Catena 213 (2022) 106200

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

# Applicability of geomorphological approaches combined with the modified Clark's model for flood hydrograph estimation

Jéssica Fernanda Ogassawara [a], Samuel Beskow [a,b,*], Mauricio Dai Prá [a,c], Maíra Martim de Moura [a], Marcelle Martins Vargas [a], Venkatesh Mohan Merwade [d], Carlos Rogério de Mello [a,e]

[a] Center for Technological Development/Postgraduate Program in Water Resources, Federal University of Pelotas, Pelotas, RS, Brazil
[b] Center for Technological Development/Water Resources Engineering, Federal University of Pelotas, Pelotas, RS, Brazil
[c] Hydraulic Research Institute, Federal University of Rio Grande do Sul, Porto Alegre, RS, Brazil
[d] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN, United States
[e] Water Resources Department, Federal University of Lavras, Lavras, MG, Brazil

ARTICLE INFO

*Keywords:*
Direct surface runoff
Lumped parameterization scheme
Semi-distributed parameterization scheme
ModClark
Relief attributes
HEC-HMS

ABSTRACT

Among the techniques available for modeling direct surface runoff (DSR), the Unit Hydrograph and the Instantaneous Unit Hydrograph (IUH) have been widely used. Clark's IUH (CIUH) stands out, mainly in its distributed version known as ModClark, which has two parameters: time of concentration ($t_c$) and storage coefficient (R). The best procedure is to determine $t_c$ and R from observed rainfall-runoff datasets, however, they usually are not available due to a lack of monitoring or insufficient temporal discretization. Thus, geomorphological approaches have been developed to allow the estimation of $t_c$ and R from relief information of the watershed, however, their use is little disseminated in literature. In addition, only a few studies have evaluated the influence of spatial discretization of the watershed on the definition of $t_c$ and R (parameterization) and its impact on the application of geomorphological approaches for the ModClark. This work aimed to evaluate the ModClark performance for estimating DSR hydrographs in two Brazilians watersheds (Cadeia river watershed and Jaguara creek watershed), using four little-known geomorphological approaches ($P_{ST}$, $P_{OA}$, $P_D$, and $P_{MC}$) for the determination of its parameters under two parameterization schemes: lumped and semi-distributed. The following findings were evidenced: i) the application of the ModClark presented a satisfactory performance for estimating DSR hydrographs; ii) the characteristics of the selected rainfall-runoff events also had a significant influence on the estimation of the DSR hydrographs; iii) the lumped parameterization scheme provided more adequate parameters for ModClark, thus resulting in more accurate DSR hydrographs; iv) $P_{ST}$ gave the most accurate estimated DSR hydrographs for the Cadeia river watershed under both schemes and for the Jaguara creek watershed under the lumped scheme, whereas $P_{MC}$ outperformed the other approaches for Jaguara creek watershed under semi-distributed; and v) for watersheds with geomorphological characteristics similar to those of the watersheds analyzed in this study, $P_{ST}$ would be the most suitable geomorphological approach for determining the ModClark's parameters.

## 1. Introduction

Countless regions of the world are affected by floods, causing significant material, social and environmental losses (Ghumman et al., 2012). This phenomenon is associated with population growth, occupation of areas both at geological risks and prone to floods, and the effects of climate change on the hydrological cycle (Brunda and Nyamathi, 2015; Ryu et al., 2016).

The successful implementation of flood management and its mitigation in watersheds depends on the knowledge of watershed response to rainfall (Hao et al., 2015). Runoff can be quantified by monitoring stream flows or using rainfall-runoff models (Ryu et al., 2016). Adequate

* Corrresponding author.
*E-mail addresses:* ogassawarajessica@gmail.com (J.F. Ogassawara), samuel.beskow@ufpel.edu.br (S. Beskow), mauricio.daipra@ufrgs.br (M. Dai Prá), vmerwade@purdue.edu (V. Mohan Merwade), crmello@ufla.br (C.R. de Mello).

https://doi.org/10.1016/j.catena.2022.106200
Received 10 March 2021; Received in revised form 11 February 2022; Accepted 4 March 2022
Available online 10 March 2022
0341-8162/© 2022 Published by Elsevier B.V.

streamflow monitoring provides more accurate information than hydrological models. However, in most cases, the hydrological information systems usually cover only medium to large watersheds (Beskow et al., 2013) and make available the datasets only on a daily basis.

Given the possibility of representing hydrological processes in ungauged watercourses, rainfall-runoff models have been used to manage water resources at the watershed scale. Additionally, these models are able to simulate impacts from land-use and climate change modeling on the hydrological cycle. Among the available models, *Lavras Simulation of Hydrology* (LASH) (Beskow et al., 2011), *Soil & Water Assessment Tool* (Arnold et al., 1998), and *LImburg Soil Erosion Model* (LISEM) (De Roo et al., 1996) should be highlighted. However, the use of these hydrological models tends to be complex, as they usually require much input information for their calibration and validation.

The adequate representation of the behavior of a process or a system by a model with the least possible number of parameters is known as the principle of parsimony (Basu et al., 2010). With regard to hydrological models, parsimony refers to the ability to explain a process with the fewest possible number of parameters (Tucci, 1998). Parsimonious hydrological models require less input datasets for streamflow simulation (Kumari et al., 2021), have the advantage of facilitating calibration and uncertainty analysis (Atkinson et al., 2002; Sivapalan, 2006; Wagener et al., 2007; Basu et al., 2010), in addition to allowing their use in validation and regionalization for watersheds without streamflow monitoring or with scarcity of hydrological data (Limbrunner et al., 2010). However, these models generally use empirical equations to represent the various hydrological processes in the rainfall-runoff transformation and ignore the spatial heterogeneity of the topography (Kumari, et al., 2021). Steefel and Van Cappellen (1998) mentioned that there is a limit for the simplicity of the model, which is reached when the model cannot adequately explain the streamflow records. In other words, parsimonious models can be a potential alternative as long as they do not hinder the simulation of streamflows (Perrin et al., 2001). That is, as long as the simulation of stream flows is not impaired, application of parsimonious models can be an alternative (Perrin et al., 2001).

According to Ghorbani et al. (2017), the Unit Hydrograph (UH) (Sherman, 1932) is one of the most used techniques for estimating DSR hydrographs in watersheds. This is a more simplified alternative and widely accepted for practical purposes of hydrological engineering, which considers the linearity between effective rainfall, i.e., the part of rainfall depth that generates direct surface runoff (DSR), and discharges. The application of UH was initially restricted to monitored watersheds, as it requires rainfall-runoff information for the characterization of discharges resulting from effective rainfall ($R_E$) in a specific time interval. In light of the difficulty of its application on watersheds with scarcity of data, some empirical methodologies have been proposed, such as the Snyder's synthetic UH (Snyder, 1938), and the Triangular and Dimensionless UHs (SCS, 1971), developed by the *Natural Resources Conservation Services* (NRCS) of *United States Department of Agriculture* (USDA).

The principle of instantaneous unit hydrograph (IUH) was thereafter proposed by Clark (1945). It refers to an instantaneous unit $R_E$ event, thereby eliminating the need for uniformity of the $R_E$ in specific time intervals (Alemngus and Mathur, 2014). There are some conceptual models based on this principle such as the Clark's IUH (Clark, 1945), hereafter abbreviated as CIUH. Although the CIUH presents a more robust methodology than UH, it has been little used due to the lack of hydrological data on sub-daily time steps for determination of its parameters (Beskow et al., 2018). Peters and Easton (1996) presented a modified version of CIUH referred to as ModClark. ModClark discretizes the hydrological processes that occur in the watershed in modules (distributed model), and the watershed's response is represented by a DSR hydrograph that is derived from spatially distributed $R_E$ values (Paudel et al., 2009).

To address the scarcity of hydrological data, scientists have used hydrologic regionalization methods for runoff predictions in ungauged catchments (Zhang and Chiew, 2009), transferring calibrated hydrological parameters from gauged to ungauged watersheds (Guo et al., 2021). Numerous regionalization studies have demonstrated some apparent progress in this matter (Clark et al., 2017; Araújo et al., 2018; Arsenault et al., 2019; Choubin et al., 2019). However, some difficulties still remain, especially related to unsatisfactory simulation results and low forecast accuracy due to the heterogeneity of the earth's surface conditions and the spatial–temporal variability of climatic inputs (Sivapalan, 2003).

In this context, geomorphological approaches have been developed to determine the CIUH's parameters based on the watershed's relief attributes (Dooge, 1973; Straub et al. 2000; Mohave County, 2009; Osman and Abustan, 2012). It is noteworthy that these approaches were generated using regression techniques to fit mathematical relationships between attributes of watersheds (e.g., area, slope, and length of the main watercourse) and CIUH's parameters, which have potential to be also applied for determination of the ModClark's parameters. Therefore, the primary justification presented for applying these geomorphological approaches is the great potential of them to derive the necessary parameters for the CIUH and ModClark using only relief attributes. These geomorphological approaches allow the CIUH and ModClark application when there is no rainfall-runoff dataset for the watershed of interest, however, they have been little used (Razmkhah 2017; Beskow et al., 2018).

It should be noted that the models based on UH and IUH can be evaluated under the following modeling spatial approaches: lumped, semi-distributed and distributed. The lumped models simplify the representation of the watershed for rainfall-runoff transformation and, generally, require less input information (Lampert and Wu, 2015), not significantly compromising the rainfall-runoff conversion (Refsgaard and Knudsen, 1996). Due to the simplicity of lumped models, they are widely applied in hydrological modeling, mainly in medium and large watersheds (Refsgaard and Knudsen, 1996). However, they may compromise the predictability in time and discharge peaks of simulated hydrographs, generally lacking the calibration of their input parameters according to the observed data (Samaniego et al., 2010). On the other hand, models representing the watershed in a semi-distributed or distributed scheme can potentially better represent the hydrological processes, e.g., evapotranspiration, and direct surface runoff (Liu et al., 2017). Nevertheless, the level of detailing necessary for distributed models might make it difficult to quantify hydrological processes in some cases, as they usually require several spatially distributed data sets and high computational demand, so they are commonly used for small watersheds (Pignotti et al., 2017; Beven, 2011). On the other hand, the application of distributed models in large watersheds allows a better representation of the variability of rainfall and soil and land-use types in the watershed. Although it is difficult to differentiate small and medium watersheds uniquely with respect to the drainage area, Pilgrim and Codery (1993) stated that upper bounds of 25 $km^2$ and 500 $km^2$ can be considered, respectively.

Studies on CIUH applying a lumped modeling can be found in different regions of the world (Ghumman et al., 2014; Dariane et al., 2016; Hosseini et al., 2016; Beskow et al., 2018; Adib et al., 2019; Steinmetz et al., 2019; Ghorbani et al., 2019). However, few studies sought to evaluate the CIUH using semi-distributed modeling (Razmkhah et al., 2017; Steinmetz et al., 2019) or distributed modeling such as the ModClark (Paudel et al., 2009; Bhattacharya et al., 2012).

The ModClark (distributed model) has provided extremely promising results for hydrological studies in some watersheds where DSR hydrographs are required. Bhattacharya et al. (2012) applied the model in watersheds with drainage areas varying from 770 to 2,300 $km^2$, located in the midwest region of the USA, with a predominant humid subtropical climate (Cfa) (Köppen, 2020), for evaluating the watersheds' response to rainfall events characterized by depths from 12 to 200 mm. Paudel et al. (2009) assessed the accuracy of ModClark for rainfall-DSR

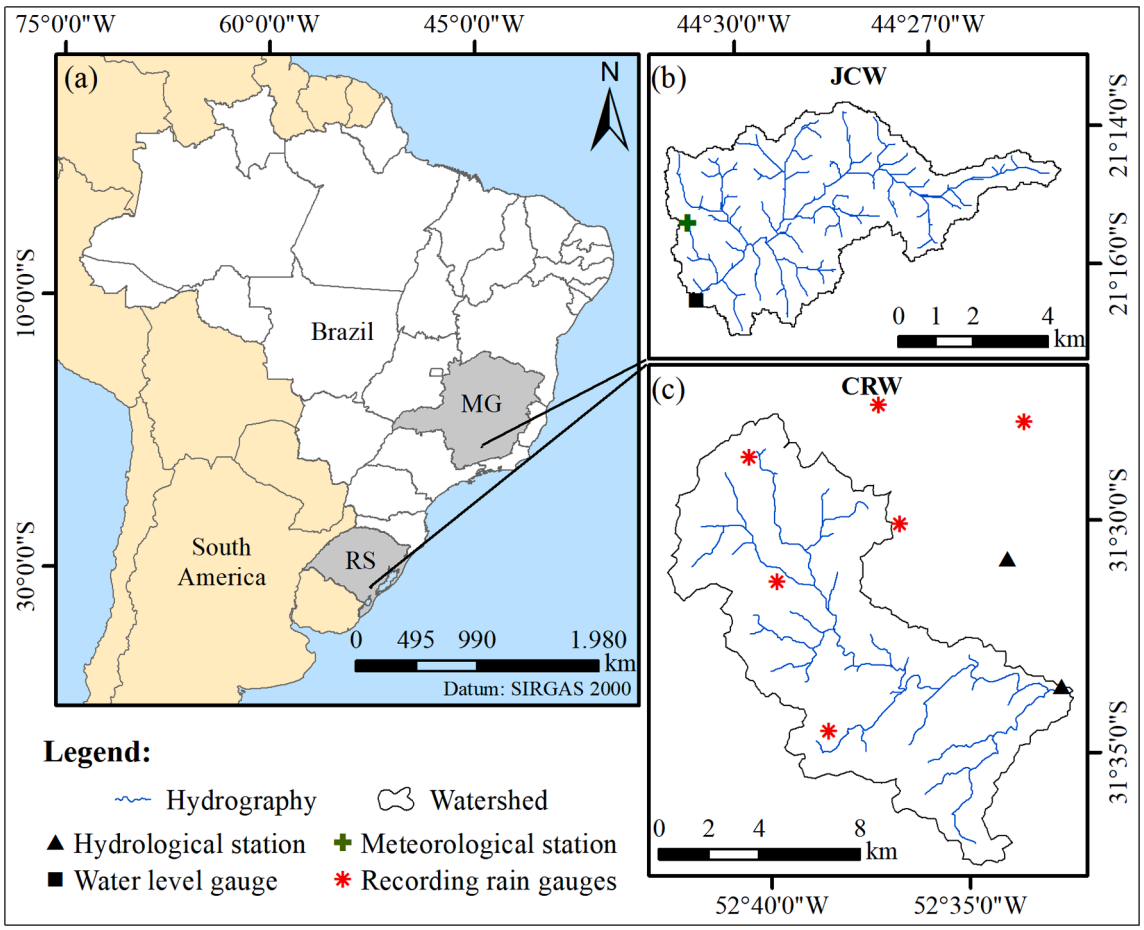



**Fig. 1.** Location of the of the Jaguara creek watershed (JCW) and the Cadeia river watershed (CRW) in the state and national context (a), as well as the existing hydrological monitoring network in each watershed (b, c).

transformation based on rainfall events monitored in two watersheds located in the western USA (160 km$^2$ and 950 km$^2$), with a predominance of the hot humid continental climate (Dfa) (Köppen, 2020). Despite these differences in the drainage area of the watersheds, the regions' climate and rainfall events, the ModClark performed well in both studies.

Despite the relevance of this kind of study for the hydrological engineering, there is a scarcity of studies focused on the applicability of geomorphological approaches combined with parameterization schemes (e.g., lumped and semi-distributed by sub-watersheds) to determine the ModClark's parameters and, consequently, estimate DSR hydrographs. The objective of this study is to help fill the aforementioned gap in literature by evaluating the performance of different geomorphological approaches coupled with the lumped and semi-distributed schemes for definition of the ModClark's parameters (Peters and Easton, 1996) and, consequently, estimation of DSR hydrographs. This evaluation was performed in two Brazilian gauged watersheds, located in two important biomes (Pampa and Atlantic Forest) with a relevant impact factor for the respective regions.

## 2. Material and methods

### 2.1. Study area

This study was conducted in the Cadeia river (CRW) and the Jaguara creek (JCW) watersheds, with drainage areas of 121.3 km$^2$ and 31.8 km$^2$, respectively. The CRW is located in the south of the Rio Grande do Sul State and JCW in the south of the Minas Gerais State, both in Brazil (Fig. 1). Cadeia river is one of the main tributaries of the Pelotas river, which is of great socio-economic importance for the region and is widely used for public water supply. Jaguara creek is located in the Upper Grande river region and flows directly into the Camargos hydropower plant reservoir, which is owned by the Companhia Energética de Minas Gerais and fundamental for the development of southern Minas Gerais State.

CRW is fully inserted in the Pampa biome, and the prevailing climate in the region is humid temperate, with no dry season and average annual rainfall of approximately 1,300 mm (Alvares et al., 2014). According to Beskow et al. (2018), the land-use classes in CRW are native forest (31.0%), bare soil (25.0%), cultivated area (13.9%), native vegetation (30.0%), and water (0.1%). The predominant soil classes in CRW, following the classification of EMBRAPA (2013), are Grayish Brown Argisol (58.4%) and Red Yellow Argisol (41.6%). Both soil classes are classified as Ultisol according to the IUSS Working Group WRB (2015).

JCW is under a humid subtropical climate, and the average annual rainfall is approximately 1,500 mm (Alvares et al., 2014), with a dry season and a rainy season. This watershed is found predominantly in the Atlantic Forest biome and comprises the following land-use classes (Beskow et al., 2013): eucalyptus (7.7%), coffee (4.1%), bare soil (9.6%), corn (22.9 %), native vegetation (13.1%), and pasture (42.6%). The predominant soil classes are Oxisols (59.8%), Haplic Cambisol (23.4%), and Fluvic Neosol (16.8%), which are classified as Oxisol, Inceptisol and Fluvent, respectively, according to IUSS Working Group WRB (2015).

### 2.2. Modified Clark's model and geomorphological approaches

The modified version of the CIUH (Clark, 1945) was used in this

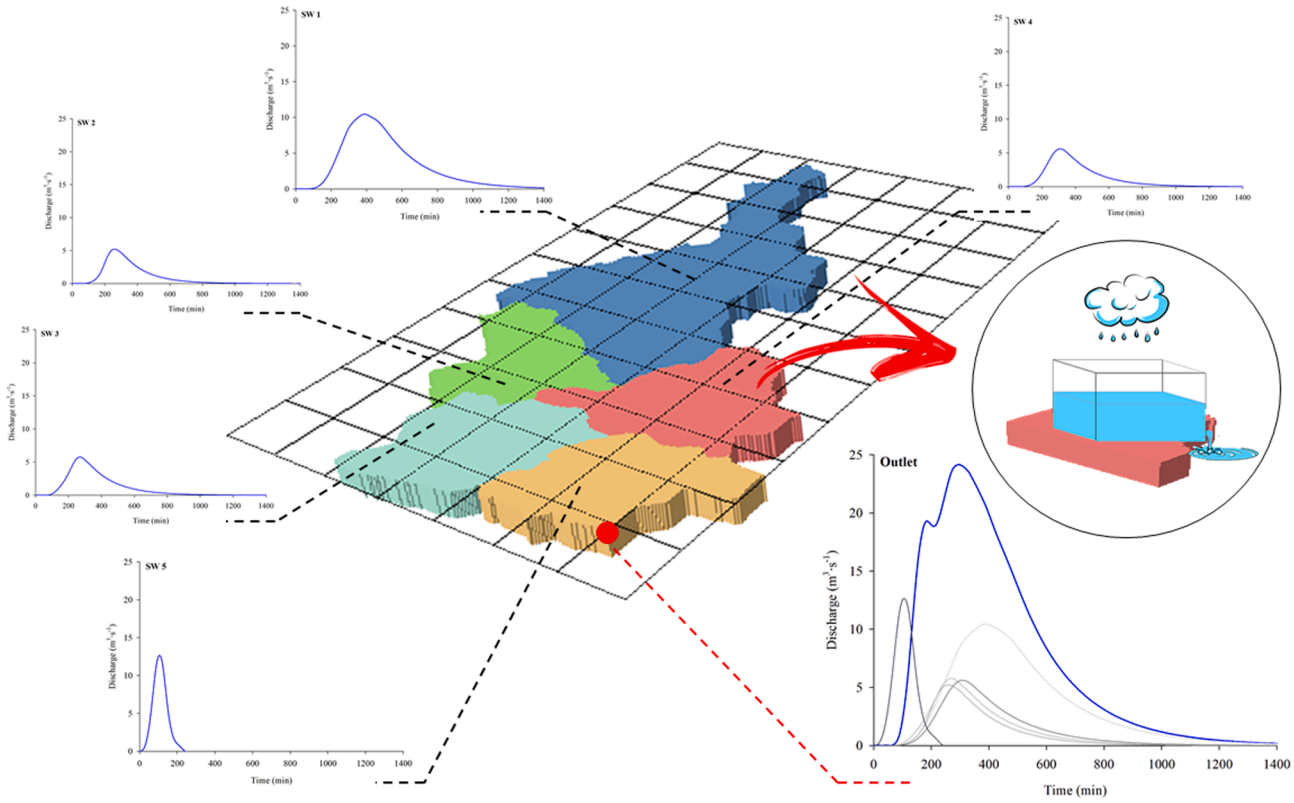



**Fig. 2.** Exemplification of how processes are computed in ModClark.

study, known as ModClark (Peters and Easton, 1996). It is grounded on the same equations as CIUH (Equations (1), 2, and 3), which considers two processes for the transformation of $R_E$ into direct surface runoff (DSR): attenuation and translation. The attenuation considers the reduction of peak discharge generated by $R_E$ due to the storage effect of the watershed, whereas the translation represents the lag time between the occurrence of $R_E$ and its contribution in the form of discharge at the watershed's outlet. In this model, the watershed is represented by a simple linear reservoir, with the storage given by the R parameter (Raghunath, 2006).

$$Q_{i+1} = 2 \bullet C_0 \bullet R_{E(i)} + C_1 \bullet Q_1 \tag{1}$$

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

$$C_1 = \frac{R - 0.5 \bullet t}{R + 0.5 \bullet t} \tag{3}$$

Where Q is the CIUH ordinate at time $i$ ($m^3 \cdot s^{-1}$); $R_E$ refers to the effective rainfall considered to be uniformly distributed (mm) and depends on the time-area histogram (TAH), which in turn depends on the time of concentration; $C_0$ and $C_1$ are dimensionless weighting coefficients (Equations (2) and (3)); t corresponds to the time step used in the modeling (h); and R refers to the storage coefficient (h).

ModClark is a distributed model which allows applying rainfall data spatially on watersheds according to a uniform grid (Bhattacharya et al., 2012). The rainfall depth on each grid cell of the watershed is converted into overland flow by using the concept of linear reservoirs (Fig. 2). Although ModClark considers the same equations as the CIUH, it simulates the processes in each cell of the grid. It is worth mentioning that it is not necessary to define TAH for the use of ModClark, as DSR travel time is computed for each grid cell representing the watershed as a function of its time of concentration, pathway traveled by overland flow from each cell to the watershed outlet, and the distance from the outlet to the most distant point.

Therefore, ModClark requires two parameters: time of concentration ($t_c$) and storage coefficient (R). These parameters were computed in the present study from four geomorphological approaches proposed by Straub et al. (2000) (Equations (4) and (5)), Osman and Abustan (2012) (Equations (6) and (7)), Dooge (1973) (Equations (8) and (9)) and Mohave County (2009) (Equations (10) and (11)), referred to as $P_{ST}$, $P_{OA}$, $P_D$, and $P_{MC}$, respectively. The values for the geomorphological attributes considered for the formulation of the four approaches as well as the $t_c$ and R values obtained for each one are presented in Table A.1 (Appendix A).

$$t_{c_{(ST)}} = \frac{0.7514 \bullet L^{0.875}}{S_0^{0.181}} \tag{4}$$

$$R_{(ST)} = \frac{3.7435 \bullet L^{0.342}}{S_0^{0.790}} \tag{5}$$

$$t_{c_{(OA)}} = 0.4444 \bullet A^{0.4867} \left(\frac{L}{S_0}\right)^{0.4868} \tag{6}$$

$$R_{(OA)} = \frac{1.2930 \bullet L^{0.5434}}{S_0^{0.3639}} \tag{7}$$

$$t_{c_{(D)}} = \frac{1.7465 \bullet A^{0.41}}{S^{0.17}} \tag{8}$$

$$R_{(D)} = \frac{80.7441 \bullet L^{0.23}}{S^{0.70}} \tag{9}$$

$$\frac{t_{c_{(MC)}} = 3.6996 \bullet A^{0.1} \bullet L^{0.25} \bullet L_{ca}{}^{0.25}}{S_0^{0.2}} \tag{10}$$

$$R_{(MC)} = \frac{0.4349 \bullet t_c{}^{1.1} \bullet L^{0.8}}{A^{0.57}} \tag{11}$$

Where $t_{c(ST)}$, $t_{c(OA)}$, $t_{c(D)}$, and $t_{c(MC)}$ refer to the time of concentration

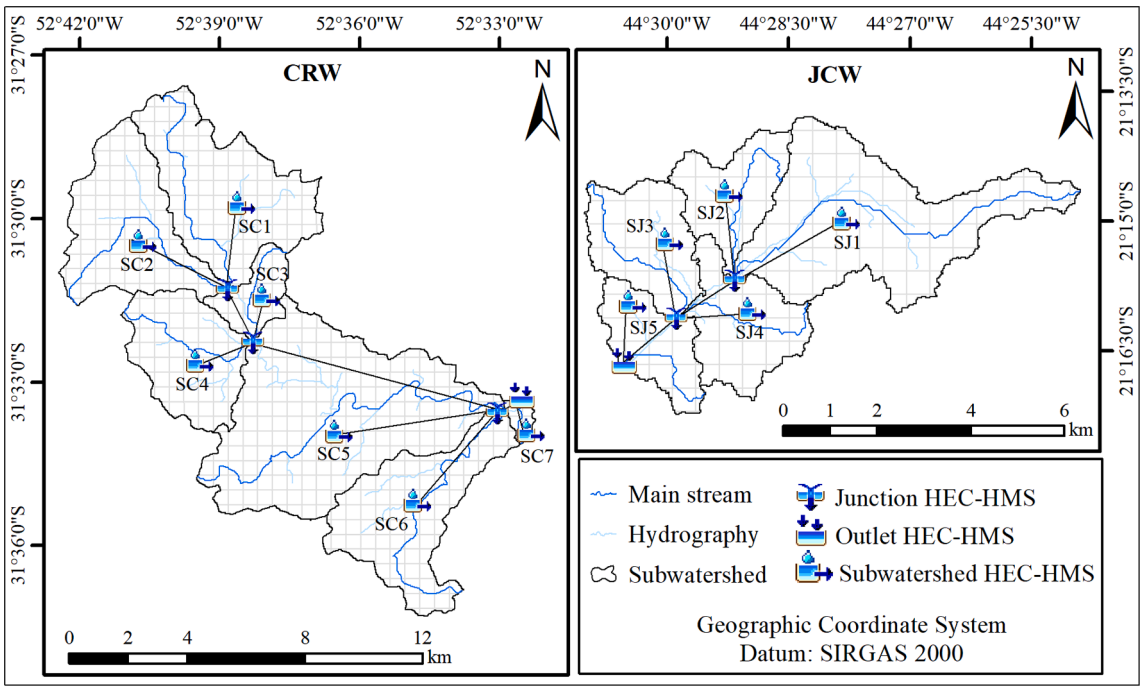



**Fig. 3.** Layout of the subwatersheds of the CRW and JCW and overlapping of the ModClark grid (0.25 km × 0.25 km).

(h); $R_{(ST)}$, $R_{(OA)}$, $R_{(D)}$ and $R_{(MC)}$ are the storage coefficients (h) for $P_{ST}$, $P_{OA}$, $P_D$, and $P_{MC}$, respectively; L corresponds to the length of the main watercourse (km); $S_0$ is the average slope of the main watercourse ($m{\cdot}km^{-1}$); A refers to the drainage area of the watershed ($km^2$); S is the average slope of the watershed (parts per 10,000), and $L_{ca}$ means the length of the watercourse from the watershed outlet to the centroid of the watershed (km).

### 2.3. Spatial database, geomorphological characterization, and parameterization schemes for ModClark

The geomorphological characterization of the watersheds and their subwatersheds is necessary for the application of $P_{ST}$, $P_{OA}$, $P_D$, and $P_{MC}$. For the CRW, contour lines and points of known altitude were extracted from the cartographic base elaborated by Hasenack and Weber (2010) in the scale of 1:50,000, whereas its digital elevation model (DEM) was obtained from the interpolation at 25 m cells using the Drainage Enforcement Algorithm (Hutchinson, 1989). In the case of JCW, its DEM was derived from the Advanced *Spaceborne Emission and Reflection Radiometer* (ASTER) sensor, with a spatial resolution of 30 m, available on the *United States Geological Survey* (USGS). The choice of DEM ASTER for JCW was due to the findings reported by Moura et al. (2021a).

The watershed delineation, geomorphological characterization, and evaluation of the geomorphological approaches for definition of the ModClark's parameters ($t_c$ and R) were performed according to two parameterization schemes: 1) lumped, and 2) semi-distributed. In other words, a single $t_c$ and R pair was obtained for the lumped parameterization scheme, whereas a pair of these values was calculated for each subwatershed in the case of the semi-distributed parameterization scheme. All the procedures related to the delineation and geomorphological characterization were performed using the ArcGIS 10.1 software (ESRI, 2014), following the methodologies described in Rai et al. (2017) and Jumbo et al. (2017).

### 2.4. Hydrological events

Eight rainfall-runoff events were selected for each watershed, covering rainfall events with different durations, depths, and average intensities. These events were organized to generate hyetographs and hydrographs with a 30-minute temporal discretization, thus making it possible a detailed temporal representation of the hydrographs since the time of concentration for CRW and JCW is 7.5 and 5.5 h, respectively (Moura et al., 2021b).

For CRW and its subwatersheds, the hyetographs were determined using datasets of six self-recording rain gauges and two hydrological stations (Fig. 1), and these records were spatialized through the Thiessen Polygon method (Thiessen and Alter, 1911). An average hyetograph was obtained for the entire watershed in the case of lumped parameterization scheme, whereas an average hyetograph was defined for each subwatershed in the semi-distributed parameterization scheme. As JCW has only one meteorological station to provide rainfall information, the resulting hyetographs for lumped parameterization scheme were the same as those for semi-distributed parameterization scheme (Fig. 1).

For each rainfall event analyzed in the present study, the watershed response was represented in terms of the variation of stream flows over time at its outlet (hydrograph). Streamflow data were obtained by combining water level monitoring at each cross section of interest and the respective stage-discharge rating curve. DSR hydrographs were computed using the Inflection Method (Chow et al., 1988) and DSR volume was determined by numerical integration. The effective rainfall ($R_{E,total}$) of each event was calculated by the ratio between the DSR volume and the area of the watershed, which was then temporally distributed in accordance with the Curve Number (CN) method (SCS, 1986).

### 2.5. Hydrological modeling in HEC-HMS

The rainfall-runoff transformation was conducted by using the ModClark with the aid of the *Hydrologic Engineering Center - Hydrologic Modeling System* (HEC-HMS) (USACE, 2015), in version 4.2.1. The grid model was generated by using a tool known as HEC-GeoHMS, which is an extension embedded in the ArcGIS 10.1 software (ESRI, 2014) and provides a set of geospatial functionalities intended for hydrological studies. This extension made it possible to deal with spatial data in GIS format and generate input files compatible with the HEC-HMS according to two parameterization schemes: lumped and semi-distributed by

**Table 1**
Geomorphological attributes of CRW, JCW and their subwatersheds.

| Watershed | A ($km^2$) | S (%) | L (km) | $S_0$ ($m \cdot km^{-1}$) | $L_{ca}$ (km) | Altitude (m) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Max | Min |
| CRW | 121.2 | 18.4 | 23.2 | 6.6 | 15.2 | 362.9 | 40.0 |
| SC1 | 21.9 | 12.3 | 9.3 | 12.7 | 4.4 | 349.5 | 179.9 |
| SC2 | 18.9 | 11.0 | 9.1 | 9.7 | 5.3 | 353.0 | 179.9 |
| SC3 | 4.7 | 22.1 | 4.2 | 4.9 | 1.9 | 331.9 | 160.0 |
| SC4 | 14.0 | 21.1 | 6.4 | 7.4 | 3.0 | 362.9 | 160.0 |
| SC5 | 41.7 | 22.0 | 16.4 | 5.9 | 9.5 | 316.8 | 54.5 |
| SC6 | 19.2 | 21.9 | 13.4 | 5.7 | 6.2 | 327.0 | 52.8 |
| SC7 | 0.9 | 11.4 | 1.5 | 80.2 | 0.5 | 157.5 | 40.0 |
| JCW | 31.9 | 13.5 | 12.6 | 6.1 | 4.5 | 1082.0 | 950.0 |
| SJ1 | 13.8 | 15.0 | 9.3 | 6.3 | 4.0 | 1082.0 | 958.0 |
| SJ2 | 4.2 | 16.6 | 4.2 | 17.1 | 2.1 | 1056.0 | 958.0 |
| SJ3 | 5.1 | 16.9 | 4.6 | 13.7 | 2.1 | 1054.0 | 954.0 |
| SJ4 | 5.2 | 15.0 | 4.0 | 16.7 | 1.8 | 1073.0 | 954.0 |
| SJ5 | 3.6 | 15.4 | 2.7 | 20.0 | 0.7 | 1053.0 | 950.0 |

A: Drainage area; S: Average watershed slope; L: Length of the main watercourse; $S_0$: Slope of the main watercourse; $L_{ca}$: length of main watercourse measured from the outlet to the centroid of the watershed.

subwatersheds. The dimension of each ModClark *grid* cell overlaid in both watersheds was 0.25 × 0.25 km, totaling 574 cells and 207 for CRW and JCW, respectively (Fig. 3).

Regardless of the parameterization scheme, the inputs for modeling the DSR hydrographs were $t_c$ and R, hyetograph, rainfall initial abstraction ($I_a$), and CN. In the original SCS/CN method, $I_a$ is often assumed to be 0.2 (SCS, 1986), however, several studies suggest that this value may be in a different range, rarely satisfying this condition (Caviedes-Voullième et al., 2012; Beck et al., 2009; Mishra et al., 2003). We followed the recommendations made by Cunha et al. (2021), who assessed the impact of using tabulated CN values on $R_E$ estimation based on rainfall-runoff events monitored in the CRW, and chose to calibrate $I_a$ and CN for each rainfall-runoff event. These researchers found that tabulated CN values, in most of the events evaluated in the CRW, were overestimated and, consequently, resulted in overestimation of $R_E$.

The initial values for the calibration parameters of the SCS/CN (SCS, 1986) – under the two parameterization schemes, were obtained by applying the SCS/CN methodology in electronic spreadsheets according to the lumped parameterization scheme for each rainfall-runoff event. Calibration was performed in the HEC-HMS environment by minimizing the sum of squared residuals between the observed and estimated hydrological data (Joo et al., 2014) with the aid of the Nelder-Mead algorithm (Nelder and Mead, 1965). Nelder and Mead's algorithm fetches the optimal values of these unknown parameters without using derivatives of the objective function to guide the search for alternative parameter values (USACE, 2015).

The calibration of CN and $I_a$ was performed together with the adjustment of the ModClark's parameters ($t_c$ and R), however, the values of $t_c$ and R were not used in the subsequent simulations of the DSR hydrographs. In other words, only the calibrated values of CN and $I_a$ were considered in the two parameterization schemes in an attempt to reduce the uncertainties associated with the estimation of the DSR volume, thereby guaranteeing a good representation of estimated DSR depths. The values used for $t_c$ and R in the simulations were those calculated through the geomorphological approaches ($P_{ST}$, $P_{OA}$, $P_D$, and $P_{MC}$).

### 2.6. Performance of the modified Clark's model combined with different geomorphological approaches

The following metrics were used to compare the observed DSR hydrographs and those estimated from ModClark combined with the geomorphological approaches ($P_{ST}$, $P_{OA}$, $P_D$, and $P_{MC}$) used for determination of its parameters under lumped and semi-distributed parameterization schemes: normalized root mean square error (NRMSE) (Equation (12)), Nash-Sutcliffe coefficient ($C_{NS}$) (Equation (13)), and peak discharge relative error ($ER_{Qp}$) (Equation (14)).

$$NMRSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Q_{i,obs}-Q_{i,est})^2}{N}}}{\overline{Q_{obs}}} \cdot 100 \quad (12)$$

$$C_{NS} = 1 - \frac{\sum_{i=1}^{N}(Q_{i,obs}-Q_{i,est})^2}{\sum_{i=1}^{N}(Q_{i,obs}-\overline{Q_{obs}})^2} \quad (13)$$

$$ER_{QP} = \frac{(Q_{p,obs}-Q_{p,est})}{Q_{p,obs}} \cdot 100 \quad (14)$$

Where $Q_{i,obs}$ is the observed discharge ($m^3 \cdot s^{-1}$) at time *i*, $Q_{i,est}$ corresponds to the estimated discharge ($m^3 \cdot s^{-1}$) at time *i*, $\overline{Q_{obs}}$ is the average observed discharge ($m^3 \cdot s^{-1}$), N refers to the number of observations, $Q_{p,obs}$ is the observed peak discharge ($m^3 \cdot s^{-1}$), and $Q_{p,obs}$ corresponds to the estimated peak discharge ($m^3 \cdot s^{-1}$).

NRMSE is used to express the quality of the results and can be classified as (Silva et al., 2018): excellent (NRMSE < 10%), good (10% < NRMSE < 20%), reasonable (20% < NRMSE < 30%) or inadequate (NRMSE > 30%). $C_{NS}$ reflects the efficiency of the application of the model for estimations, mainly of flood hydrographs. Considering that $C_{NS}$ classifications were not found for hydrographs estimated at sub-daily time steps, so we opted to use the classification suggested by Moriasi et al. (2015): very good ($C_{NS} > 0.80$), good ($0.80 \leq C_{NS} \leq 0.70$), satisfactory ($0.70 \leq C_{NS} \leq 0.50$), and unsatisfactory ($C_{NS} < 0.50$). $ER_{Qp}$ relates the estimated peak discharges with those observed. The thresholds proposed by Van Liew et al. (2007) were applied for $ER_{Qp}$ assessment: very good ($|ER_{Qp}| < 10\%$), good ($10\% < |ER_{Qp}| < 15\%$), satisfactory ($15\% < |ER_{Qp}| < 25\%$), and inadequate ($|ERQp| > 25\%$).

The aforementioned metrics were also applied to evaluate the ModClark's performance with respect to the calibration of its parameters used in the modeling. This option would generate the best results when applying the ModClark, reinforcing the need for the calibration methodology adopted in section 2.5.

## 3. Results and discussion

### 3.1. Geomorphological attributes and the modified Clark's model parameters

CRW and JCW were discretized, respectively, in seven (SC1 - SC7) and five subwatersheds (SJ1 - SJ5) (Fig. 3). The geomorphological attributes of these watersheds (lumped parameterization scheme) and their subwatersheds (semi-distributed parameterization scheme) necessary for the geomorphological approaches evaluated in this study to determine the ModClark's parameters are presented in Table 1.

The drainage area of JCW is 73.7% smaller than that of CRW, while its average slope is 26.6% lower. The subwatersheds named as SC1, SC2, and SC7 have undulated slope, and the others present strong-undulated slope (EMBRAPA, 1979). All the JCW subwatersheds were categorized as "undulated slope" (EMBRAPA, 1979). Although altitudes in JCW are higher than those observed in CRW, their amplitude is smaller for JCW, thereby justifying the lower average slope of this watershed and of its subwatersheds (Table 1).

Greater values of $S_0$ for the JCW subwatersheds resulted from their lower values of L combined with the smaller amplitude of altitudes. For SC7, the high $S_0$ value is directly related to the watershed size and the scale of the DEM. However, since this subwatershed has a small drainage area (equivalent to 0.74% of CRW), its geomorphological attributes had less impact on the modeling performance. The values of $L_{ca}$ are directly related to L, i.e., the subwatersheds with the highest values of L are the same as those with the highest values of $L_{ca}$ (Table 1).

The lower $t_c$ and R values obtained for JCW in the lumped parameterization scheme are related to its smaller drainage area in comparison

**Table 2**
Characteristics of the rainfall-runoff events used in the modeling of CRW and JCW.

| Event | Beginning of the event | | End of the event | | $R_{total}$ | $i_m$ | DSR Vol | $Q_{PEAK}$ |
|---|---|---|---|---|---|---|---|---|
| | Date | Hour | Date | Hour | (mm) | (mm·h$^{-1}$) | (mm) | (m$^3$·s$^{-1}$) |
| CRW | | | | | | | | |
| E1 | 18/07/2015 | 22:00 | 21/07/2015 | 15:00 | 113.3 | 1.7 | 34.5 | 72.2 |
| E2 | 20/09/2015 | 17:00 | 22/09/2015 | 17:00 | 47.5 | 1.1 | 7.5 | 25.7 |
| E3 | 22/09/2015 | 21:30 | 24/09/2015 | 06:30 | 41.6 | 1.7 | 13.2 | 74.8 |
| E4 | 20/10/2015 | 04:30 | 21/10/2015 | 09:00 | 37.3 | 1.3 | 9.9 | 48.1 |
| E5 | 06/01/2016 | 11:00 | 07/01/2016 | 07:00 | 36.9 | 1.8 | 8.3 | 57.5 |
| E6 | 12/06/2017 | 22:00 | 14/05/2017 | 04:30 | 105.0 | 2.5 | 15.0 | 48.8 |
| E7 | 28/06/2017 | 22:00 | 01/07/2017 | 17:00 | 42.5 | 0.6 | 3.0 | 7.1 |
| E8 | 29/09/2018 | 10:00 | 01/10/2018 | 06:30 | 37.8 | 0.8 | 12.1 | 41.3 |
| JCW | | | | | | | | |
| E1 | 26/06/2007 | 16:10 | 27/01/2007 | 16:10 | 68.0 | 2.8 | 14.5 | 14.4 |
| E2 | 08/12/2011 | 17:21 | 09/12/2011 | 00:18 | 101.0 | 3.2 | 14.0 | 13.1 |
| E3 | 03/01/2012 | 19:46 | 05/01/2012 | 01:16 | 58.0 | 1.9 | 15.9 | 17.5 |
| E4 | 29/01/2012 | 14:18 | 30/01/2012 | 05:48 | 49.0 | 2.5 | 19.3 | 22.9 |
| E5 | 28/12/2012 | 12:06 | 29/12/2012 | 15:06 | 78.0 | 2.8 | 9.3 | 17.7 |
| E6 | 22/03/2015 | 08:50 | 24/03/2015 | 07:20 | 87.0 | 1.9 | 15.4 | 14.4 |
| E7 | 03/01/2016 | 07:49 | 04/01/2016 | 21:49 | 83.0 | 2.2 | 14.2 | 17.9 |
| E8 | 15/01/2016 | 16:19 | 17/01/2016 | 13:19 | 94.0 | 2.1 | 13.2 | 12.8 |

$R_{total}$: total rainfall depth; $i_m$: average rainfall intensity; DSR Vol: direct surface runoff volume; $Q_{PEAK}$: peak discharge.

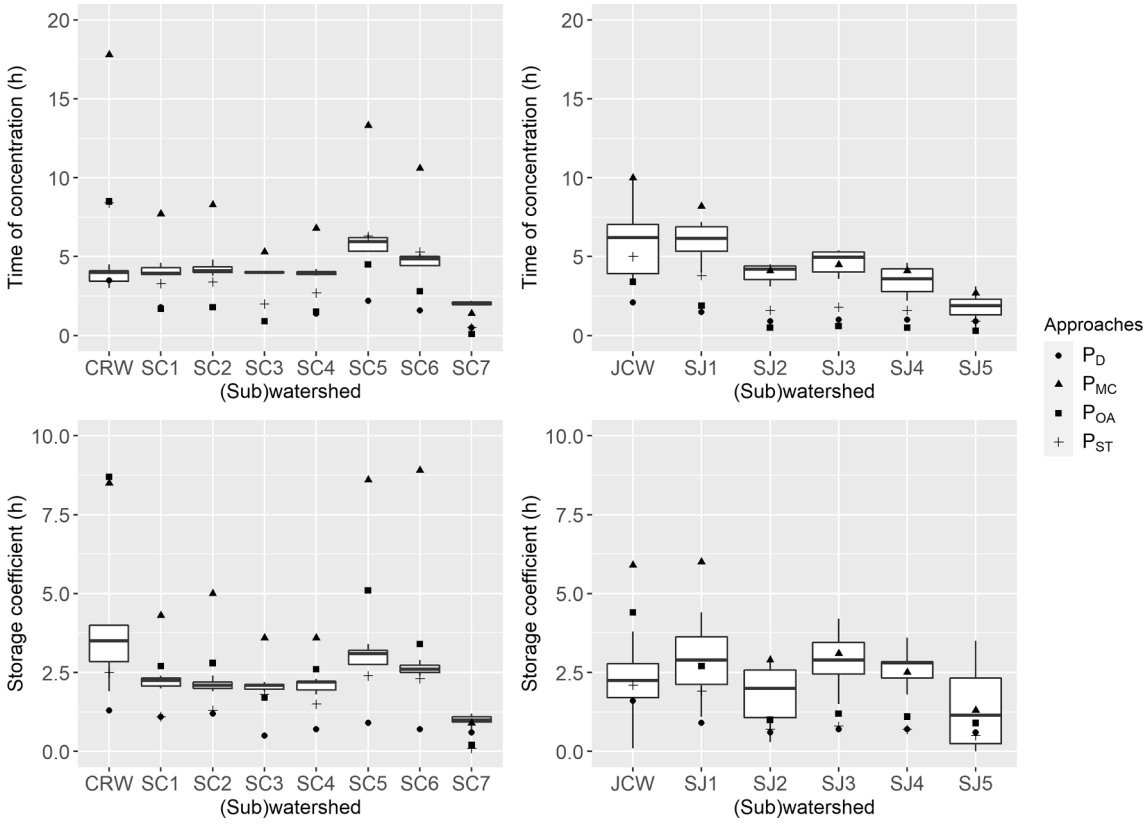



**Fig. 4.** Representation of the variation in calibrated $t_c$ and R values among both rainfall-runoff events and subwatersheds using boxplots as well as $t_c$ and R values derived from geomorphological approaches ($P_D$, $P_{MC}$, $P_{OA}$, $P_{ST}$) for both parameterization schemes (see scattered points overlapped on boxplots).

to CRW (see Table B.1 in Appendix B). The magnitude of the R parameter indicates that JCW has a shorter residence time of water in the linear reservoir than CRW, that is, the contribution of the furthest areas of the watershed to the discharges occurs more quickly. For the semi-distributed parameterization scheme, in general, the subwatersheds with larger areas and lower values of $S_0$ resulted in the highest $t_c$ and R values, except for SC7, for which the $S_0$ value was too high due to the DEM scale.

### 3.2. Rainfall-runoff events: Characterization and calibrated parameters

Although peak discharges ($Q_{PEAK}$) were greater in CRW (10.8 to 50.5 m$^3$·s$^{-1}$) than those observed in JCW (12.8 to 22.9 m$^3$·s$^{-1}$), in general, the rainfall events in the former watershed presented smaller rainfall depths ($R_{total}$) (Table 2). These peculiarities concerning discharges are associated with different factors, such as rainfall regime, watershed slope and area, land use, type of soil, and antecedent soil moisture content. These factors may exert influence on the generation of DSR

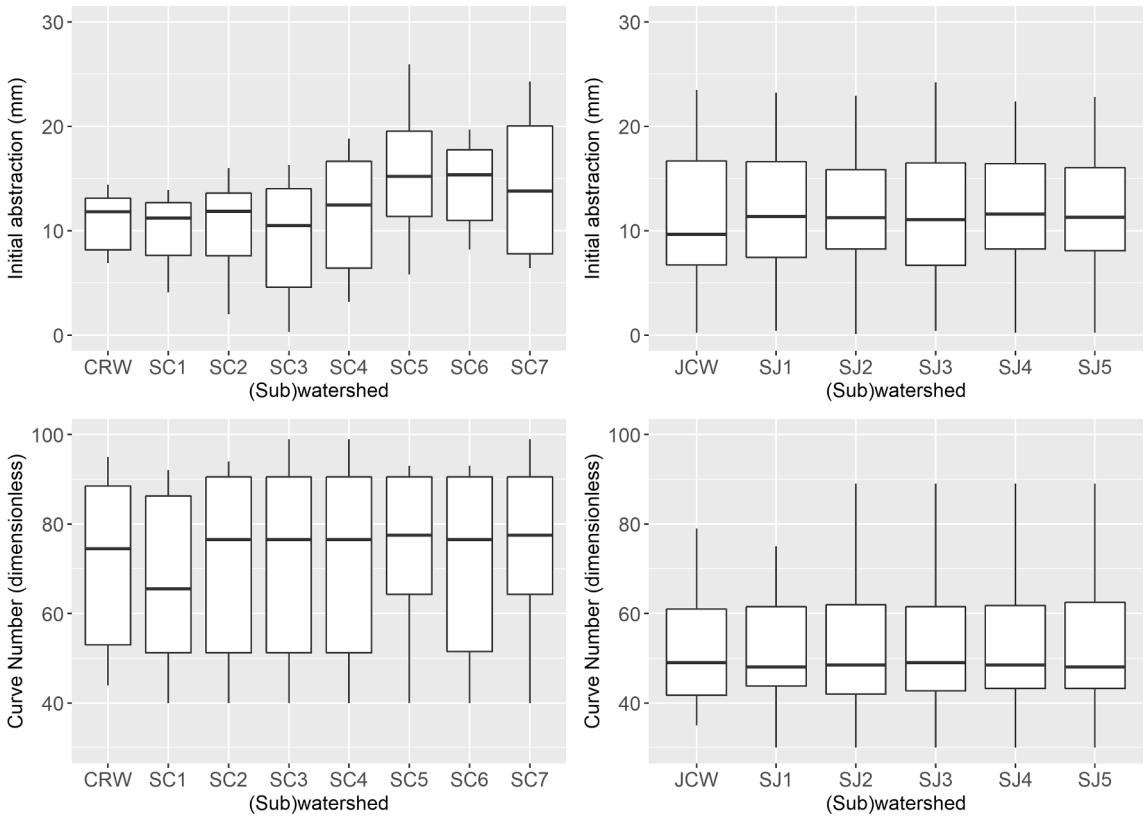



**Fig. 5.** Representation of the variation in calibrated $I_a$ and CN values (for both parameterization schemes) among both rainfall-runoff events and subwatersheds using boxplots.

throughout watersheds, and control different hydrological processes linked to DSR over time and space.

The duration of the rainfall events evaluated in the CRW varied from 20 to 67 h and its average value was 39.6 h. In contrast, the average duration of rainfall events in JCW was 28.7 h, ranging from 7 to 46 h. The highest average intensities ($i_m$) were observed in JCW (1.9 to 3.2 $mm{\cdot}h^{-1}$), whereas CRW had $i_m$ values varying between 0.6 and 2.5 $mm{\cdot}h^{-1}$. As most of the rainfall events in CRW had a longer duration and more evenly distributed depths over time, their intensity tended to be attenuated. Based on Table 2, one can observe that the most intense rainfall events in the CRW occurred in the winter and autumn (April to September), corresponding to events generated by frontal systems. On the other hand, the rainiest events in the JCW were concentrated in the summer (December to March), i.e., most of them from convective events.

Although the values of $t_c$ and R considered in the modeling have been derived from the geomorphological approaches (see Table B.1 in Appendix B), they were also calibrated for each rainfall-runoff event (see Table B.2 in Appendix B) in conjunction with CN and $I_a$ under both parameterization schemes in an attempt to reduce the uncertainty in CN determination, as mentioned in section 2.5. One can compare $t_c$ and R values derived from the geomorphological approaches (Table B.1 - Appendix B and scattered points in Fig. 4) with the variation in their values found after calibration event by event (boxplots in Fig. 4 and Table B. 2 - Appendix B) for both parameterization schemes.

It can be inferred from Fig. 4 that the calibrated $t_c$ values found for the lumped parameterization scheme in CRW and in JCW were similar to those determined from $P_D$ and $P_{ST}$, respectively. With respect to the semi-distributed scheme, $P_{ST}$ and $P_{MC}$ generated the most coherent $t_c$ values for the subwatersheds of CRW and JCW, respectively. Overall, $P_{ST}$ was the approach that generated the most accurate R values in both schemes, however, it should be mentioned that $P_{MC}$ also resulted in good estimates of R for the subwatersheds of JCW.

Still analyzing the $t_c$ and R results in Fig. 4 (semi-distributed scheme), one can notice that $P_{MC}$ gave estimations greater than the maximum values calibrated for the subwatersheds of CRW (see boxplots). On the other hand, $t_c$ and R values derived from $P_{MC}$ for JCW (semi-distributed scheme) were close to the median values obtained from the calibrated values for different rainfall-runoff events (see boxplots for SJ2, SJ3, SJ4, SJ5). In the case of CRW, $t_c$ and R values calculated from $P_{ST}$ were similar to the median values found for its subwatersheds. $P_D$, on the other hand, resulted in underestimations of $t_c$ and R compared to their calibrated values for both watersheds and parameterization schemes. These observations are in agreement with the hypothesis that these geomorphological approaches may not be able to generate accurate DSR hydrographs for the studied watersheds. Nevertheless, it is still necessary to apply them in the modeling in order to appraise how much the underestimations and overestimations in $t_c$ and R can impact the performance of ModClark for simulating DSR hydrographs in the studied watersheds.

In general, the calibrated values of $I_a$ and CN (Fig. 5) did not present discrepancies when comparing the two parameterization schemes. $I_a$ was the parameter with the greatest sensitivity in relation to the parameterization schemes for both watersheds (e.g., events 2, 6 and 7 for CRW and events 4, 5 and 6 for JCW). Overall, JCW had higher initial abstractions than CRW (see characteristics of the boxplots in Fig. 5). However, the subwatersheds of CRW had more variation in $I_a$ values than the subwatersheds of CRW (Fig. 5). It can be inferred from Fig. 5 that the subwatersheds of JCW presented similar median $I_a$ values; on the other hand, there was a perceptible difference of median $I_a$ values among the subwatersheds of CRW, especially in the case of SC4, SC5, SC6 and SC7. This behavior was expected due to differences between CRW and JCW linked to their geomorphological characteristics. For instance, JCW has a less steep slope and deeper soils with higher infiltration than CRW, thereby resulting in lower DSR generation and greater values of $I_a$. Nevertheless, the $I_a$ values in the CRW were also significant.

**Table 3**
Performance statistics obtained after both calibration of ModClark and its use combined with four geomorphological approaches under two parameterization schemes, based on the assessment of rainfall-runoff events monitored in CRW and JCW.

| Scheme/Approach | | NRMSE (%) | | | $C_{NS}$ | | | $ER_{Qp}$ (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| CRW | | | | | | | | | | |
| Lumped | Cal | 12.1 | 34.0 | 22.5 | 0.9 | 1.0 | 1.0 | 0.0 | 9.9 | 4.3 |
| | $P_{ST}$ | 41.6 | 75.0 | 56.7 | 0.2 | 0.9 | 0.7 | 0.0 | 9.9 | 4.3 |
| | $P_{OA}$ | 65.6 | 100.5 | 83.0 | 0.0 | 0.7 | 0.4 | 32.6 | 70.9 | 45.9 |
| | $P_D$ | 22.6 | 82.6 | 58.5 | 0.3 | 0.9 | 0.7 | 5.0 | 73.0 | 44.4 |
| | $P_{MC}$ | 97.4 | 147.0 | 117.5 | −0.2 | 0.3 | −0.1 | 38.7 | 75.3 | 54.9 |
| Semi-distributed | Cal | 18.2 | 88.3 | 45.5 | 0.5 | 1.0 | 0.8 | 3.1 | 24.1 | 12.7 |
| | $P_{ST}$ | 26.4 | 96.7 | 51.7 | 0.1 | 1.0 | 0.7 | 7.7 | 38.0 | 18.4 |
| | $P_{OA}$ | 21.0 | 89.1 | 47.1 | 0.3 | 1.0 | 0.8 | 5.5 | 40.0 | 18.2 |
| | $P_D$ | 76.7 | 199.3 | 129.5 | −1.3 | 0.6 | −0.2 | 45.5 | 114.3 | 72.5 |
| | $P_{MC}$ | 65.3 | 115.9 | 88.6 | −0.3 | 0.5 | 0.3 | 27.9 | 73.1 | 48.8 |
| JCW | | | | | | | | | | |
| Lumped | Cal | 11.6 | 61.1 | 30.6 | 0.8 | 1.0 | 0.9 | 4.4 | 25.4 | 13.1 |
| | $P_{ST}$ | 24.9 | 84.9 | 48.1 | 0.7 | 0.9 | 0.8 | 5.3 | 55.9 | 26.0 |
| | $P_{OA}$ | 35.7 | 73.1 | 46.4 | 0.7 | 0.9 | 0.8 | 2.6 | 35.5 | 17.8 |
| | $P_D$ | 54.3 | 252.5 | 122.3 | −1.8 | 0.6 | −0.2 | 11.2 | 153.0 | 80.1 |
| | $P_{MC}$ | 72.5 | 134.6 | 95.2 | 0.0 | 0.6 | 0.3 | 28.8 | 77.2 | 45.0 |
| Semi-distributed | Cal | 10.2 | 67.7 | 30.3 | 0.8 | 1.0 | 0.9 | 1.6 | 11.1 | 6.2 |
| | $P_{ST}$ | 67.6 | 213.9 | 115.9 | −0.9 | 0.7 | 0.0 | 11.2 | 149.9 | 79.0 |
| | $P_{OA}$ | 68.9 | 220.4 | 122.3 | −1.1 | −0.7 | −0.1 | 3.3 | 136.8 | 65.0 |
| | $P_D$ | 114.1 | 335.1 | 196.7 | −4.1 | 0.2 | −1.5 | 47.3 | 292.2 | 154.7 |
| | $P_{MC}$ | 26.3 | 91.8 | 48.3 | 0.5 | 0.9 | 0.8 | 0.6 | 68.5 | 22.2 |

Cal: calibrated; NRMSE: Normalized Root Mean Square Error; $C_{NS}$: Nash-Sutcliffe coefficient; $ER_{QP}$: Relative peak discharge error.

This occurs because frontal rains are predominant in the CRW, which leads to more relevant $I_a$ values as they are longer and present lower intensity.

Considering all the rainfall-runoff events evaluated in this study, the mean values of CN for CRW and JCW (Fig. 5) were 72 and 53, respectively, presenting only a slight difference between the parameterization schemes. One can infer that the CN values calibrated by event in the semi-distributed parameterization scheme differed minimally from those obtained in the lumped parameterization scheme, remaining practically constant among the sub-watersheds (see median CN values in Fig. 5). CRW presented CN values ranging, between events, from 40 to 99, whereas it varied between 30 and 89 for JCW. However, Bahremand and De Smedt (2008) reported that the calibration of this parameter does not guarantee the reliability of its predictions, that is, even after calibration there might be great uncertainty in the results. Another issue is related to the algorithm used for CN calibration (Nelder-Mead), which has intrinsic limitations (Laouacheria and Mansouri, 2015; Masoud, 2016; Steinmetz et al., 2019).

The types of soil and land use, antecedent soil moisture content, and magnitude and temporal distribution of the rainfall events influenced both the CN parameter and peak discharges (Agirre et al., 2005; Ahmad et al., 2009), thus directly reflecting on the DSR generation. An important characteristic of the CRW is that this watershed has predominance of soils with reduced infiltration capacity and these are more susceptible to water erosion. In addition, CRW has ~ 70% of its area with bare soils or small vegetation (cultivated area and native vegetation), which hinders water infiltration and, consequently, favors DSR generation (Sartori et al., 2005). Likewise, some land-use types (pasture and corn) in JCW also hinder infiltration and contribute to the generation of DSR. Overall, JCW presents soils characterized by a good infiltration capacity (Sartori et al., 2005), culminating in lower CN values.

### 3.3. Statistical analysis based on the estimated hydrographs: Overview of results and discussions

The statistics obtained from the hydrographs estimated for CRW (Table 3, Fig. 6) indicate that $P_{ST}$ and $P_D$ were the approaches with the best performance for the lumped parameterization scheme. However, the $Q_{PEAK}$ values derived from $P_D$ were in general overestimated, but the shape of the hydrographs was well represented, thereby justifying $C_{NS}$ values classified as "very good" or "satisfactory" for most of the events. $P_{ST}$ made it possible to represent the shape of the hydrographs and the corresponding $Q_{PEAK}$ values satisfactorily for the lumped scheme, however, the $Q_{PEAK}$ values were estimated with a slight time lag in relation to the observed ones. Thus, although $ER_{Qp}$ values were low, this time lag implied in unsatisfactory $C_{NS}$ values for some events. According to Vannametee et al. (2013) and Yu (2000), if the travel time of runoff is neglected along the main channels (at grid cell or sub-watershed levels), DSR hydrograph responses tend to be quite instantaneous, following the pattern of rainfall pulses. This aspect can be applied to the present study, as no river flow routing method was used in conjunction with the hydrological modeling approach. Furthermore, it is possible that the calibration of time of concentration, while neglecting a river routing method, has resulted in all discharge peaks from all subwatersheds arriving at a similar time, whereas in reality they are staggered in time. This may also be related to the multimodal hydrographs (Event 6, Fig. 6). On the other hand, $P_{OA}$ and $P_{MC}$ resulted in hydrographs with unsatisfactory statistical performance, resulting in underestimated discharges.

For the semi-distributed parameterization scheme, $P_{ST}$ and $P_{OA}$ outperformed the other geomorphological approaches for CRW (Table 3, Fig. 7), resulting predominantly in $C_{NS}$ values categorized as "very good". $P_D$ and $P_{MC}$ provided unacceptable estimated hydrographs, overestimating and underestimating discharges, respectively. The NRMSE values reinforce these findings, as they resulted in "reasonable" classification. It is noteworthy that the good estimation of hydrographs applying $P_{ST}$, in both parameterization schemes, is explained by the similarities between the geomorphological characteristics of the watersheds evaluated by Straub et al. (2000) and those of the CRW (Table A.1 - Appendix A and Table 1). Furthermore, one can notice that the events with poor accuracy had bimodal or multimodal estimated hydrographs (e.g., Event 2, 6 and 7; see Fig. 7). These behaviors result from the events with short periods with rainfall followed by periods with no rainfall and then with rainfall again, as also reported by Beskow et al. (2018).

With respect to JCW, $P_{ST}$ and $P_{OA}$ performed better than the other geomorphological approaches when assessing the lumped parameterization scheme (Table 3, Fig. 8). These approaches provided a good

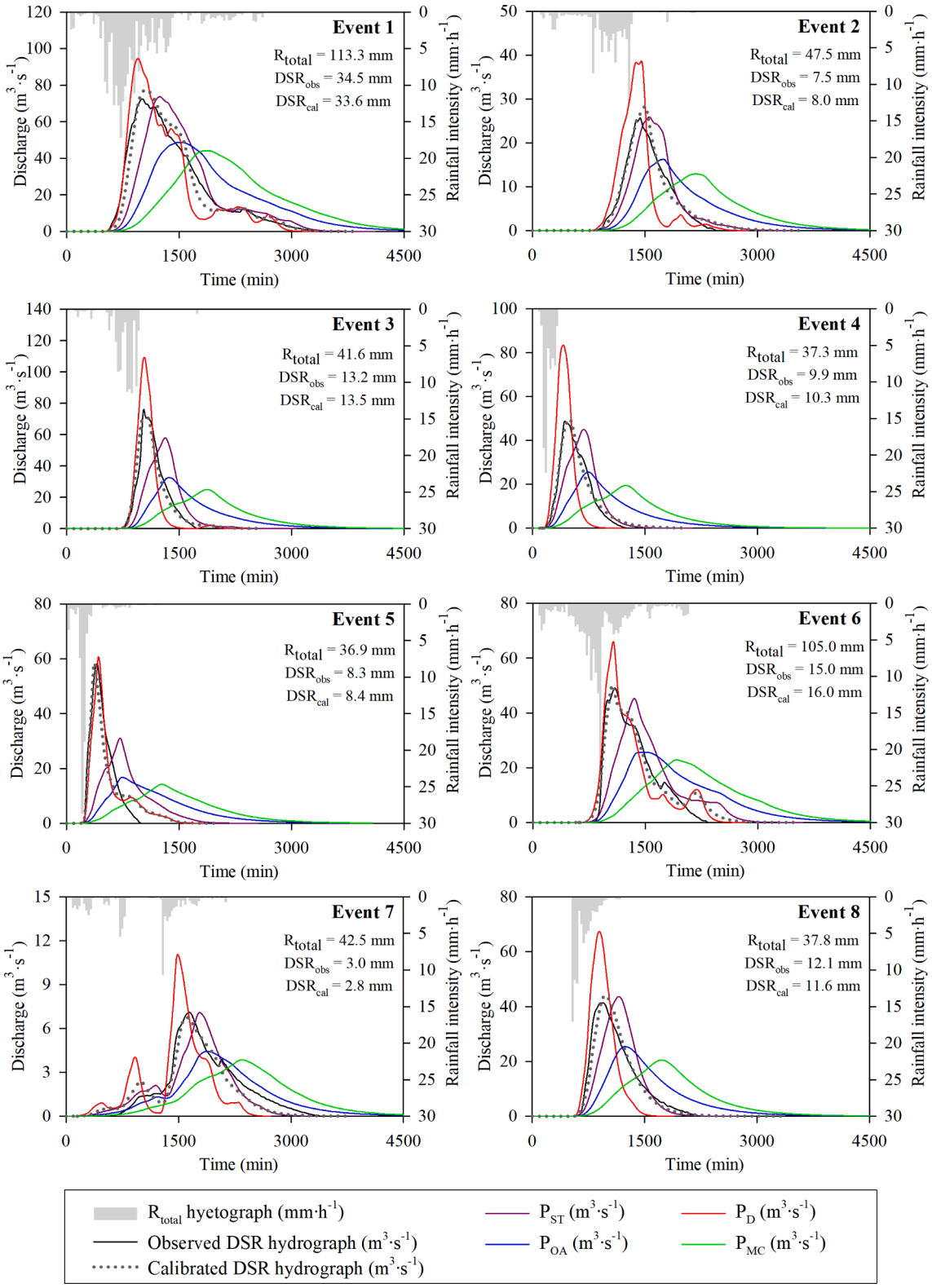



**Fig. 6.** $R_{total}$ hyetograph in the CRW, observed and calibrated DSR hydrograph, and DSR hydrograph estimated at the CRW's outlet by means of the ModClark combined with different geomorphological approaches considering the lumped parameterization scheme and different rainfall-runoff events, as well as information on total rainfall rainfall depth ($R_{total}$) and observed and calibrated DSR depth ($DSR_{obs}$ and $DSR_{cal}$) for each event.

representation of the hydrographs shape and accurate estimations of $Q_{PEAK}$ with performance categorized as "very good" according to $C_{NS}$, whereas $P_D$ and $P_{MC}$ overestimated and underestimated the $Q_{PEAK}$ values, respectively. For the semi-distributed parameterization scheme, $P_{MC}$ outperformed the other approaches (Table 3, Fig. 9), with low $ER_{Qp}$ and $C_{NS}$ values that fell within a "very good" category for most of the events. The other approaches overestimated discharges, presenting high $Q_{PEAK}$ values for most of the events. This may have occurred due to the

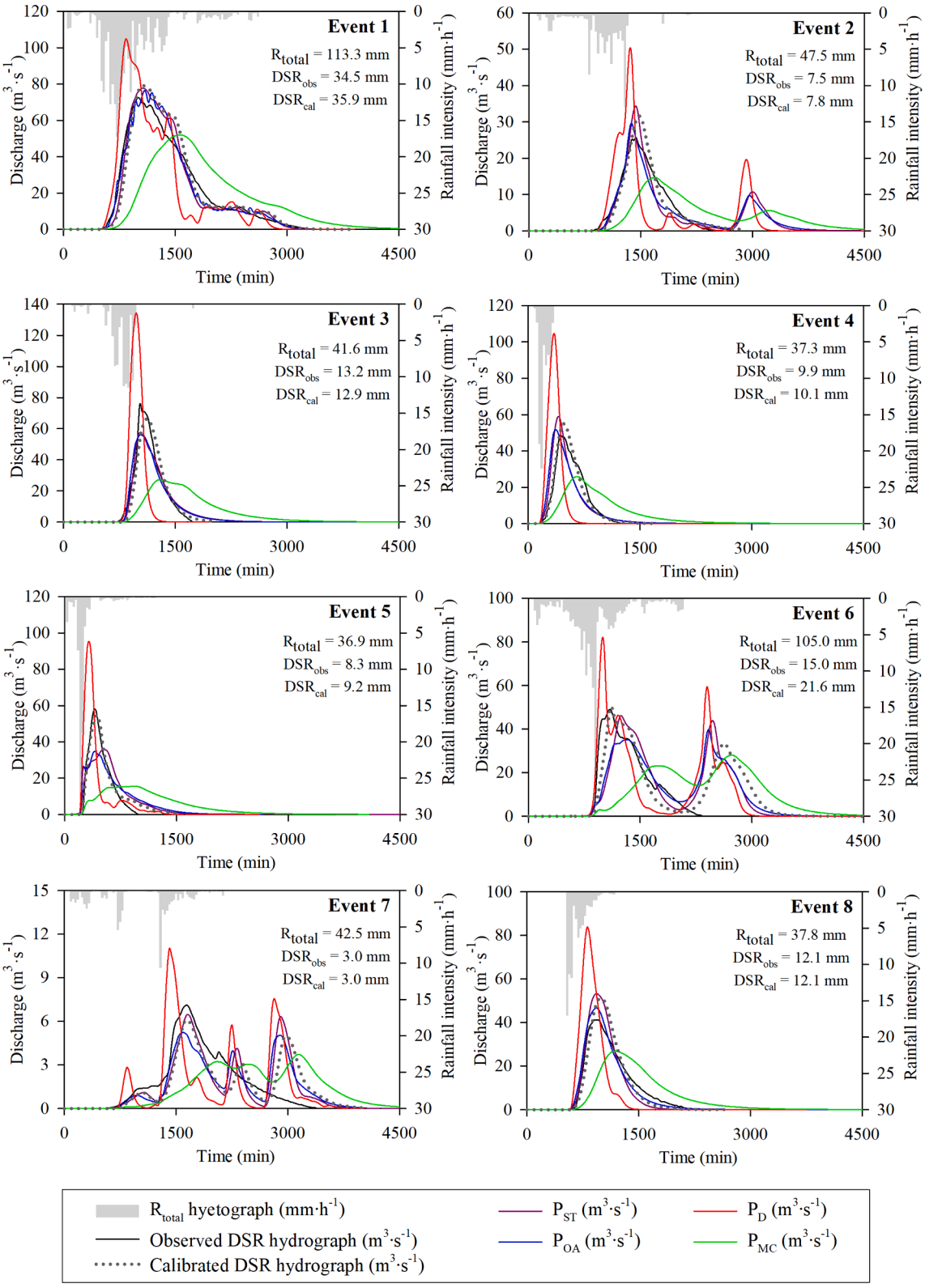



**Fig. 7.** $R_{total}$ hyetograph in the CRW, observed and calibrated DSR hydrograph, and DSR hydrograph estimated at the CRW's outlet by means of the ModClark combined with different geomorphological approaches considering the semi-distributed parameterization scheme and different rainfall-runoff events, as well as information on total rainfall rainfall depth ($R_{total}$) and observed and calibrated DSR depth ($DSR_{obs}$ and $DSR_{cal}$) for each event.

very small subwatersheds generated by spatial discretization of JCW, which resulted in a great dissimilarity between the geomorphological characteristics of JCW (Table 1) and those of the subwatersheds used in the original studies of the geomorphological approaches (Table A.1 - Appendix A). It should be also noted that the events with poor performance in both parameterization schemes are those with a pause of rainfall for some time during the events, resulting in bimodal or multimodal hydrographs (e.g., Event 2 and 6; see Figs. 8 and 9).

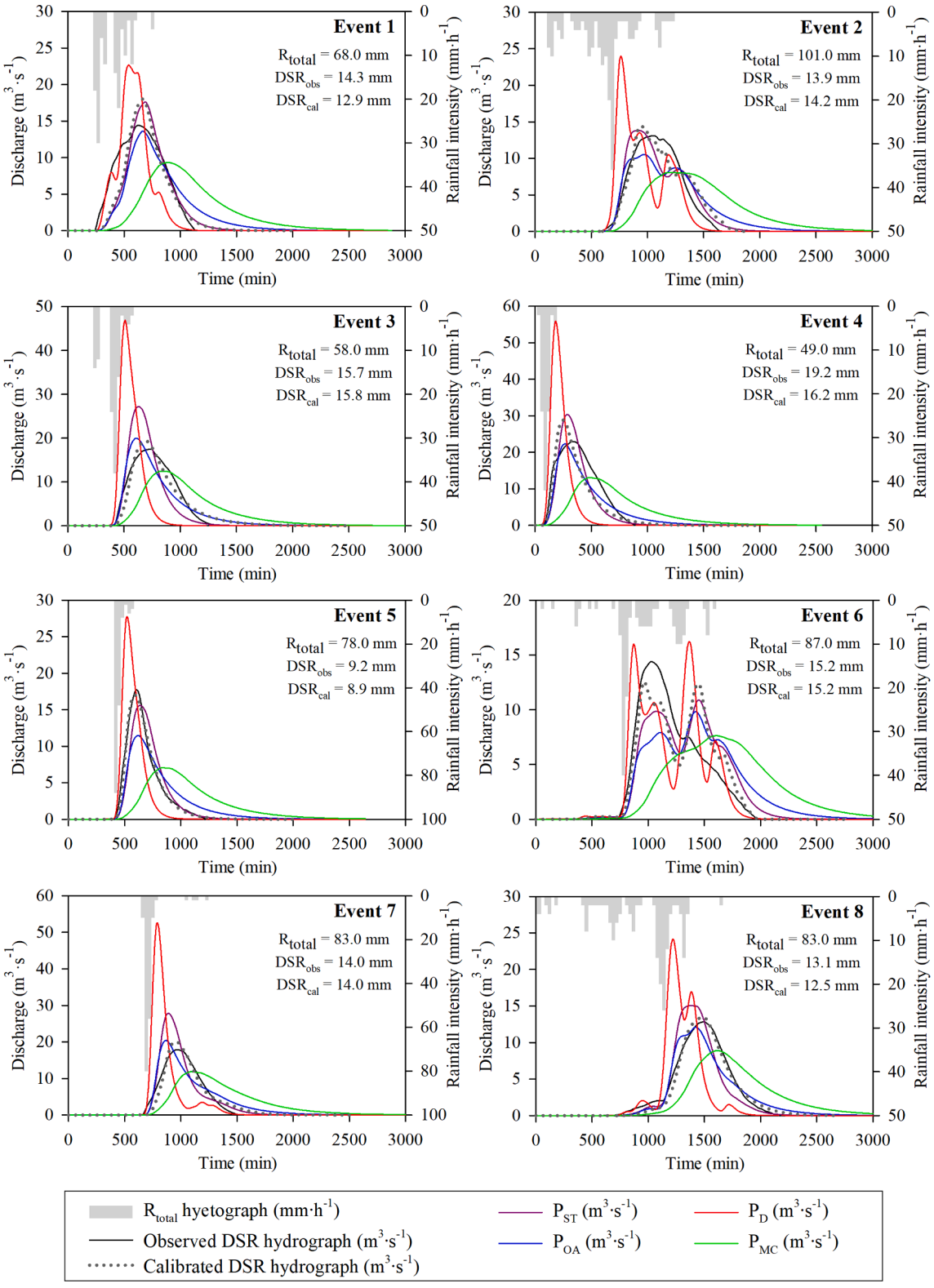



**Fig. 8.** $R_{total}$ hyetograph in the JCW, observed and calibrated DSR hydrograph, and DSR hydrograph estimated at the JCW's outlet by means of the ModClark combined with different geomorphological approaches considering the lumped parameterization scheme and different rainfall-runoff events, as well as information on total rainfall rainfall depth ($R_{total}$) and observed and calibrated DSR depth ($DSR_{obs}$ and $DSR_{cal}$) for each event.

The results presented in Table 3 also suggest that the ModClark was successfully calibrated for all the rainfall-runoff events observed in CRW and JCW considering both parameterization schemes. It is noteworthy that there was not a significant improvement in the calibration for both watersheds when using the semi-distributed parameterization scheme, maintaining practically the same performance obtained in the lumped scheme. Furthermore, it should be highlighted that the estimated DSR volumes ($DSR_{cal}$) after calibration ($DSR_{obs}$) were close to those observed for both watersheds (see legend on Figs. 6 to 9). Considering the lumped scheme, the differences ranged from 1.2% to 6.7% (average = 4.3%) and

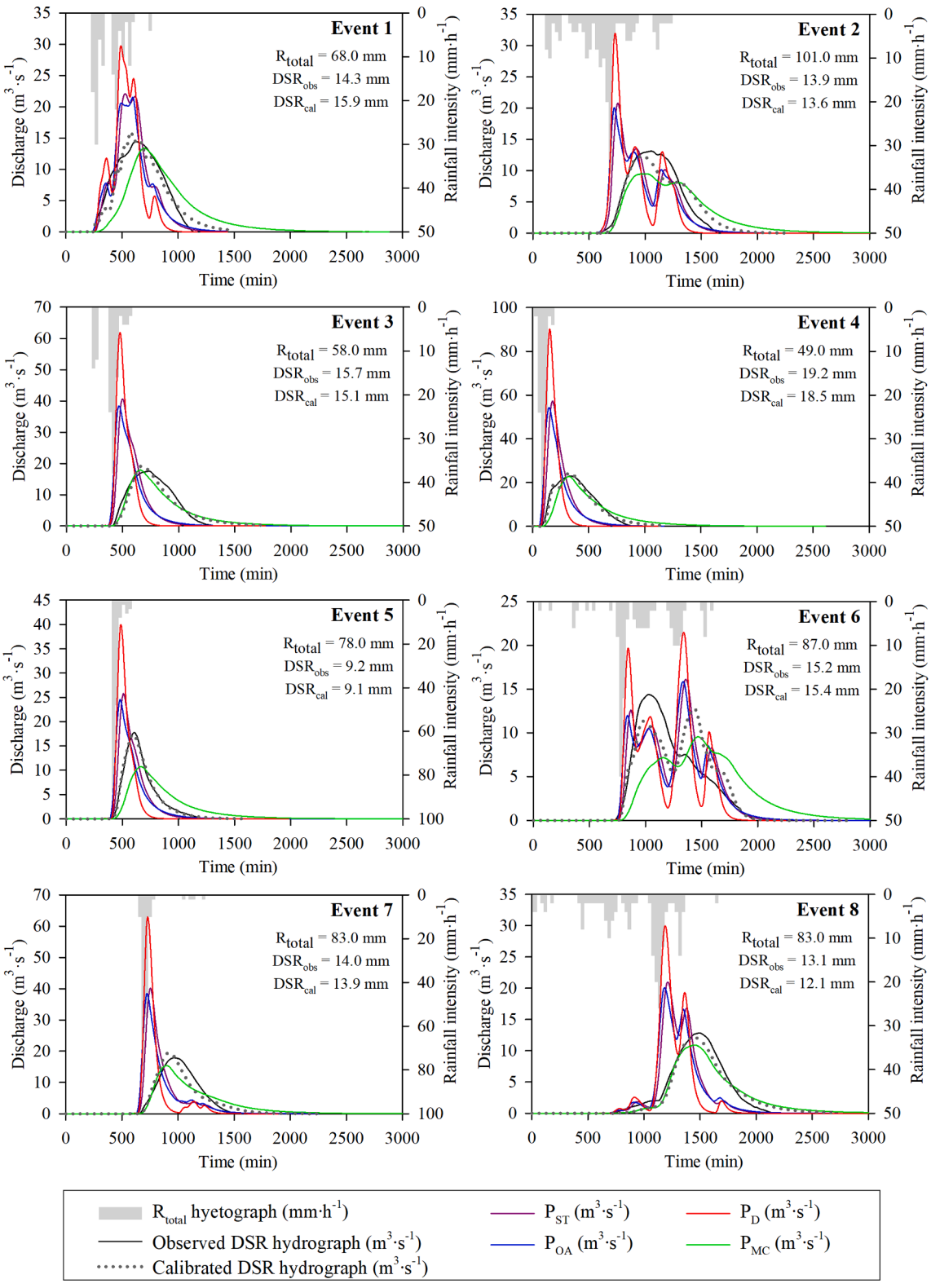



**Fig. 9.** $R_{total}$ hyetograph in the JCW, observed and calibrated DSR hydrograph, and DSR hydrograph estimated at the JCW's outlet by means of the ModClark combined with different geomorphological approaches considering the semi-distributed parameterization scheme and different rainfall-runoff events, as well as information on total rainfall rainfall depth ($R_{total}$) and observed and calibrated DSR depth ($DSR_{obs}$ and $DSR_{cal}$) for each event.

from 1.3% to 16.1% (average = 5.3%) for CRW and JCW, respectively, whereas the differences in the semi-distributed scheme varied from 0% to 44.0% (average = 7.9%) and from 0% to 9.7% (average = 4%). The DSR hydrographs derived from the combination of ModClark with different geomorphological approaches and parameterization schemes also resulted in estimated DSR volumes close to those observed ($DSR_{obs}$), with the same amplitudes of percentage differences as those mentioned above for the calibrated model, except for JCW under the semi-distributed scheme which presented differences ranging between 0% and 7.6% (average = 2.9%). Furthermore, the DSR volumes obtained

**Table A1**
Values of the geomorphological attributes used in the formulation of the geomorphological approaches and the resulting parameters for CIUH.

| Approaches | A ($km^2$) | S (%) | L (km) | $S_0$ ($m \cdot km^{-1}$) | $t_c$ (h) | R (h) |
|---|---|---|---|---|---|---|
| $P_{ST}$ | 0.1 – 6.0 | – | 0.2 – 10.3 | 0.6 – 10.6 | 0.3 – 13.1 | 0.5 – 15.7 |
| $P_{OA}$ | 130.0 – 1500.0 | – | 41.0 – 75.1 | 6.7 – 45.8 | 4.3 – 19.6 | 5.4 – 17.0 |
| $P_D$ | 145.0 – 948.0 | 0.4 – 6.6 | – | – | 3.3 – 32.3 | 4.1 – 16.1 |
| $P_{MC}$ | 3.8 – 35.1 | – | 1.9 – 6.9 | 32.6 – 87.5 | 0.7 – 2.9 | 0.4 – 2.5 |

$P_{ST}$: Straub et al. (2000); $P_{OA}$: Osman and Abustan (2012); $P_D$: Dooge (1973); $P_{MC}$: Mohave County (2009); A: Drainage area; S: Average watershed slope; L: Length of the main watercourse; $S_0$: Slope of the main watercourse; $t_c$: Time of concentration; R: Storage coefficient.

**Table B1**
Time of concentration ($t_c$) and storage coefficient (R) values necessary for the Modified Clark's model, derived from four geomorphological approaches for both watersheds considering the two parameterization schemes.

| Watershed | $t_c$ (h) | | | | R (h) | | | |
|---|---|---|---|---|---|---|---|---|
| | $P_{ST}$ | $P_{OA}$ | $P_D$ | $P_{MC}$ | $P_{ST}$ | $P_{OA}$ | $P_D$ | $P_{MC}$ |
| CRW | 8.4 | 8.5 | 3.5 | 17.8 | 2.5 | 8.7 | 1.3 | 8.5 |
| SC1 | 3.3 | 1.7 | 1.8 | 7.7 | 1.1 | 2.7 | 1.1 | 4.3 |
| SC2 | 3.4 | 1.8 | 1.8 | 8.3 | 1.3 | 2.8 | 1.2 | 5.0 |
| SC3 | 2.0 | 0.9 | 0.9 | 5.3 | 1.8 | 1.7 | 0.5 | 3.6 |
| SC4 | 2.7 | 1.5 | 1.4 | 6.8 | 1.5 | 2.6 | 0.7 | 3.6 |
| SC5 | 6.3 | 4.5 | 2.2 | 13.3 | 2.4 | 5.1 | 0.9 | 8.6 |
| SC6 | 5.3 | 2.8 | 1.6 | 10.6 | 2.3 | 3.4 | 0.7 | 8.9 |
| SC7 | 0.5 | 0.1 | 0.5 | 1.4 | 0.1 | 0.2 | 0.6 | 0.9 |
| JCW | 5.0 | 3.4 | 2.1 | 10.0 | 2.1 | 4.4 | 1.6 | 5.9 |
| SJ1 | 3.8 | 1.9 | 1.5 | 8.2 | 1.9 | 2.7 | 0.9 | 6.0 |
| SJ2 | 1.6 | 0.5 | 0.9 | 4.1 | 0.7 | 1.0 | 0.6 | 2.9 |
| SJ3 | 1.8 | 0.6 | 1.0 | 4.5 | 0.8 | 1.2 | 0.7 | 3.1 |
| SJ4 | 1.6 | 0.5 | 1.0 | 4.1 | 0.7 | 1.1 | 0.7 | 2.5 |
| SJ5 | 0.9 | 0.3 | 0.9 | 2.7 | 0.5 | 0.9 | 0.6 | 1.3 |

$P_{ST}$: Straub et al. (2000); $P_{OA}$: Osman and Abustan (2012); $P_D$: Dooge (1973); $P_{MC}$: Mohave County (2009); $t_c$: Time of concentration; R: Storage coefficient.

from ModClark did not differ for the same parameterization scheme among the geomorphological approaches. This demonstrates the importance of calibrating CN and $I_a$ per event, making it possible to guarantee the reliable estimated DSR volumes. In this context, readers are encouraged to disregard the events whose DSR depths cannot be predicted accurately, as it would be unfair to evaluate the geomorphological approaches under these circumstances.

### 3.4. ModClark performance: An analysis focused on geomorphological approaches

One can infer from the graphs of estimated DSR hydrographs (Figs. 6 - 9) presented in Section 3.3 that the delay in the estimated hydrographs is directly linked to the geomorphological approaches used in the parameterization of the ModClark. Bhaskar et al. (1997) stated that good or poor performances of geomorphological approaches can be justified based on the equations used to estimate the parameters, which have coefficients that are subjected to regression errors and cannot be considered universal as such coefficients are dependent on the geomorphological characteristics of the watersheds for which they were obtained.

Analyzing Figs. 6 - 9, it can be verified that $P_{MC}$ usually produces flatten hydrographs with relatively long time to peak discharge compared to other approaches. On the other hand, $P_D$ tends to generate hydrographs with instantaneous peak discharge responses and overestimate discharge for most events in both watersheds. To better understand the aforementioned results, a more specific analysis was made regarding the characteristics of the watersheds used by the authors of the geomorphological approaches (Straub et al., 2000; Osman and Abustan, 2012; Dooge, 1973; Mohave County, 2009) in relation to the watersheds and sub-watersheds evaluated as case study in the present article. This analysis is key to appraise the applicability of different geomorphological approaches for estimating DSR hydrographs from ModClark under lumped and semi-distributed parameterization schemes.

The drainage areas of the CRW and its subwatersheds (Table 1) differ from those of the watersheds used for generating $P_{ST}$ (Table A.1 - Appendix A) (Straub et al. 2000), however, the values of L and $S_0$ are within the bounds for most of the subwatersheds (Table 1). The drainage area of the CRW is close to the lower bound used in the formulation of $P_{OA}$ (Osman and Abustan, 2012) and $P_D$ (Dooge, 1973), while $S_0$ is within the limits for $P_{OA}$. On the other hand, the watersheds' areas considered in the $P_{OA}$ and $P_D$ are larger than those of the CRW's subwatersheds. It should be highlighted that the watersheds evaluated for $P_D$ generation are flatter than CRW, JCW, and their respective subwatersheds. For $P_{MC}$ (Mohave County, 2009), the CRW's subwatersheds present areas similar to the watersheds considered for $P_{MC}$, however, L and $S_0$ values are contrasting.

The values obtained for A and L for JCW (Table 1) are greater than the respective upper limits of the watersheds evaluated for generating

**Table B2**
Calibrated values of the ModClark's parameters ($t_c$ and R) for each rainfall-runoff event evaluated in CRW and JCW considering the two parameterization schemes.

| $t_c$ (h) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Events | CRW | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 | SC7 | JCW | SJ1 | SJ2 | SJ3 | SJ4 | SJ5 |
| E1 | 4.1 | 3.8 | 3.8 | 3.9 | 3.8 | 5.8 | 4.8 | 1.9 | 4.1 | 5.7 | 1.8 | 4.1 | 2.2 | 0.2 |
| E2 | 4.1 | 3.9 | 4.8 | 4.0 | 4.0 | 6.4 | 4.8 | 2.0 | 10.1 | 7.2 | 4.4 | 5.0 | 3.7 | 2.3 |
| E3 | 3.6 | 4.0 | 4.0 | 4.0 | 4.0 | 5.9 | 4.9 | 2.2 | 5.7 | 7.1 | 4.3 | 5.3 | 4.2 | 2.3 |
| E4 | 4.0 | 4.2 | 4.2 | 4.2 | 4.2 | 6.2 | 5.2 | 2.2 | 3.3 | 6.5 | 3.7 | 4.9 | 3.5 | 1.9 |
| E5 | 2.3 | 2.7 | 4.0 | 3.9 | 2.7 | 4.0 | 3.3 | 1.3 | 3.4 | 4.0 | 3.1 | 3.6 | 2.7 | 1.4 |
| E6 | 3.0 | 6.0 | 6.0 | 6.0 | 6.0 | 4.0 | 3.3 | 2.0 | 6.7 | 4.3 | 4.1 | 3.8 | 2.8 | 1.0 |
| E7 | 4.5 | 4.6 | 4.2 | 4.0 | 3.9 | 6.0 | 5.0 | 2.0 | 7.2 | 6.8 | 4.4 | 5.4 | 4.3 | 1.9 |
| E8 | 4.0 | 3.9 | 4.0 | 4.0 | 4.0 | 6.2 | 5.0 | 2.1 | 7.0 | 5.8 | 4.5 | 5.3 | 4.6 | 3.1 |
| R (h) | | | | | | | | | | | | | | |
| E1 | 2.7 | 2.4 | 1.9 | 1.9 | 1.8 | 3.2 | 2.4 | 1.0 | 2.2 | 3.1 | 0.3 | 2.8 | 1.8 | 0.1 |
| E2 | 4.0 | 2.3 | 2.2 | 2.1 | 2.2 | 3.4 | 2.8 | 1.0 | 0.1 | 2.2 | 2.5 | 2.7 | 2.5 | 1.7 |
| E3 | 3.1 | 2.0 | 2.0 | 2.0 | 2.0 | 3.0 | 2.5 | 1.1 | 3.8 | 4.3 | 1.5 | 3.6 | 3.6 | 3.5 |
| E4 | 3.9 | 2.2 | 2.2 | 2.2 | 2.2 | 3.2 | 2.7 | 1.2 | 3.0 | 3.4 | 2.5 | 3.0 | 2.8 | 0.0 |
| E5 | 1.9 | 0.9 | 2.0 | 1.3 | 1.3 | 2.0 | 2.5 | 0.7 | 2.3 | 2.7 | 1.1 | 1.7 | 2.8 | 0.6 |
| E6 | 2.9 | 3.0 | 2.0 | 3.0 | 3.0 | 2.0 | 2.9 | 0.7 | 0.2 | 1.1 | 1.0 | 1.5 | 1.0 | 0.3 |
| E7 | 4.0 | 2.3 | 2.4 | 2.1 | 2.3 | 3.0 | 2.5 | 1.0 | 2.2 | 1.9 | 2.9 | 3.4 | 3.0 | 2.3 |
| E8 | 4.0 | 2.1 | 2.2 | 2.1 | 2.2 | 3.2 | 2.7 | 1.1 | 2.7 | 4.4 | 2.8 | 4.2 | 2.8 | 2.4 |

$P_{ST}$ (Table A.1 - Appendix A) (Straub et al. 2000), whereas its subwatersheds (Table 1) are characterized by A and L values that are within (or close to) the ranges observed in the watersheds considered by Straub et al. (2000). Nevertheless, the subwatersheds of JCW present $S_0$ values higher than those included in $P_{ST}$. $P_{OA}$ (Osman and Abustan, 2012) and $P_D$ (Dooge, 1973) were conceived using data from watersheds with A values much larger than the JCW's area, but the former approach used $S_0$ values close to that of JCW's and its subwatersheds. JCW (and subwatersheds) has geomorphological attributes with values in the bounds of $P_{MC}$ (Mohave County, 2009), except $S_0$.

It can be inferred from the results that the watercourse slope and the length of the main watercourse had great influence on the determination of the geomorphological approaches' parameters and, consequently, on the estimation of the DSR hydrographs. Rousseau et al. (2012) reported that the sensitivity of the model's parameters is different from one watershed to another due to its location, physiographic characteristics, as well as duration and temporal and spatial distribution of the rainfall.

In the study by Bhattacharya et al. (2012), the authors applied the ModClark to six watersheds located in Kansas and Oklahoma, the Midwest USA, to estimate DSR hydrographs. The hydrological modeling was carried out in a lumped parameterization scheme with the aid of HEC-HMS, considering the calibration of $t_c$ and R for each of the 25 events assessed in the study. Comparing the estimated hydrographs with the observed hydrographs, Bhattacharya et al. (2012) concluded that the ModClark provided an excellent performance in calibration since low peak discharge errors were identified and the shapes of the estimated hydrographs were very similar to those of the corresponding observed hydrographs. However, time to peak discharge in the estimated hydrographs was found to occur before that in the observed hydrographs for most events. This behavior agrees with that observed in the results of our study for CRW when evaluating $P_{ST}$ and $P_{OA}$ in conjunction with the lumped parameterization scheme.

The results obtained in other watersheds differed from those found in the present study. Razmkhah et al. (2015) appraised CIUH for a subwatershed of the Karoon watershed, located in southwest Iran, along with $P_{ST}$ for determination of the model's parameters. These authors investigated the uncertainty of the CIUH's parameters ($t_c$ and R) used as input in the HEC-HMS in a semi-distributed parameterization scheme. In general, the results indicated underestimation of the discharges, i.e., the results do not agree with those observed in the present study, as ModClark combined with $P_{ST}$ resulted in the best agreement between observed and estimated hydrographs for both watersheds under the two parameterization schemes (except for the semi-distributed scheme in JCW). Sheridan (1994) and da Silveira (2005) evaluated the performance of $t_c$ equations, including the one proposed by Dooge (1973) ($P_D$), in the Little river watershed and in rural and urban watersheds in Illinois, California and Arizona, in the United States. The authors found a poor performance of $P_D$, with errors greater than those obtained by the other equations analyzed (e.g., Kirpich, Corps Engineers and Ven Te Chow), indicating that the choice of this equation is not the most adequate.

### 3.5. Influence of the characteristics of the rainfall-runoff events on ModClark performance

The characteristics of rainfall-runoff events also have a significant impact on the results obtained. According to Vannametee et al. (2012), rainfall intensity and duration, and slope gradient are factors that are directly linked to the accuracy of estimated DSR hydrographs. These researchers stated that the accuracy of the estimated hydrographs decreases as DSR decreases. This situation occurs when a low intensity rainfall event associated with high infiltration capacity and low slope gradient is considered, as such a combination tends to reduce DSR runoff responses (Vannametee et al., 2012).

Furthermore, Vannametee et al. (2013) emphasized that lumped conceptual models provide a more accurate DSR hydrograph estimation for high intensity rainfall events due to the reduction in spatial variability in the watershed responses. According to these authors, during heavy rainfall events, infiltration rate is spatially uniform and DSR tends to be generated throughout the watershed area, i.e., the event can be considered spatially homogeneous. However, infiltration rate becomes spatially variable after the high-intensity period of the rainfall event, thus only some regions of the watershed yield direct surface runoff and, in these cases, the spatial variability of rainfall is evidenced (Vannametee et al., 2013).

The results of the present study are in accordance with the conclusions reported by Vannametee et al. (2013), as the application of the ModClark model (mainly in the lumped parameterization scheme) performed better when simulating high rainfall intensity events, which generated greater direct surface runoff depths (e.g., events 1 and 5 for CRW and events 4 and 5 for JCW). On the other hand, ModClark combined with the two parameterization schemes failed to predict hydrographs for the events with low rainfall intensity and small DSR volume (e.g., event 7 in both watersheds), resulting in bimodal and multimodal hydrographs.

The poor performance for some rainfall-runoff events may have also occurred due to the nature of the model (IUH), as the watershed responses to rainfall are simulated instantaneously. This issue is evident in the simulation for event 7 to CRW and event 6 to JCW, where several discharge peaks corresponding to individual rainfall pulses were observed on the hydrograph. In addition, the poor accuracy for some estimated hydrographs may be connected with the use of the SCS/CN. According to Woodward et al. (2002), the SCS/CN method was not designed to consider time throughout the simulation, instead, it allows the calculation of the total volume of direct surface runoff from a watershed, and this may justify why it does not fit easily to particular temporal rainfall patterns or to watersheds that have significant direct surface runoff evolution over time (Caviedes-Voullième et al., 2012).

The spatial distribution of rain gauges over the watersheds may also have impacted the modeling, since only one rain gauge was considered for JCW, whereas eight stations were used for CRW. As a result, CRW had simulations with more satisfactory results than JCW, especially when considering the semi-distributed parameterization scheme. The characteristics of the rainfall-runoff events used in this study along with the application of geomorphological approaches might also exert a significant influence on the estimation of DSR hydrographs (Figs. 6-9). $P_{MC}$ is likely to be suitable for rainfall events and watersheds that result in slow and attenuated discharge responses, since the hydrographs generated by the ModClark combined with this approach presented underestimated discharges and a relatively long time to reach the peak discharge, as discussed in the previous section. On the other hand, the overestimated hydrographs produced by ModClark in conjunction with the $P_D$ indicate that the application of this approach should be more appropriate for high intensity rainfall events and watersheds that usually present fast discharge responses.

### 3.6. ModClark performance versus parameterization schemes

In general, the DSR hydrographs estimates for CRW were more accurate than those estimated for JCW. Considering the parameterization schemes, the lumped parameterization scheme performed better for JCW, while the semi-distributed parameterization scheme provided slightly greater performance for CRW. It should be mentioned that, in the case of CRW, the lumped parameterization scheme was also capable of estimating DSR hydrographs with good agreement in relation to the observed hydrographs. Even though the performance statistics for the semi-distributed parameterization scheme have provided satisfactory values, several peaks (multimodal) were detected on the estimated hydrographs for some events (Figs. 7 and 9). Therefore, it is noticeable that the performance of the hydrological simulation using the lumped parameterization scheme stood out for both watersheds. There are several reasons for these results, including i) the discretization of

watersheds in small subwatersheds; ii) the use of geomorphological approaches whose watersheds used for modeling have some relief characteristics quite different in relation to those identified for the watersheds in the present study; iii) discretization of the parameters of the geomorphological approaches in subwatersheds; iv) the disregard of a river routing method; v) *grid* cell size used in the ModClark application; vi) the uncertainty involved in the CN and $I_a$ calibration; vii) characteristics of the events; and viii) the use of rainfall data from only one station for estimation in the subwatersheds of JCW..

In the case of JCW, the parameterization schemes provided similar results. It can be inferred that the lumped parameterization scheme may be more convenient due to parsimony because this scheme requires a smaller number of parameters to represent rainfall-runoff transformation process in a watershed. Although requiring a restricted number of parameters for DSR estimation, lumped conceptual models are capable of generating more accurate and meaningful results after their calibration (Fernández-Pato and García-Navarro 2016). Oppositely to the lumped parameterization scheme, the uncertainties of the calibration of parameters increase if the watershed is discretized into subwatersheds because there are more parameters, which impact the sensitivity of the model (Ghomash et al., 2019). It is worthwhile to mention that the lumped and semi-distributed schemes were used in the present study in association with ModClark for definition of $t_c$ and R. Therefore, the results are in agreement with the aforementioned statements, as the performance of the DSR hydrographs simulations was satisfactory using the lumped parameterization scheme for both watersheds.

The efficiency of ModClark was discussed in the study conducted by Paudel et al. (2009) using the HEC-HMS software. These authors applied the CIUH in its original form and in its modified form (ModClark), considering the lumped parameterization scheme, in two watersheds located in the Utah State/USA, to estimate DSR hydrographs by spatially varying the CN values over the watersheds. They concluded that the estimated hydrographs were practically identical when CIUH and ModClark were applied with the same CN value. On the other hand, when the CN value was varied for each grid cell in the watershed, the estimated peak discharges and runoff volumes of the estimated hydrographs were considerably higher when compared to those estimated using the CIUH with a single CN value. They reported that the ModClark is more conservative than CIUH concerning DSR rate and volume estimation.

The results obtained in the present study corroborate those reported in other studies for the same watersheds and also for a contiguous watershed (Beskow et al., 2018; Caldeira et al., 2019; Steinmetz et al., 2019; Vargas et al., 2021) and for watersheds in the same region (Caldeira et al., 2019). Steinmetz et al. (2019) reported that the calibration of CIUH under the semi-distributed parameterization scheme, in general, did not result in significant accuracy increase of estimated hydrographs at the CRW's outlet when compared to the lumped scheme. Beskow et al. (2018) found overestimated $Q_{PEAK}$ values for CRW and underestimated values for JCW when applying the CIUH under the lumped parameterization scheme. It is important to note that the study conducted by Beskow et al. (2018) applied $P_D$ and $P_{MC}$ to determine the CIUH's parameters, however, these geomorphological approaches were not assessed in conjunction with the modified version of CIUH (ModClark). Vargas et al. (2021) applied the LISEM for estimating DSR hydrographs at CRW's outlet considering the lumped parameterization scheme. In this model, the rainfall-runoff transformation is spatially represented in a similar way to ModClark. In their study, the authors also identified estimates of hydrographs with several peaks (bimodal and multimodal) as well as their anticipation in relation to the peaks of the observed hydrographs, however, these results were observed only for some events, most of the estimated hydrographs were accurate in accordance with statistics. It should be noted that LISEM requires manual calibration of some parameters, which makes it challenging to apply it in watersheds with scarce or unavailable data sets. Caldeira et al. (2019) evaluated the performance of the LASH model, in which all the hydrological processes were represented according to distributed and semi-distributed approaches and the calibration was performed considering the lumped parameterization scheme, to estimate daily hydrographs in the Fragata river watershed that is contiguous with CRW. Although the distributed model has outperformed its semi-distributed version, the latter spatial approach also gave an accurate daily hydrograph and has potential to be applied in the aforementioned watershed.

## 4. Conclusions

The application of different geomorphological approaches for determination of ModClark's parameters impacted the estimated DSR hydrographs. Based on the results reported in the present study, the following conclusions can be drawn:

i) The results were promising since it was possible to demonstrate the potential of a distributed conceptual model (ModClark) to estimate DSR hydrographs based on geomorphological approaches available in literature that are not widely applied by hydrologists.
ii) The watersheds' morphometric characteristics had a significant influence on the geomorphological approaches, in particular the slope and length of the main course, and, consequently, exerted influence on the performance of ModClark for estimation of DSR hydrographs.
iii) For watersheds with geomorphological characteristics similar to those of the watersheds analyzed in this study, $P_{ST}$ would be the most suitable geomorphological approach for the calculation of ModClark's parameters.
iv) The characteristics of the selected rainfall-runoff events also significantly influenced the estimation of DSR hydrographs. It should be mentioned that high intensity rainfall events should be preferred. Briefly, the application of $P_{MC}$ may be more suitable when considering rainfall events and watersheds that result in slow and attenuated discharge responses. In contrast, $P_D$ should be applied for watersheds and high intensity rainfall events that usually yield quick discharge responses.
v) The efficiency of ModClark stood out when considering the lumped parameterization scheme, which can be partially attributed to the large number of parameters considered in the semi-distributed parameterization scheme. This finding reaffirms that parsimonious models are handy for applications in hydrological engineering.
vi) ModClark under the lumped parameterization scheme may be a suitable alternative for estimating DSR hydrographs in small and medium-sized watersheds. High efficiency is expected in the modeling, even considering the lumped parameterization scheme because ModClark considers the discretization of the hydrological processes distributed throughout the watershed.
vii) The study underlines the need for further studies that evaluate the influence of the grid cell size on the performance of the ModClark when applying little-used geomorphological approaches as those appraised here to subsidize engineering projects and establish adequate characteristics for their application.

## 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.

## Appendix A

(SEE Table A1).

## Appendix B

(SEE Tables B1 and B2).

## References


Adib, Arash, Lotfirad, Morteza, Haghighi, Ali, 2019. Using uncertainty and sensitivity analysis for finding the best rainfall-runoff model in mountainous watersheds (Case study: the Navrood watershed in Iran). J. Mountain Science 16 (3), 529–541. https://doi.org/10.1007/s11629-018-5010-6.

Agirre, U., Goñi, M., López, J.J., Gimena, F.N., 2005. Application of a unit hydrograph based on subwatershed division and comparison with Nash's instantaneous unit hydrograph. Catena 64 (2-3), 321–332. https://doi.org/10.1016/j.catena.2005.08.013.

Ahmad, Muhammad Masood, Ghumman, Abdul Razzaq, Ahmad, Sajjad, 2009. Estimation of Clark's Instantaneous Unit Hydrograph parameters and development of direct surface runoff hydrograph. Water Resour. Manage. 23 (12), 2417–2435. https://doi.org/10.1007/s11269-008-9388-8.

Alemngus, A., Mathur, B.S., 2014. Geomorphologic Instantaneous Unit hydrographs for rivers in Eritrea (East Africa). J. Indian Water Resources Society 34, 1–14.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Koppen's climate classification map for Brazil. Meteorol. Z. 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Araújo, F.C., Mello, E.L.D., Gollin, G.M., Quadros, L.E.D., Gomes, B.M., 2018. Streamflow regionalization in Piquiri river basin. Engenharia Agrícola 38, 22–31. https://doi.org/10.1590/1809-4430-Eng.Agric.v38n1p22-31/2018.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment: part I: model development. J. Am. Water Resources Association 34 (1), 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x.

Arsenault, Richard, Breton-Dufour, Mélissa, Poulin, Annie, Dallaire, Gabrielle, Romero-Lopez, Rabindranarth, 2019. Streamflow prediction in ungauged basins: analysis of regionalization methods in a hydrologically heterogeneous region of Mexico. Hydrol. Sci. J. 64 (11), 1297–1311. https://doi.org/10.1080/02626667.2019.1639716.

Atkinson, S.E., Woods, R.A., Sivapalan, M., 2002. Climate and landscape controls on water balance model complexity over changing timescales. Water Resour. Res. 38 (12), 50-1–50-17. https://doi.org/10.1029/2002WR001487.

Bahremand, A., De Smedt, F., 2008. Distributed hydrological modeling and sensitivity analysis in Torysa Watershed, Slovakia. Water Resour. Manage. 22 (3), 393–408. https://doi.org/10.1007/s11269-007-9168-x.

Basu, N.B., Rao, P.S.C., Winzeler, H.E., Kumar, S., Owens, P., Merwade, V., 2010. Parsimonious modeling of hydrologic responses in engineered watersheds: Structural heterogeneity versus functional homogeneity. Water Resour. Res. 46, WR007803. https://doi.org/10.1029/2009WR007803.

Beck, Hylke E., de Jeu, Richard A.M., Schellekens, Jaap, van Dijk, Albert I.J.M., Bruijnzeel, L. Adrian, 2009. Improving curve number based storm runoff estimates using soil moisture proxies. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 2 (4), 250–259. https://doi.org/10.1109/JSTARS.2009.2031227.

Beskow, S., Mello, C.R., Norton, L.D., Silva, A.M., 2011. Performance of a distributed semi-conceptual hydrological model under tropical watershed conditions. Catena 86, 160–171.

Beskow, Samuel, Norton, Lloyd D., Mello, Carlos R., 2013. Hydrological prediction in a tropical watershed dominated by oxisols using a distributed hydrological model. Water Resour. Manage. 27 (2), 341–363. https://doi.org/10.1007/s11269-012-0189-8.

Beskow, S., Nunes, G.S., Mello, C.R., Caldeira, T.L., Norton, L.D., Steinmetz, A.A., Vargas, M.M., Ávila, L.F., 2018. Geomorphology-based unit hydrograph models for flood risk management: case study in Brazilian watersheds with contrasting physiographic characteristics. Anais da Academia Brasileira de Ciências 90, 1873–1890. https://doi.org/10.1590/0001-3765201820170430.

Beven, K.J., 2011. Rainfall-runoff modelling: the primer. John Wiley & Sons 488 pp.

Bhaskar, Nageshwar Rao, Parida, Bhagabat P., Nayak, Atul Kumar, 1997. Flood estimation for ungauged catchments using the GIUH. J. Water Resour. Plann. Manage. 123 (4), 228–238. https://doi.org/10.1061/(ASCE)0733-9496(1997)123:4(228).

Bhattacharya, A.K., Mcenroe, B.M., Zhao, H., Kumar, D., Shinde, S., 2012. Modclark model: improvement and application. IOSR Journal of Engineering 2, 100–118. https://doi.org/10.9790/3021-0271100118.

Brunda, G.S., Nyamathi, S.J., 2015. Derivation and analysis of dimensionless hydrograph and S curve for cumulative watershed area. Aquat. Procedia 4, 964–971. https://doi.org/10.1016/j.aqpro.2015.02.121.

Caldeira, T.L., Mello, C.R., Beskow, S., Timm, L.C., Viola, M.R., 2019. LASH hydrological model: An analysis focused on spatial discretization. Catena 173, 183–193.

Caviedes-Voullième, D., García-Navarro, P., Murillo, J., 2012. Influence of mesh structure on 2D full shallow water equations and SCS Curve Number simulation of rainfall/runoff events. J. Hydrol. 448, 39–59. https://doi.org/10.1016/j.jhydrol.2012.04.006.

Choubin, B., Solaimani, K., Rezanezhad, F., Roshan, M.H., Malekian, A., Shamshirband, S., 2019. Streamflow regionalization using a similarity approach in ungauged basins: Application of the geo-environmental signatures in the Karkheh River Basin. Iran. Catena 182, 104–128. https://doi.org/10.1016/j.catena.2019.104128.

Chow, V.T., Maidment, D., Mays, L., 1988. Applied hydrology. McGraw-Hill, New York, p. 572.

Clark, C.O., 1945. Storage and the Unit Hydrograph. Transactions American Society Civil, Engineers 110 (1), 1419–1446. https://doi.org/10.1061/TACEAT.0005800.

Clark, Gordon E., Ahn, Kuk-Hyun, Palmer, Richard N., 2017. Assessing a Regression-Based Regionalization Approach to Ungauged Sites with Various Hydrologic Models in a Forested Catchment in the Northeastern United States. J. Hydrol. Eng. 22 (12), 05017027. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001582.

Cunha, Zandra Almeida da, Beskow, Samuel, Moura, Maíra Martim de, Beskow, Tamara Leitzke Caldeira, Mello, Carlos Rogério de, 2021. Adequacy of methodologies for determining SCS / CN in a watershed with characteristics of the Pampa biome. Ambiente e Agua 16 (4), 1. https://doi.org/10.4136/ambi-agua.2715.

Dariane, Alireza B., Javadianzadeh, M.M., James, L. Douglas, 2016. Developing an efficient auto-calibration algorithm for HEC-HMS program. Water Resour. Manage. 30 (6), 1923–1937. https://doi.org/10.1007/s11269-016-1260-7.

De Roo, A. P. J., Wesseling, C. G., Ritsema, C. J. 1996. LISEM: a single-event physically based hydrological and soil erosion model for drainage basins. I: theory, input and output. Hydrological Processes, 1107-1117. https://doi.org/10.1002/(SICI)1099-1085(199608)10:8<1107::AID-HYP415>3.0.CO;2-4.

Dooge, J., 1973. Linear theory of hydrologic systems. Agricultural Research Service, US Department of Agriculture, p. 337.

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. 1979. Serviço Nacional de Levantamento e Conservação de Solos. Súmula da 10. Reunião Técnica de Levantamento de Solos. Rio de Janeiro.

EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária. 2013. Sistema Brasileiro de Classificação de Solos, 3nd ed., Brasília, 353 pp.

ESRI – Environmental Systems Research. 2017. ArcGIS Desktop 10.1. Redlands: Environmental Systems Research Institute, Inc., CD-ROM.

Fernández-Pato, J., García-Navarro, P., 2016. 2D zero-inertia model for solution of overland flow problems in flexible meshes. J. Hydrol. Eng. 21 (11), 04016038. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001428.

Ghomash, S.K.B., Caviedes-Voullieme, D., Hinz, C., 2019. Effects of erosion-induced changes to topography on runoff dynamics. J. Hydrol. 573, 811–828. https://doi.org/10.1016/j.jhydrol.2019.04.018.

Ghorbani, K., Salarijazi, M., Abdolhosseini, M., Eslamian, S., Ahmadianfar, I., 2019. Evaluation of Clark IUH in rainfall-runoff modelling (case study: Amameh Basin). Int. J. Hydrology Sci. Technology 9, 137–153. https://doi.org/10.1504/IJHST.2019.098131.

Ghorbani, Mohammad Ali, Singh, Vijay P., Sivakumar, Bellie, H. Kashani, Mahsa, Atre, Atul Arvind, Asadi, Hakimeh, 2017. Probability distribution functions for unit hydrographs with optimization using genetic algorithm. Appl. Water Sci. 7 (2), 663–676. https://doi.org/10.1007/s13201-015-0278-y.

Ghumman, Abdul Razzaq, Ahmad, Muhammad Masood, Hashmi, Hashim Nisar, Kamal, Mumtaz Ahmad, 2012. Development of geomorphologic instantaneous unit hydrograph for a large watershed. Environ. Monit. Assess. 184 (5), 3153–3163. https://doi.org/10.1007/s10661-011-2179-3.

Ghumman, A.R., Khaled, K., Hashmi, H.N., Ahmad, M.M., 2014. Comparison of Clark and Geographical Instantaneous Unit Hydrograph Models for Arid and Semi Arid Regions. Int. J. Water Resources Arid Environments 3, 43–50. https://doi.org/10.1134/S0097807814040071.

Guo, Yuhan, Zhang, Yongqiang, Zhang, Lu, Wang, Zhonggen, 2021. Regionalization of hydrological modeling for predicting streamflow in ungauged catchments: A comprehensive review. Wiley Interdisciplinary Reviews: Water 8 (1). https://doi.org/10.1002/wat2.1487.

Hao, Fanghua, Sun, Mingze, Geng, Xiaojun, Huang, Weijia, Ouyang, Wei, 2015. Coupling the Xinanjiang model with geomorphologic instantaneous unit hydrograph for flood forecasting in northeast China. Int. Soil Water ConservatiResearch 3 (1), 66–76. https://doi.org/10.1016/j.iswcr.2015.03.004.

Hasenack, H., Weber, E. 2010. Base cartográfica vetorial contínua do Rio Grande do Sul – escala 1:50.000. Porto Alegre: UFRGS/Centro de Ecologia, CD-ROM.

Hosseini, Seiyed Mossa, Mahjouri, Najmeh, Riahi, Samaneh, 2016. Development of a direct geomorphologic IUH model for daily runoff estimation in ungauged watersheds. J. Hydrol. Eng. 21 (6), 05016008. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001333.

Hutchinson, M.F., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. J. Hydrol. 106 (3-4), 211–232. https://doi.org/10.1016/0022-1694(89)90073-5.

Joo, Jaewon, Kjeldsen, Thomas, Kim, Hyeon-Jun, Lee, Hyosang, 2014. A comparison of two event-based flood models (ReFH-rainfall runoff model and HEC-HMS) at two Korean catchments, Bukil and Jeungpyeong. KSCE J. Civ. Eng. 18 (1), 330–343. https://doi.org/10.1007/s12205-013-0348-3.

Jumbo, F., Zea, M., Loja, N., Morocho, R., Cartuche, J., Loján, E., 2017. Delimitation and Codification of Hydrographic Units Through the Use of Geographic Information Systems. Int. Conf. Technology Trends. Springer, Cham 798, 185–198. https://doi.org/10.1007/978-3-319-72727-1_14.

Köppen, W., 2020. Die klimate der Erde. De Gruyter, Berlim, p. 404.

Kumari, Nikul, Srivastava, Ankur, Sahoo, Bhabagrahi, Raghuwanshi, Narendra Singh, Bretreger, David, 2021. Identification of suitable hydrological models for streamflow assessment in the Kangsabati River Basin, India, by using different model selection scores. Nat. Resour. Res. 30 (6), 4187–4205. https://doi.org/10.1007/s11053-021-09919-0.

Laouacheria, Fares, Mansouri, Rachid, 2015. Comparison of WBNM and HEC-HMS for runoff hydrograph prediction in a small urban catchment. Water Resour. Manage. 29 (8), 2485–2501. https://doi.org/10.1007/s11269-015-0953-7.

Lampert, D.J., Wu, M., 2015. Development of an open-source software package for watershed modeling with the Hydrological Simulation Program in Fortran. Environ. Modell. Software 68, 166–174. https://doi.org/10.1016/j.envsoft.2015.02.018.

Limbrunner, J. F., Vogel, R. M., Chapra, S. C. 2010. A parsimonious watershed model. Capítulo 22. In: Singh, V. P., Frevert, D. F. Watershed Models. Editora CRC Press, Colorado, 549-567pp.
Liu, J., Zhu, A.X., Qin, C.Z., Wu, H., Jiang, J., 2016. A two-level parallelization method for distributed hydrological models. Environ. Modell. Software 80, 175–184. https://doi.org/10.1016/j.envsoft.2016.02.032.
Masoud, M.H., 2016. Geoinformatics application for assessing the morphometric characteristics' effect on hydrological response at watershed (case study of Wadi Qanunah, Saudi Arabia). Arabian J. Geosci. 9, 280. https://doi.org/10.1007/s12517-015-2300-y.
Mishra, Surendra Kumar, Tyagi, J.V., Singh, Vijay P., 2003. Comparison of infiltration models. Comparison of infiltration models. Hydrological processes 17 (13), 2629–2652. https://doi.org/10.1002/hyp.1257.
Mohave County, 2009. Drainage design manual for Mohave County 70, pp..
Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: Performance measures and evaluation criteria. Trans. ASABE 58, 1763–1785. https://doi.org/10.13031/trans.58.10715.
Martim de Moura, Maíra, Beskow, Samuel, da Silva Terra, Fabrício, Rogério de Mello, Carlos, Almeida da Cunha, Zandra, Cassalho, Felício, 2021. Evaluation of geomorphological approaches combined with digital elevation models for the Nash's instantaneous unit hydrograph. J. S. Am. Earth Sci. 107, 103153. https://doi.org/10.1016/j.jsames.2020.103153.
Moura, M.M., Beskow, S., Terra, F.S., Mello, C.R., Cunha, Z.A., Cassalho, F., 2021. Influence of different relief information sources on the geomorphological characterization of small watersheds. Anais da Academia Brasileira de Ciências 93. https://doi.org/10.1590/0001-3765202120191317 e20191317.
Nelder, J.A., Mead, R., 1965. A simplex method for function minimization. Computer J. 7 (4), 308–313. https://doi.org/10.1093/comjnl/7.4.308.
Osman, S., Abustan, I., 2012. Estimating the Clark Instantaneous Unit Hydrograph parameters for selected gauged catchments in the west Coast of Peninsular Malaysia. ASEAN Eng. J. 1, 126–141. https://doi.org/10.11113/aej.v1.15303.
Paudel, Murari, Nelson, E. James, Scharffenberg, William, 2009. Comparison of lumped and quasi-distributed Clark runoff models using the SCS curve number equation. J. Hydrol. Eng. 14 (10), 1098–1106. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000100.
Perrin, C., Michel, C., Andréassian, V., 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. J. Hydrol. 242 (3-4), 275–301. https://doi.org/10.1016/S0022-1694(00)00393-0.
Peters, John C., Easton, Daniel J., 1996. Runoff Simulation Using Radar Rainfall Data. J. Am. AWRA J. Am. Water Resour. Association 32 (4), 753–760. https://doi.org/10.1111/j.1752-1688.1996.tb03472.x.
Pignotti, G., Rathjens, H., Cibin, R., Chaubey, I., Crawford, M., 2017. Comparative analysis of HRU and grid-based SWAT models. Water 9, 272. https://doi.org/10.3390/w9040272.
Pilgrim, D. H.; Cordery, I.1993. Flood runoff, in: Maidment, D. R (Eds.), Handbook of hydrology. McGraw-Hill, New York, 9.1-9.42pp.
Rai, Praveen Kumar, Mohan, Kshitij, Mishra, Sameer, Ahmad, Aariz, Mishra, Varun Narayan, 2017. A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. Appl. Water Sci. 7 (1), 217–232. https://doi.org/10.1007/s13201-014-0238-y.
Raghunath, H.M., 2006. Hydrology: principles, analyses and design. New Age International, New Delhi, p. 476.
Razmkhah, Homa, AkhoundAli, Ali-Mohammad, Radmanesh, Fereydoun, 2017. Correlated Parameters Uncertainty Propagation in a Rainfall-Runoff Model, Considering 2-Copula; Case Study: Karoon III River Basin. Environ. Model. Assess. 22 (5), 503–521. https://doi.org/10.1007/s10666-017-9569-z.
Refsgaard, J.C., Knudsen, J., 1996. Operational validation and intercomparison of hydrological models. Water Resour. Res. 32, 2189–2202. https://doi.org/10.1029/96WR00896.
Rousseau, M., Cerdan, O., Ern, A., Maitre, O.L., Sochala, P., 2012. Study of overland flow with uncertain infiltration using stochastic tools. Adv. Water Resour. 38, 1–12. https://doi.org/10.1016/j.advwatres.2011.12.004.
Ryu, J., Jang, W.S., Kim, J., Choi, J.D., Engel, B.A., Yang, J.E., Lim, K.J., 2016. Development of a watershed-scale long-term hydrologic impact assessment model with the asymptotic curve number regression equation. Water 8, 153. https://doi.org/10.3390/w8040153.
Samaniego, L., Kumar, R., Attinger, S., 2010. Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale. Water Resour. Res. 46, 1–25. https://doi.org/10.1029/2008WR007327.
Sartori, A., Lombardi Neto, F., Genovez, A.M., 2005. Classificação Hidrológica de Solos Brasileiros para a Estimativa da Chuva Excedente com o Método do Serviço de Conservação do Solo dos Estados Unidos Parte 1: Classificação. Revista Brasileira de Recursos Hídricos 10, 05–18. https://doi.org/10.21168/rbrh.v10n4.p5-18.
SCS - SOIL CONSERVATION SERVICE. 1986. Urban hydrology for small watersheds. Natural Resources Conservation Service, US Dept of Agriculture. Technical Release 55, 2nd ed, Springfield, 164pp.
SCS - SOIL CONSERVATION SERVICE. 1971. Hydrology. National Engineering Handbook. U.S. Dept. of Agriculture, section 4, chap. 10, Washington, 127pp.
Sheridan, J.M., 1994. Hydrograph time parameters for flatland watersheds. Trans. ASAE 37, 103–113. https://doi.org/10.13031/2013.28059.
Sherman, L.K., 1932. Streamflow from rainfall by the unit-graph method. Eng. News Record 108, 501–505.
Silva, V.P.R., Silva, M.T., Singh, V.P., Souza, E.P., Braga, C.C., Holanda, R.M., Almeida, R.S.R., Sousa, F.A.S., Braga, A.C.R., 2018. Simulation of stream flow and hydrological response to land-cover changes in a tropical river basin. Catena 162, 166–176. https://doi.org/10.1016/j.catena.2017.11.024.
da Silveira, A.L.L., 2005. Desempenho de fórmulas de tempo de concentração em bacias urbanas e rurais. Revista Brasileira Recursos Hídricos 10, 5–23.
Sivapalan, M., 2006. Pattern, process and function: elements of a unified theory of hydrology at the catchment scale. Encyclopedia Hydrological Sci. 1–27 https://doi.org/10.1002/0470848944.hsa012.
Sivapalan, Murugesu, 2003. Prediction in ungauged basins: a grand challenge for theoretical hydrology. 2003. Hydrol. Process. 17 (15), 3163–3170. https://doi.org/10.1002/hyp.5155.
Snyder, F.F., 1938. Synthetic unit-graphs. Eos, Trans. Am. Geophysical Union 19, 447–454. https://doi.org/10.1029/TR019i001p00447.
Straub, T.D., Melching, C.S., Kocher, K.E., 2000. Equations for estimating Clark unithydrograph parameters for small rural watersheds in Illinois. US Department of the Interior. US Geological Survey 30, pp. https://doi.org/10.3133/wri004184.
Steefel, C.I., Van Cappellen, P., 1998. Reactive transport modeling of natural systems. J. Hydrology (Amsterdam) 209, 390.
Steinmetz, A.A., Beskow, S., Terra, F.D.S., Nunes, M.C.M., Vargas, M.M., Horn, J.F.C., 2019. Spatial discretization influence on flood modeling using unit hydrograph theory. Revista Brasileira de Recursos Hídricos 24. https://doi.org/10.1590/2318-0331.241920180143.
Thiessen, A., Alter, J.C., 1911. Precipitation averages for large areas. Mon. Weather Rev. 39, 1082–1089. https://doi.org/10.1175/1520-0493(1911)39<1082b:PAFLA>2.0.CO;2.
Tucci, C. E. M. Modelos hidrológicos.1998. Editora da UFRGS, Porto Alegre. 680pp.
USACE – US Army Corps of Engineers. 2015. Hydrologic Modeling System HEC-HMS Version 4.1. Washington: U. S. Army Corps of Engineers, Release Notes.
Vannametee, E., Karssenberg, D., Hendriks, M.R., Bierkens, M.F.P., 2013. Hortonian runoff closure relations for geomorphologic response units: evaluation against field data. Hydrol. Earth Syst. Sci. 17, 2981–3004. https://doi.org/10.5194/hess-17-2981-2013.
Vannametee, E., Karssenberg, D., Bierkens, M.F.P., 2012. Towards closure relations in the Representative Elementary Watershed (REW) framework containing observable parameters: Relations for Hortonian overland flow. Adv. Water Resour. 43, 52–66. https://doi.org/10.1016/j.advwatres.2012.03.029.
Van Liew, Michael W., Veith, Tamie L., Bosch, David D., Arnold, Jeffrey G., 2007. Suitability of SWAT for the Conservation Effects Assessment Project: Comparison on USDA Agricultural Research Service Watersheds. J. Hydrol. Eng. 12 (2), 173–189. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:2(173).
Vargas, M.M., Beskow, S., de Mello, C.R., de Moura, M.M., Nunes, M.C.M., Faria, L.C., Aquino, L.S., 2021. Capability of LISEM to estimate flood hydrographs in a watershed with predominance of long-duration rainfall events. Nat. Hazards 106, 593–614. https://doi.org/10.1007/s11069-021-04850-2.
Wagener, T., Sivapalan, M., Troch, P., Woods, R., 2007. Catchment classification and hydrologic similarity. Geography Compass 1, 901–931. https://doi.org/10.1111/j.1749-8198.2007.00039.x.
Woodward, D., Hawkings, R., Hjelmfelt, A., Van Mullen, J., Quan., Q. 2002. Curve Number method: origins, applications and limitations. In: Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada.
Yu, Z, 2000. Assessing the response of subgrid hydrologic processes to atmospheric forcing with a hydrologic model system. Global Planet. Change 25 (1-2), 1–17. https://doi.org/10.1016/S0921-8181(00)00018-7.
Zhang, Y. Q., Chiew, F. H. S. 2009. Evaluation of regionalisation methods for predicting runoff in ungauged catchments in southeast Australia. In: 18th World IMACS/MODSIM Congress, 3442-3448.