Evaluation of the Velocity Parameter Estimation Methods in a Geomorphological Instantaneous Unit Hydrograph (GIUH) Model for Simulating Flood Hydrograph in Ungauged Catchments

Water Resources Management

Grum, B.; Abebe, B.A.; Degu, A.M.; Goitom, H.; Woldearegay, K. et al

https://doi.org/10.1007/s11269-022-03360-5

Water Resources Management (2023) 37:157–173
https://doi.org/10.1007/s11269-022-03360-5

Evaluation of the Velocity Parameter Estimation Methods in a Geomorphological Instantaneous Unit Hydrograph (GIUH) Model for Simulating Flood Hydrograph in Ungauged Catchments

B. Grum[1] · B. A. Abebe[1] · A. M. Degu[1] · H. Goitom[1] · K. Woldearegay[2] · R. Hessel[3] · C. J. Ritsema[4] · V. Geissen[4]

Received: 25 February 2021 / Accepted: 8 October 2022 / Published online: 21 December 2022

Abstract

Runoff data is crucial for development of water resources. Runoff data is however rarely available for ungauged catchments, especially in developing countries. Geomorphological instantaneous unit hydrographs (GIUH) models can be used for predicting runoff in poorly gauged catchments, but a challenge with these models is estimating the dynamic velocity parameter. In this study, three GIUH models were developed based on estimation of flow velocity using calibration of Manning's *n* (GIUH-cal), peak discharge (GIUH-pq) and 30-min rain intensity (GIUH-I30). The objectives of this study were to (a) assess suitability of a GIUH model for simulating runoff in Gule catchment, northern Ethiopia and (b) evaluate performance of three velocity parameter estimation methods in simulating runoff using GIUH models. Runoff hydrographs of the GIUH models matched well with observed hygrographs for most rain events. The GIUH-cal model had the best performance, 18 out of 20 rain events resulting in Nash–Sutcliffe model efficiency (NSE) values of 0.53 to 0.95. The GIUH-pq and GIUH-I30 models performed satisfactorily with 12 of the 20 rain events resulting in NSE values greater than 0.50. Overall, the GIUH models underestimated peak discharge compared to observed data. The GIUH models were moderately sensitive to changes in flow velocity. Peak discharge and time to peak discharge were highly sensitive to changes in flow velocity. The developed GIUH models could be used for simulating flood hydrographs of the Gule catchment. Particularly, the GIUH-I30 model will be very useful for estimating direct surface runoff in the absence of streamflow data.

Keywords Direct surface runoff · Flood hydrograph · Geomorphological instantaneous unit hydrograph (GIUH) · Northern Ethiopia · Velocity parameter

✉ B. Grum
berhanegr@gmail.com

Extended author information available on the last page of the article

1 Introduction

Runoff data is necessary for planning, development and management of water resources. Runoff should literally be obtained from streamflow measurements at catchment outlets. Many small and medium size catchments in developing countries are however rarely gauged hence runoff data is not readily available (Kumar et al. 2007; Gunawardhana et al. 2020). Among several empirical methods, the synthetic unit hydrograph (SUH) approach is commonly used to estimate direct surface runoff (DSRO) for ungauged catchments. Although SUH methods such as the Snyder (1938) and Soil Conservation Service (1957) are widely applied for estimating DSRO in ungauged catchments, results from these methods have so far been inconsistent (Singh et al. 2014; Niyazi et al. 2021). Moreover, model parameters of these methods need to be updated from time to time because of changing land use and climatic conditions of catchments (Sahoo et al. 2006; Kumar et al. 2007).

The geomorphologic instantaneous unit hydrograph (GIUH), introduced by Rodriguez-Iturbe and Valdes (1979), has evolved in the past 30+years and is considered a promising option for estimating DSRO for ungauged catchments (Bhadra et al. 2008; Singh et al. 2014). The GIUH method integrates hydrologic systems with quantitative geomorphological and climatic characteristics to predict DSRO responses from catchments. Since its development, the concept of GIUH has been improved over the years (e.g., Gupta et al. 1980; Rodriguez-Iturbe et al. 1982; Chutha and Dooge 1990; Rinaldo and Rodriguez-Iturbe 1996; Shamseldin and Nash 1998; Cudennec et al. 2004; Rigon et al. 2016). The applicability of the GIUH model was evaluated in various hydro-climatic and geomorphologic settings. It has been commonly used for simulating hydrologic responses of arid and semi-arid catchments (e.g., Bhadra et al. 2008; Nourani et al. 2009; Khaleghi et al. 2011; Ghumman et al. 2012; Jaiswal et al. 2014; Niyazi et al. 2021). Recent studies show that a GIUH can also be applied for simulating runoff hydrograph in humid climates (e.g., Kumar 2015; Hosseini et al. 2016; Chen et al. 2019). Kumar et al. (2007) successfully applied Clark and Nash based GIUH models for simulating DSRO hydrograph for the ungauged Ajay catchment, eastern India. A study by Bhadra et al. (2008) showed that a GIUH model can satisfactorily be applied for estimating DSRO response in scantily gauged catchments. Ghumman et al. (2012) simulated DSRO for a large catchment in Pakistan using a GIUH model which resulted in a Nash–Sutcliffe model efficiency of more than 90%. Recently, Babaali et al. (2021) adapted a GIUH model for predicting subsurface flow hydrographs of two catchments in Taiwan.

One of the most difficult tasks in the derivation of a GIUH model is estimation of the velocity parameter (Kumar et al. 2007). Flow velocity is an important parameter for determining peak discharge and time to peak discharge in a GIUH model. In the earlier times of the GIUH development, the velocity parameter was recommended to be estimated by mean velocity of flow (Rodriguez-Iturbe and Valdes 1979) or flow velocity at peak discharge (Rodriguez-Iturbe et al. 1979). Furthermore, Rodriguez-Iturbe et al. (1982) suggested the use of basin geomorphological parameters and rainfall characteristics for estimating the velocity parameter. As a result, several researchers tried to estimate the velocity parameter by formulating a correlation between flow velocity and effective rain intensity (e.g., Bhaskar et al. 1997; Sahoo et al. 2006; Kumar 2015). Zelazinski (1986) proposed the use of peak discharge to estimate the velocity parameter in the GIUH model. Other researchers (e.g., Khaleghi et al. 2011; Ghumman et al. 2012) also applied a similar approach to determine the velocity parameter in their GIUH models. Al-Wagdany and Rao (1997) investigated the relationship between the velocity parameter and climatic as well as basin geomorphologic parameters. Recently, Chen et al. (2019) developed a multi-variate regression model to estimate flow velocity using geomorphologic factors from 120 catchments in the Yangtze River basin in China.

Despite all these efforts, it still remains to be a complicated task to select a reasonable value of the velocity parameter for simulating DSRO in a GIUH model (Kumar et al. 2007; Tarahi et al. 2021). This necessitates evaluation of different flow velocity estimation methods in a GIUH model. This study undertakes a comparative performance evaluation of three GIUH models which were developed based on estimation of the velocity parameters using calibration of Manning's *n*, peak discharge and 30-min rain intensity. The GIUH models were applied in a 12 km^2 catchment located in northern Ethiopia. Therefore, the objectives of this study were to (a) assess the suitability of a GIUH model for simulating DSRO in Gule catchment, northern Ethiopia and (b) evaluate the performance of three velocity parameter estimation methods in simulating runoff using GIUH models.

2 Materials and Methods

2.1 Study Area

The GIUH model was applied for simulating flood hydrograph of Gule catchment located in northern Ethiopia (Fig. 1). Gule catchment has a drainage area of about 12 km^2 and lies between 13°51′59″ to 13°54′40″N and 39°27′16″ to 39°29′49″E. Gule is part of the upper Geba catchment and drains to Tekeze river basin (Fig. 1). The study area has a rugged and mountainous topography whose altitude ranges between 2008 and 2408 m a.s.l.

Gule catchment has a semi-arid climate with rainy season occurring in the months of June to September. The dry season occurs from October to May and is characterized by no rain or some showers of rain towards the start of the rainy season. Average annual rainfall for the study area is about 465 mm (Grum et al. 2017). The study area has a tropical climate, in which average daily temperature ranges between 15 and 25 °C. The land use of Gule catchment is dominantly cultivated and shrub lands, with small patches of grass and wood lands. The catchment is also managed with several rain water harvesting techniques such as stone terraces, check dams, deep trenches and percolation ponds (Fig. 1). Rain harvested in the different water harvesting structures is used for domestic water supply and irrigation.

2.2 Geomorphological Characteristics

Geomorphological and climatic characteristics of a catchment are essential elements in the development of a GIUH model. The geomorphological properties for this study were generated from a digital elevation model of 30 × 30 (ASTER 2009) using ArcGIS 10.2.1. Stream order analysis was carried out in ArcGIS based on the Strahler's ordering system (Strahler 1957) as described in Hydrology of the Spatial Analyst Tools. Description about existing stream orders in the drainage network, number, mean and total length of each stream order in Gule catchment is summarized in Table 1.

Based on the results of stream order analysis, drainage network of Gule catchment (Fig. 2) was classified into four stream orders. The highest number ($n = 30$) of stream segments was observed for stream order 1 (Table 1). The length of the highest stream order (L_Ω), which belonged to stream order 4, is 1.75 km.

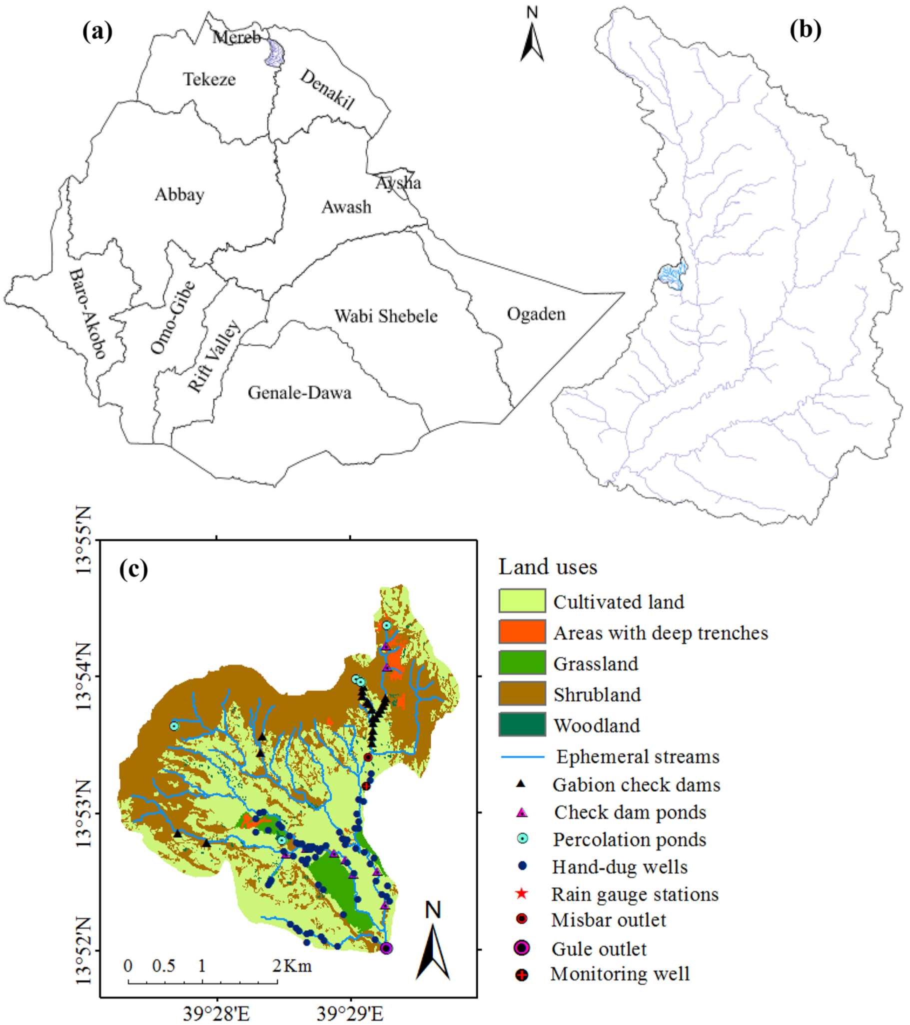

Fig. 1 Location map of study area **a** river basins of Ethiopia and location of upper Geba in Tekeze river basin **b** location of Gule in upper Geba catchment **c** land uses of Gule catchment

The stream area ratio (R_A) was determined by dividing the drainage area of a given stream order to the drainage area of all lower stream orders. The bifurcation ratio (R_B), was computed by dividing the number of stream segments of a given stream order to the number of

Table 1 Details of number, length and mean area of stream orders in Gule catchment

Stream order	Number	Total length (km)	Mean length (km)	Mean area (km^2)
1	30	36.8	0.90	0.20
2	7	10.00	1.42	1.50
3	3	5.20	1.70	3.60
4	1	1.75	1.75	11.60

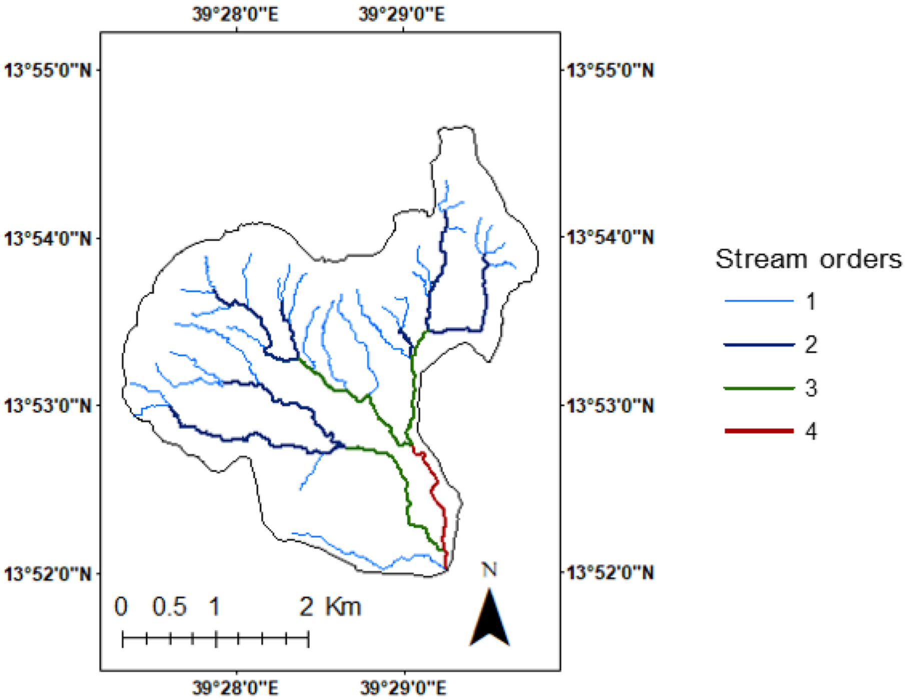

Fig. 2 Stream order of Gule Catchment after Strahler (1957)

stream segments of next higher stream order. Similarly, the stream length ratio (R_L) was calculated by dividing the mean length of a given stream order to the mean length of next lower stream order. The computed R_A, R_B and R_L values for Gule catchment are 4.03, 3.25 and 1.46, respectively.

2.3 The Geomorphological Instantaneous Unit Hydrograph (GIUH) Model

A GIUH model uses geomorphological characteristics to simulate DSRO from a catchment. The GIUH model development utilizes parameters of the Horton's order laws of drainage network composition and Strahler's stream ordering. Hence, the GIUH model is expressed in terms of peak discharge (q_p) and time to peak (t_p) discharge of a rainfall-runoff event.

$$q_p = 1.31 \times R_L^{0.43} \times \frac{V}{L_\Omega} \tag{1}$$

$$t_p = 0.44 \times \frac{L_\Omega}{V} \times \left(\frac{R_B}{R_A}\right)^{0.55} \times \left(R_L\right)^{-0.38} \tag{2}$$

where q_p is peak flow in hr^{-1}, t_p is time to peak in hr, R_B, R_L, and R_A are Horton's bifurcation, length and area ratios of stream numbers respectively, L_Ω is length of the highest stream order in km, and V is velocity parameter in m s^{-1}.

The Nash model (Nash 1957) can be used to derive an instantaneous unit hydrograph (IUH) by the concept of series of n reservoirs and storage coefficient (K).

$$u(\mathrm{t}) = \frac{1}{K \times \Gamma(n)} \times \left(\frac{t}{K}\right)^{n-1} \times e^{-t/K} \tag{3}$$

where, u(t) is ordinate of the IUH in hr^{-1}, t is time in hr, $\Gamma(n)$ is partial gamma function, n and K are Nash's shape and scale parameters, respectively.

According to Kumar et al. (2007), a complete shape of the hydrograph can be produced by linking q_p and t_p to Nash's n and K.

$$n = 3.29 \times \left(\frac{R_B}{R_A}\right)^{0.78} \times R_L{}^{0.07} \tag{4}$$

$$K = \frac{0.44 \times L_\Omega}{V} \times \left(\frac{R_B}{R_A}\right)^{0.55} \times R_L{}^{-0.38} \times \frac{1}{n-1} \tag{5}$$

2.4 Estimation of the Velocity Parameter

Flow velocity is an important parameter in the development of a GIUH model. Rodriguez-Iturbe et al. (1982) related the velocity parameter with geomorphology of a catchment and effective rain intensity (Eq. (6)).

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

where V is velocity parameter in m s^{-1}, A_Ω is area of the largest stream order in km^2, i_r is effective rain intensity in cm h^{-1}.

The kinematic wave parameter of the highest order (α_Ω) for a rectangular channel is estimated using Eq. (7).

$$\alpha_\Omega = \frac{S^{1/2}}{n \times b^{2/3}} \tag{7}$$

where S is slope, b is width, n is the Manning's roughness coefficient of a channel.

If discharge measurements are available, the velocity parameter, V can be estimated using the method (Eq. (8)) proposed by Zelazinski (1986).

$$V = \alpha \times \left(Q_{max}\right)^{\beta} \tag{8}$$

where $Q_{\max}$ is peak flow of a rain event, α and β are parameters derived from discharge measurements at outlet of a catchment.

2.5 Model Performance Evaluation

The overall performance of DSRO hydrographs simulated using GIUH models was evaluated by the Nash–Sutcliffe model efficiency (NSE) coefficient (Nash and Sutcliffe 1970), percentage error in peak (PER_p) discharge and percentage error in time to peak (PER_{tp}) discharge.

$$NSE = 1 - \frac{\sum_i^n \left(Q_{oi} - Q_{si}\right)^2}{\sum_i^n \left(Q_{oi} - \overline{Q}_o\right)^2} \tag{9}$$

where Q_{oi} is observed discharge for the i^{th} ordinate, $\overline{Q}_o$ is average of observed discharge and Q_{si} is simulated discharge for the i^{th} ordinate.

$$PER_p = \frac{Q_{op} - Q_{sp}}{Q_{op}} \times 100 \tag{10}$$

where, Q_{op} is observed peak discharge, Q_{sp} is simulated peak discharge.

$$PER_{tp} = \frac{T_{op} - T_{sp}}{T_{op}} \times 100 \tag{11}$$

where, T_{op} is observed time to peak discharge, T_{sp} is simulated time to peak discharge.

Sensitivity of the overall model performance, peak discharge and time to peak discharge was evaluated using the sensitivity index (*SI*) proposed by Lenhart et al. (2002), as described in Eq. (12).

$$SI = \frac{\left(y_2 - y_1\right)/y_0}{2\Delta x/x_0} \tag{12}$$

where *SI* is sensitivity index, y_0 is initial model output, x_0 is initial parameter value, y_1 and y_2 are model outputs at x_0-Δx and $x_0 + \Delta x$, respectively.

According to Lenhart et al. (2002), the *SI* classes are small to negligible ($0 \leq SI < 0.05$), medium ($0.05 \leq SI < 0.20$), high ($0.20 \leq SI < 1.0$) and very high ($SI \geq 1.0$).

3 Results and Discussion

3.1 Estimation of the Velocity Parameter

Estimation of the velocity parameter using the method proposed by Zelazinski (1986) resulted in a very good agreement ($r^2 = 0.90$) of velocity with measured peak discharge at the catchment outlet (Fig. 3). Similarly, a good fit ($r^2 = 0.61$) was obtained for a linear relationship between observed velocity and 30-min rain intensity (I30) as shown in Fig. 4. These results show that both peak discharge and I30 could be used for estimating the velocity parameter of a GIUH model for Gule catchment.

Estimation of flow velocity using measured peak discharge is highly dependent on the availability of discharge data at a catchment outlet (Al-Wagdany and Rao 1997). Hence, the applicability of peak discharge for estimating flow velocity is quite limited because streamflow data are not readily available for ungauged catchments. In the absence of streamflow data, climatic and geomorphological characteristics of a catchment can be useful for estimating velocity parameter in a GIUH model (Rodriguez-Iturbe et al. 1982; Al-Wagdany and Rao 1997).

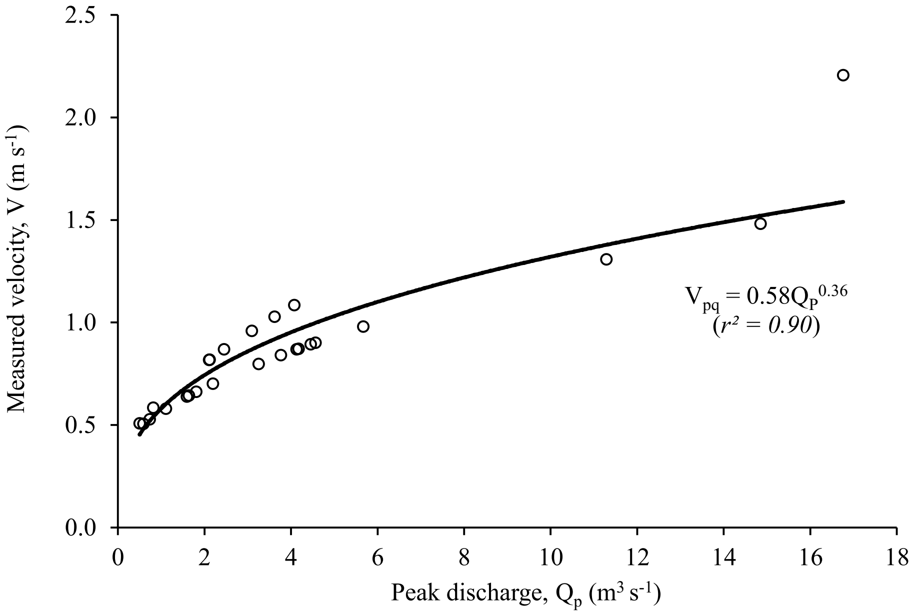

Fig. 3 Flow velocity estimation using measured peak discharge

3.2 Evaluation of the GIUH Models

Results for flow velocity (V), storage coefficient (K), peak discharge (Q_p) and time to peak (t_p) discharge of three GIUH models are summarized in Table 2. The GIUH models were

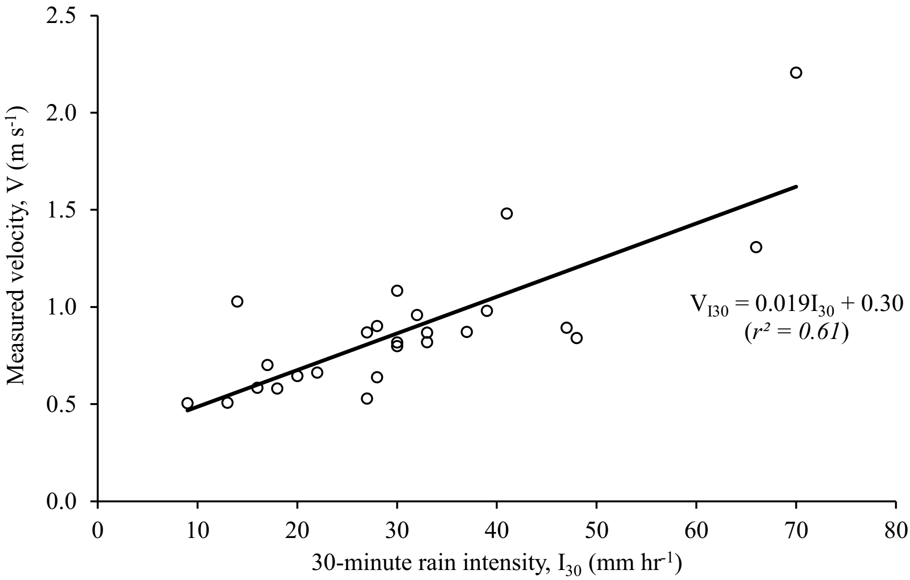

Fig. 4 Flow velocity estimation using 30-min rain intensity (I30)

Table 2 Velocity (V, m s^{-1}), storage coefficient (K), peak discharge (q_p, m^3 s^{-1}) and time to peak (t_p, hr) discharge descriptions of the GIUH models

Event	GIUH-cal[a]				GIUH-pq[b]				GIUH-I30[c]			
	V	K	q_p	t_p	V	K	q_p	t_p	V	K	q_p	t_p
090714	0.50	0.67	0.35	1.25	0.52	0.64	0.37	1.17	0.81	0.41	0.57	1.17
300714	0.88	0.38	4.37	0.67	1.08	0.31	5.82	0.58	1.03	0.32	5.56	0.58
030814	0.95	0.35	2.01	0.67	0.93	0.36	1.96	0.67	1.20	0.28	2.53	0.50
050814	0.79	0.42	5.92	0.75	1.38	0.24	10.32	0.42	1.54	0.22	11.53	0.42
160814	0.83	0.51	0.97	0.92	0.69	0.51	0.98	0.92	0.83	0.40	1.25	0.75
180814	0.95	0.35	4.00	0.67	1.00	0.33	4.21	0.58	0.83	0.40	3.50	0.75
290814	0.85	0.39	3.39	0.75	0.96	0.35	3.82	0.67	0.92	0.36	3.67	0.67
310814	0.68	0.49	1.11	0.92	0.72	0.46	1.18	0.83	0.71	0.47	1.16	0.83
030914	0.65	0.51	1.07	0.92	0.69	0.48	1.13	0.92	0.68	0.49	1.12	0.92
060914	0.66	0.50	0.62	0.92	0.60	0.55	0.56	1.00	0.64	0.51	0.61	0.92
070914	0.81	0.41	1.51	0.75	0.77	0.43	1.44	0.83	0.62	0.54	1.16	1.00
100914	0.65	0.51	2.12	0.92	0.99	0.34	3.24	0.58	1.19	0.28	3.94	0.59
110715	0.36	0.82	1.34	1.50	0.76	0.44	2.49	0.83	0.86	0.39	2.82	0.75
230715	0.61	0.54	1.14	0.83	0.76	0.44	1.42	0.83	0.92	0.36	1.73	0.67
240715	1.11	0.3	10.41	0.42	1.59	0.21	14.83	0.42	1.62	0.21	15.06	0.42
290715	0.59	0.62	1.38	1.00	0.92	0.36	2.37	0.67	0.56	0.59	1.44	1.08
020815	0.73	0.45	0.69	0.83	0.54	0.62	0.51	1.17	0.60	0.55	0.56	1.00
030815	0.49	0.68	1.03	1.17	0.80	0.42	1.69	0.75	0.81	0.41	1.71	0.75
140815	0.45	0.73	1.06	1.33	0.96	0.35	2.25	0.67	0.86	0.39	2.01	0.75
150815	0.73	0.45	1.89	0.83	0.87	0.38	2.24	0.67	0.90	0.37	2.32	0.67

[a] Velocity calculated from calibration of Manning's n

[b] Velocity calculated using measured peak discharge

[c] Velocity calculated from linear relationship between velocity and 30-min rain intensity (I30)

developed based on estimation of flow velocity using calibration of Manning's *n* (GIUH-cal), peak discharge (GIUH-pq) and 30-min rain intensity (GIUH-I30).

Evaluation of the three GIUH models using observed discharge for 20 rain events at Gule outlet showed good performance for most of the events (Table 3). Out of the three GIUH models, the GIUH-cal had the best performance, 18 out of 20 events resulting in NSE values which ranged between 0.53 and 0.95. The remaining two events, 020815 and 140815 resulted in NSE values of 0.47 and 0.42 respectively. Model performance for GIUH-cal was quite similar to results obtained from the physically-based Limburg Soil Erosion Model (LISEM) as shown in Table 3. For GIUH-pq, 12 out of 20 events resulted in good model performance, whose NSE values ranged between 0.54 and 0.9. Similar model performance was also observed in the GIUH-I30 model, 12 of the 20 events resulting in NSE values which ranged between 0.5 and 0.92.

The observed and simulated DSRO hydrographs matched well for the GIUH and LISEM models for most rain events (Fig. 5). In most cases, there is good resemblance in the overall shape of the hydrographs between GIUH models and observed discharge. Overall, the GIUH models underestimated peak discharge compared to observed data. Similar results were also obtained in other GIUH simulations (Gupta et al. 1980; Kumar 2015;

Table 3 Model performance evaluation of the GIUH and LISEM models. NSE: Nash–Sutcliffe efficiency, PER: percentage error

Event	GIUH-cal			GIUH-pq			GIUH-I30			LISEM		
	NSE	PERp	PERtp	NSE	PERp	PERtp	NSE	PERp	PERtp	NSE	PERp	PERtp
090714	0.72	50.9	–6.8	0.71	48.7	0.0	0.35	20.0	0.0	0.66	0.4	3.8
300714	0.95	16.0	33.0	0.83	–2.8	42.0	0.88	1.9	42.0	0.83	–5.8	29.2
030814	0.83	45.4	–15.5	0.83	46.7	–15.5	0.72	31.3	13.8	0.77	19.1	–53.7
050814	0.77	47.2	18.5	0.16	7.9	54.3	–0.10	–2.9	54.3	0.80	–6.2	–28.6
160814	0.85	22.0	8.0	0.85	35.7	8.0	0.73	17.8	25.0	0.89	–9.6	5.8
180814	0.87	29.4	33.0	0.86	25.6	41.7	0.86	38.2	25.0	0.80	30.4	23.3
290814	0.93	16.6	–28.6	0.91	6.1	–14.9	0.92	9.8	–14.9	0.54	–10.6	–54.4
310814	0.83	36.6	8.0	0.81	32.7	16.7	0.82	33.7	16.7	0.90	19.7	18.7
030914	0.81	32.8	21.4	0.79	28.9	21.4	0.80	29.9	21.4	0.63	8.9	21.7
060914	0.85	41.0	30.8	0.84	46.6	24.8	0.85	42.2	30.8	0.74	4.2	33.6
070914	0.89	29.3	35.9	0.89	32.6	28.8	0.77	45.6	14.5	0.83	17.2	24.5
100914	0.59	52.1	21.7	0.02	26.7	50.2	–0.50	10.6	49.6	0.83	14.1	–9.7
110715	0.66	43.3	–33.3	–1.30	–20.0	33.3	–2.00	–35.6	40.0	0.76	15.7	–34.0
230715	0.84	45.0	24.8	0.77	31.5	37.6	0.50	17.0	49.6	0.51	25.0	19.2
240715	0.79	20.1	0.0	0.46	37.7	27.6	0.43	9.9	27.6	0.94	–10.1	–37.9
290715	0.53	57.1	7.4	0.03	33.2	38.0	0.53	59.3	0.0	0.48	52.4	–41.2
020815	0.47	8.9	–43.1	0.38	32.9	–101.7	0.42	25.4	–72.4	0.39	–7.6	–14.9
030815	0.59	56.6	25.1	0.05	29.1	55.1	0.02	28.2	55.1	0.82	–0.8	9.7
140815	0.42	73.6	24.0	–0.37	44.3	61.7	–0.16	50.2	57.1	0.63	–3.5	–9.0
150815	0.62	37.9	9.8	0.54	26.4	27.2	0.51	23.7	27.2	0.74	23.4	4.9
/Mean/		38.1	21.4		29.8	35.0		26.7	31.9		14.2	23.9

Hosseini et al. 2016). The hydrographs of the GIUH models also indicate an early rise of discharge and relatively shorter time to peak discharge compared to the observed hydrographs (Fig. 5).The failure of the GIUH models to reproduce DSRO hydrographs could be due to an error introduced by assuming a constant infiltration rate to calculate effective rain intensity (Bhaskar et al. 1997). Overall, there is also non-linearity of rainfall-runoff transformation processes in mountainous catchments (Kumar 2015) such as this study area.

The absolute mean PER_p values for GIUH-I30, GIUH-pq and GIUH-cal models were 26.7, 29.8 and 38.1%, respectively. In terms of the PER_p, LISEM had the lowest error with absolute mean value of 14.2%. Out of the three GIUH models, GIUH-cal has the lowest PER_{tp}. Absolute mean PER_{tp} values were 21.4, 31.9, and 35.0% for the GIUH-cal, GIUH-I30 and GIUH-pq models, respectively. The PER_{tp} value for LISEM was 23.9%, which is in similar order with the GIUH models.

Overall evaluation of the GIUH models showed that GIUH-cal performed as good as the physically-based LISEM model. However, the GIUH-cal model tends to underestimate peak discharge compared to LISEM. The better performance of the GIUH-cal compared to the GIUH-pq and GIUH-I30 models is most likely attributed to calibration of Manning's *n* with measured discharge. Moreover, the simultaneous consideration of geomorphological properties of a catchment and calibration of model parameters equips GIUH models with the capacity to properly simulate DSRO hydrographs (Nourani et al. 2009).

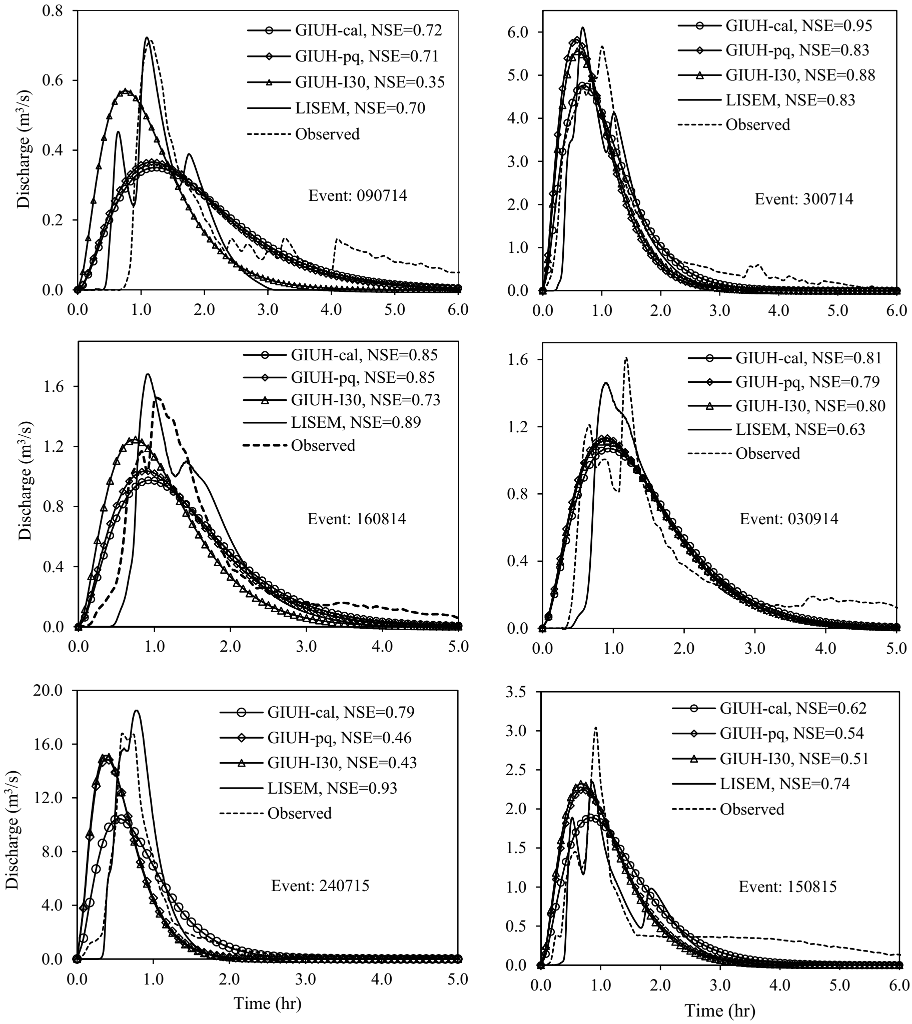

Fig. 5 Comparison of observed and simulated DSRO hydrographs of different GIUH models

The GIUH-pq and GIUH-I30 models had relatively lower performances in simulating DSRO compared to GIUH-cal and LISEM. This was expected as these two models were developed from regression relationship between flow velocity and peak discharge and I30 for the GIUH-pq and GIUH-I30 models, respectively. On the other hand, the three GIUH models and LISEM had similar performance for PER_p and PER_{tp}, except that LISEM outperformed the other models with lower PER_p.

The limitation with the GIUH-cal and GIUH-pq models is that they require discharge measurements for estimating flow velocity. The applicability of any GIUH model which depends on estimation of flow velocity using measured discharge becomes limited for ungauged catchments (Hosseini et al. 2016). It is therefore advantageous to utilize GIUH models which do not require measured discharge for runoff simulation (Al-Wagdany and

Rao 1997; Kumar 2015). The GIUH-I30 model does not need measured streamflow data. Hence, it can be used for simulating DSRO hydrograph when rain intensity is available.

This study and other researchers (e.g., Kumar et al. 2007; Khaleghi et al. 2011; Chen et al. 2019) demonstrate the applicability of GIUH models for simulating DSRO hydrograph in small and medium size catchments. For large catchments, however, soil properties and land cover become very important in addition to geomorphological and climatic conditions. There are recent attempts (e.g., Lee and Chang 2005; Babaali et al. 2021) to incorporate subsurface flow into a GIUH model so that the effects of land cover and soil properties on infiltration is reflected in the developed hydrographs.

3.3 Sensitivity Analysis

Keeping the geomorphologic and meteorological parameters constant, flow velocity was varied from -20% to + 20% of the calibrated velocity values in the GIUH-cal model. The sensitivity analysis result showed that overall performance of the calibrated GIUH model was moderately sensitive to changes in velocity with *SI* of 0.15 (Table 4). Overall, the GIUH model performance decreased when the magnitude of velocity was varied between -20% and + 20% (Fig. 6). The change in NSE values ranged between 5.6 and 20.2%, with mean value of 12.3, when velocity was increased by 20%. On the other hand, the change in NSE values ranged between 2.1 and 12.5%, with mean value of 7.5, when velocity was decreased by 20%. This shows that the overall performance of GIUH models seems

Table 4 Model sensitivity analysis to flow velocity for different rain events

Event	Velocity, V	Peak discharge, q_p	Time to peak discharge, t_p	Nash–Sutcliffe efficiency, NSE	Sensitivity index, SI		
					q_p	t_p	NSE
90714	0.40	0.35	1.5	0.68	1.00	–0.84	–0.03
300714	0.71	4.76	0.83	0.9	0.98	–0.91	–0.13
30814	0.76	2.01	0.83	0.78	0.99	–1.23	–0.06
50814	0.63	5.92	1.0	0.70	1.00	–1.11	0.04
160814	0.52	0.97	1.17	0.78	1.00	–1.14	0.02
180814	0.76	4.00	0.83	0.83	0.99	–1.24	–0.10
290814	0.74	3.67	0.83	0.90	0.99	–0.93	–0.29
310814	0.54	1.11	1.17	0.78	1.00	–1.13	–0.18
30914	0.52	1.07	1.17	0.75	1.00	–1.13	–0.18
60914	0.53	0.62	1.17	0.78	1.00	–1.13	0.01
70914	0.65	1.51	0.92	0.80	0.99	–0.84	0.07
100914	0.52	2.12	1.17	0.56	0.99	–1.39	–0.43
110715	0.29	1.18	2.17	0.61	1.00	–1.13	–0.30
230715	0.49	1.14	1.25	0.74	1.00	–1.05	0.17
240715	0.89	10.41	0.67	0.75	0.98	–1.06	–0.18
290715	0.47	1.52	1.25	0.48	1.00	–1.04	–0.34
20815	0.59	0.69	1.08	0.42	1.00	–1.26	–0.26
30815	0.39	1.03	1.58	0.53	1.00	–1.17	–0.10
140815	0.36	1.06	1.67	0.38	1.00	–1.10	–0.02
150815	0.59	1.89	1.08	0.56	1.00	–1.26	–0.12
/Mean/					0.995	1.100	0.150

to be not significantly affected by changes in flow velocity. Comparatively, an increase in flow velocity seems to have slightly higher impact on model performance compared to a decrease in flow velocity.

Peak discharge was highly sensitive to changes in velocity with a *SI* close to 1. The positive *SI* values of peak discharge for all rain events shows a co-directional response of peak discharge to changes in velocity. Time to peak discharge was very highly sensitive to changes in velocity with *SI* value slightly greater than 1.0. Negative *SI* values for time to peak discharge indicate an inverse response of time to peak to changes in velocity.

When flow velocity was increased, the DSRO hydrograph shifted to the left shortening time to peak discharge as well as increasing peak discharge for all events (Fig. 6). An increase in velocity tends to quickly flatten the falling limb of the DSRO hydrograph. On the other hand, the DSRO hydrograph shifted to the right elongating time to peak discharge and decreasing peak discharge when velocity was decreased. Furthermore, a decrease in velocity caused a rise in the ordinates of the falling limb of the DSRO hydrograph resulting in longer duration of DSRO.

The findings of this study indicated that hydrograph of a GIUH model is highly influenced by changes in flow velocity. This result is in agreement with a study by Khaleghi et al. (2011). Khaleghi et al. (2011) indicated that there is a significant change in timing and magnitude of peak discharge of a GIUH model when velocity was varied between 50 and 200%. The increase in magnitude of peak discharge when velocity is increased is most

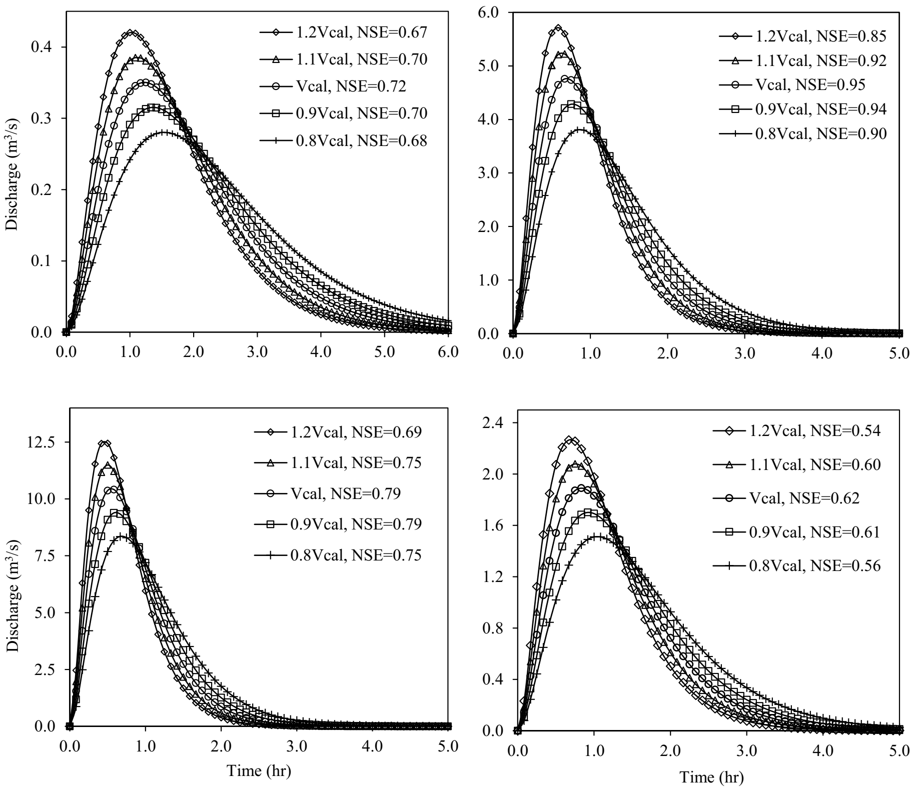

Fig. 6 Sensitivity of the calibrated GIUH model to changes in flow velocity

likely attributed to the shortening of travel time of water flow. This is reflected by the shortening of time to peak discharge in the DSRO hydrographs (Fig. 6). Similarly, the widening of DSRO hydrographs of the GIUH models when velocity is decreased could be due to the lowering of peak discharge values and delay in travel time of water flow.

This study highlights the performance of three velocity parameter estimation methods in GIUH models. Moreover, the developed GIUH models will be applicable for designing rain water harvesting and flood control structures in Gule and other similar ungauged catchments. Particularly, the GIUH-I30 model will be very useful as it does not require measured streamflow data. As noted by Kumar et al. (2007) small and medium size catchments are poorly gauged for streamflow especially in developing countries such as Ethiopia.

4 Conclusion

The geomorphological instantaneous unit hydrograph (GIUH) model was found to be a viable option for determining direct surface runoff (DSRO) in Gule catchment, northern Ethiopia. This is based on the result obtained by comparison of GIUH models both with observed hydrograph and a physically-based Limburg Soil Erosion Model (LISEM). Furthermore, the following conclusions can be drawn from the findings of this study.

- The GIUH model derived from calibration of Manning's *n* has performed better in simulating DSRO hydrograph compared to the GIUH models developed from measured peak discharge and 30-min rain intensity.
- A satisfactory performance of the GIUH-I30 model for most rain events in Gule catchment indicates that a GIUH model can be used for simulating DSRO when discharge measurements are missing for a catchment.
- The GIUH models underestimated peak discharge compared to observed data.
- The highly sensitive response of peak discharge to changes in flow velocity reveals that an appropriate method need to be used to determine the dynamic velocity parameter of a GIUH model.

Acknowledgements We are thankful to the European Union for financing this study via the European Union's Seventh Framework Program (FP7/2007-2013) under grant agreement n° 265570 (WAHARA project), and Mekelle University for providing logistic support during the field measurements.

Authors' Contributions [B. Grum], [B. A. Abebe], [A. M. Degu], [H. Goitom], [K. Woldearegay], [R. Hessel], [C. J. Ritsema] and [V. Geissen] contributed to the study conception and design. Material preparation and data collection was performed by [B. Grum]. Data analysis was performed by [B. Grum], [B. A. Abebe], [A. M. Degu] and [H. Goitom]. The first draft of the manuscript was written by [B. Grum]. [B. A. Abebe], [A. M. Degu], [H. Goitom], [K. Woldearegay], [R. Hessel], [C. J. Ritsema] and [V. Geissen] commented on previous versions of the manuscript. [B. Grum], [B. A. Abebe], [A. M. Degu], [H. Goitom], [K. Woldearegay], [R. Hessel], [C. J. Ritsema] and [V. Geissen] read and approved the final manuscript.

Funding The European Union via the European Union's Seventh Framework Program (FP7/2007–2013) under grant agreement n° 265570 (WAHARA project).

Availability of Data and Material All data and material comply with field standards.

Code Availability Not applicable.

Declarations

Conflicts of Interest/Competing Interests No conflict of interest from all the authors.

References

Al-Wagdany AS, Rao AR (1997) Estimation of the velocity parameter of the geomorphologic instantaneous unit hydrograph. Water Resour Manag 11:1–16. https://doi.org/10.1023/A:1007923906214

ASTER (2009) ASTER Global Digital Elevation Model. Release Year 2009, Version 2

Babaali HR, Sabzevari T, Ghafari S (2021) Development of the Nash instantaneous unit hydrograph to predict subsurface flow in catchments. Acta Geophys. https://doi.org/10.1007/s11600-021-00638-x

Bhadra A, Panigrahy N, Singh R, Raghuwanshi NS, Mal BC, Tripathi MP (2008) Development of a geomorphological instantaneous unit hydrograph model for scantily gauged watersheds. Environ Model Softw 23(8):1013–1025. https://doi.org/10.1016/j.envsoft.2007.08.008

Bhaskar NR, Parida BP, Nayak AK (1997) Flood estimation for ungauged catchments using the GIUH. J Water Resour Plan and Manag 123(4):228–238

Chen Y, Shi P, Ji X, Qu S, Zhao L, Dong F (2019) New method to calculate the dynamic factor–flow velocity in geomorphologic instantaneous unit hydrograph. Sci Rep 9:14201. https://doi.org/10.1038/s41598-019-50723-x

Chutha P, Dooge JCI (1990) The shape parameters of the geomorphologic unit hydrograph. J Hydrol 117:81–97. https://doi.org/10.1016/0022-1694(90)90087-E

Cudennec C, Fouad Y, Gatot IS, Duchesne J (2004) A geomorphological explanation of the unit hydrograph concept. Hydrol Process 18:603–621. https://doi.org/10.1002/hyp.1368

Ghumman AR, Ahmad MM, Hashmi HN, Kamal MA (2012) Development of geomorphologic instantaneous unit hydrograph for a large watershed. Environ Monit Assess 184:3153–3163. https://doi.org/10.1007/s10661-011-2179-3

Grum B, Woldearegay K, Hessel R, Baartman JEM, Abdulkadir M, Yazew E, Kessler A, Ritsema C, Geissen V (2017) Assessing the effect of water harvesting techniques on event-based hydrological responses and sediment yield at a catchment scale in northern Ethiopia using the Limburg Soil Erosion Model (LISEM). CATENA 159:20–34. https://doi.org/10.1016/j.catena.2017.07.018

Gunawardhana LN, Al-rawas GA, Baawain MS (2020) Spatial regression approach to estimate synthetic unit hydrograph by geomorphic characteristics of watersheds in arid regions. J Arid Land 12(6):950–963. https://doi.org/10.1007/s40333-020-0101-y

Gupta VK, Waymire E, Wang CT (1980) A representation of an instantaneous unit hydrograph from geomorphology. Water Resour Res 16(5):855–862. https://doi.org/10.1029/WR016i005p00855

Hosseini SM, Mahjour N, Riahi S (2016) Development of a direct geomorphologic IUH model for daily runoff estimation in ungauged watersheds. J Hydrol Eng 05016008:1–17. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001333

Jaiswal RK, Thomas T, Galkate RV, Ghosh NC, Lohani AK, Kumar R (2014) Development of geomorphology based regional Nash model for data scares central India region. Water Resour Manag 28:351–371. https://doi.org/10.1007/s11269-013-0486-x

Khaleghi MR, Gholami V, Ghodusi J, Hosseini H (2011) Efficiency of the geomorphologic instantaneous unit hydrograph method in flood hydrograph simulation. CATENA 87:163–171. https://doi.org/10.1016/j.catena.2011.04.005

Kumar A (2015) Geomorphologic instantaneous unit hydrograph based hydrologic response models for ungauged hilly watersheds in India. Water Resour Manag 29:863–883. https://doi.org/10.1007/s11269-014-0848-z

Kumar R, Chatterjee C, Singh RD, Lohani AK, Kumar S (2007) Runoff estimation for an ungauged catchment using geomorphological instantaneous unit hydrograph (GIUH) models. Hydrol Process 21:1829–1840. https://doi.org/10.1002/hyp.6318

Lee KT, Chang C-H (2005) Incorporating subsurface-flow mechanism into geomorphology-based IUH modeling. J Hydrol 311:91–105. https://doi.org/10.1016/j.jhydrol.2005.01.008

Lenhart T, Eckhardt K, Fohrer N, Frede H-G (2002) Comparison of two different approaches of sensitivity analysis. Phys Chem Earth 27:645–654. https://doi.org/10.1016/S1474-7065(02)00049-9

Nash JE (1957) The form of the instantaneous unit hydrograph. Int Assoc Sci Hydrol Publ 45(3):114–121

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I — a discussion of principles. J Hydrol 10:282–290

Niyazi B, Khan AA, Masoud M, Elfeki A, Basahi J, Zaidi S (2021) Morphological-hydrological relationships and the geomorphological instantaneous unit hydrograph of Makkah Al-Mukarramah watersheds. Arab J Geosci 14(751):1–17. https://doi.org/10.1007/s12517-021-07063-w

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

Rigon R, Bancheri M, Formetta G, de Lavenne A (2016) The geomorphological unit hydrograph from a historical-critical perspective. Earth Surf Process Landf 41:27–37. https://doi.org/10.1002/esp.3855

Rinaldo A, Rodriguez-Iturbe I (1996) Geomorphological theory of the hydrological response. Hydrol Process 10:803–829. https://doi.org/10.1002/(SICI)10991085(199606)10:6%3c803::AID-HYP373%3e3.0.CO;2-N

Rodriguez-Iturbe I, Devoto G, Valdés JB (1979) Discharge response analysis and hydrologic similarity: the interrelation between the geomorphologic IUH and the storm characteristics. Water Resour Res 15(6):1435–1444. https://doi.org/10.1029/WR015i006p01435

Rodriguez-Iturbe I, González-Sanabria M, Bras RL (1982) A geomorphoclimatic theory of the instantaneous unit hydrograph. Water Resour Res 18(4):877–886. https://doi.org/10.1029/WR018i004p00877

Rodriguez-Iturbe I, Valdes JB (1979) The geomorphologic structure of hydrologic response. Water Resour Res 15(6):1409–1420. https://doi.org/10.1029/WR015i006p01409

Sahoo B, Chatterjee C, Raghuwanshi NS, Singh R, Kumar R (2006) Flood estimation by GIUH-based Clark and Nash models. J Hydrol Eng 11:515–525. https://doi.org/10.1061/(ASCE)1084-0699(2006)11:6(515)

Shamseldin AY, Nash JE (1998) The geomorphological unit hydrograph-a critical review. J Hydrol Earth Syst Sci 2(1):1–8. https://doi.org/10.5194/hess-2-1-1998

Singh PK, Mishra SK, Jain MK (2014) A review of the synthetic unit hydrograph: from the empirical UH to advanced geomorphological methods. Hydrol Sci J 59(2):239–261. https://doi.org/10.1080/02626667.2013.870664

Snyder FF (1938) Synthetic unit-graphs. Eos, Trans Am Geophys Union 19(1):447–454. https://doi.org/10.1029/TR019i001p00447

Soil Conservation Service SCS (1957) Use of storm and watershed characteristics in synthetic hydrograph analysis and application. US Department of Agriculture, Soil Conservation Service, Washington, DC

Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38:913–920

Tarahi M, Sabzevari T, Fattahi MH, Derikvand T (2021) Estimating runoff in ungauged catchments by Nash-GIUH model using image processing and fractal analysis. Stochastic Environ Res Risk Assess. https://doi.org/10.1007/s00477-021-02068-z

Zelazinski J (1986) Application of the geomorphological instantaneous unit hydrograph theory to development of forecasting models in Poland. Hydrol Sci J 31(2):263–270. https://doi.org/10.1080/02626668609491043

Authors and Affiliations

B. Grum[1] · B. A. Abebe[1] · A. M. Degu[1] · H. Goitom[1] · K. Woldearegay[2] · R. Hessel[3] · C. J. Ritsema[4] · V. Geissen[4]

[1] School of Civil Engineering, Ethiopian Institute of Technology-Mekelle, Mekelle University, P.O. Box 3185, Mekelle, Ethiopia

[2] Department of Earth Sciences, Mekelle University, P.O. Box 231, Mekelle, Ethiopia

[3] Soil, Water and Land Use Team, Wageningen Environmental Research, P.O. Box 47 6700 AA, Wageningen, The Netherlands

[4] Soil Physics and Land Management Group, Wageningen University, P.O. Box 47 6700 AA, Wageningen, The Netherlands