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Evaluating the impact of lower resolutions of digital elevation model on rainfall-runoff modeling for ungauged catchments

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Abstract Geomorphological instantaneous unit hydrograph (GIUH) usually uses geomorphologic parameters of catchment estimated from digital elevation model (DEM) for rainfall-runoff modeling of ungauged watersheds with limited data. Higher resolutions (e.g., 5 or 10 m) of DEM play an important role in the accuracy of rainfall-runoff models; however, such resolutions are expansive to obtain and require much greater efforts and time for preparation of inputs. In this research, a modeling framework is developed to evaluate the impact of lower resolutions (i.e., 30 and 90 m) of DEM on the accuracy of Clark GIUH model. Observed rainfall-runoff data of a 202-km^2 catchment in a semiarid region was used to develop direct runoff hydrographs for nine rainfall events.

Geographical information system was used to process both the DEMs. Model accuracy and errors were estimated by comparing the model results with the observed data. The study found (i) high model efficiencies greater than 90% for both the resolutions, and (ii) that the efficiency of Clark GIUH model does not significantly increase by enhancing the resolution of the DEM from 90 to 30 m. Thus, it is feasible to use lower resolutions (i.e., 90 m) of DEM in the estimation of peak runoff in ungauged catchments with relatively less efforts. Through sensitivity analysis (Monte Carlo simulations), the kinematic wave parameter and stream length ratio are found to be the most significant parameters in velocity and peak flow estimations, respectively; thus, they need to be carefully estimated for calculation of direct runoff in ungauged watersheds using Clark GIUH model.

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Introduction

There are many water-stressed countries around the globe (WRI 2016). Estimation of surface runoff using rainfall-runoff modeling plays an important role for planning and development of the limited water resources in these countries. Under current water crises, it is critical to simulate unit hydrographs for ungauged watersheds, in addition to gauged ones, to develop

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rational water conservation strategies. Rainfall-runoff models have mainly been classified into two broad categories, including physical-based and conceptual (Pumo et al. 2016; Devi et al. 2015; Bhimjiani 2015). Large data requirements for physical-based models limit their application for catchments with poor or no flow records (i.e., common in developing countries). The other type of models based on geographical information system (GIS) techniques, such as geomorphological instantaneous unit hydrograph (GIUH) used in this study, may be preferred for catchments with scanty data (Hosseini et al. 2016; Jena et al. 2016; Marconi et al. 2016; Kar et al. 2015; Sadeghi et al. 2015).

The movement of rainwater in the catchment is a function of its geomorphologic elements, such as slope, shape, area, stream density of the catchment, length of main channel, length of the highest-order stream, length ratio, etc. Horton (1945) introduced stream-ordering of catchments which was later modified by Strahler in 1952. Rodriguez-Iturbe and Valdes (1979) invented the idea of GIUH which estimates the velocity and peak-flow of an instantaneous unit hydrograph (IUH) using geomorphologic parameters of the catchment estimated by GIS tools. Catchment-digital elevation model (DEM) is used in this process. The process initiates with delineating the area of the catchment and stream networks, followed by estimation of the above-mentioned geomorphic parameters. Most of the parameters are estimated for an area using empirical relationships; the applicable ranges of these parameters are established for different physical and environmental conditions for the area under study. As there are many parameters involved in estimation of final runoff, it is important to evaluate the model sensitivity to identify the parameters with the highest influence on the final outcomes (i.e., velocity and peak flow). Based on the sensitivity analysis results, only the most important parameters can later be measured in the field for model calibration.

GIUH models were improved and used by several researchers time to time (Gupta et al. 1980; Mondal et al. 2012; Ghumman et al. 2012; Altaf et al. 2013; Singh and Sarkar 2013; Ghumman et al. 2014; Kumar 2015; Zafer 2015). In the recent past, several advancements have been made in GIS tools and satellite images which certainly have improved the resolution of DEM and subsequently the accuracy of GIUH models. Several researchers studied the impact of DEM resolution on geomorphic parameters (Dixon and Earls 2009; Jing and Wong 2010; Lin et al. 2010; Mirza et al. 2011;

Ghaffari 2011; Tan et al. 2015; Buakhao and Kangrang 2016; Cornelissen et al. 2016). Mirza et al. (2011) investigated the impacts of 5- and 10-m resolution on two global DEMs for their suitability in engineering applications in the Kingdom of Saudi Arabia and found that 5-m resolution was more accurate than the 10-m resolution. Ghaffari (2011) used SWAT model to evaluate the impact of DEMs' resolutions (ranging from 10 to 500 m) on runoff and sediments modeling of a watershed located in Northwest of Iran and found that resolutions lower than 50 m did not significantly affect the accuracy of results. Recently, Buakhao and Kangrang (2016) investigated the impact of 5- to 90-m resolution of DEM on the delineation process of different catchments' sizes with varying topographical conditions using SWAT model. They recommended the use of lower resolution (i.e., 30 m) instead of 5 m for water resource modeling to save time for the development of model inputs.

It has been well established in the literature that higher resolution of DEM plays an important role in the accuracy of rainfall-runoff models; however, higher resolutions (i.e., 5 or 10 m) require much greater efforts and time for analysis and preparation of inputs. In addition, higher resolution DEMs (i.e., ≤5 m) are expansive and are difficult to obtain for most of research, academic, and planning purposes, particularly in developing countries with limited resources. It has also been reported that errors produced by different DEMs depend on the specific nature of the study region and the type of land covers; consequently, selection of right resolution of DEM is important for a particular study area (Hasan et al. 2015). Therefore, the contradicting findings presented in the above studies suggest the need for further investigations, particularly using rainfall-runoff models which include detailed watershed characteristics (i.e., GUIH) to further improve the prevailing rationale on this topic.

In this study, an effort is made to investigate the effect of lower resolutions of DEM on geomorphic parameters and hence on the direct runoff (DRO) simulations using GIUH. In developing countries, there are several ungauged watershed sometimes with significant runoff, and it is not possible to install permanent gauging stations due to restricted resources. Moreover, the significant model parameters are identified through sensitivity analysis which can be monitored (limited number of observations) for calibrating the model.

The main objectives of this research are to (i) explore the effects of lower resolutions (30 and 90 m which still are significantly different in terms of efforts required to

generate model inputs) of DEM on Clark GIUH model and (ii) perform sensitivity analysis based on Monte Carlo simulations to identify the most contributing factors to runoff calculations. The findings of this research will be useful for scientists, engineers, managers, and planners in the field of water resources. In this research, two digital elevation models with 30- and 90-m resolutions have been evaluated based on their impact on rainfall-runoff modeling. Here, 30- and 90-m resolutions correspond to higher and lower resolutions, respectively.

Study area

The catchment area under study shown in Fig. 1 is located at 33° 37′ 30″ N and 72° 41′ 51 ″E. This 202-km² area lies in a semiarid region of Kala Chitta Range. The rainwater from the catchment travels downstream towards a reservoir behind Shahpur Dam through a stream which finally discharges into Indus River. The Shahpur Dam reservoir is at the outlet of the catchment area under investigation. The elevation of the study area from mean sea level ranges between 424 and 540 m. The land use of the area is baron with negligible residential/commercial activity. Mostly sandy-silty-clay soil with some vegetation cover can be found in the area. In the past, no study has been conducted to estimate surface runoff in this ungauged catchment which justifies the need of this research.

Methodology

Modeling framework

A modeling framework is developed in this research to evaluate the impact of resolution of DEM on Clark geomorphological model for DRO estimation of ungauged watersheds. The proposed framework presented in Fig. 2 consists of four main components, including data collection for model parameters, runoff estimation, model evaluation, and sensitivity analysis. The required data was obtained from satellite images with the help of ArcGIS-10.1 software regarding geomorphologic parameters, including catchment area, stream order, stream areas, and stream lengths. Clark GIUH model was then used to simulate DRO. Model results are evaluated in terms of efficiency and errors in peak discharge and time to peak. Finally, Monte Carlo simulations are performed to identify the most significant parameters based on their % contribution towards the velocity and peak discharge estimates. The details of these steps are described in the following sub-sections.

Data collection and analysis

The inputs to Clark GIUH model include excess rainfall, rainfall intensity, and catchment geomorphological parameters. Its validation and evaluation needs observed direct runoff data. The framework shown in Fig. 2 is implemented on the study area (Shahpur Dam's catchment) presented
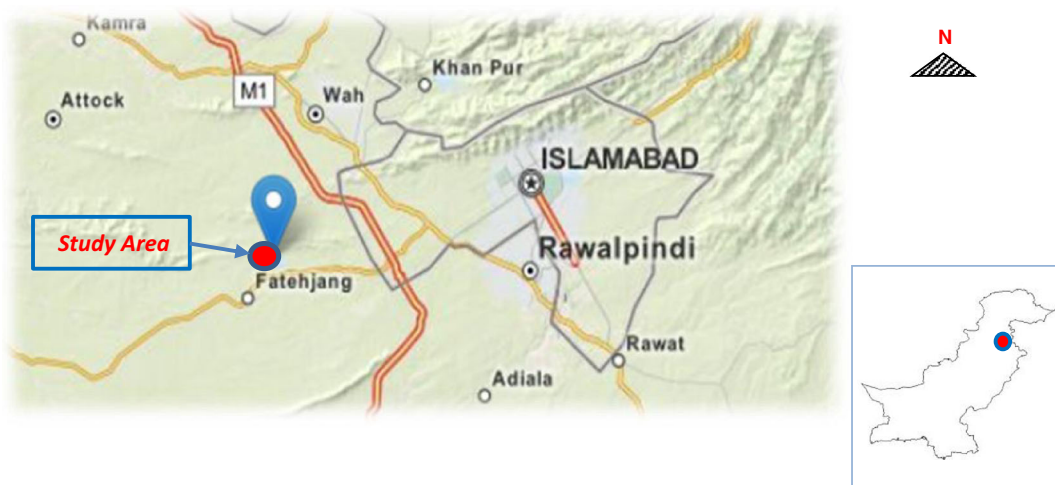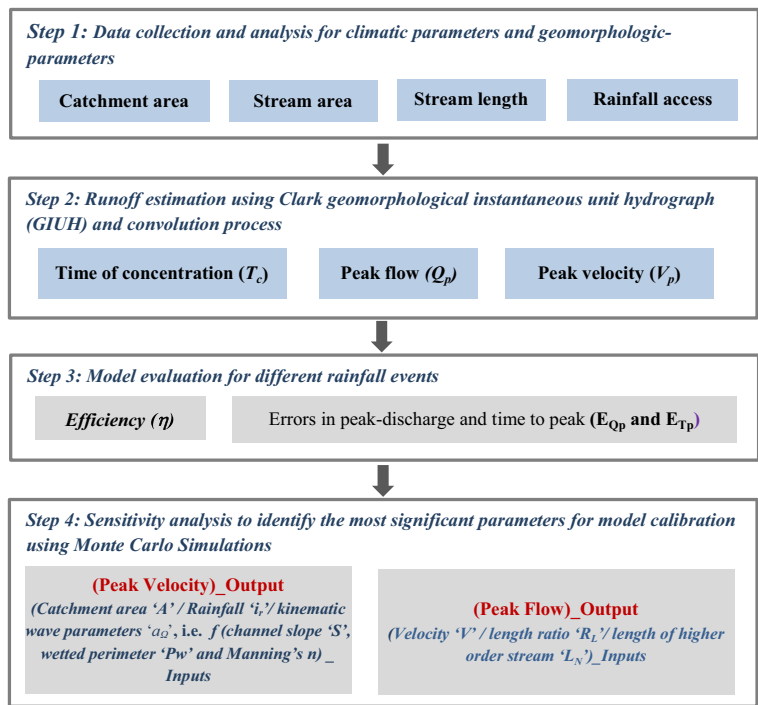

Fig. 1 Location map of study area

Fig. 2 Proposed modeling
framework

Step 1: Data collection and analysis for climatic parameters and geomorphologic-parameters

| Catchment area | Stream area | Stream length | Rainfall access |

Step 2: Runoff estimation using Clark geomorphological instantaneous unit hydrograph (GIUH) and convolution process

| Time of concentration (T_c) | Peak flow (Q_p) | Peak velocity (V_p) |

Step 3: Model evaluation for different rainfall events

| Efficiency (η) | Errors in peak-discharge and time to peak (E_{Qp} and E_{Tp}) |

Step 4: Sensitivity analysis to identify the most significant parameters for model calibration using Monte Carlo Simulations

(Peak Velocity)_Output
(Catchment area 'A' / Rainfall 'i_r'/ kinematic wave parameters 'a_Ω', i.e. f (channel slope 'S', wetted perimeter 'Pw' and Manning's n) _ Inputs

(Peak Flow)_Output
(Velocity 'V' / length ratio 'R_L'/ length of higher order stream 'L_N')_Inputs

in Fig. 1. The data collection and its analysis are explained in the following sections.

Geomorphological parameters

DEMs of 90- and 30-m resolutions were obtained from relevant agency (Survey of Pakistan, Rawalpindi, Pakistan) and processed to obtain the geomorphological parameters for the catchment under study. Stream ordering for both the 30- and 90-m resolutions is shown in

Fig. 3a, b. The geomorphologic parameters determined with the help of ArcGIS version 10.1 for both 30- and 90-m digital elevation models are presented in Table 1.

Rainfall and runoff observations

Recorded rainfall and runoff for nine events were collected from Small Dams Organization, Rawalpindi, Pakistan. The rainfall data is being recorded by this organization at Meteorological Station Fatehjang near Shahpur Dam.
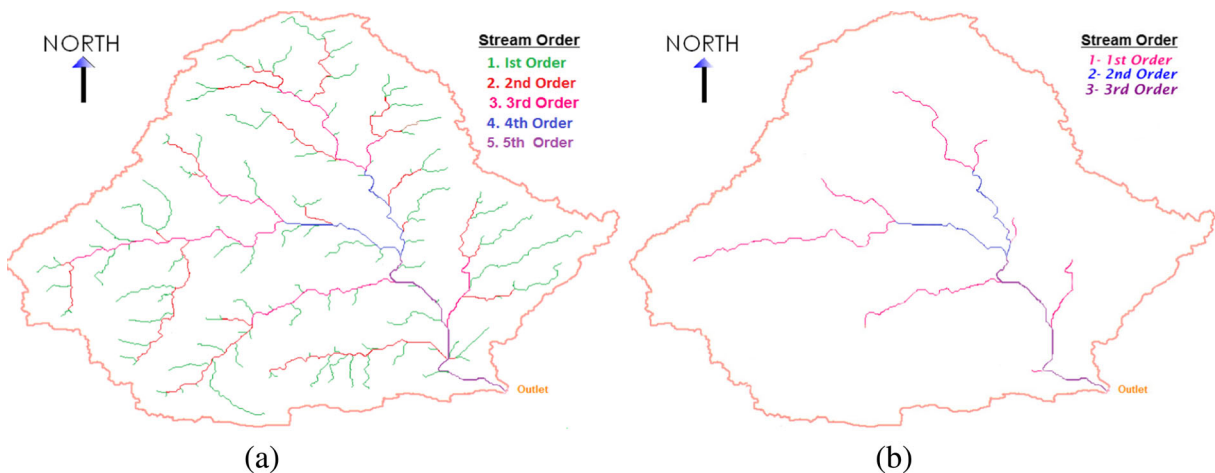

(a)

(b)

Fig. 3 Stream ordering for Shahpur Dam watershed. **(a)** 30-m DEM; **(b)** 90-m DEM

Table 1 Geomorphological parameters determined from 30- and 90-m DEMs

No.	Parameter	Unit	Symbol	30 m (DEM[a])	90 m (DEM)	Difference (% of 90DEM)
1	Catchment area	km^2	A	204.80	206.40	−0.80
2	Number of streams	–	N	172.00	11.00	>100
3	Basin perimeter	km	P_b	94.70	80.958	17.00
4	Basin length	km	L_b	17.35	17.13	0.013
5	Length of the highest-order stream	km	L_Ω	8.88	7.59	17.00
6	Main channel length	km	L	21.60	19.20	12.50
7	Stream area ratio[b] (for the highest-order steam)	–	R_a	3.94	3.25	21.20
8	Stream length ratio[c] (for the highest-order steam)	–	R_L	1.94	1.58	22.80
9	Drainage density[d]	–	D	0.28	0.25	12.00
10	Stream frequency[e]	no.	F	0.839	0.053	14.83
11	Drainage intensity[f]	–	Di	2.50	0.19	>100
12	Storage coefficient	–	R	2.10	1.95	7.70
13	Time of concentration	hours	T_c	5.20	4.83	7.70

[a] Digital elevation model

[b] $R_a = A_i / A_{(i+1)}$, where R_a is stream area ratio and A_i is the total area of sub-basins that contributes to the channel segment of order i and all lower-order channel

[c] $R_l = L_i / L_{(i+1)}$, where R_l is stream area ratio and L_i is the total length of order i and all lower-order channels

[d] Drainage density is the ratio of the total length of streams to the total watershed area

[e] Stream frequency is the number of the streams per unit area $= N / A$

[f] Drainage intensity is the ratio of stream frequency to the drainage density

Average rain over the area was estimated by Isohyetal method, and excess rainfall was determined by subtracting the losses from total rainfall. The percentage runoff approach (Linsley et al. 1982) was used to find the direct runoff depth in this research. Excess precipitation of nine events obtained after processing of total rain and losses is presented in Fig. 4.

Clark GIUH model

In Clark original model, the instantaneous unit hydrograph (IUH) was derived by means of routing excess rainfall of unit amount with the help of a time-area diagram through a linear-reservoir method. The storage coefficient (R), the concentration time (Tc), and the time-area diagram are

Fig. 4 Excess precipitation for nine rainfall events with the dates of observations in the study area
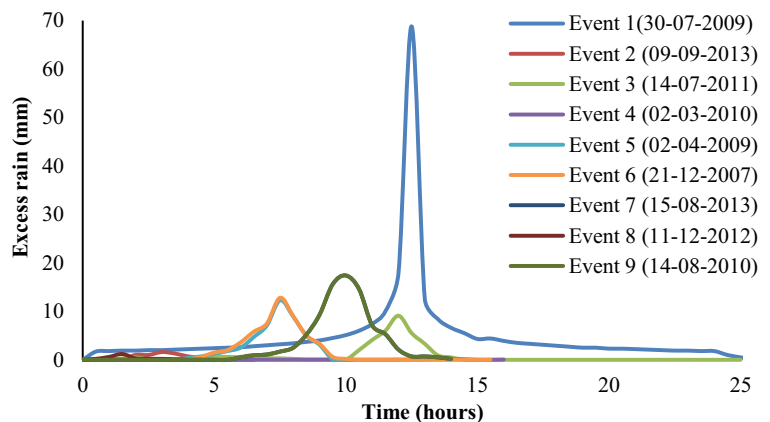
required to develop the IUH. General equations of Clark IUH are given in the following (Clark 1945):

$$Q_{i+1} = 2C_0 I_{(i)} + C_1 Q_i, \tag{1}$$

where Q_{i+1} is the $(i+1)^{\text{th}}$ ordinate of the Clark's IUH, $I_{(i)}$ is ith ordinate of time-area diagram, and i is an index varying from 1 to n where n is the number of ordinates of the time area diagram. Weighting coefficients C_0 and C_1 are defined as (see Ponce 1980 and Ponce 1989):

$$C_0 = \frac{0.5t}{(R+0.5t)} \tag{2}$$

$$C_1 = \frac{(R-0.5t)}{(R+0.5t)}, \tag{3}$$

where t is the time interval in hours and R is the storage coefficient. The value of $R_{(i)}$ is usually obtained by using the slope of the recession curve at the point of inflection.

The Clark GIUH basically modifies the idea of original Clark's IUH with the addition of geomorphic parameters. The time of concentration, peak velocity, and peak flow are determined on the basis of excess rainfall using the following equations (Rodriguez-Iturbe et al. 1982):

$$T_c = \frac{0.2778L}{V} \tag{4}$$

$$Q_p = \frac{1.31R_L^{0.43}V_p}{L_\Omega} \tag{5}$$

$$V_p = 0.665(a_\Omega)^{0.6}(i_r A)^{0.4}, \tag{6}$$

where T_c is time of concentration in hours, L is the length of the main channel in km, V_p is the expected peak velocity in m/s, Q_p is the peak flow in m³/s, R_L is the length ratio, L_Ω is the length of the highest-order stream (i.e., the last stream collecting runoff from the entire watershed) in km, a_Ω is the kinematic wave parameter for highest-order streams, i_r is the intensity of excess rainfall in cm/h, and "A" is watershed area in km².

The kinematic wave perimeter "a_Ω" was estimated using the following equation given by Rodriguez-Iturbe et al. (1982) and Ponce (1989):

$$a_\Omega = (S)^{0.5}\Big/\left(nPw^{0.666}\right), \tag{7}$$

where Pw is approximate value of channel wetted perimeter and n is Manning's constant. Both S and Pw are geomorphological parameters and depend on DEM resolution. The values of both of these parameters should be carefully used.

Model efficiency and errors

The model efficiency and errors between measured and simulated quantities are calculated by the following equations (Nash and Sutcliffe 1970; Mutreja 1986):

$$\eta = \left(1 - \frac{\sum_{i=1}^{n}(Q_{\text{oi}}-Q_{\text{si}})^2}{\sum_{i=1}^{j}(Q_{\text{oi}}-\bar{Q}_{\text{oi}})^2}\right) \times 100 \tag{8}$$

$$E_{\text{Qp}} = \left(1 - \frac{Q_{\text{ps}}}{Q_{\text{po}}}\right) \times 100 \tag{9}$$

$$E_{\text{Tp}} = \left(\frac{T_{\text{ps}}}{T_{\text{po}}}\right) \times 100, \tag{10}$$

\where η is the model efficiency (%), Q_{oi} is the observed discharge of ith ordinate of recorded hydrograph, Q_{si} is simulated discharge of ith ordinate of direct-runoff hydrograph, "n" is the total number of ordinates of hydrograph, E_{Qp} and E_{Tp} are the errors in peak-discharge and time to peak respectively, Q_{ps} and T_{ps} are simulated peak discharge and time to peak, and Q_{po} and T_{po} are the measured peak discharge and time to peak, respectively.

Sensitivity analysis

Sensitivity of a model can be described as the changeability in the output with the changing input(s). Using the sensitivity analysis results, the inputs can be ranked based on their relative contributions to the variability of the model output. In the past, several methods have been developed for sensitivity analysis, e.g., differential analysis, response surface methodology and factorial design, Monte Carlo analysis, statistical methods, and variance decomposition procedures (Haider et al. 2016). In this research, Monte
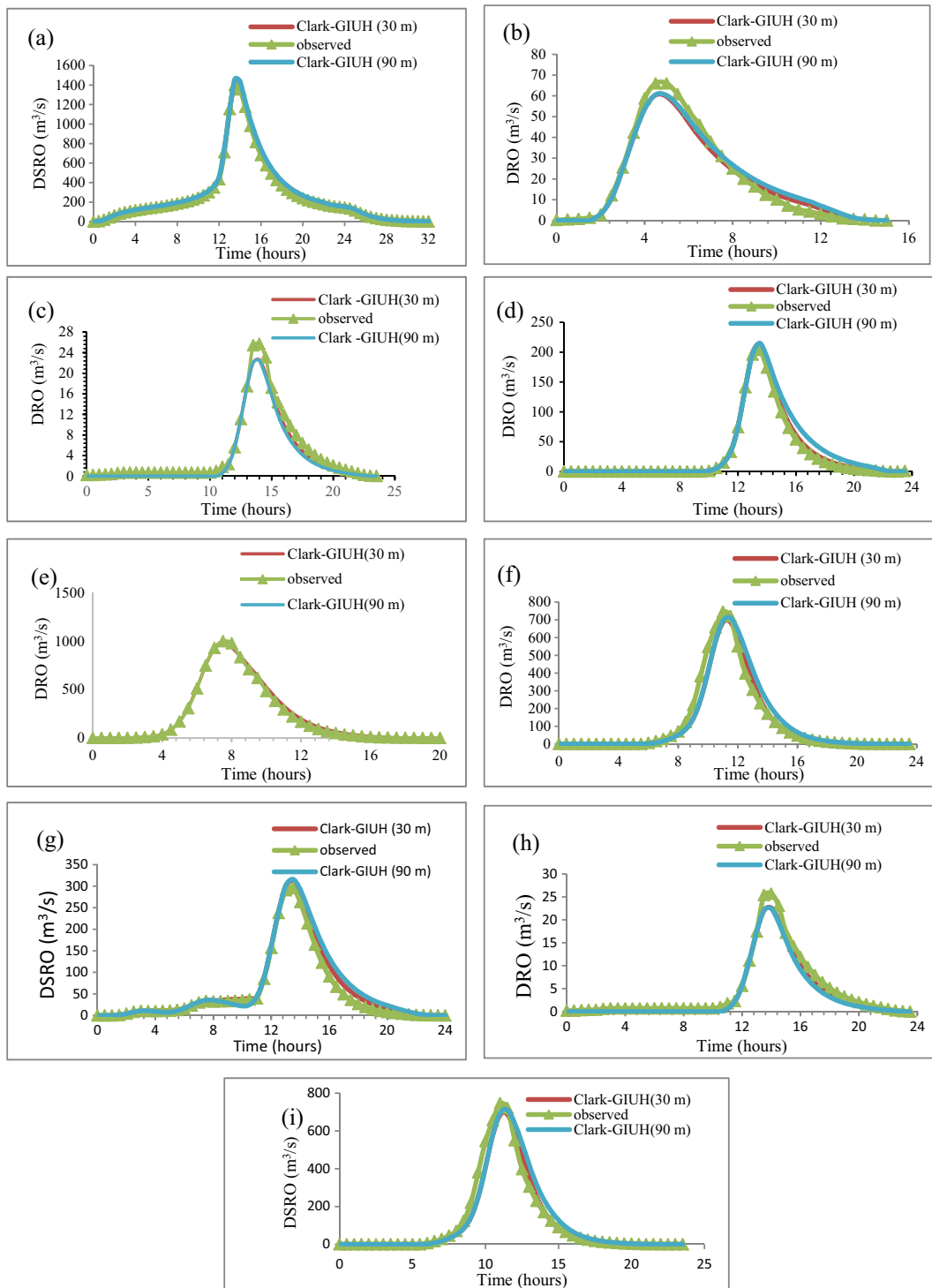
Fig. 5 Observed and simulated direct runoff hydrographs for event 1 (**a**), event 2 (**b**), event 3 (**c**), event 4 (**d**), event 5 (**e**), event 6 (**f**), event 7 (**g**), event 8 (**h**), and event 9 (**i**)

Carlo simulations are performed with the help of Crystal Ball (i.e., an excel add-in) to estimate the

contribution of each input parameter for estimating time of concentration and peak flow using Eqs. (4)

Fig. 6 Comparison of
efficiencies η (%) for 30- and 90-
m DEMs
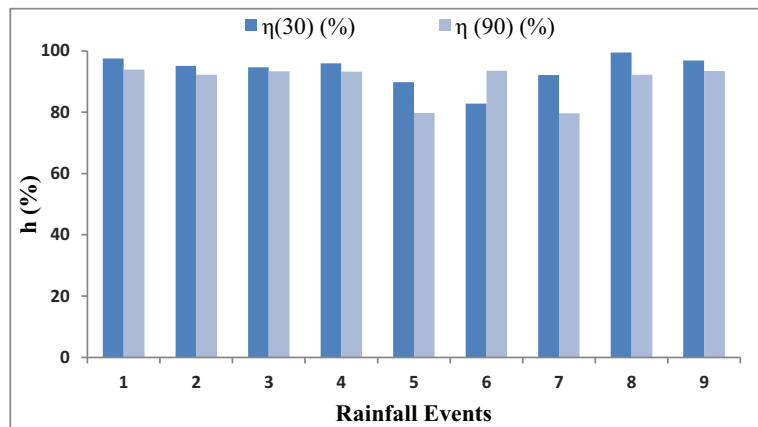
and (5). In this research, triangular distribution is
used due to its simplicity and because it reasonably
approximates normal and lognormal distributions
(Lampe and Platten 2015). The triangular area math-
ematically represents the likelihood of possible out-
comes by defining lower, upper, and the mode (i.e.,
most likely value).

Results and discussions

Geomorphologic characteristics of the watershed under the study

A significant difference between the values of stream
ordering (5 and 3, respectively) obtained from 30- and

Fig. 7 Comparison of errors for
30- and 90-m DEMs. **(a)** Peak flow
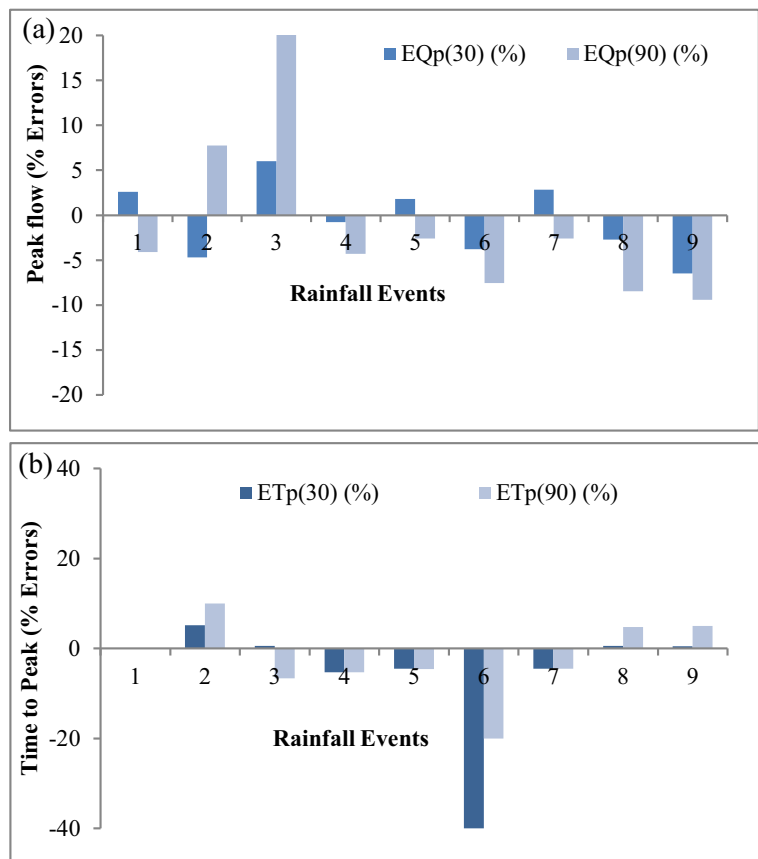"Q_p"; **(b)** Time to peak flow "T_p"

Table 2 Ranges for the parameters from the study area used for sensitivity analysis

Sr.	Parameter	Unit	Symbol	Minimum	Mode	Maximum
1	Kinematic wave parameter for highest-order streams	–	a_Ω	0.2	0.234	0.26
2	Intensity of excess rainfall	cm/h	i_r	90	100	110
3	Watershed area	km^2	A	200	205	208
4	Expected peak-velocity	m/s	V	0.8	3.0	7.0
5	Length of the highest-order stream	km	L_Ω	5	8	12
6	Length ratio	–	R_L	1.5	1.8	2.0

90-m DEMs can be observed in Fig. 3a, b. Table 1 presents the values of various geomorphologic parameters estimated by processing both 30- and 90-m DEMs. The important geomorphological parameters, including catchment area, number of streams, basin length, stream length ratio, stream area ratio, storage coefficient, and time of concentration, obtained from 30- and 90-m DEMs, differ by about 0.8, greater than 100, 17, 22.8, 21.2, 7.7, and 7.7 respectively.

Model evaluation

Hydrograph analysis

A comparison between the direct runoff hydrographs developed by using the Clark GIUH and the measured hydrographs for all the nine events are shown in Fig. 5a–i. It can be observed that both the hydrographs obtained from 30- and 90-m DEMs show relatively close agreement between the model results and the measured values.

Model efficiency and errors

The estimated model efficiencies comparing the simulated results with the measured values of peak flow and time to peak, using Eq. (8), for both the 30- and 90-m

DEM, are presented in Fig. 6. The maximum efficiencies for 30- and 90-m DEMs are found to be 99 and 93%, respectively. These results show that stream order and its pattern do not significantly depend on difference in lower resolutions of DEM.

Figure 7a presents the errors using Eq. (9) for the calculated and measured values of peak flow for both the 30- and 90-m DEMs. It can be seen that that the maximum percentage error in peak discharge (E_{Qp}) does not go higher than 7% with the minimum value of 0.8% in case of 30-m DEM. Similarly, in case of 90-m DEM, the error in peak discharge approaches to 9% with a minimum value of 2.6% with an exception of event 3. These results reflect that based on average difference of errors, there is no significant difference between the two resolutions. Figure 7b presents the errors using Eq. (10) for the calculated and measured values of time to reach the peak discharge for both the 30-.and 90-m DEMs.

Sensitivity analysis

Sensitivity analyses are performed to deal with inherent uncertainties in estimation of various parameters using GIS. Random variables are generated assuming triangular distribution for the ranges of climatic and geomorphologic parameters listed in Table 1. The ranges of the
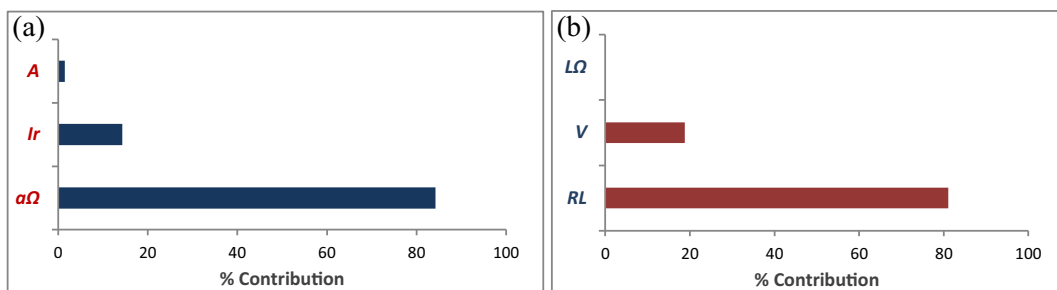

Fig. 8 Sensitivity analysis results showing % contribution of parameters for velocity (**a**) and peak flow (**b**)

input parameters for sensitivity analysis are listed in Table 2. Monte Carlo simulations were performed with 1000 runs to identify the % contribution of the inputs towards the calculated outputs (i.e., velocity and peak flow) in Eqs. (5) and (6). For various rainfall occasions in this study, the peak velocity "V" estimated using DEM's resolution of 90 m was in the range of 6.05 to 1.095 m/s and 5.87 to 1.06 m/s in case of DEM's resolution of 30 m.

The results presented in Fig. 8a, b reveal that kinematic wave parameter is the most significant parameter in velocity estimations, while stream length ratio has the higher % contribution for estimating peak flow. These results suggest for careful estimation of these parameters for assessing the runoff in ungauged watersheds using Clark GIUH model. Interestingly, kinematics wave coefficient "a_Ω" depends on slope, Manning's n, and wetted parameter of the highest-order stream which is the same for both the cases and does not directly depends on the resolution of DEM. Stream length ratio "R_L" however depends on the resolution and is higher (see Table 1) in case of 30-m resolution and can be considered as the most significant parameter affecting the difference of peak flow estimations in both the cases.

Conclusions and recommendations

A modeling framework is developed to investigate the impact of lower resolutions of DEM (i.e., 30 and 90 m) on the catchment parameters and runoff generated by Clark GIUH model. Recorded rainfall-runoff data from a 202-km^2 catchment area having semiarid climate was used to develop direct runoff hydrograph using Clark GIUH method. ArcGIS 10.1 software was used to process satellite images of the catchment for estimating various parameters of GIUH.

The direct runoff hydrographs simulated by Clark GIUH, using DEMs of 30- and 90-m resolutions, for various rainfall events revealed insignificant (i.e., 1 to 6% for different events) difference in efficiency of the two models in terms of agreement between the model results and measured values. Similarly, only 2% difference was found in estimated maximum percentage error in peak discharge (E_{Qp}) for the two models. Thus, it is feasible to use lower resolutions (i.e., 90 m) of DEM in the estimation of peak runoff in ungauged catchments using unit hydrograph-based methods such as Clark

GUIH with relatively less time (approximately half) and efforts required to generate model inputs.

Sensitivity analysis based on Monte Carlo simulations revealed that the kinematic wave parameter and the stream length ratio are the most significant parameters for velocity and peak flow estimations, respectively. Based on these results, researchers can put more efforts on careful estimation of these parameters for accurate results.

It is expected that the framework developed in this research will be applied on other studies with varying catchment characteristics, geographical conditions, and resolutions of DEM than the ones used in this research to validate its practicality.

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