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Evaluation of geomorphological approaches combined with digital elevation models for the Nash's instantaneous unit hydrograph

Maíra Martim de Moura [a], Samuel Beskow [a,*], Fabrício da Silva Terra [a,b], Carlos Rogério de Mello [a,c], Zandra Almeida da Cunha [a], Felício Cassalho [d]

[a] Center for Technological Development, Federal University of Pelotas, Campus Porto, Rua Gomes Carneiro, N. 01, 96010-610, Pelotas, Rio Grande do Sul, Brazil
[b] Institute of Agricultural Sciences, Federal University of Jequitinhonha and Mucuri Valleys, Ave. Ver. João Narciso 1380, 38610-000, Unaí, Minas Gerais, Brazil
[c] Water Resources Department, Federal University of Lavras, 37200-000, Lavras, Minas Gerais, Brazil
[d] Department of Civil, Environmental and Infrastructure Engineering, George Mason University, 650 Mason Ferry Avenue, Woodbridge, VA, 22191, USA

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ABSTRACT

Methodologies for estimation of direct surface runoff (DSR) hydrographs have been proposed, especially for the Unit Hydrograph (UH) and Instantaneous Unit Hydrograph (IUH). The widely used IUH developed by Nash (NIUH) has two main parameters: number of reservoirs (n) and storage coefficient (k), which by definition are determined based on observed rainfall-runoff events. In order to overcome the need for hydrological data for application of NIUH, geomorphological approaches (GAs) have been developed to provide the aforementioned parameters for ungauged watersheds, thus allowing for the estimation of DSR hydrographs using only relief information. The aim of this study was to evaluate the performance of 4 GAs (GA_1 - Nash, 1960; GA_2 - Wu, 1963; GA_3 - Rosso, 1984; GA_4 - Bhaskar et al., 1997). Moreover, this study sought to investigate the influence of different digital elevation models (DEMs) (TOPO, ASTER, SRTM-30 and SRTM-90) on the determination of geomorphological attributes necessary for the application of the above-mentioned GAs. Twenty rainfall-runoff events observed in a small Brazilian watershed were used to evaluate the performance of NIUH combined with different GAs and DEMs for estimation of DSR hydrographs. In view of the results found in this study, the main conclusions are: i) the GAs exert more influence on the parameters n and k than the DEMs; ii) GA_1 and GA_2 outperformed GA_3 and GA_4; and iii) GA_2 coupled with the ASTER DEM results in the best estimates of DSR hydrographs.

1. Introduction

Hydrological modeling plays a key role in the planning, development and management of water resources (Ahmad et al., 2010; Hosseini et al., 2016). The estimation of streamflows in watersheds has been the focus of several studies, since it is of great importance for engineering projects (Ghumman et al., 2014), water resources management (Bhagwat et al., 2011; Kumar et al., 2007), and mitigation and prevention of natural hazards, such as floods and droughts (Kahleghi et al., 2011; Sahoo et al., 2006).

Several methodologies have been proposed for the estimation of direct surface runoff (DSR) hydrographs from isolated rainfall events in order to provide tools for studies on natural hazards caused by floods, particularly the Unit Hydrograph (UH) (Sherman, 1932) and the Instantaneous Unit Hydrograph (IUH) (Clark, 1945). According to Cleveland et al. (2006), the greatest advantage of IUH over UH is that it is not established for an effective rainfall event with a specific duration; instead, it explores the concept of instantaneous effective rainfall. However, the application of these methodologies generally requires data derived from hydrological monitoring. In this context, some methodological alternatives have been presented, including: i) the empirical techniques recommended by the Soil Conservation Service (SCS, 1971), e.g. dimensionless UH (DUH) and triangular UH (TUH); and ii) the Geomorphological IUH (GIUH) (Rodriguez-Iturbe and Valdes, 1979), which relates the concepts of IUH to relief-based attributes.

The IUH model developed by Nash (1957) (NIUH) is widely used (Choi et al., 2011; Hosseini et al., 2016; Li et al., 2008), and it consists of only two parameters: number of reservoirs (n) and storage coefficient (k). The determination of these parameters is based on hyetographs and respective hydrographs (observed rainfall-runoff events), commonly

* Corresponding author.
E-mail address: samuel.beskow@ufpel.edu.br (S. Beskow).

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with sub-daily temporal discretization. Owing to scarcity and/or inexistence of hydrological data on a sub-daily basis, the NIUH application is difficult, especially in small to medium watersheds (Kumar et al., 2007). Therefore, some geomorphological approaches (GAs) have been developed to determine NIUH parameters in order to overcome the need for rainfall-runoff data with temporal discretization that is compatible with the watershed of interest.

Nash (1960) and Wu (1963) formulated empirical relationships between the parameters n and k and geomorphological attributes considering data from gauged experimental watersheds. Despite being widely disseminated in the literature (Croley II, 1980; Fang et al., 2008; Rosso, 1984; Singh and Singh, 1985; Zakizade and Malekinezhad, 2015), the GAs recommended by Nash (1960) and Wu (1963) have not been extensively evaluated with respect to the estimation of design hydrographs.

Based on the relationships between peak discharge (Q_P) and time to peak discharge (T_P) from GIUH and NIUH, Rosso (1984) and Bhaskar et al. (1997) proposed new equations for the parameters n and k using rainfall-runoff events from gauged watersheds. The GAs developed by Rosso (1984) and Bhaskar et al. (1997) have been assessed in a series of studies worldwide (Ghumman et al., 2012; Kahleghi et al., 2011; Rosso, 1984; Zakizadeh and Malekinezhad, 2015). The main reason presented for applying these approaches is their great potential to derive DSR hydrographs by only using relief information (Adib et al., 2010; Kumar et al., 2004). However, Bhaskar et al. (1997) pointed out that GAs cannot be universally applied, as they were grounded on geomorphological attributes with specific ranges of values. In addition, these researchers highlighted that GAs are subject to errors due to the estimation of their parameters.

Relief information for GAs is usually extracted from digital elevation models (DEMs), which can be obtained through different methods: i) synthetic aperture radar interferometry - such as the Shuttle Radar Topography Mission - SRTM (Farr et al., 2007); ii) interpolation of contour lines and/or points of known altitude - topographic maps; and iii) aerial and/or orbital stereoscopic sensors, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer - ASTER (ASTER GDEM Validation Team, 2011). It is well known that different DEMs can result in different values for the same geomorphological attribute (Chavan and Srinivas, 2015; Moura et al., 2021; Thomas et al., 2014). Thus, it is necessary to comprehend how much these different sources of information can influence DSR hydrographs estimated through NIUH when determining n and k from GAs. In general, recent studies have sought to compare GAs for estimation of flood hydrographs using the same DEM (Beskow et al., 2018) or evaluate a single GA varying the spatial resolution of DEMs (Ghumman et al., 2019; Sahoo et al., 2006).

In view of the above, the present study aimed to: i) evaluate the applicability of different GAs (Bhaskar et al., 1997; Nash, 1960; Rosso, 1984; Wu, 1963) for the determination of the NIUH parameters; and ii) investigate the influence of different DEMs on both the estimated DSR hydrographs and determination of the watershed geomorphological attributes necessary for the application of these GAs. The main hypothesis is that the value of a given geomorphological attribute varies according to DEM, changing the estimates of n and k and, consequently, exerting influence on DSR hydrographs estimated from NIUH.

2. Material and methods

2.1. Characterization of the study area

The proposed method was implemented in the Jaguara creek watershed (JCW), located in the Upper Grande river basin, in southeastern Brazil (Fig. 1). JCW has an area of about 32 km^2 and drains into the reservoir of Camargos Hydropower Plant (installed capacity of 45,000 KW), which is fundamental for the development of southern Minas Gerais State. The altitudes in the watershed vary between 948 and 1080 m, and according to the categories proposed by EMBRAPA (1979), JCW presents a predominance of flat (0–3%) to undulated (8–20%) slope classes (Fig. 2).

JCW is found predominantly in the Atlantic Forest biome and its climate is the Cwa Köppen's type, characterized as mesothermal, with mild and rainy summers and dry winters (Alvares et al., 2014). The predominant soil classes are Oxisols and Cambisols, whereas the dominant land uses are annual crops and pasture (Andrade et al., 2013) (Fig. 2).

According to Beskow et al. (2013), the high clay concentration and high porosity are the main physical characteristics of Oxisols existing in the JCW. These characteristics can be explained by the presence of Granite-Gneiss (Araújo et al., 2018) in the area, which experiences a higher weathering in humid and warmer weather (compared to temperate regions). Thus, this results in the formation of granular structures and, consequently, soils with high infiltration capacity. The lithology for the area was obtained from geological mapping of Minas Gerais (CODEMIG, 1997), as illustrated in Fig. 2.

2.2. Hydrological monitoring and rainfall-runoff events

JCW has been hydrologically monitored since 2006. The existing hydrological monitoring network (Fig. 1) consists of an automatic meteorological station and an automatic water level gauging station,

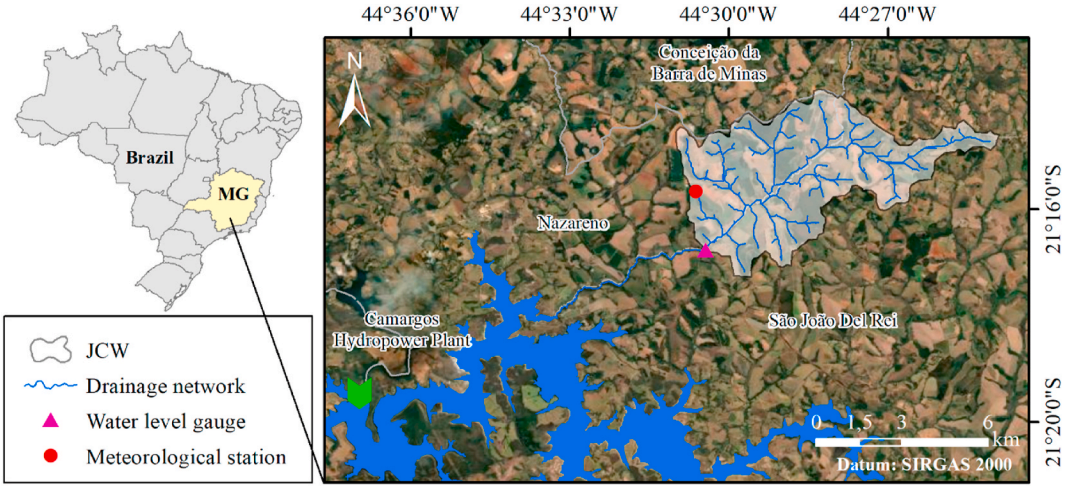


Fig. 1. Location of the Jaguara creek watershed (JCW) and its hydrological monitoring network.

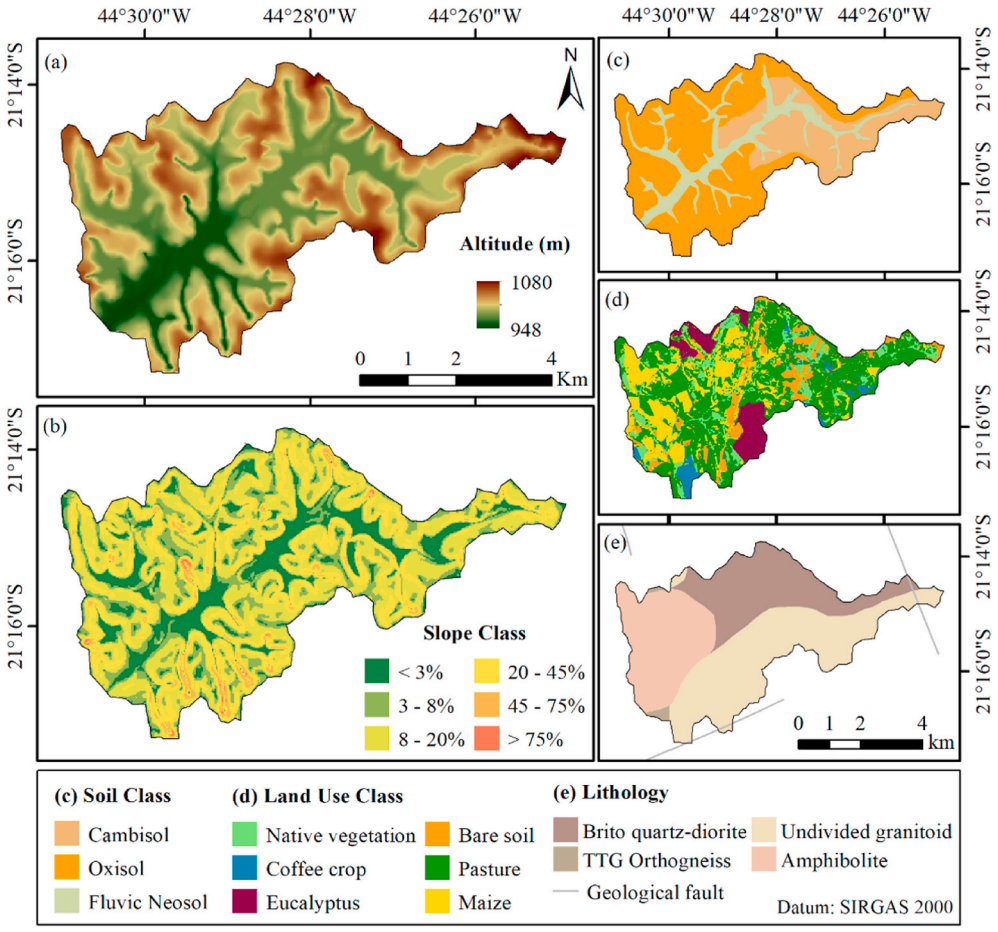


Fig. 2. Maps of (a) altitudes, (b) slope classes, (c) soil classes, (d) land uses and (e) lithology of the Jaguara creek watershed (JCW).

with records every 30 min. For conversion of monitored water levels into streamflows, a stage-discharge rating curve determined for the JCW outlet was used (Alves et al., 2019).

Twenty rainfall-runoff events were then selected to evaluate the NIUH considering the combination of different GAs and DEMs. We chose rainfall events from 2006 to 2016, characterized by different durations, depths, and intensities, preferably resulting in unimodal hydrographs. It is important to highlight that most of the rainfall-runoff events chosen for this study occurred between December and February, as this is the rainy period observed in the region. The separation of streamflow hydrographs into baseflow and DSR components was performed by applying the inflection point methodology (Chow et al., 1988), allowing the determination of the DSR hydrograph of each event. The volume of DSR was computed through numerical integration for each event, making it possible to calculate the corresponding total effective rainfall (R_E). The DSR hydrograph for each event was used to evaluate the NIUH performance considering different GAs together with different DEMs for the determination of NIUH parameters.

The temporal distribution of R_E was performed using the Curve Number method (CN-Method) (SCS, 1986), so that the sum of the R_E increments of the event resulted in the total R_E. The CN parameter was calibrated for each event following recommendations from Beskow et al. (2018) by using the observed value of the initial rainfall abstraction (Ia), which is the cumulative rainfall until the start time of the DSR observed on the hydrograph. The results were then applied as R_E hyetographs for each rainfall-runoff event analyzed in this study.

2.3. Rainfall-runoff transformation

The IUH model proposed by Nash (1957) (NIUH) considers a uniform rainfall event over a watershed, such that streamflows are routed to the watershed outlet through a cascade of n linear reservoirs with an average drainage time represented by the parameter k (Equation (01)). Subsequently, the convolution equation (Equation (02)) was used to convert the NIUH into a UH corresponding to a unit effective rainfall (R_u) of 1 mm occurring uniformly in 30 min (D).

$$u(t) = \frac{1}{k \cdot \Gamma(n)} \cdot \left(\frac{t}{k}\right)^{n-1} \cdot e^{\frac{-t}{k}} \tag{1}$$

where, u(t) denotes the NIUH ordinates (T^{-1}); t is the time interval (T); n (dimensionless) and k (T) are the NIUH parameters; and Γ refers to the Gamma function. The parameters n and k can be derived either from rainfall-runoff data for specific events or from GAs.

$$q(t) = \frac{R_u \cdot A_w}{\Delta t} \cdot \int_0^{t^*} u(t-\tau)d\tau, \quad \begin{cases} t^* = t, & t < \Delta t \\ t^* = \Delta t, & t \geq \Delta t \end{cases} \tag{2}$$

where, q (t) are the UH ordinates ($L^3\ T^{-1}$) at time t, t - τ refers to the time lag in relation to instantaneous rainfall, R_u is the unit effective rainfall (L) (1 mm), A_w corresponds to the watershed area (L^2) and Δt is the time interval (T) for the simulation of UH (30 min). It is important to note that the result of the integral is dimensionless.

The estimation of DSR hydrographs was performed by combining the UH with the R_E hyetograph which was defined using the CN Method (SCS, 1986). A routine was written in the R programming language with the aid of RStudio (RStudio Team, 2015) in order to calculate IUHs, convert them to UHs, and estimate DSR hydrographs.

2.4. Geomorphological approaches for determining the NIUH parameters

The following GAs were selected for characterization of the parameters n (dimensionless) and k (hours): GA_1 (Nash, 1960), GA_2 (Wu, 1963), GA_3 (Rosso, 1984) and GA_4 (Bhaskar et al., 1997).

GA_1 is based on the study by Nash (1960) conducted in 90 UK watersheds with a drainage area varying from 12.4 to 2224.8 km^2. Drainage area, mean watershed slope and main stream length were the most appropriate geomorphological attributes for the mathematical formulation of n (Equation (03)) and k (Equation (04)) proposed by Nash (1960).

$$n = 2.44 \cdot L^{0.1} \tag{3}$$

$$k = \frac{11.31 \cdot A^{0.3}}{S^{0.3} \cdot L^{0.1}} \tag{4}$$

where, L is the main stream length (mi), A refers to the drainage area (mi^2) and S denotes the mean watershed slope (parts per 10,000).

GA_2 originated from the study by Wu (1963), who conducted in 21 small watersheds in the state of Indiana (United States) with a drainage area between 18.13 km^2 and 259 km^2. In this approach, the best equations for T_P (Equation (05)) and k (Equation (06)) were obtained when considering drainage area, main stream length, and mean stream slope. Equation (07) is applied to calculate the parameter n.

$$T_P = \frac{31.42 \cdot A^{1.085}}{L^{1.233} \cdot St^{0.668}} \tag{5}$$

$$k = \frac{780 \cdot A^{0.937}}{L^{1.474} \cdot St^{1.473}} \tag{6}$$

$$T_P = (n-1) \cdot k \tag{7}$$

where, T_P is the time to peak discharge (h), A corresponds to the drainage area (mi^2), L is the main stream length (mi) and S_t refers to the mean stream slope (parts per 10,000).

GA_3 and GA_4 were founded on the relationships presented by Rodriguez-Iturbe and Valdes (1979) for GIUH. The multiplication of the equations for Q_P and T_P from GIUH results in IR (dimensionless), which represents the IUH of the watershed. Q_P and T_P vary according to bifurcation ratio (R_B), stream length ratio (R_L) and area ratio (R_A), and the length of the highest order stream (L_Ω). Flow velocity (v) is also required for both approaches. Such a parameter was determined in this study through a curve that relates streamflows and respective velocities obtained from hydrological field campaigns carried out at the JCW outlet (Alves et al., 2019).

Rosso (1984) formulated GA_3 after evaluating datasets from five watersheds (4.7–831 km^2) located in southern Italy, with R_B, R_L and R_A values between 2.7 and 4.9, 1.8 and 2.5, and 4.2 and 5.1, respectively. The author made some modifications to the constants of the Q_P and T_P equations (Rodriguez-Iturbe and Valdes, 1979) taking into account the values acquired from monitored rainfall-runoff events in the study watersheds. In this approach, the regression equation for calculation of parameter n (Equation (08)) was obtained by equalling IR to the NIUH equation and applying 126 combinations of R_B, R_L and R_A values. Equation (09) (parameter k) was found by substituting the T_P equation modified by Rosso (1984) in Equation (07).

$$n = 3.29 \cdot \left(\frac{R_B}{R_A}\right)^{0.78} \cdot {R_L}^{0.07} \tag{8}$$

$$k = 0.70 \cdot \left(\frac{R_A}{R_B \cdot R_L}\right)^{0.48} \cdot \frac{L_\Omega}{v} \tag{9}$$

where, R_B, R_L and R_A denote bifurcation ratio (dimensionless), stream length ratio (dimensionless) and area ratio (dimensionless), respectively, L_Ω is the length of the highest order stream (km) and v refers to the flow velocity ($km \cdot h^{-1}$). It should be noted that v in $km \cdot h^{-1}$ is used due to the simplification of the L_Ω/v ratio in the analyses performed.

GA_4 was developed by Bhaskar et al. (1997) who preserved the relationships for Q_P e T_P by equalling IR to the general NIUH equation, thus resulting in an equation for calculation of the parameter n (Equation (10)). Equation (11) (parameter k) originated from Equation (07) in combination with T_P from GIUH. These authors used data from 12 events monitored in an Indian watershed (A = 615 km^2) to compare the values of n and k with those calculated from the proposed relationships.

$$\frac{1}{\Gamma(n)} \cdot (n-1)^n \cdot e^{-(n-1)} = 0.5764 \cdot \left(\frac{R_B}{R_A}\right)^{0.55} \cdot R_L^{0.05} \tag{10}$$

$$k = \frac{0.44}{(n-1)} \cdot \frac{L_\Omega}{v} \cdot \left(\frac{R_B}{R_A}\right)^{0.55} \cdot R_L^{-0.38} \tag{11}$$

where, v^* corresponds to the flow velocity ($m \cdot s^{-1}$).

2.5. Determination of relief-based attributes for the GAs of the NIUH

The geomorphological attributes needed in GA_1, GA_2, GA_3 and GA_4 were extracted from different DEMs (Table 1). The TOPO DEM was derived from interpolation of contour lines and altitudes, which were determined using aerophotogrammetry and provided by the Brazilian Institute of Geography and Statistics (IBGE) (https://mapas.ibge.gov.br/bases-e-referenciais/bases-cartograficas/cartas). The Drainage Enforcement Algorithm written by Hutchinson (1989) was used to interpolate altimetric information. All the DEMs used in this study were georeferenced for the UTM zone 23 S cartographic projection system and SIRGAS 2000 datum.

The automatic delimitation of the JCW was performed following four steps, as recommended by Bajjali (2018) and Ray (2018): i) filling of spurious depressions, ii) analysis of flow directions, iii) determination of accumulated flows, and iv) delimitation of watershed considering the point allocated as the outlet. All the equations and methodological criteria used in the present study to obtain the geomorphological attributes were in accordance with Moura et al. (2021). Drainage area (A) was computed taking the number of cells upstream of the JCW outlet, whereas mean watershed slope (S) was calculated using the algorithm described in Burrough and McDonell (1998).

Considering only the interior portion of the watershed, its hydrography was numerically delineated (Ozdemir and Bird, 2009) from a drainage area threshold of 0.08 km^2. The topographic map from IBGE was taken as a reference to identify the main stream, measure its length (L), and compute its mean slope (S_t) using the equivalent slope method (Taylor and Schwarz, 1952).

The hydrography was then organized hierarchically according to Strahler (1952). Subsequently, the following geomorphological attributes were computed: length of the highest order stream (L_Ω), mean bifurcation ratio (R_B) and mean stream length ratio (R_L) (Horton, 1945), and mean drainage area ratio (R_A) (Schumm, 1956).

Table 1
Characteristics of each digital elevation model (DEM) used in this study.

DEM	Spatial resolution (m)	Acquisition technique	Source	Reference
TOPO	25	Altitude data interpolation at 1:50,000 scale	IBGE	–
SRTM-30	30	SAR Interferometry	USGS	Farr et al. (2007)
SRTM-90	90	SAR Interferometry	EMBRAPA	Miranda (2005)
ASTER	30	Satellite stereo images	USGS	ASTER GDEM Validation Team (2011)

2.6. Model performance

The Nash and Sutcliffe coefficient (C_{NS}) (Nash and Sutcliffe, 1970) (Equation (12)) and Normalized Root Mean Square Error (NRMSE) (Equation (13)) were used to evaluate the shape of estimated DSR hydrographs, in addition to the relative errors in estimating peak discharge (REQ_P) (Equation (14)) and time to peak discharge (RET_P) (Equation (15)).

$$C_{NS} = 1 - \frac{\sum_{i=1}^{N}\left(Q_{i_{obs}} - Q_{i_{est}}\right)^2}{\sum_{i=1}^{N}\left(Q_{i_{obs}} - \overline{Q_{obs}}\right)^2} \quad (12)$$

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(Q_{i_{obs}} - Q_{i_{est}}\right)^2}{N}}}{\overline{Q_{obs}}} \cdot 100 \quad (13)$$

$$REQ_P = \frac{\left|Q_{P_{obs}} - Q_{P_{est}}\right|}{Q_{P_{obs}}} \cdot 100 \quad (14)$$

$$RET_P = \frac{\left|t_{P_{obs}} - t_{P_{est}}\right|}{t_{P_{obs}}} \cdot 100 \quad (15)$$

where $Q_{i_{obs}}$ is the discharge observed at time i, $Q_{i_{est}}$ corresponds to the discharge estimated at time i, $\overline{Q_{obs}}$ refers to the average observed discharge, N denotes the number of ordinates of the hydrographs, $Q_{P_{obs}}$ is the observed peak discharge, $Q_{P_{est}}$ refers to the estimated peak discharge, $t_{P_{obs}}$ is the observed time to peak discharge; and $t_{P_{est}}$ corresponds to the estimated time to peak discharge.

The classification recommended by Moriasi et al. (2015) was chosen to evaluate the accuracy of the estimated DSR hydrographs: $C_{NS} \geq 0.80$: very good; $0.80 > C_{NS} \geq 0.70$: good; $0.70 > C_{NS} \geq 0.50$: satisfactory and $CNS < 0.50$: unsatisfactory. Silva et al. (2018) suggested the following criterion for accuracy assessments of long-term hydrographs: excellent for NRMSE < 10%; good if 10% < NRMSE < 20%; reasonable when 20% < NRMSE < 30%; and poor for NRMSE > 30%. It is worthwhile to note that the aforementioned classifications were suggested taking as a reference hydrographs discretized at time steps greater than or equal to 1 day. Therefore, such classifications must be used as guiding references and should not be effectively considered for evaluation of hydrographs on a sub-hourly basis. With respect to the REQ_P, Van Liew et al. (2007) presented a classification for definition of Q_P accuracy as follows: $|REQ_P| < 10\%$: very good; $10\% < |REQ_P| < 15\%$: good; $15\% < |REQ_P| < 25\%$: satisfactory and $|REQ_P| > 25\%$: unsatisfactory. In this study, the same classification was adopted for the RET_P values.

3. Results and discussion

3.1. Characteristics of the rainfall-runoff events used in this study

The rainfall-runoff events selected in this study (Table 2) presented R and R_E values varying from 23 to 101 mm and 2.5–18.7 mm, respectively. Considering all the events, CN ranged from 29.9 to 93.9 with average and median values of 57.2 and 54.6, respectively. Q_P varied between 2.75 and 22.93 $m^3 \cdot s^{-1}$ and v between 1.21 and 3.40 $m \cdot s^{-1}$, whereas the average, minimum and maximum values of DSR duration were, respectively, 15.7 h, 11 h and 25 h.

Several events were found to have Ia values equal to zero (Table 2). This can be attributed to the behavior of rainfall in the JEW where both high rainfall intensities occur in relation to infiltration capacity and an advanced rainfall pattern is predominantly experienced, that is, the peak of rainfall intensity takes place in the first 25% of rainfall duration (Alves et al., 2019). It is worth mentioning that the JCW has a predominance of Oxisols, which have a high infiltration capacity (Sartori et al., 2005). However, the generation of DSR is favored when Oxisols are combined with pasture or annual crops (Beskow et al., 2013), as these land uses result in low values of canopy interception and their management facilitates soil compaction owing to a reduction in pore space and an increase in bulk density (Ferreira et al., 2010).

Table 2
DSR duration (D), total rainfall (R), initial rainfall abstraction (Ia), effective rainfall (R_E), Curve Number (CN), peak discharge (Q_P) and flow velocity (v) of the rainfall-runoff events selected for analysis in the JCW.

Event	D (h)	R (mm)	Ia (mm)	R_E (mm)	CN	Q_P ($m^3 \cdot s^{-1}$)	v ($m \cdot s^{-1}$)
1	13.0	40.0	6.0	4.4	52.7	5.89	1.75
2	11.0	47.0	11.0	8.7	69.1	11.43	2.42
3	15.0	68.0	9.0	14.0	57.3	14.42	2.71
4	19.0	27.0	3.0	2.5	54.8	2.75	1.21
5	13.0	23.0	0.0	6.3	80.7	10.21	2.29
6	15.5	50.0	0.0	6.5	43.3	8.24	2.07
7	15.5	45.0	8.0	6.7	60.1	8.34	2.08
8	18.0	101.0	37.0	13.7	51.9	13.12	2.59
9	16.0	58.0	13.0	15.5	74.7	17.46	2.98
10	14.0	78.0	0.0	9.0	29.9	17.72	3.00
11	15.5	70.0	4.0	9.4	38.9	11.59	2.44
12	15.0	60.0	10.0	3.9	30.2	5.30	1.67
13	21.0	87.0	9.0	15.0	43.7	14.37	2.71
14	14.5	83.0	5.0	13.8	41.2	17.88	3.01
15	25.0	94.0	22.0	13.0	43.6	12.84	2.56
16	15.5	34.0	2.0	8.3	73.6	8.84	2.14
17	14.0	49.0	0.0	9.2	54.3	11.95	2.48
18	15.5	59.0	32.0	16.8	93.9	17.93	3.02
19	14.5	49.0	13.0	18.7	88.4	22.93	3.40
20	13.5	61.0	35.0	3.6	61.1	5.27	1.66

3.2. Geomorphological attributes for obtaining the NIUH parameters

In view of the DEMs evaluated in this study, the delimitation of the JCW generated different water divides and drainage networks (Fig. 3). Among the analyzed geomorphological attributes, L_Ω, R_L and S_t presented the highest coefficients of variation (CV), while the lowest CV values were observed for A and L (Table 3). As the DEMs resulted in diverging L_Ω values, R_L ratio varied considerably (Table 3). S_t was also impacted by the use of different DEMs because this attribute depends on both L and altitudes extracted from the analyzed DEM.

One can infer from Fig. 3 that the DEMs culminated in different water divides, although considerable differences in the values of A were not found (Table 3). The main stream length was one of the attributes with the smallest differences among the DEMs, whereas S_t values were clearly different. S_t is greatly sensitive to the DEM because each DEM is grounded on a specific method to derive altitude information. Similarly, S also varied with DEM such that its lowest value was obtained from SRTM-90 and its highest value from ASTER DEM. Moura et al. (2021) highlighted that the JCW is more susceptible to altitude errors due to its undulated relief.

In Fig. 3, one can observe the differences with regard to the hierarchy of the drainage network derived from the DEMs. The ASTER and SRTM-30 DEMs gave L_Ω values equivalent to twice the values found when extracting from the TOPO and SRTM-90 DEMs. The ASTER and SRTM-30 DEMs generated a greater number of first-order streams, thus indicating higher values of R_B, R_L and R_A, which range from 3 to 5, 1.5 to 3.5, and 3 to 6, respectively (Rodriguez-Iturbe and Valdés, 1979). In general, the values of R_B, R_L and R_A calculated for the JCW fell within the above-mentioned intervals.

Differences in the values of geomorphological attributes derived from DEMs have been publicized in the literature. Sahoo et al. (2006) evaluated the Ajay river basin (India) by using topographic maps in the scales of 1: 50,000 and 1: 250,000. These researchers got an order of streams (Ω) equal to 7 and 5, and L_Ω equal to 33.490 and 36.908 km, respectively, which influenced R_B, R_L and R_A. Ghumman et al. (2019) performed a hydrological modeling of the Nandna River, in Pakistan, using DEMs with spatial resolution of 30 m and 90 m. The authors

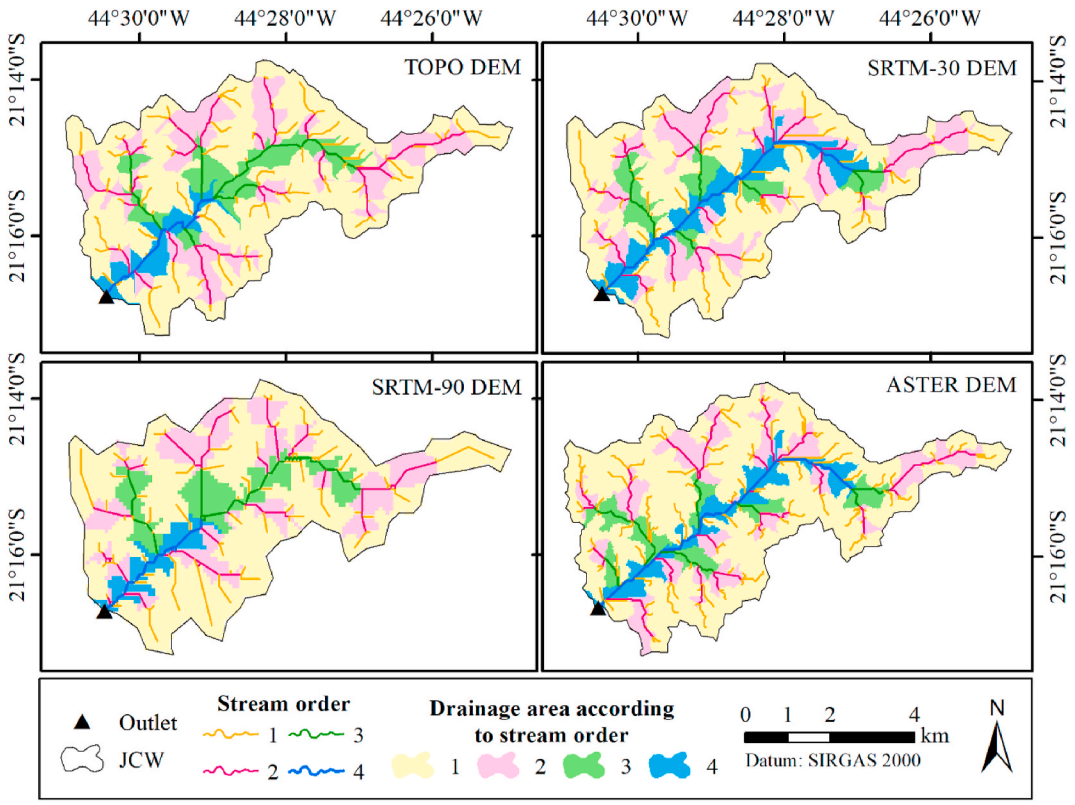


Fig. 3. Water divide, hierarchical structure of drainage network, and drainage area according to stream order, obtained for the JCW from the different DEMs evaluated in this study.

Table 3
The JCW geomorphological attributes* derived from the selected DEMs, and the coefficient of variation (CV) for each attribute.

DEM	A (km^2)	L (km)	S (%)	S_t (%)	R_B	R_L	R_A	L_Ω (km)
TOPO	31.77	12.33	11.46	0.28	4.33	2.24	5.13	4.05
SRTM-30	32.32	11.92	11.34	0.31	4.48	3.72	5.48	8.27
SRTM-90	32.12	12.42	9.42	0.38	4.37	2.36	5.23	3.80
ASTER	32.34	11.65	13.47	0.45	5.08	3.60	5.96	8.07
CV (%)	0.83	2.95	8.61	21.12	7.60	26.44	6.79	40.57

*A = drainage area; L = main stream length; S = mean watershed slope; S_t = main stream slope; R_B = bifurcation ratio; R_L = stream length ratio; R_A = area ratio; L_Ω = length of the highest order stream.

identified streams with order of 5 and 3, respectively, resulting in differences in the values of R_B (3.589 and 3.00), R_L (1.948 and 1.576) and R_A (3.943 and 3.245). Moura et al. (2021) evaluated the results regarding several geomorphological attributes extracted from different DEMs for five Brazilian watersheds (including JCW). They observed that the differences in the values of the geomorphological attributes extracted from different DEMs were more accentuated for watersheds with flatter and smaller drainage areas.

3.3. NIUH parameters obtained from the GAs

The parameters *n* and *k* calculated from geomorphological attributes (Table 3) varied according to the GAs and DEMs (Table 4). Similar values of *n* and *k* were detected for GA_3 and GA_4, however, the DEMs exerted more influence on such parameters than the GAs. As GA_1 and GA_2 are independent of flow velocity in the stream, constant values of *n* and *k* were assigned to each DEM. A single value of *n* was fixed for the JCW in the case of GA_3 and GA_4, whereas a value of *k* was determined for each rainfall-runoff event. In general, GA_2 resulted in the lowest *n* values, while GA_3 and GA_4 generated the lowest *k* values (Table 4). The

Table 4
Values of the parameters *n* and *k* calculated from the GAs in combination with different DEMs.

DEM	GA_1		GA_2		GA_3		GA_4	
	n	k (h)	n	k (h)	n	k (h)	n	k (h)
TOPO	2.99	2.37	2.40	3.00	3.05	0.17–0.48	3.04	0.17–0.48
SRTM-30	2.98	2.39	2.52	2.70	3.09	0.28–0.78	3.07	0.28–0 .79
SRTM-90	2.99	2.52	2.80	1.88	3.04	0.16–0.44	3.04	0.16–0.44
ASTER	2.97	2.28	3.02	1.65	3.18	0.27–0.76	3.15	0.27–0.77
CV (%)	0.32	4.14	10.40	27.96	2.01	29.11	1.74	29.40

high CV values identified for n and k were a consequence of the marked differences in S_t for GA_2, and R_L and L_Ω for GA_3 and GA_4. The low k values for GA_3 and GA_4 are directly related to the low L_Ω values, which are associated with the high flow velocity values.

The values of k calculated from GA_3 and GA_4 indicate a set of reservoirs that drain extremely fast. In such cases, the response of the watershed to a rainfall event occurs faster than for GA_1 and GA_2, which had a smaller number of reservoirs with a longer drainage time (Table 4). In addition, GA_1 generated values of n greater than GA_2, therefore, the former approach indicated more attenuation of peak discharges. This was not noticed for GA_3 and GA_4 due to the low values of k computed from both approaches. In view of the values obtained for k, higher peak discharges are expected for DSR hydrographs derived from GA_3 and GA_4, and higher peak discharges when calculating DSR hydrographs through P_2 in relation to P_1. The effect of n and k values can be exemplified in Fig. 4, which illustrates the DSR hydrographs estimated for event 15 using the four GAs in conjunction with the ASTER DEM.

The best performance of the NIUH was found when its parameters were computed from GA_2 and GA_1 (Fig. 4). Furthermore, GA_3 and GA_4 resulted in DSR hydrographs occurring before those observed and containing more than one peak discharge. This characteristic observed for GA_3 and GA_4 is associated with the very low values of k, which indicate a rapid increase and decrease of discharges in response to pulses of effective rainfall.

3.4. Potential of the NIUH combined with GAs and DEMs for estimation of DSR hydrographs

The NIUH was capable of representing the general shape of the DSR hydrographs when its parameters were determined from GA_1 and GA_2 (Table 5). On the other hand, GA_3 and GA_4 culminated in an unsatisfactory performance, as the values of n and k derived from such approaches did not adequately represent the response of the watershed to the rainfall events (see exemplification in Fig. 4).

One can deduce from the C_{NS} values presented in Table 5 that the best results were obtained from the combinations of GA_2 and ASTER DEM ($\overline{C_{NS}} = 0.76$), and of GA_2 and SRTM-90 DEM ($\overline{C_{NS}} = 0.75$). GA_2 in conjunction with TOPO DEM ($\overline{C_{NS}} = 0.54$) and SRTM-30 DEM ($\overline{C_{NS}} = 0.57$) provided an intermediate performance. It should be pointed out that only 3 out of 20 estimated DSR hydrographs had an unsatisfactory C_{NS}. GA_3 and GA_4 resulted in unsatisfactory C_{NS} values for 19 out of 20 events analyzed. GA_1 led to an intermediate performance of the NIUH such that higher C_{NS} values were identified for GA_1 along with ASTER DEM ($\overline{C_{NS}} = 0.51$), and lower values with SRTM-90 DEM ($\overline{C_{NS}} = 0.39$).

The NRMSE values (Table 5) reinforced that GA_3 and GA_4 generated unsatisfactory estimated DSR hydrographs. GA_2 coupled with ASTER DEM ($\overline{NRMSE} = 32.91\%$) and SRTM-90 DEM ($\overline{NRMSE} = 33.71\%$) produced the smallest errors, however, unsatisfactory estimates were found when the geomorphological attributes were taken from TOPO DEM ($\overline{NRMSE} = 48.62\%$) and SRTM-30 DEM ($\overline{NRMSE} = 46.39\%$). P_1 led to high and unsatisfactory NRMSE values, except when geomorphological attributes were extracted from ASTER DEM ($\overline{NRMSE} = 49.49\%$).

Regardless of the GA assessed in this study, ASTER DEM provided the best average values of C_{NS} and NRMSE. TOPO DEM, which is traditionally used (Alves et al., 2019; Beskow et al., 2018), provided lower mean values of C_{NS} and NRMSE. Although the DEMs exerted less influence on the estimated DSR hydrographs compared with the GAs, the representation of the estimated hydrographs changed according to the DEM. By way of example, GA_2 with attributes taken from ASTER and SRTM-90 DEMs yielded only 3 estimated DSR hydrographs with unsatisfactory C_{NS} values. Nevertheless, GA_2 together with TOPO and SRTM-30 DEMs resulted in, respectively, 8 and 7 estimated DSR hydrographs with unsatisfactory C_{NS} values.

3.5. Performance of the GAs in estimating peak discharges

Given the precision statistics presented in Table 6, GA_3 and GA_4 gave poor Q_P estimates regardless of the DEM evaluated in this study,

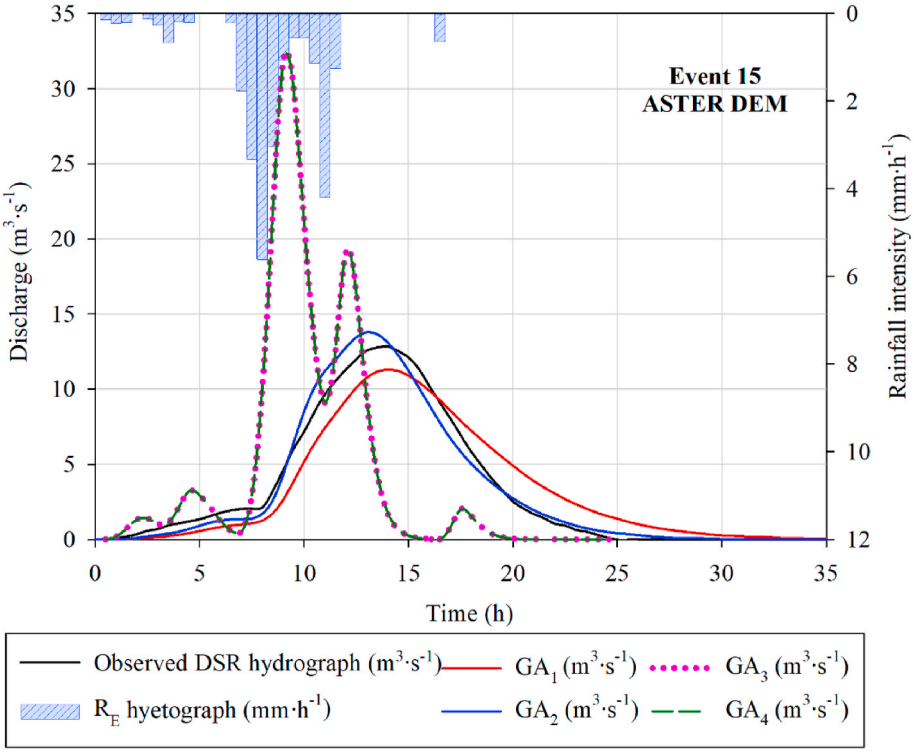


Fig. 4. R_E hyetograph and DSR hydrograph observed for event 15, as well as DSR hydrographs estimated through NIUH considering its parameters determined from the GAs combined with the ASTER DEM.

Table 5
Minimum, maximum and average values of C_{NS} and NRMSE for the rainfall-runoff events analyzed in the present study.

Approach	DEM	C_{NS}			NRMSE (%)		
		Min	Max	$\overline{C_{NS}}$	Min	Max	$\overline{NRMSE}$
GA_1	TOPO	−0.52	0.87	0.46	29.32	81.93	52.51
	SRTM-30	−0.53	0.87	0.45	29.94	82.09	52.95
	SRTM-90	−0.63	0.82	0.39	34.82	84.90	56.47
	ASTER	−0.43	0.91	0.51	25.28	79.41	49.49
GA_2	TOPO	−0.24	0.88	0.54	26.58	74.02	48.62
	SRTM-30	−0.22	0.91	0.57	22.91	73.32	46.39
	SRTM-90	0.12	0.98	0.75	12.03	62.25	33.71
	ASTER	0.14	0.98	0.76	13.70	61.72	32.91
GA_3	TOPO	−12.14	0.76	−4.33	40.09	274.51	166.41
	SRTM-30	−8.43	0.86	−2.50	30.46	232.59	131.94
	SRTM-90	−12.83	0.70	−4.66	44.58	281.71	171.93
	ASTER	−8.49	0.86	−2.53	30.89	233.26	132.51
GA_4	TOPO	−12.09	0.77	−4.31	39.76	273.97	165.99
	SRTM-30	−8.35	0.86	−2.46	30.57	231.57	131.12
	SRTM-90	−12.78	0.71	−4.63	44.20	281.14	171.49
	ASTER	−8.42	0.86	−2.50	30.91	232.48	131.90

Table 6
Minimum, maximum and average values of REQ_P (%) and RET_P (%) for the selected events.

Approach	DEM	REQ_P (%)			RET_P (%)		
		Min	Max	$\overline{REQ_P}$	Min	Max	$\overline{RET_P}$
GA_1	TOPO	10.52	49.83	27.49	0.00	160.00	49.12
	SRTM-30	11.21	50.20	28.71	3.57	170.00	50.60
	SRTM-90	15.28	52.63	30.38	0.00	160.00	52.13
	ASTER	7.02	47.68	24.75	0.00	160.00	41.34
GA_2	TOPO	16.56	53.24	32.08	0.00	150.00	41.15
	SRTM-30	11.67	50.30	28.23	0.00	150.00	39.36
	SRTM-90	1.38	35.34	13.11	0.00	150.00	28.38
	ASTER	0.03	30.65	12.37	0.00	150.00	29.21
GA_3	TOPO	46.48	488.35	207.35	12.50	70.00	44.79
	SRTM-30	2.55	329.45	144.27	0.00	110.00	40.66
	SRTM-90	55.83	504.06	216.53	12.50	70.00	46.15
	ASTER	3.28	329.45	145.38	0.00	110.00	39.31
GA_4	TOPO	45.75	487.00	206.55	12.50	70.00	44.79
	SRTM-30	1.82	325.52	142.64	0.00	110.00	40.25
	SRTM-90	55.10	502.92	215.75	12.50	70.00	45.73
	ASTER	2.67	328.40	144.28	0.00	110.00	39.31

whereas GA_2 yielded the best Q_P estimates. It should be highlighted the excellent results when the geomorphological attributes needed for GA_2 were derived from ASTER DEM ($\overline{REQ_P}$ = 12.37%) and SRTM-90 DEM ($\overline{REQ_P}$ = 13.11%), resulting in only 3 out of the 20 estimated DSR hydrographs with REQ_P classified as unsatisfactory. However, REQ_P was classified as unsatisfactory for 14 events when TOPO DEM ($\overline{REQ_P}$ = 32.08%) and SRTM-30 DEM ($\overline{REQ_P}$ = 28.23%) were used for extraction of attributes necessary for GA_2. GA_1 presented Q_P estimates with intermediate accuracy in which the largest errors were identified when SRTM-30 DEM ($\overline{REQ_P}$ = 28.71%) and SRTM-90 DEM ($\overline{REQ_P}$ = 30.38%) were used for derivation of geomorphological attributes, and the smallest errors were found for ASTER DEM ($\overline{REQ_P}$ = 24.75%).

The results regarding RET_P summarized in Table 6 demonstrate that GA_2 together with ASTER DEM ($\overline{RET_P}$ = 29.21%) and SRTM-90 DEM ($\overline{RET_P}$ = 28.38%) gave the best estimates of T_P. The other approaches showed similar behavior, with an average of 14 events having RET_P classified as unsatisfactory. In these cases, the ASTER DEM resulted in the best estimates, while TOPO DEM had the worst estimates. Although GA_3 and GA_4 have yielded good results for T_P, these approaches were not representative because they caused more than one peak discharge in the estimated DSR hydrographs (Fig. 4).

In general, GA_2 made it possible the most accurate estimation of peak discharges in terms of magnitude and time to peak. Among the DEMs, ASTER resulted in the best estimates, followed by SRTM-90. The good results obtained for GA_2 in estimating peak discharges may be related to the fact that this approach was designed for the direct estimation of T_P and k, while the others were formulated for estimation of n and k. The low accuracy of GA_3 and GA_4 is probably linked to the values of v and R_L, as this ratio exerts influence on Q_P and T_P more significantly (Khaleghi et al., 2011). It should be emphasized that R_L was one of the geomorphological attributes with the highest CV among the DEMs and had discrepant values compared with those used in the formulation of GA_3 and GA_4.

3.6. Applicability of the GAs

Fig. 5 illustrates the DSR hydrographs estimated through NIUH coupled with GA_1 and GA_2, as well as information from ASTER and SRTM-90 DEMs, for the events in which such combinations yielded the best precision statistics. One can deduce from the hydrographs depicted in Fig. 5 that both GA_1 and GA_2 when combined with SRTM-90 DEM generated peak discharges less than those obtained from ASTER DEM (Fig. 5). This behavior can be justified by the lower values of S and S_t derived from SRTM-90 DEM, thus increasing values of k.

Overall, the events with the lowest REQ_P and RET_P values were those with the greatest C_{NS} values as well as low NRMSE values (e.g. Events 11 and 14 in Fig. 5). GA_2 stood out from the other GAs, especially when combined with ASTER DEM. The best results found from this combination can be attributed some factors: i) the use of geomorphological

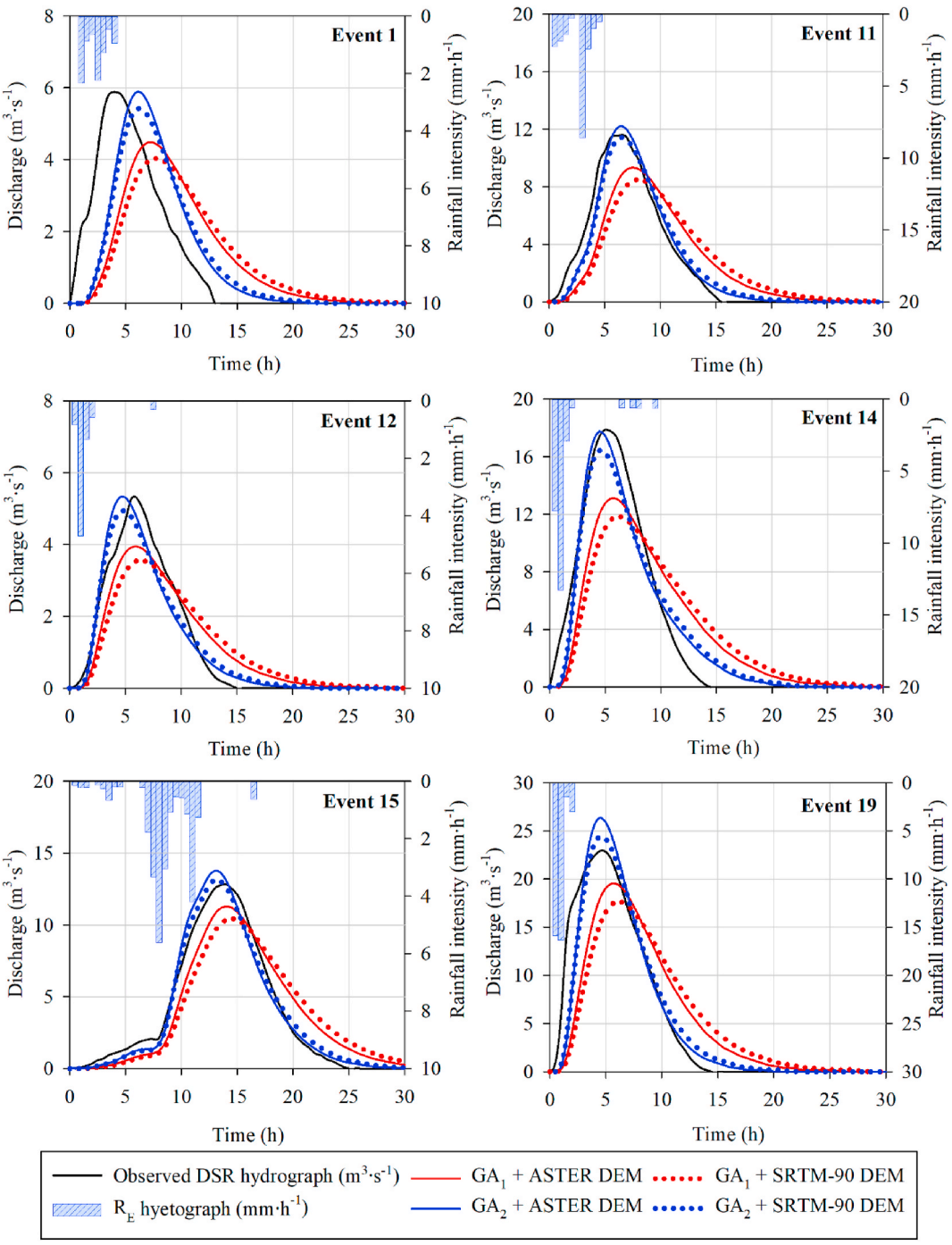


Fig. 5. R_E hyetograph, observed DSR hydrograph and DSR hydrograph estimated through NIUH in combination with GA_1 and GA_2 considering geomorphological attributes derived from ASTER DEM and SRTM-90 DEM for some events in the JCW.

attributes with low CV values, particularly A and L; ii) the greatest value of S_t was derived from ASTER, culminating in more representative values of *n* and *k* for JCW; and iii) the geomorphological attributes of JCW are similar to those of the watersheds used as a basis to formulate GA_2.

A characteristic observed in some estimated DSR hydrographs was that the C_{NS} values were not satisfactory according to the classification by Moriasi et al. (2015), despite having low REQ_P values (Tables 5 and 6). This occurred when the use of the GAs along with different DEMs resulted in a lag time between the observed and estimated discharges and unsatisfactory values of C_{NS} and NRMSE, even though discharges have been satisfactorily estimated. An example of this case can be noted for event 1, specifically for GA_2 used in conjunction with ASTER DEM (Fig. 5). However, it is important to mention that the classifications used for C_{NS} (Moriasi et al., 2015) and NRMSE (Silva et al., 2018) were based on daily hydrographs. Therefore, such values may not be suitable for 30-min time step hydrographs, as the representation of runoff is much more complex at this fine level of temporal discretization.

The unsatisfactory performance of the DSR hydrographs estimated for some events may be related to the fact that they presented short periods with rainfall followed by periods with no rainfall and then with rainfall again, which also occurred in some events evaluated by Beskow et al. (2018). This behavior of rainfall makes it difficult to model DSR hydrographs, tending to generate bimodal hydrographs and inferior

performance. It is important to stress the difficulty modeling DSR hydrographs generated by more complex rainfall events, such as those mentioned. Studies involving this type of events are scarce in the literature, and the results obtained herein serve as a basis for studies in regions with similar behavior of rainfall.

Another finding was the low performance of the GAs when their geomorphological attributes were extracted from TOPO and SRTM-30 DEMs, which have been normally used in similar studies due to their better spatial resolution (Beskow et al., 2018; Ghumman et al., 2019; Sahoo et al., 2006). This may have occurred owing to the size of the JCW (~31.8 km^2), since most of the similar studies have been carried out in larger watersheds. Another factor to consider is how altitudes were acquired in each DEM. For instance, the SRTM DEM is influenced by vegetation and steep slopes (Bourgine and Baghdadi, 2005; Li et al., 2013). The TOPO DEM, on the other hand, tends to smooth altitudes in some regions (Brubacher et al., 2012), which justifies the lower values of S and S_t in this study. The similar values for the geomorphological attributes derived from the TOPO and SRTM-30 DEMs, and their difference in relation to those taken from the ASTER DEM, were also observed by Moura et al. (2021).

In addition, it is important to stress that little is known about the influence of DEMs on DSR hydrograph estimation. Overall, other researchers have evaluated different GAs for IUH models using only one DEM (Beskow et al., 2018; Steinmetz et al., 2019) or have appraised a unique GA for an IUH model in combination with DEMs characterized by different spatial resolutions (Ghumman et al., 2019; Sahoo et al., 2006). Given the results yielded in this study, it was found that the process of acquiring information on altitudes exerted more influence on modeling than the spatial resolution of DEMs.

The results obtained for the JCW are similar to those reported by Zakizadeh and Malekinezhad (2015) who evaluated GA1 and GA3. For GA_1, these authors got C_{NS}, REQ_P and RET_P values ranging from −0.98 to 0.65, 6.9–66.0%, and 15.0–44.3%, respectively. Zakizadeh and Malekinezhad (2015) found unsatisfactory values for GA_3 as well, with average values of C_{NS}, REQ_P and RET_P equal to −2.86, 42.3% and 68.3%, respectively. On the other hand, the results found in the present study differ from those publicized by Ghumman et al. (2019) in a sub-basin of the Nandna river watershed (202 km^2) in Pakistan. These authors evaluated the impact of the spatial resolution of a DEM on DSR hydrographs estimated through NIUH together with GA_3, and got good results when using a 30-m DEM ($\overline{C_{NS}} = 0.80$; $\overline{REQ_P} = 4.67\%$) and intermediate results with a 90-m DEM ($\overline{C_{NS}} = 0.69$; $\overline{REQ_P} = 12.64\%$). The difference in performance of the estimated hydrographs that were reported by Ghumman et al. (2019) in relation to those informed herein can be justified by the size of the watershed (larger than JCW) and by the behavior of rainfall as these authors evaluated only short duration rainfall events.

The DSR hydrographs generated from GA_4 corroborated those estimated by Beskow et al. (2018) for other 20 events in the JCW. These authors assessed NIUH in conjunction with GA_4 and TOPO DEM and found average C_{NS} and REQ_P values equal to −4.66 and 193.9%, respectively. However, the results of the present study derived from the use of GA_4 differed from those publicized by Kumar et al. (2007) and Adib et al. (2010), both using TOPO DEM. Kumar et al. (2007) studied 10 events in the Indian Ajay river watershed (1191.4 km^2) and obtained average values of C_{NS}, REQ_P and RET_P equal to 0.77, 7.23% and 16.78%, respectively. Adib et al. (2010) analyzed 13 events in the Kasilian watershed (67.5 km^2), which resulted in DSR hydrographs with average values of C_{NS}, REQ_P and RET_P equal to 0.53, 4.92% and 4.37%, respectively.

Given the fact that the use of GA_3 and GA_4 is more widespread in the literature, many studies have focused on evaluating these approaches, even in ungauged watersheds where there is no data for comparison between observed and estimated DSR hydrographs (Ali and Sil, 2017; Bhagwat et al., 2011; Rao, 2018). In addition, these approaches also require information regarding flow velocity, which can be another parameter to be estimated in ungauged watersheds (Ahmad et al., 2010). In this study, the low performance of GA_3 and GA_4 is directly related to the fact that some geomorphological attributes, such as R_L and v, differ from those used by the authors for the formulation of GA_3 (Rosso, 1984) and GA_4 (Bhaskar et al., 1997).

Readers are encouraged to proceed with caution when analyzing the values of the geomorphological attributes used for the formulation of the approaches. In the case of the JCW, the promising results for GA_2 and GA_1 can be partially explained by the similarities between the geomorphological attributes observed in the JCW and those of the watersheds used by Nash (1960) and Wu (1963) for the formulation of such GAs. The differences observed between the results obtained in this study and those reported in other studies demonstrate that this type of analysis should be conducted in more watersheds and at different locations, particularly in smaller watersheds in view of the spatial resolutions of the DEMs available in the literature.

4. Conclusions

The DEM used for extraction of geomorphological attributes exerts influence on the parameters n and k and, consequently, affects DSR hydrographs derived from NIUH. It should be emphasized that the results previously discussed and the following conclusions are valid for the watershed analyzed in this study:

i) GAs provoke greater variation in the parameters n and k than the DEM, as the approaches were founded on different attributes for their formulation.
ii) GA_1 (Nash, 1960) and GA_2 (Wu, 1963) outperform GA_3 (Rosso, 1984) and GA_4 (Bhaskar et al., 1997), even though GA_3 and GA_4 have a higher level of complexity. The use of GA_1 and GA_2 is promising, especially in ungauged watersheds and data-scarce watersheds, as they only require data extracted from a DEM and from rainfall events.
iii) The ASTER and SRTM-90 DEMs combined with GA_1 and GA_2 yield the best estimates of DSR hydrographs, such that GA_2 allows for a satisfactory estimation of DSR hydrographs resulting from high rainfall intensities and concentrated rainfall events. The results obtained in this study are of great importance, since the DEMs derived from topographic data (TOPO DEM) are commonly used in hydrology.
iv) The NIUH in conjunction with the GAs have potential to assist engineers with drainage projects and to support flood warning systems, using only watershed geomorphological attributes and rainfall events.

Author statement

The authors declare that they have seen and approved the final version of the manuscript being submitted. They warrant that the article is the authors' original work, hasn't received prior publication and isn't under consideration for publication elsewhere.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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