

where t_r is the duration of excess rainfall (h), Q_P is the peak discharge of the flood (CMS), and Π_i is the geomorphoclimatic parameter (h).

$$\Pi = \frac{L_\Omega^{2.5}}{i_r A_\Omega R_L \alpha_\Omega^{1.5}} \tag{8}$$

In this research, the stepwise procedure based on the Clark model to obtain GIUH is as follows:

The GcIUH-Clark model requires the ordinates of the time-area diagram as an input to the model. The concentration time of the watershed was initially estimated as 7 h.

The DEM of the Kasilian watershed was prepared and employed to compute the travel time from various locations throughout the watershed. Using the interpolation technique, a map of time distribution was then drawn through those points and, subsequently, the time-area ordinates, in the form of cumulative watershed area versus time of travel, were determined for the Kasilian watershed.

A map at an interval of 1 h was prepared. A plot of time of travel versus cumulative area could be plotted, as shown in Figure 2.
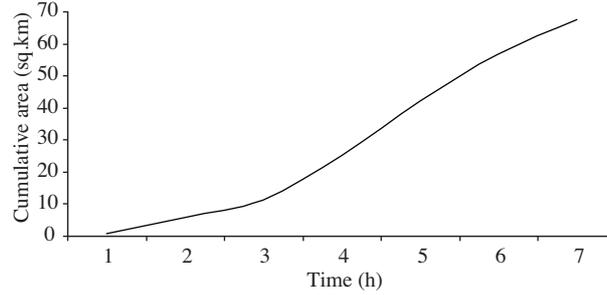
Figure 2. Time of travel versus cumulative area.

This information was used to formulate the nondimensional time-area relationship of the watershed considering the normalized isochronal areas as the ordinates and the corresponding normalized times of travel as abscissas. The normalized isochronal areas were the ratios of the isochronal areas to the total watershed area. The stepwise procedure for derivation of the GcIUH -Clark model was as follows:

(i) Determining the excess rainfall hyetograph.

(ii) Estimating the peak velocity V for a given storm using the relationship between peak velocity and intensity of excess-rainfall.

(iii) Computing the concentration time using the equation $T_c = 0.2778\frac{L}{V}$, where L is the length of the main channel (km).

(iv) Considering this T_c as the largest time of travel, the ordinates of the cumulative isochronal areas, corresponding to integral multiples of computational time intervals, can be derived using the nondimensional time-area diagram. This interval describes the ordinates of the time-area diagram, the I_i at each computational time interval in the domain $[0,T_c]$.

(v) Computing the peak discharge (Q_p) of GcIUH given by Eq. (7).

(vi) Computing the values of the storage coefficient (R), by using a nonlinear optimization procedure so that the estimated peak of the DSRO hydrograph by the GcIUH-Clark model matches the computed peak by the GcIUH model in step (v).

Results

In this research, it was assumed that the infiltration rate was constant. For the sake of comparing the results of different models, 13 storm events were studied. The parameters of the Clark-IUH model option of HEC-HMS (T_c and R) and the Nash-IUH model (n and k) were calculated by using the historical data of all 13 rainfall-runoff events. In the Clark-IUH model, the concentration time and storage coefficient ranged from 2.21 to 8.09 h and from 2.5 to 6.7 h, respectively. In the Nash-IUH model, the shape and scale parameters ranged 1.76 to 4.66 h and 1.34 to 3.17 h, respectively. The calculated values of concentration time, storage coefficient, shape parameter, and scale parameter, as well as their arithmetic means and geometric means, are shown in Table 2.

Table 2. The calculated values of parameters in different models.

Model	Nash-IUH		GIUH-Nash		Clark-IUH (HEC-HMS)		GcIUH-Clark	
Event number	n	k	n	K	(R)	T_c	(R)	T_c
1	4.66	1.37	2.83	2.23	2.86	7.65	5.70	6.39
2	3.73	1.47	2.83	1.83	2.50	5.98	4.62	5.24
3	2.97	3.17	2.83	2.23	6.64	5.07	5.57	6.39
4	3.30	1.43	2.83	1.28	4.42	4.52	3.22	3.66
5	3.84	2.67	2.83	2.12	6.70	7.15	5.23	6.06
6	3.07	1.53	2.83	1.66	3.36	4.18	4.10	4.76
7	3.87	2.22	2.83	1.78	5.54	8.09	4.47	5.11
8	1.76	2.19	2.83	1.97	3.08	2.21	5.00	5.65
9	2.23	2.25	2.83	3.40	3.11	4.08	9.50	9.72
10	2.71	2.11	2.83	2.58	4.31	5.82	7.43	7.39
11	4.23	2.03	2.83	1.96	4.70	7.60	5.02	5.60
12	4.35	1.34	2.83	1.50	2.52	5.94	3.49	4.28
13	3.33	2.68	2.83	3.11	5.07	6.50	9.40	8.90
Arithmetic mean	3.39	2.04	2.83	2.13	4.22	5.75	5.60	6.09
Geometric mean	3.28	1.96	2.83	2.05	3.99	5.47	5.30	5.88

The storm events were divided into 2 parts; 9 storm events were used for calibration and the remaining 4 storm events were used for validation of the Clark-IUH and Nash-IUH models. The calibrated parameters of the Clark- and Nash-IUH models were estimated by taking the geometric mean of the parameters. The values of the calibrated parameters obtained for the Clark- and Nash-IUH models were $T_c = 5.09$ h, $R = 3.98$ h, $n = 3.15$, and $k = 1.95$ h. These values were applied to the last 4 events to derive the IUH model. The convolution of the IUH with the excess rainfall hyetograph produces the DSRO hydrograph.

As the geometric properties of the gauging section and the value of Manning's roughness coefficient, as well as the velocities corresponding to discharges passing through the gauging section at different depths of water

flow, were available for the gauging site of the considered watershed, the kinematic wave parameter for the highest-order channel was estimated to be $0.61(s^{-1}.m^{-\frac{1}{3}})$.

The values of the parameters of the GIUH-Nash and GcIUH-Clark models were calculated by estimating the maximum velocity in the outlet of the watershed and the geomorphoclimatic parameters. For 13 storm events, the range of concentration time and storage coefficient was between 3.66 and 9.72 h and between 3.22 and 9.5 h, respectively, in the GcIUH-Clark model. The shape parameter was equal to 2.83 and the range of scale parameter was from 1.28 to 3.4 h in the GIUH-Nash model.

Based on the values of the calibrated parameters of the Clark- and Nash-IUH models, the outlet DSRO hydrographs were computed using the GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models for the last 4 events and compared with the observed outlet DSRO hydrographs. Figures 3-6 show these hydrographs for the last 4 events.
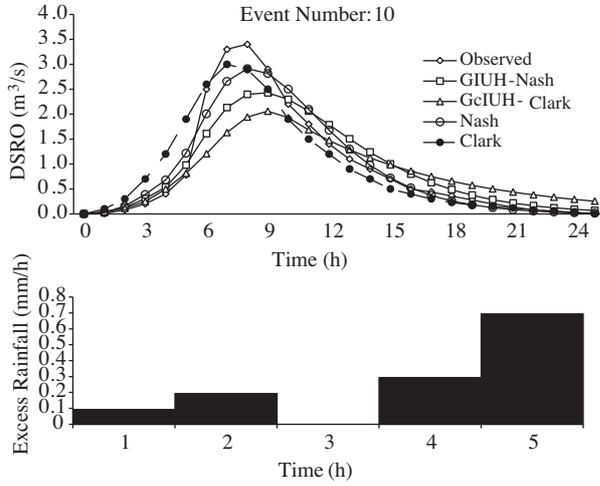
Figure 3. The simulated outlet DSRO hydrographs by the GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models, and observed outlet DSRO hydrograph for storm event 10.
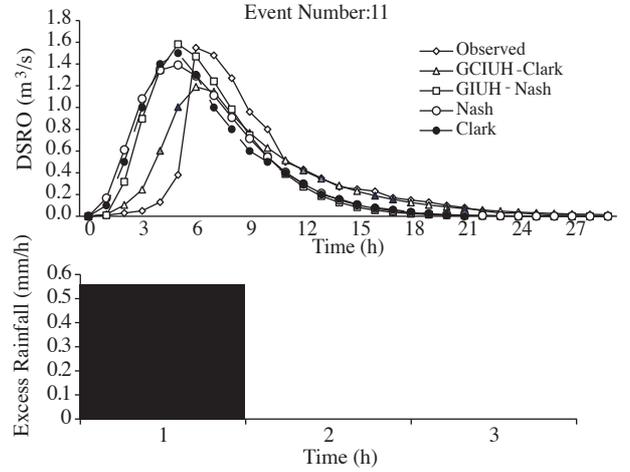
Figure 4. The simulated outlet DSRO hydrographs by the GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models, and observed outlet DSRO hydrograph for storm event 11.

For this purpose, some of the commonly used error functions have been used.

In this study, the following 3 error functions were utilized:

1) Model efficiency

$$EFF = (1 - \frac{\sum\limits_{i=1}^{m}(Q_{oi} - Q_{ci})^2}{\sum\limits_{i=1}^{m}(Q_{oi} - \overline{Q}_o)^2}) \times 100 \tag{9}$$

where EFF is the model efficiency (%), Q_{oi} is ith ordinate of the observed discharge (m^3/s), $\overline{Q}_o$ is the average of the ordinates of the observed discharge (m^3/s), Q_{ci} is the computed discharge (m^3/s), and m is the number of ordinates.

2) Percentage error in peak:

$$PEP = (1 - \frac{Q_{pc}}{Q_{po}}) \times 100 \tag{10}$$

where PEP is the percentage error in peak (%), Q_{po} is the observed peak discharge(m^3/s), and Q_{pc} is the computed peak discharge(m^3/s).
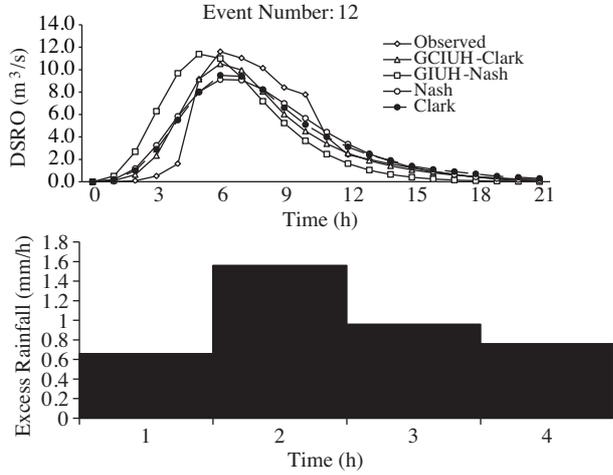
Figure 5. The simulated outlet DSRO hydrographs by the GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models, and observed outlet DSRO hydrograph for storm event 12.
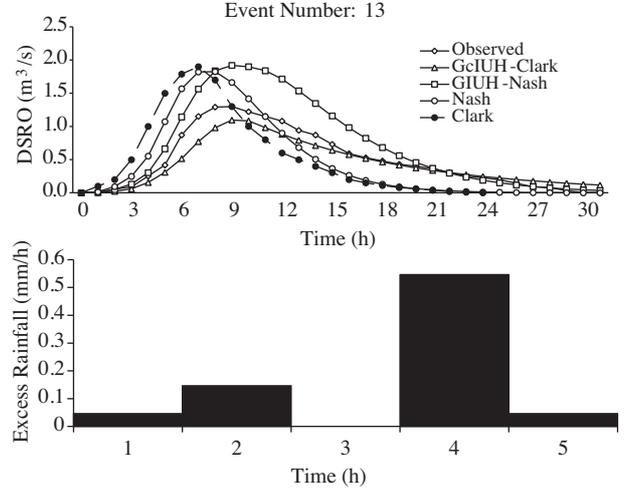
Figure 6. The simulated outlet DSRO hydrographs by the GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models, and observed outlet DSRO hydrograph for storm event 13.
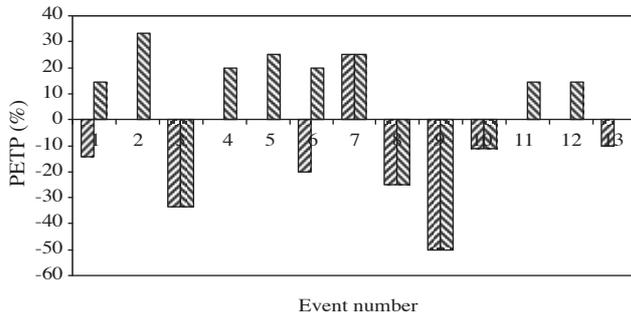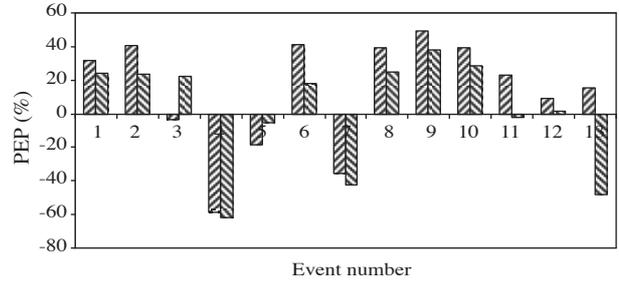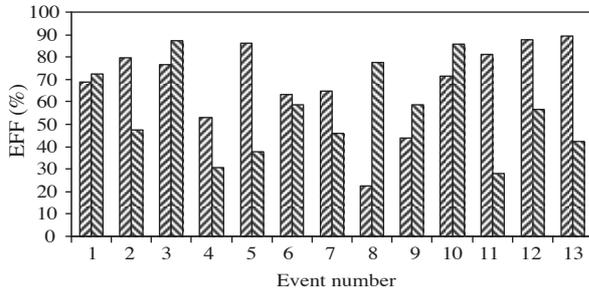
Figure 7. *EFF*, *PEP*, and *PETP* of the GcIUH-Clark and GIUH-Nash models for 13 storm events.

3) Percentage error in time to peak:

$$PETP = (1 - \frac{T_{pc}}{T_{po}}) \times 100 \tag{11}$$

where *PETP* is the percentage error in time to peak (%), T_{po} is the time to peak of observed discharge (h), and T_{pc} is the time to peak of computed discharge (h).

Figures 7 and 8 show the values of the above functions for the 13 and 4 storm events.
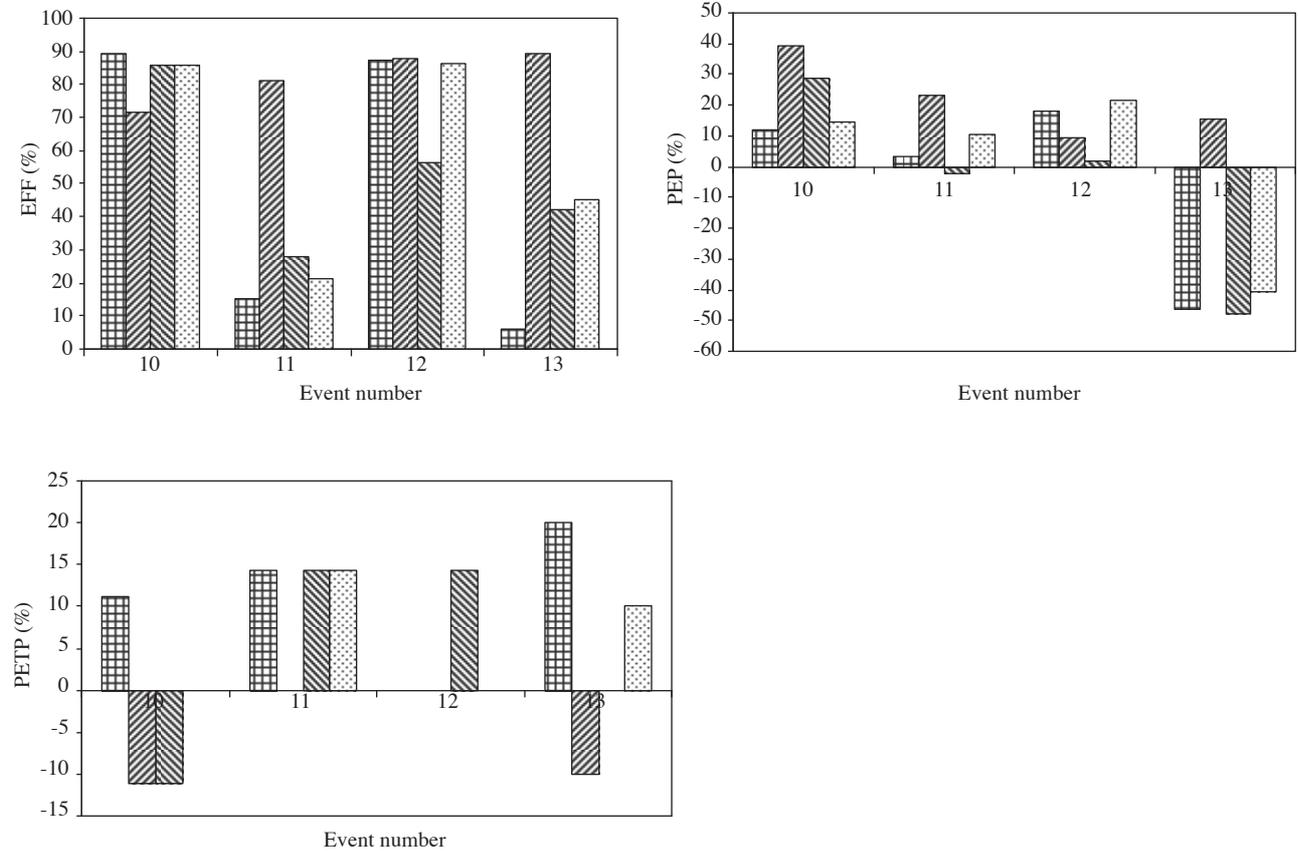
Figure 8. *EFF*, *PEP*, and *PETP* of the GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models for 4 storm events.

Figures 3-6 and Figure 8 show the following results:

1- The GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models were suitable for simulation of the time to peak and the shape of the hydrograph for event 10. However, the GcIUH-Clark model could not simulate the peak discharge of the hydrograph accurately. The Clark-IUH model was the best model for simulation of an outlet DSRO hydrograph for event 10.

2- The GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models were suitable for simulation of the time to peak and the peak discharge of the hydrograph for event 11. The GcIUH-Clark model could simulate the shape of the hydrograph accurately for event 11, while the other models were weak for simulating the shape of the hydrograph for event 11.

3- The GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models were suitable for the simulation of the time to peak, the shape of the hydrograph, and the peak discharge of the hydrograph for event 12. The GcIUH-Clark model was the best model for simulation of the outlet DSRO hydrograph for event 12.

4- The GcIUH-Clark, GIUH-Nash, Clark-IUH, and Nash-IUH models were suitable for the simulation of the time to peak for event 13. However, the GcIUH-Clark model could only simulate the shape of the hydrograph

and the peak discharge of the hydrograph in event 13 exactly.

The mean values of *EFF* for the Nash-IUH, GIUH-Nash, GcIUH-Clark, and Clark-IUH models were 59.68%, 53.06%, 82.39%, and 49.52%, respectively. In addition, the mean values of *PEP* for the Nash-IUH, GIUH-Nash, GcIUH-Clark, and Clark-IUH models were 1.37%, -4.92%, 21.87%, and -3.32%, respectively.

Finally, the mean values of *PETP* for the Nash-IUH, GIUH-Nash, GcIUH-Clark, and Clark-IUH models were 6.07%, 4.37%, -5.28%, and 11.35%, respectively.

Conclusion

The GIUH-Nash and GcIUH-Clark models can properly simulate direct surface runoff hydrographs. Since these models do not require historical rainfall-runoff data, calibration of these models is not necessary. GIUH-Nash and GcIUH-Clark models have widespread application in the field of hydrology.

In this research, the geomorphologic parameters of a watershed were determined by GIS. The kinematic wave parameter was calculated using information obtained from a gauging station in the outlet of the watershed.

The shape parameter of GIUH-Nash, which is a function of the geomorphologic characteristics of a watershed, is constant for different storm events. On the other hand, the scale parameter, which is a function of the geomorphologic characteristics of a watershed and the kinematic velocity parameter in the outlet of the watershed, varies for different storm events.

In the GcIUH-Clark model, the concentration time estimated through a linear relation is a function of the kinematic wave parameter, rainfall characteristics, and the length of the main channel of the watershed. The storage coefficient is a function of geomorphoclimatic characteristics and the time-area diagram. As can be seen from Figure 8, the GIUH-Nash and GcIUH-Clark models can properly simulate the shape, peak discharge, and time to peak of direct surface runoff hydrographs.

The mean of the *EFF* of the GcIUH-Clark model was greater than those of the other models for 3 of 4 storm events. The *EFF* of this model was very high for 4 storm events, while the *EFF* of the Clark-IUH model was very low for 2 storm events.

It was observed that the GcIUH-Clark and GIUH-Nash models can simulate the peak discharge of direct surface runoff hydrographs more accurately than the Nash-IUH or Clark-IUH models, as both models estimate the peak discharge of direct surface runoff hydrographs to be less than the observed peak discharge of direct surface runoff hydrographs.

The GIUH-Nash and GcIUH-Clark models are more accurate than the Nash-IUH or Clark-IUH models for calculation of time to peak. The GIUH-Nash model estimates the time to peak of direct surface runoff hydrographs to be less than the observed time to peak of direct surface runoff hydrographs, while the GcIUH-Clark model estimates the time to peak of direct surface runoff hydrographs to be more than the observed time to peak of direct surface runoff hydrographs.

The GcIUH-Clark model can simulate the shape of direct surface runoff hydrographs better than the GIUH-Nash model, but the GIUH-Nash model can simulate the peak discharge and time to peak of direct surface runoff hydrographs better than the GcIUH-Clark model.

Although the Nash-IUH and Clark-IUH models use historical rainfall-runoff data, they cannot simulate the direct surface runoff hydrographs of some storm events. For example, the Clark-IUH model was not appropriate for simulation of storm events 11 or 13, and the Nash-IUH model was not appropriate for simulation of storm event 10. In contrast, the GcIUH-Clark and GIUH-Nash models can be applied not only in watersheds without rainfall-runoff data, but also in watersheds with historical rainfall-runoff data.

Nomenclature

S	storage of reservoir (MCM)	i_r	excess rainfall intensity (cm/h)
Q	outflow from reservoir (CMS)	α_Ω	kinematic wave parameter for highest-order channel ($\mathrm{s}^{-1}.\mathrm{m}^{-1/3}$)
c	a constant known as *lag* time of reservoir		
$u(t)$	the value of Nash-IUH model in time step t	t_r	duration of excess rainfall (h)
n	shape parameter denoting the number of reservoirs	Q_P	peak discharge of flood (CMS)
		Π_i	geomorphoclimatic parameter (h)
k	scale parameter showing storage coefficient (h)	L	length of the main channel (km)
R_B	bifurcation ratio	EFF	model efficiency (%)
R_A	stream area ratio	Q_{oi}ith	ordinate of the observed discharge (m^3/s)
R_L	stream length ratio	$\overline{Q}_o$	average of the ordinates of observed discharge (m^3/s)
L_Ω	length of the highest order stream (km)		
V	peak flow velocity in watershed outlet (m/s)	Q_{ci}	computed discharge (m^3/s)
t_p	time to peak (h)	m	number of ordinates
T_C	time of concentration (h)	PEP	percentage error in peak (%)
R	storage coefficient (h)	Q_{po}	observed peak discharge (m^3/s)
$u_i$ith	ordinate of the IUH	Q_{pc}	computed peak discharge (m^3/s)
Δt	computational time interval (h)	$PETP$	percentage error in time to peak (%)
$I_i$ith	ordinate of the time-area diagram	T_{po}	time to peak of observed discharge (h)
A_Ω	watershed area (km^2)	T_{pc}	time to peak of computed discharge (h)

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