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USE OF GEOTECHNOLOGIES FOR MORPHOMETRIC ANALYSIS OF EXPERIMENTAL BASIN IN THE SEMIARID REGION TO SUPPORT HYDROLOGICAL SIMULATION

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Pixel thresholds

ABSTRACT

The morphometric characteristics help to regulate the hydrological processes of a basin. The understanding of these characteristics is essential for an adequate planning of water resources. The aim of this study was to analyze the sensitivity of the hydrological simulation to different pixel thresholds for the generation of the drainage network and to perform a detailed morphometric characterization of the sub-basin upstream of a fluviometric section (SBSF) installed in the experimental basin of the Jatobá stream, semiarid region of Pernambuco. The following thresholds were considered: 264, 132, 66, 55 and 44 pixels, corresponding to scenarios 1 to 5, respectively. The morphometric analyses were performed through hydrological modeling and the use of mathematical equations, where 25 morphometric indices were evaluated. The results indicated that scenarios 3, 4 and 5 adequately represented the hydrological processes. The physical parameters indicate that the basin has an elongated shape, with a low tendency for flood peaks under normal conditions of climatic events. Although the SBSF presents a low average slope, it was verified the existence of regions with high slopes, favoring the surface runoff, which requires the adoption of conservationist practices and the maintenance of native vegetation.

Palavras chave:
QSWAT
Parâmetros morfométricos
Limiares de pixels

USO DE GEOTECNOLOGIAS NA ANÁLISE MORFOMÉTRICA DE BACIA EXPERIMENTAL NO SEMIÁRIDO PARA SUPORTE À SIMULAÇÃO HIDROLÓGICA

RESUMO

As características morfométricas contribuem para regular os processos hidrológicos de uma bacia, e a compreensão dessas características é fundamental para um adequado planejamento dos recursos hídricos. O objetivo deste estudo foi analisar a sensibilidade da simulação hidrológica a diferentes limiares de pixels para geração da rede de drenagem e realizar uma detalhada caracterização morfométrica da sub-bacia a montante de uma seção fluviométrica (SBSF) instalada na bacia experimental do riacho do Jatobá, semiárido de Pernambuco. Foram considerados os seguintes limiares: 264, 132, 66, 55 e 44 pixels, correspondentes aos cenários de 1 ao 5, respectivamente. A análise morfométrica foi realizada por meio da modelagem hidrológica e da utilização de equações matemáticas, onde foram avaliados 25 índices morfométricos. Os resultados indicaram que os cenários 3, 4 e 5 representaram adequadamente os processos hidrológicos. Os parâmetros físicos indicaram que a bacia possui formato alongado, com baixa tendência de picos de enchentes em condições normais de eventos climáticos. Embora a SBSF apresente baixa declividade média, verificou-se a existência de regiões de altas declividades, favorecendo o escoamento superficial, requerendo a adoção de práticas conservacionistas e a manutenção da vegetação nativa.

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INTRODUCTION

Hydrological studies in semiarid watersheds, where there are high restrictions on water availability as a result of irregular rainfall and high evapotranspiration rates (OLIVEIRA & SILVA, 2020), are of great relevance for the creation of strategies that make the best possible use of water resources and enable coexistence with water scarcity. Thus, knowledge of the physical parameters of the watershed is essential, since such variables influence its water dynamics.

The morphometric characterization of a watershed consists of estimating physical parameters that influence various hydrological and hydrosedimentological processes, including surface runoff, water infiltration into the soil, concentration time and sediment production (RODRIGUES *et al.*, 2020; LEAL & TONELLO, 2017; SOUSA & OLIVEIRA, 2017). The information generated will support the integrated planning of these management units and water resources, and thus guide the implementation of more suitable economic activities in the basin (VAZ *et al*., 2021; SOARES *et al*., 2016).

Thus, for an adequate planning of water resources, it is necessary to be aware of the dimension of the studied basin. According to Lemos Filho *et al*. (2017), planning actions that consider smaller watersheds enable a better understanding of hydrological processes. Schumman *et al*. (2015) emphasize that studies in experimental basins are essential for an adequate understanding of the complex interrelationship between physical, hydrological and ecological processes.

Morphometric analysis has been improved with the advent of geotechnologies, including Geographic Information Systems (GIS), since the use of a GIS enables the distribution of parameters to be represented (VEITH *et al*., 2010), in addition to increasing processing agility and reliability in obtaining results (FRAGA *et al*., 2014). Among the various software based on GIS, there is QGIS, a free computational tool that allows the visualization, analysis, consultation and interactive exploration of geographic data, and the identification and selection of geometries (ALMEIDA, 2011; ÁVILA, 2013). Associated with GIS, hydrological models have been developed, including the *Soil and Water Assessment Tool* (SWAT).

SWAT is a software developed with the objective of simulating the impacts of changes in land use on the production of water, sediments, nutrients and agrochemicals in watersheds (ARNOLD *et al*., 1998; GASSMAN *et al*., 2007). However, this software is little adopted as a support tool in the morphometric characterization of watersheds. Another aspect related to the model is the determination of thresholds for the generation of the drainage network, which influence the greater or lesser detail of the watercourses, and consequently, the result of the morphometric characterization and hydrological processes.

Within this context, the objective of this study is to analyze the sensitivity of the hydrological simulation to different pixel thresholds for the generation of the drainage network and to perform a detailed morphometric characterization of the sub-basin upstream of a fluviometric section (SBSF) installed in the experimental basin from the Jatobá stream, in the semiarid region of Pernambuco.

MATERIAL AND METHODS

Study area characterization

The study was performed in the sub-basin upstream of the fluviometric section of the Jatobá stream experimental basin (SBSF), which is located at coordinates 8.4140ºS and 36.8648ºW (Figure 1). The Jatobá basin is located in the Ipanema River basin, which is a contributor to the São Francisco basin (Figure 1).

The SBSF of the Jatobá stream is one of the basins integrated in the Semiarid Hydrology Network (REHISA), created in 2000, in order to increase knowledge and investigate the hydrological and climatic behavior of experimental and representative micro-basins of the semiarid region. Therefore, the SBSF of the Jatobá stream will enable regionalization studies of hydrological variables (REHISA, 2004) and comparative analyses between similar basins (LIMA *et al*., 2014).

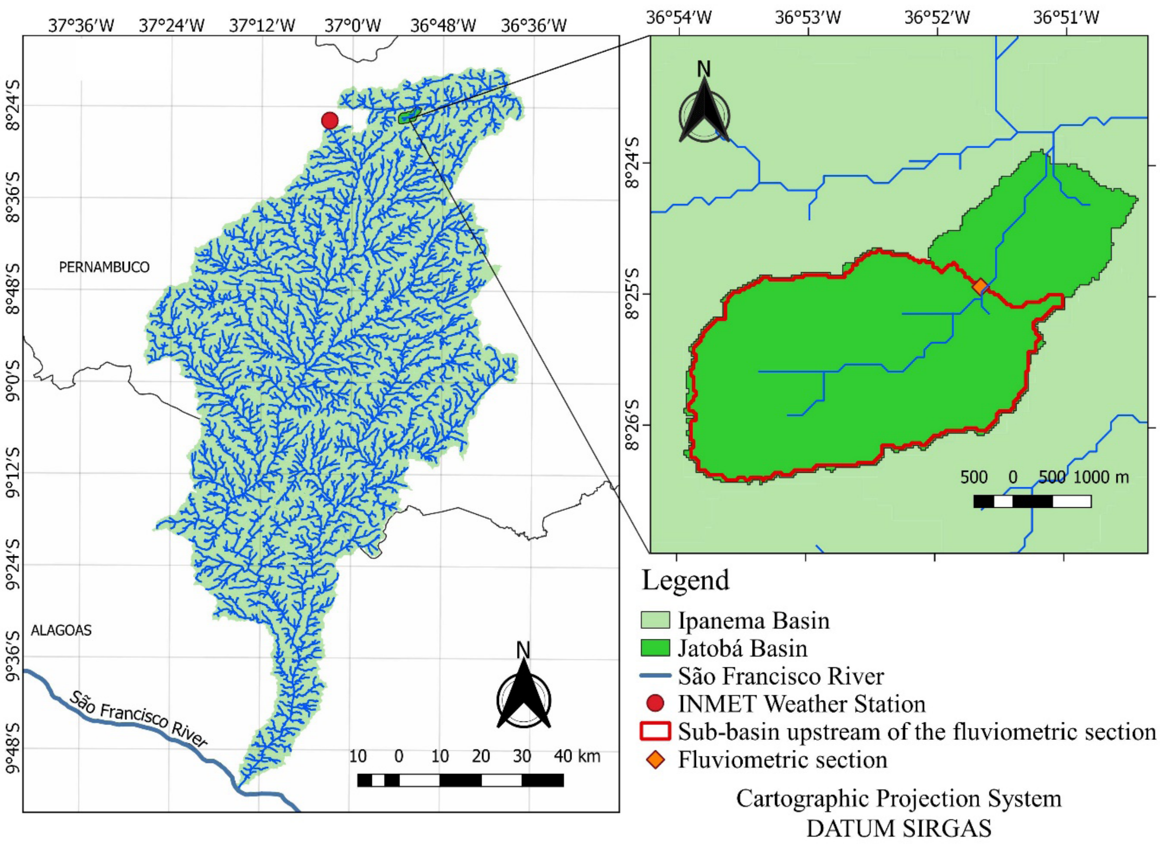

Figure 1. Location of the sub-basin upstream of the fluviometric basin of the Jatobá stream experimental basin, inserted in the watershed of the Ipanema River

The climate in the region is BSsh (semiarid, very hot), according to the Köppen classification, with average annual precipitation of approximately 600 mm, average temperature of 23ºC and reference evapotranspiration (ETr) of approximately 2,000 mm per year (SILVA JÚNIOR *et al.*, 2016). The rainy season occurs between February and July, and the dry season occurs between August and January (SILVA *et al.*, 2013).

SRTM data processing

The Digital Elevation Model (DEM) was obtained from INPE's TOPODATA project (http://www.dsr.inpe.br/topodata/) which provided information on the SRTM mission with a 30 m resolution. To use the DEM in the calculation of morphometric parameters, it is necessary to project this data to the Plane Coordinate System. The coordinate system used was the UTM/Sirgas 2000, 24S zone. The delimitation of the studied basin, as well as the generation of the drainage network, was performed through the SWAT model (QSWAT v. 1.9 plugin) coupled to QGIS (v. 3.10), based on the MDE.

Threshold scenarios for the generation of the drainage network

For hydrological modeling, the SWAT model considers three levels of spatial scale: river basin, sub-basins and Hydrological Response Units (HRUs), where the sub-basins are connected through the drainage network (MELO NETO *et al.*, 2014). A proper division of sub-basins and the detailing of the drainage network is essential for representative hydrological studies.

Thus, before starting a simulation, it is necessary to delimit the sub-basins through a threshold that corresponds to the number of pixels associated with a certain area value to create the drainage network. This value defines the minimum area for the formation of the drainage network and, therefore, is important in the detailing of the network and in the number of sub-basins generated (BUENO *et al.*, 2017). After inserting the DEM in the model, different pixel threshold scenarios were considered and the models' sensitivity was evaluated regarding the number of basins, order of channels, and total length of channels under these scenarios. Scenarios 1, 2, 3, 4 and 5 were established for thresholds of 264, 132, 66, 55 and 44 pixels, respectively, which represent the minimum area values of the sub-basins generated by the model, with areas of 25.8 ha, 12.9 ha, 6.45 ha, 5.37 ha and 4.30 ha, respectively. Thus, the smaller the number of pixels, the greater the number of sub-basins and the more detailed the simulation. In the case of small basins, such as the SBSF in the Jatobá stream basin, it is necessary to evaluate the number of pixels that allow the model to generate a more complete hydrographic network, which is possible with the reduction in the number of pixels.

It should be clarified that the threshold of 264 was the *default* SWAT model for the SBSF, automatically established for the user. The other values were heuristic selected to perform the sensitivity test, initially adopting a geometric progression and then an arithmetic progression between the number of pixels.

Morphometry sensitivity analysis was performed from flow hydrographs generated by simulation with the QSWAT plugin, which is an interface between QGIS and the SWAT model. They were considered calibrated and validated hydrological parameters for Jatoba basin obtained by Magalhães *et al*. (2018). The coefficient of determination (r^2) and the Nash-Sutcliffe (NS) statistical indices were evaluated to verify the performance of the hydrological simulations, using Equations 1 and 2 respectively:

$$r^2 = \frac{\left[\sum_i \left(Q_{obs,i} - \bar{Q}_{obs}\right)\left(Q_{sim,i} - \bar{Q}_{sim}\right)\right]^2}{\sum_i \left(Q_{obs,i} - \bar{Q}_{obs}\right)^2 \sum_i \left(Q_{sim,i} - \bar{Q}_{sim}\right)^2} \quad (1)$$

$$NS = 1 - \frac{\sum_i \left(Q_{obs} - Q_{sim}\right)_i^2}{\sum_i \left(Q_{obs,i} - \bar{Q}_{obs}\right)^2} \quad (2)$$

where: Q_{obs} – Observed flow; Q_{sim} – Simulated flow; $\bar{Q}_{obs}$ - Average of observed flows; $\bar{Q}_{sim}$ - Average of simulated flows.

Soil types, land use and SBSF hydroclimatic data

In the SBSF of the Jatobá stream, three types of soil are found: Red-Yellow Argisol (63.66%), Regolithic Neosol (6.96%) and Litholic Neosol (29.38%). The soil map for the basin was obtained from the Agroecological Zoning of the Pernambuco State (ZAPE), available on the Embrapa Solos Portal, available at https://www.embrapa.br/busca-de-solucoes-tecnologicas/-/product-service/4697/agroecological-zoning-of-the-state-of-pernambuco-zape. The physical characteristics of the soils were based on a study performed by Montenegro and Ragab (2010).

As for land use, the basin has four predominant classes: sparse Caatinga (72.98%), dense Caatinga (0.62%), agriculture (2.48%) and pasture (23.92%), according to the Mapbiomas Project – Collection 5.0, considering the map for the year 2019 (http://mapbiomas.org).

The climate data used in the simulation were obtained from the National Institute of Meteorology (INMET) for the period from 2015 to 2018 at the station in the municipality of Arcoverde - PE (Code 82890) which had a Climatological Normal of 721 mm in the period from 1981 to 2010. The flow data were obtained in the period of February and March 2018, from the fluviometric station monitored by the Water and Soil Laboratory of the Federal Rural University of Pernambuco (UFRPE) installed in 2002, with a rectangular section 5.80 m wide and a maximum height of 2.50 m. The station provides sub-daily flow information, however, data collection is performed from field campaigns, in a non-regular way, since the stream is intermittent.

Characterization of morphometric parameters

The first stage of the characterization was developed for the physical parameters that relate the main geometric measures of the basin, such as drainage area, perimeter, form factor, compactness coefficient, circularity index and elongation ratio, as shown in Table 1.

In Table 2 are presented the equations for calculating the relief parameters. These characteristics refer to the altitudes and slopes of the basin, with the hypsometric curve for the basin area being determined, and the average slope, roughness index and relief ratio being calculated.

Through the "Statistic Raster" tool available in QGIS, it was possible to evaluate the slope maps and determine the maximum, minimum and average slope for the basin. The "*hypsometry"* tool of QGIS was used to create the hypsometric curve.

Table 1. Physical parameters and their respective equations used for the morphometric characterization of the sub-basin upstream of the fluviometric section of the Jatobá stream

Parameters	Description	Equation and Unit	Source
Area (A)	-	m²	-
Perimeter (P)	-	m	-
Form factor (Kf)	Ratio between the area of the basin (A) and the length of the axis of the basin (L) (from the mouth to the farthest point from the watershed).	$Kf = A/L^2$ ($km^2\ km^{-1}$)	Horton (1945)
Compactness coefficient (Kc)	Relation between the perimeter (P) (km) and of the area (km²).	Kc=0.28($P/\sqrt{A}$) ($km\ km^{-2}$)	Lima (1969)
Circularity index (IC)	Relation between the area of the basin (A) (km²) and the perimeter (P) of the basin (km).	IC = 12.57(A/P2)	Miller (1953)
Elongation ratio (Re)	Relation between predetermined indices, basin area (A) and basin axis length (L)	Re=1.128[(A0,2)/L)]	Schumm (1963)

Table 2. Relief parameters and their respective equations used for the morphometric characterization of the sub-basin upstream of the fluviometric section of the Jatobá stream

Parameters	Description	Equation and Unit	Source
Average Altitude	-	m	-
Maximum altimetric amplitude of the basin (Hm)	Altimetric difference between the mouth altitude and the altitude of the highest point of the topographic divider.	m	-
Average slope (%)	-	-	-
Roughness index (Ir)	Ratio between elevation variation (ΔH) (km) and the length of the axis of the basin (Dd) ($km\ km^{-2}$).	$Ir = \Delta H\ Dd$	Christofoletti (1969)
Relief Ratio (Rr)	Ratio between the variation of the elevation (ΔH) and the length of the axis of the basin (L).	$Rr = \Delta H/L$	Christofoletti (1969)
Hypsometric curve	It is a way of graphically representing the relief of a basin, through the relation of the area with the altitude above a level.	-	Christofoletti (1981)

The third and last stage of the characterization aimed to determine the hydrological parameters of the basin based on the first (physical) parameters already calculated. At this stage, with the help of the "*Stream, Reach"* and *"Watershed*" products obtained in the simulation with the QSWAT and based on the equations presented in Table 3, it was possible to determine the ordering of the channels by hierarchy, the bifurcation ratio, the frequency of channels, the average lengths of the channels, the drainage density, the hydrographic density, the maintenance coefficient, the extension of the surface path, the sinuosity index, the gradient of the main channel, topography texture, sinuosity of the main channel, alveal slope and the texture ratio. The '*Profile tools'* tool of QSWAT was used to determine the alveal slope. This tool consists of performing the elevation profile of the main river's thalweg.

Table 3. Hydrological parameters and their respective equations used for the morphometric characterization of the sub-basin upstream of the fluviometric section of the Jatobá stream

Parameters	Description	Equation and Unit	Source
Ordering of the channels by hierarchy		-	Strahler (1957)
Ratio de bifurcation (Rb)	It is the ratio between the total number of channels of one order and the total number of channels of another order immediately above.	Rb = Nu/(Nu+1)	Horton (1945)
Frequency of channels (Fr)	Represents the total number of channels in hierarchical order. Nu: Number of channels in order; NT: Total number of channels.	Fr = (Nu/Nt)100 (%)	Horton (1945)
Average lengths of the channels (Lm)	It refers to the average length of the watercourses of each order. Lu: Length of the channels of each order; Nu: Number of channels in order.	Lm = Lu/Nu (m)	Horton (1945)
Drainage density (Dd)	Ratio between the length of the drainage network (Cr) and the basin area (A).	Dd= Cr/A (km km^{-2})	Horton (1945)
Hidrographic desity (Dh)	Ratio between the number of river segments (Nt) and the basin area (A).	Dh = Nt/A (channels km^{-2})	Christofoletti (1969)
Sinuosity index (IS)	Ratio between the length of the main river (R) and the perimeter of the main river's thalweg (L_{RP}).	IS= 100(Rp-L_{RP})/RP (%)	Schumm (1963)
Sinuosity of the main channel (Sin)	Ratio between the length of the main river (R) and the perimeter of the main river's thalweg (L_{RP}).	Sin = R/L_{RP} (km km^{-1})	Schumm (1963)
Concentration Time (T_c)	Time it takes for a raindrop that reaches the most remote region of the basin to reach the outlet. L is the length of the watercourse (km); and Δh is the difference in altitude along the main watercourse (m).	Tc=57[(L^3)/∆h)0.385] (min)	Collischonn and Tassi (2008)
Maintenance coefficient (Cm)	Expresses the minimum area necessary to maintain the maintenance of 1m of a channel.	Cm = 1/Dd(1000) (m^2 m^{-1})	Christofoletti (1981)
Extension of the surface path (Eps)	It represents the average distance covered by rainwater that would have to flow in a straight line to a permanent channel.	Eps = 1/2Dd (km)	Christofoletti (1981)
Gradient of the main channel (Gcp)	It is the relationship between the length and altimetric amplitude of a channel. Acp: Altimetric amplitude of the channel; Ccp: Length of the channel.	Gcp = Acp/Ccp (%)	Horton (1945)
Ratio texture (T)	Ratio between the number of river segments (Nt) and the perimeter of the basin (P).	T = Nt/P (unit km^{-1})	França (1968) Smith (1950)
Topography texture (Tt)	It is mainly based on drainage density. Tt: coarse (below 4), medium (between 4 and 10) and fine (above 10).	LogTt=0.219649+1.115logDd (km)	França (1968)

RESULTS AND DISCUSSION

In Table 4 are presented the characteristics of the drainage network for each threshold analyzed in the sub-basin upstream of the fluviometric section of the Jatobá stream. For the studied scenarios, it is possible to observe different details in the basin's drainage network. The scenarios 3, 4 and 5 presented an order of the main channel equal to 4 and greater length of the drainage network, implying a greater detailing of the network in these scenarios. The scenario 5 presented greater detail in the number of sub-basins generated by the model compared to the other analyzed scenarios (Table 4).

In Figure 2 is shown the coefficient of determination (r^2) of scenario 3 correlated with the other scenarios (A), and the coefficient of determination (r^2) of the simulated flows with the different scenarios correlated with the observed flow (B).

Comparing Table 4 with Figure 2A, it can be seen that although scenario 5 presents a more detailed drainage network, in the hydrological simulation there is no difference between the hydrographs generated for scenarios 3, 4 and 5. The scenarios 4 and 5 presented coefficients of determination (r^2) equal to 1, compared to scenario 3, indicating that there is no difference between the three scenarios, unlike scenarios 1 and 2 (r^2=0.75).

In Figure 2B the scenarios were grouped into two groups (scenarios 1 and 2, and scenarios 3, 4 and 5) due to the similarity of the simulated results. It can be seen in Figure 2B that the r^2 for scenarios 1 and 2 was r^2=0.34, far from the value of 1. However, for scenarios 3, 4 and 5, the coefficients of determination were high (r^2= 0.94), indicating good agreement between simulated and observed data. As for the Nash-Sutcliffe coefficient (NS), for scenarios 1 and 2, a value of -0.30 was found, below what was considered satisfactory (NS > 0.5) by Moriasi *et al.* (2007). For scenarios 3, 4 and 5, the NS was estimated at 0.66, which is considered satisfactory, according to the same authors.

Table 4. Characteristics of the drainage network for each threshold analyzed in the SBSF of the Jatobá stream

Scenarios	Number of sub-basins	Channel order	Total length of the drainage network (km)
Scenario 1	27	3	11.77
Scenario 2	36	3	16.50
Scenario 3	78	4	23.18
Scenario 4	104	4	27.15
Scenario 5	123	4	30.48

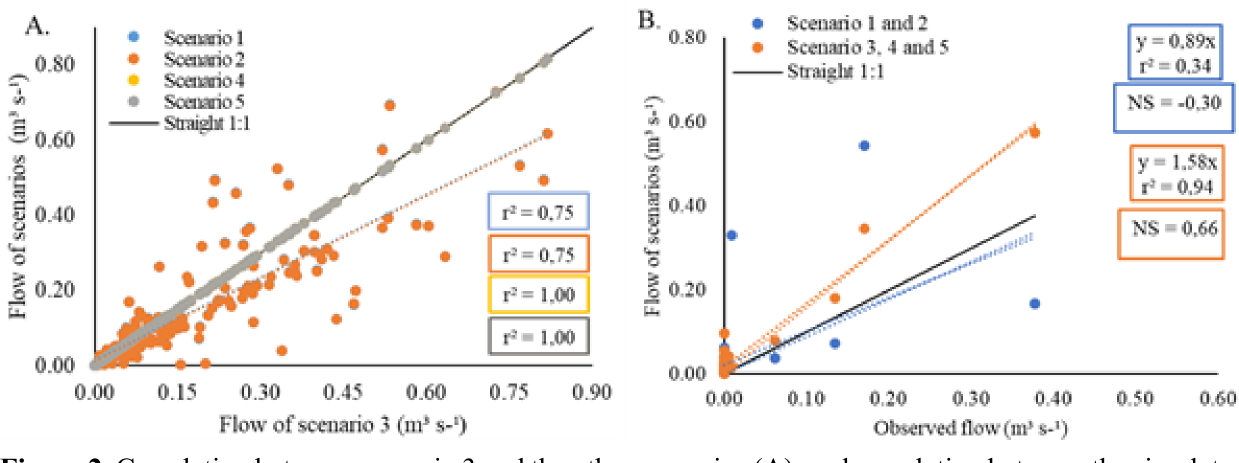

Figure 2. Correlation between scenario 3 and the other scenarios (A), and correlation between the simulated flows and the observed flows (B) for the scenarios. (NS – Nash-Sutcliffe)

In Figure 3 is shown the hydrograph of the hydrological simulations for the different scenarios in the SBSF of the Jatobá stream basin, from February to March 2018, in the fluviometric station. As in Figure 2, in Figure 3 the scenarios were grouped into two groups (scenarios 1 and 2, and scenarios 3, 4 and 5).

It can be seen in Figure 3 that scenarios 1 and 2 did not differ from each other, however, there was a lag between the simulated flow and the observed flow. Scenarios 3, 4 and 5 were similar and presented adequate adherence to the experimental hydrograph. Given the results found, scenario 3 was considered for the development of the morphometric analysis. This scenario provided faster processing than scenarios 4 and 5 and with similar results. Scenario 3 corresponds to a minimum sub-basin area of 6.45 ha, and with a total of 78 sub-basins generated by the QSWAT model, for the SBSF of the Jatobá stream.

The results of the physical morphometric characteristics (area, perimeter, shape factor, compactness coefficient, circularity index and elongation ratio) calculated for the sub-basin upstream of the fluviometric section (SBSF) is presented in Table 5.

The form factor (Kf) for the SBSF indicates that the basin has low circularity and low probability of flooding for normal events. Melo and Montenegro (2015) found distinct patterns of precipitation in BERJ, along its main axis, with trends of greater precipitation in the higher upstream part, contributing to a denser vegetation cover in this sub-region. Gomes *et al.* (2020) found similar results when performing the hydro-morphological characterization of the Exu stream watershed, semiarid in Pernambuco, with a form factor value of approximately 0.39, indicating that the basin also has a low tendency of flow concentration, and consequently less prone to flooding. Ferreira *et al.* (2010), evaluating the morphometric characteristics of the watershed of

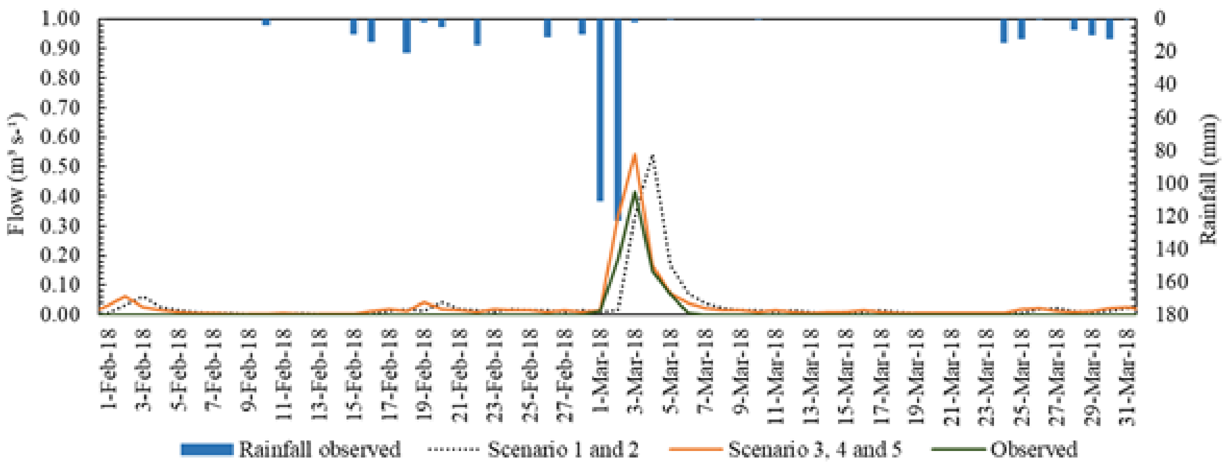

Figure 3. Hydrograph of hydrological simulations for different scenarios in the SBSF of the Jatobá stream basin, from February to March 2018, in the fluviometric station

Table 5. Physical morphometric characteristics in the sub-basin upstream of the fluviometric section of the Jatobá stream

Physical parameters	Sub-basin upstream of the fluviometric section of the Jatobá stream
Area (A)	8.76 km²
Perimeter (P)	16.38 km
Form factor (Kf)	0.48
Compactness coefficient (Kc)	1.55
Circularity index (IC)	0.41
Elongation ratio (Re)	0.46

the Cachoeira II Dam, in the municipality of Serra Talhada, highlighted those results of the form factor far from 1.0 indicate that the contribution of the tributaries reaches the main watercourse in several points, implying a basin with little circularity, with less probability of flooding.

Regarding the compactness coefficient (Kc), the value found indicates that the basin has little susceptibility to floods under average rainfall conditions, excluding extreme events. According to Bariani and Bariani (2016), the more irregular a basin is, the greater its perimeter compared to a circle in the same area, which leads to an increase in the compactness coefficient.

The result found for the circularity index (CI) reinforces what was found for the form factor, indicating that the basins have an elongated shape. According to Soares *et al*. (2016), the shape factor and the circularity index are associated with the geometric shape of the basin and the values found indicate, according to Schumm (1956), greater generation of runoff.

Analyzing the elongation ratio parameter (Re), it can be seen that this value corroborates the fact that the basin has an elongated shape. Similar results were obtained in the Grossos stream watershed, Paraíba state and in the Ipaneminha stream microbasin, São Paulo state, indicating that the greater the distance of this parameter from the unit, the lower the susceptibility to flooding (PINHEIRO *et al*., 2011; LACERDA *et al*., 2019).

The analysis of the morphometric characteristics of relief in the SBSF of the Jatobá stream allowed an observation of the spatial behavior of altitude, through the digital elevation model and generation of the hydrographic network, as shown in Figure 4A. From this MDE, it was possible to create the MDD (Digital Slope Model), shown in Figure 4B.

The characteristics of the morphometric parameters of the relief for the basin are presented in Table 6. The maximum and minimum altitudes of the SBSF of the Jatobá stream resulted in a low altimetric amplitude, according to Benatti *et al*. (2015). The basin's amplitude influences the flow velocity and has a high correlation with the temperature and precipitation variables of a watershed (GERBER *et al*., 2018). A low amplitude tends to uniform the amount of incident radiation and, consequently, reduces the spatial variability of temperature and evapotranspiration (BENATTI *et al*., 2015).

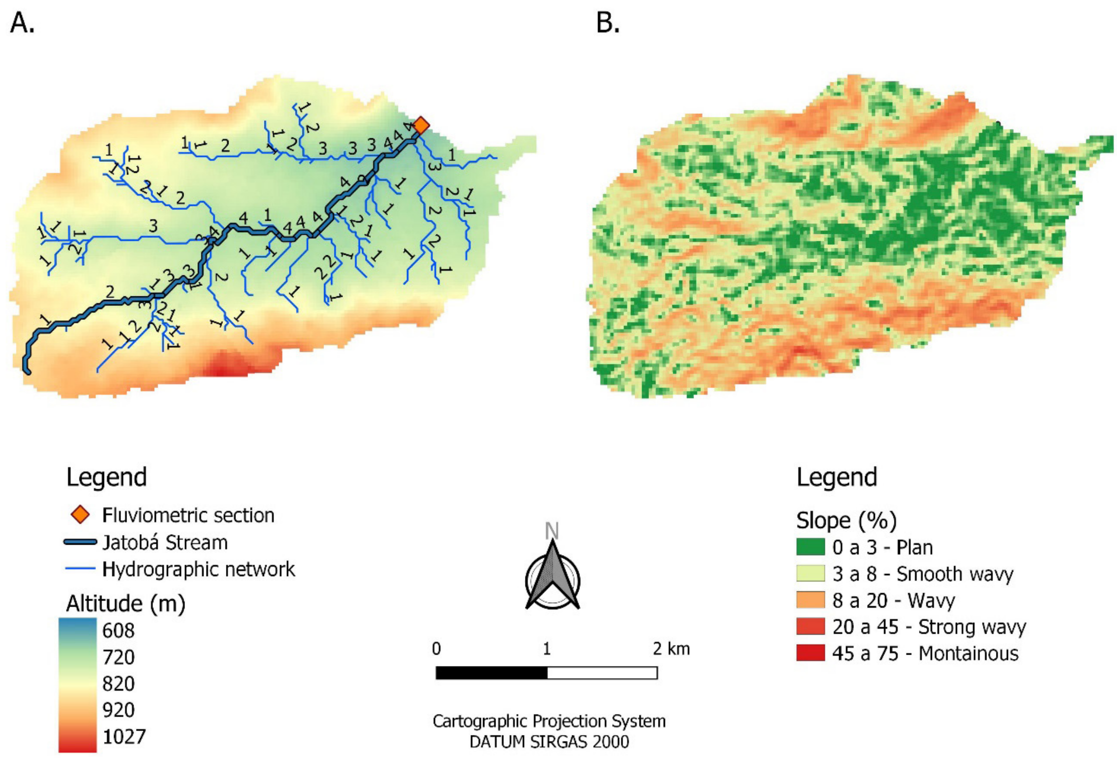

Figure 4. Digital elevation model (DEM) and hydrographic network generated by scenario 3, classified by the Strahler method (1957) (A) and SBSF slope of the Jatobá stream (B)

The average slope of the SBSF fits as undulating relief, according to the Brazilian system of soil classification (EMBRAPA, 2018). Thus, it is recommended to adopt conservation practices, such as mulch and vegetative palm ridges (LOPES *et al.*, 2019), in order to reduce surface runoff and sediment transport, which can lead to silting of water bodies, and can also reduce probable problems related to productivity and quality of agricultural production (MIOTO *et al.*, 2014). The SBSF of the Jatobá stream has 40.13% of its area with slopes between 8 to 20%, and 6.63% of its area with slopes above 45% (Figure 4). In accordance with the new Brazilian Forest Code, Law No. 12,651 (BRASIL, 2012), regions with a slope above 45% must be characterized as permanent preservation areas (APPs).

The roughness index (Ir) presented values considered low for the SBSF of the Jatobá stream. According to Alves *et al.* (2016), the higher the roughness index, the greater the risk of degradation of the basin when the slopes are steep and long. Cherem *et al.* (2011), based on morphometric analysis and compartmentalization of the Upper Rio das Velhas watershed – Central Region of Minas Gerais, obtained a roughness index equal to 462, being considered high by the authors due to the high altimetric amplitude of the basin (1,050 m).

Rodrigues & Werlang (2009), when evaluating the relief of small watersheds in the southwest of the municipality of São Pedro do Sul- Rio Grande do Sul, found that the higher the relief ratio, the greater the flow, as well as the greater the flow velocity, towards the longest length of the basin. The result of this parameter for the SBSF of the Jatobá stream (Table 6) indicates a low relief ratio, a low slope, contributing to a low speed of runoff towards the longer rivers in the basins, thus favoring a greater water infiltration (DORIGUEL *et al.*, 2015). Geostatistical studies performed by Araújo *et al.* (2018) corroborate with such low values for relief ratio, having been found greater spatial dependences for the silt fraction than for the sand fraction in the soils of the Jatobá basin, which are associated with lower runoff velocities.

In Table 7 it is possible to observe the fluvial hierarchy of the SBSF hydrographic network of the Jatobá stream. According to Strahler's (1957) method, the sub-basin presents a drainage network with a 4th order hierarchy. The 1st order channels are predominant, with a frequency greater than 50.0%, indicating more accentuated reliefs, which favor the formation of springs. Costa *et al.* (2020) emphasize that this characteristic indicates that the waters of the basin flow in a relatively short distance to the channels of an immediately higher order.

Table 6. Results for the relief parameters of the sub-basin upstream of the fluviometric section of the Jatobá stream

Relief parameters	Sub-basin upstream of the fluviometric section of the Jatobá stream
Average altitude	791.00 m
Minimum altitude	683.00 m
Maximum altitude	1027.00 m
Average altitude	344.00 m
Maximum altimetric amplitude of the basin (Hm)	10.54 %
Average slope (%)	0.90
Roughness index (Ir)	0.080 m m^{-1}

Table 7. Fluvial hierarchy of the sub-basin upstream of the fluviometric section of the Jatobá stream

Order	Bifurcation ratio	Channel frequency	Average length (Lm)
1^{st}	2.29	50.65%	297.17 m
2^{nd}	1.89	22.08%	307.20 m
3^{rd}	0.75	11.69%	381.44 m
4^{th}	-	15.58%	217.03 m

In relation to the Bifurcation Ratio (Rb), the average value is 1.63 in the SBSF of the Jatobá stream. According to Khanday and Javed (2017), bifurcation ratios commonly range between 3.0 and 5.0 for watersheds where geological structures do not exert significant control over the drainage pattern. Although the values found indicate that the basin has a low propensity to erosion, the low vegetation cover during the dry seasons implies a susceptibility to the occurrence of erosive phenomena. The drainage network of the basins is of the dendritic type, according to the classification defined by Christofoletti (1969) (Figure 4).

The results of the analysis of the hydrological morphometric parameters referring to the drainage network of the basin under study is presented in Table 8. The study of drainage density allows identifying areas with occurrence of greater or lesser speed of runoff (MELO NETO & MELLO, 2015). The result of the drainage density (Table 8) indicates that the SBSF of the Jatobá stream is characterized as a very good drainage basin. According to Villela and Mattos (1975), this index can range from 0.5 km km^{-2}, in basins with poor drainage, to 3.5 km km^{-2} or greater, in exceptionally well-drained basins.

By analyzing the hydrographic density (Dh), it was found that the SBSF of the Jatobá stream has a high number of channels per km^2, indicating that there is a high surface runoff associated with good conditions for the formation of new water courses (SANTOS *et al.*, 2012). The results of drainage and hydrographic densities corroborate the result found for the texture ratio. These results confirm that the basin has a high capacity to generate new watercourses and tends to vary consistently with drainage density (BORSATO & MARTONI, 2004).

The sinuosity index for the studied basin was 17.87%. Lacerda *et al*. (2019), performing the morphometric characterization of the watershed of the Grossos stream, Paraíba, Brazil, found higher values of IS (38.17%), indicating, in that case, that the main channel can be considered rambling, which means that it constantly changes position along its route. Observing the sinuosity of the main river (Sin), it is verified that the basin presented a value of 1.22 km km^{-1}. The sinuosity of the main channel close to 1 indicates that they tend to be straight, intermediate values indicate transactional forms, and sinuosity greater than 2.0 km km^{-1} indicates that the channels tend to be tortuous (FREITAS, 1952). Thus, the studied channel has a tendency to be straight, with few irregularities (SCHUMM, 1963), which favors processes such as drainage and surface runoff.

The concentration time found for the SBSF of the Jatobá stream is coherent with that found for the sinuosity of the main river. The result of the main channel gradient was higher than the value found by Lacerda *et al*. (2019) for the Grossos basin with (0.27%), which presents (as well as the SBSF) a predominance of areas with undulating relief (8 to

Table 8. Results of the hydrological morphometric characteristics of the sub-basin upstream of the fluviometric section of the Jatobá stream

Hydrological parameters	Sub-basin upstream of the fluviometric section of the Jatobá
Drainage density (Dd)	2.61 km km^{-2}
Hidrographic desity (Dh)	8.79 channels km^{-2}
Sinuosity Index (IS)	17.87%
Sinuosity of the main channel (Sin)	1.22 km km^{-1}
Concentration time (min)	40.71 min
Maintenance coefficient (Cm)	383.36 m^2 m^{-1}
Extension of the surface path (Eps)	1.30 km
Gradient of the main channel (Gcp)	3.10 %
Ratio texture (T)	4.70 unit km^{-1}
Topography texture (Tt)	4.83 km

20%). According to the authors, low values such as those found in the study may represent relevant evidence of a relief that does not favor surface runoff in the basin. In the case of the present study, the result points to a trend of favoring the flow process.

The maintenance coefficient for the basin was 383.63 m^2 m^{-1}. This coefficient is directly related to the drainage density and the result indicates that the basins are rich in water courses. This result is related to the length of first-order channels, which have short lengths, reflecting in low maintenance coefficients (MEDEIROS *et al*., 2020).

The extension of the surface path (Eps) for SBSF of the Jatobá stream indicates that the basin has a long runoff distance, thus providing longer concentration time, mitigating the risk of flooding (ALVES *et al*., 2016). The parameters of maintenance coefficient and extension of the surface path do not consider the slope of the channels and basins, but help to understand the dynamics of the drainage network of the basins. Indeed, the extension of the surface path represents the distance that the surface runoff travels to reach the next watercourse. Thus, the smaller the slope, the greater the distance between one watercourse and another, which is consistent with the previously calculated indices.

The texture ratio varies depending on aspects such as infiltration capacity, lithology and basin relief (HAMDAN, 2020). Thus, in relation to the texture ratio, the result found indicates that there are 4.70 watercourse segments for each km of the perimeter of the SBSF of the Jatobá stream. These watercourse segments can be classified as coarse texture, as it presents a reduced number of channels on the ground, with low bifurcation values, and texture ratio less than 8 channels km^{-1} (SMITH, 1950; MORISAWA, 1958). Hamdan (2020) performing the hydro-morphometric characterization of watersheds in Southern Egypt and Northern Sudan, found coarse texture for the sub-basins, with an average texture ratio of 5.39 channels per km.

The topography texture (Tt) presented a value of 4.83 km for the SBSF of the Jatobá stream, indicating an average texture, according to the classification of França (1968) (Table 3). Normally, when the basin has characteristics of low-resistance rocks, and no vegetation cover is present, the texture of the topography is characterized as fine, while the presence of resistant rocks provides coarser textures, with greater spacing of level curves (slight reliefs accidents) and rarefaction of drainage lines (lower erosive potential) (CHRISTOFOLETTI, 1969).

In Figure 5 is shown the hypsometric curve (A) and the profile of the main channel of the SBSF in the Jatobá stream (B). Regarding the hypsometric curve, it is observed that the basin has approximately 60% of its area with altitudes between 700 and 800 m, and 9.55% of its area with altitudes above 900 m. As for the profile of the main channel of the basin, the average elevation of the main river in the basin is 742.27 m. It was also observed that there is a reduced slope variation in the watercourse of the main channel.

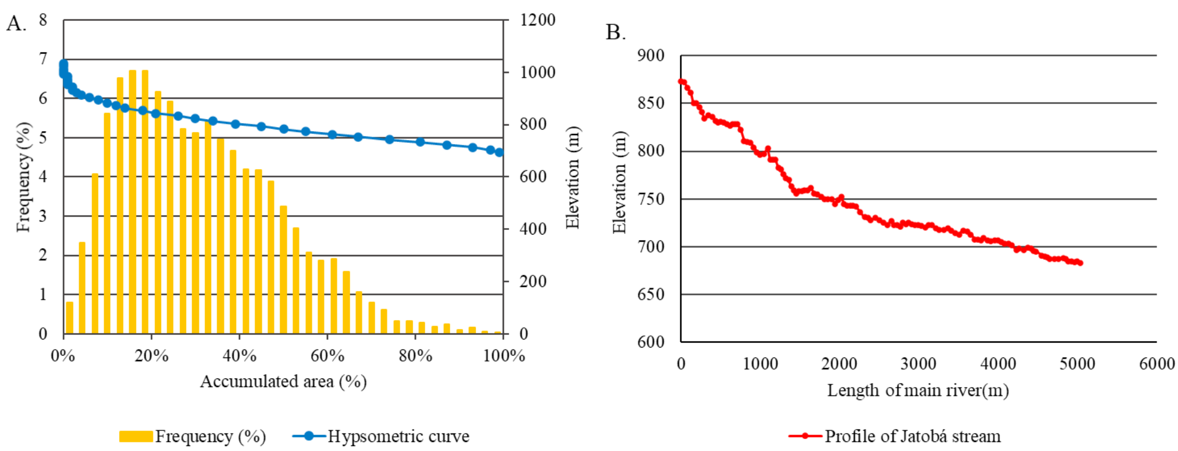

Figure 5. Hypsometric curve (A) and profile of the main river (B) of the sub-basin upstream of the fluviometric section of the Jatobá stream

Based on the previous procedures and the results presented, an area of 12.98 km² and a perimeter of 22.57 km was estimated for the Jatobá basin, which provides a circularity index of 0.32.

CONCLUSIONS

- Scenarios 3, 4 and 5 presented a more detailed drainage network, and produced equivalent hydrological simulations, with adequate representation of the processes involved. Scenario 3 was chosen because the detailing of the drainage network requires less processing time when compared to the other scenarios.
- The physical parameters indicated that the SBSF of the Jatobá stream has an elongated shape, with a low tendency for flood peaks under normal weather conditions.
- Although the SBSF of the Jatobá stream presents a low average slope, it was verified the existence of regions with high slopes, favoring surface runoff, requiring the adoption of conservation practices and the maintenance of native vegetation.
- The use of GIS technologies proved to be efficient with regard to obtaining the morphometric characteristics of the SBSF of the Jatobá stream in a simple and automated way. Thus, these technologies can be considered valuable tools for understanding the dynamics of hydrological processes, and to support the management of water resources.

AUTHORSHIP CONTRIBUTION STATEMENT

CHAGAS, A.M.S.: Conceptualization, Formal Analysis, Resources, Writing – original draft, Writing – review & editing; **MONTENEGRO, A.A.A.:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing; **FARIAS. C.W.L.A.:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing; **LINS, F.A.C.:** Data curation, Formal Analysis, Methodology, Software, Writing – review & editing; **SILVA, J.R.I.:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

DECLARATION OF INTERESTS

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

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