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Spatial and temporal variability of pluviometric precipitation in the hydrographic region of Paraguaçu - BA

Variabilidade espacial e temporal da precipitação pluviométrica na região hidrográfica do Paraguaçu - BA

Variabilidad espacial y temporal de las precipitaciones en la región hidrográfica del Paraguaçu - BA

Tailan Santos de Souza
Universidade Estadual de Feira de Santana - UEFS, Feira de Santana (BA), Brasil
tailan_santoss@hotmail.com

Patricia dos Santos Nascimento
Universidade Estadual de Feira de Santana - UEFS, Feira de Santana (BA), Brasil
psnascimento@uefs.br

Abstract

The evaluation of the pluviometric regime is an essential tool to plan and properly manage water resources. The objective of this work was to analyze the spatio-temporal variability of rainfall in the hydrographic region of Paraguaçu - BA. Based on precipitation data from 50 stations situated within and around the region, dating from 1989 to 2018, graphs and maps were prepared for spatiotemporal assessment of average precipitation, Rainfall Anomaly Index (RAI) and Precipitation Concentration Index (PCI). Homogeneous rainfall zones were also identified through cluster analysis. The results revealed that the rainy period is well defined between November and April, the highest precipitation rates (above 700 mm) occurred in the eastern and western extremities and the lowest (below 400 mm) in the portions influenced by the semiarid region. The downward trend of the RAI indicated a high possibility for the occurrence of extreme drought events, while the historical average of 17.04 % for the PCI, which classified the distribution of rainfall as moderately irregular, indicated the occurrence of concentrated rainfall. Three homogeneous clusters were identified in relation to rainfall variability.

Keywords: Rainfall indices. Interpolation. Geostatistics. Homogeneous zones.

Resumo

A avaliação do regime pluviométrico constitui uma ferramenta indispensável para planejar e gerir adequadamente os recursos hídricos. O objetivo deste trabalho foi analisar a variabilidade espaço-temporal da precipitação pluviométrica na região hidrográfica do Paraguaçu - BA. Baseado nos dados de precipitação pluviométrica de 50 postos pluviométricos inseridos e no entorno da região, datados de 1989 a 2018, foram elaborados gráficos e mapas para avaliação espaço-temporal da precipitação média, do Índice de Anomalia de Chuva (IAC) e do Índice de Concentração de Precipitação (ICP). Ainda foram identificadas zonas de pluviosidades homogêneas, através da análise de agrupamentos. Os resultados revelaram que o período chuvoso é bem definido entre novembro e abril, os maiores índices de precipitação (acima dos 700 mm) ocorreram nas extremidades leste e oeste e os menores (abaixo dos 400 mm) nas porções influenciadas pelo semiárido. A tendência decrescente do IAC apontou alta possibilidade para ocorrência de eventos extremos de seca, enquanto a média histórica de 17,04 % para o ICP, que classificou a distribuição de chuvas como medianamente irregular, indicou a ocorrência de precipitações concentradas. Foram identificados três agrupamentos homogêneos em relação à variabilidade pluviométrica.

Palavras-chave: Índices pluviométricos. Interpolação. Geoestatística. Zonas homogêneas.

Resumen

La evaluación del régimen pluviométrico constituye una herramienta indispensable para planificar y gestionar adecuadamente los recursos hídricos. El objetivo de este trabajo fue analizar la variabilidad espacio-temporal de las precipitaciones en la región hidrográfica del Paraguaçu - BA. Con base en los datos de precipitación de 50 estaciones de precipitación insertadas en la región y sus alrededores, que datan de 1989 a 2018, se prepararon gráficos y mapas para la evaluación espacio-temporal de la precipitación media, del Índice de Anomalía de la Lluvia (IAL) y del Índice de Concentración de Precipitación (ICP). También se identificaron zonas de lluvia homogéneas, mediante análisis de conglomerados. Los resultados revelaron que lo período de lluvias está bien definido entre noviembre y abril, las mayores tasas de precipitación (más de 700 mm) ocurrieron en los extremos este y oeste y las más bajas (menos de 400 mm) en las porciones influenciadas por la región semiárida. La tendencia a la baja del IAL apuntó a una alta posibilidad de ocurrencia de eventos extremos de sequía, mientras que la media histórica de 17,04 % para el ICP, que clasificaba la distribución de lluvia como moderadamente irregular, indicó la ocurrencia de lluvias concentradas. Se identificaron tres conglomerados homogéneos en relación a la variabilidad de las precipitaciones.

Palabras-clave: Índices de precipitación. Interpolación. Geoestadística. Áreas homogéneas.

Introduction

Climate change is caused by natural cycles of variability in temperature and precipitation. However, they are being enhanced by human actions such as changes in land use and greenhouse gas emissions (ANDRADE et al., 2018; SCHMIDT et al., 2018). These changes can cause a sudden variation in the patterns of rainfall, through the occurrence of extreme events, such as prolonged droughts or intense rains, which are accompanied by great socioeconomic losses for the population (EBI; BOWEN, 2016; PERKINS-KIRKPATRICK; PITMAN, 2018).

Along with climatic fluctuations, a change in the behavior of the hydrological cycle is expected, due to the strong variability and seasonality of rainfall (CALDERON; UHLENBROOK, 2016). The semi-arid climate dominates in the northeastern region of Brazil and is present in part of the Paraguaçu region, where changes in rainfall patterns intensify problems with regard to access to water, especially the competition for water resources, given that rainfall directly affects the water supply of a region (GOMES et al., 2019).

The study of spatial and temporal scales of the pluviometric regime is relevant in the incorporation of climatic variability in the planning and management of different applications of water resources, such as in agriculture and in hydraulic structures (ONYUTHA; WILLEMS, 2017). According to Gomes et al. (2019), the understanding of these spatiotemporal variations contributes significantly to the prevention of environmental risks, in addition to assisting in the preservation of water resources.

The monitoring of the spatiotemporal variability of rainfall can be performed with the use of some indexes, which may indicate changes in rainfall patterns or concentration of distribution over time (NÓBREGA; SANTIAGO, 2016). Goswami (2018) used the Rainfall Anomaly Index (RAI), an accessible method that classifies the positive and negative magnitudes of rainfall events. Sangüesa et al. (2018) used the Precipitation Concentration Index (PCI), recommended to inform how precipitation totals are distributed over a period.

A technique that has been used in the analysis of rainfall variability is geostatistics, which is statistics associated with the natural sciences that establishes inferences about a variable distributed in space or time (LANDIM, 2010). Gundogdu (2017) states that most programs for making maps or Geographic Information Systems (GIS) have options for applying geostatistical methods. Such methods consist mainly of interpolators, traditional tools for spatializing punctual information (HU et al., 2019).

In meteorology, it is common to associate geostatistical techniques with multivariate analysis. A very recurrent application is the determination of homogeneous regions regarding rainfall, which manages to harmonize rainfall behavior (SINGH et al., 2017; GEBERT et al., 2018). This delimitation is performed through cluster analysis, a multivariate tool that groups the sampling points in such a way that the individuals in the same group are more similar to each other, in relation to rainfall (MRAD et al., 2020; ALAM; PAUL, 2020).

In the context of the Paraguaçu hydrographic region, this spatiotemporal analysis of precipitation and derived indicators, in the short term, should contribute positively to the management of water stocks and the determination of agricultural periods. In the long term, the competent institutions acquire subsidies for the formulation of an effective hydrological planning, which aims at the preservation of water resources and promotes a management that anticipates adverse scenarios caused by the concentration or the scarcity of rainy events.

The present study aims to analyze the spatiotemporal variability of rainfall in the hydrographic region of Paraguaçu, state of Bahia, through the spatial and temporal evaluation of rainfall indices and the determination of homogeneous precipitation zones.

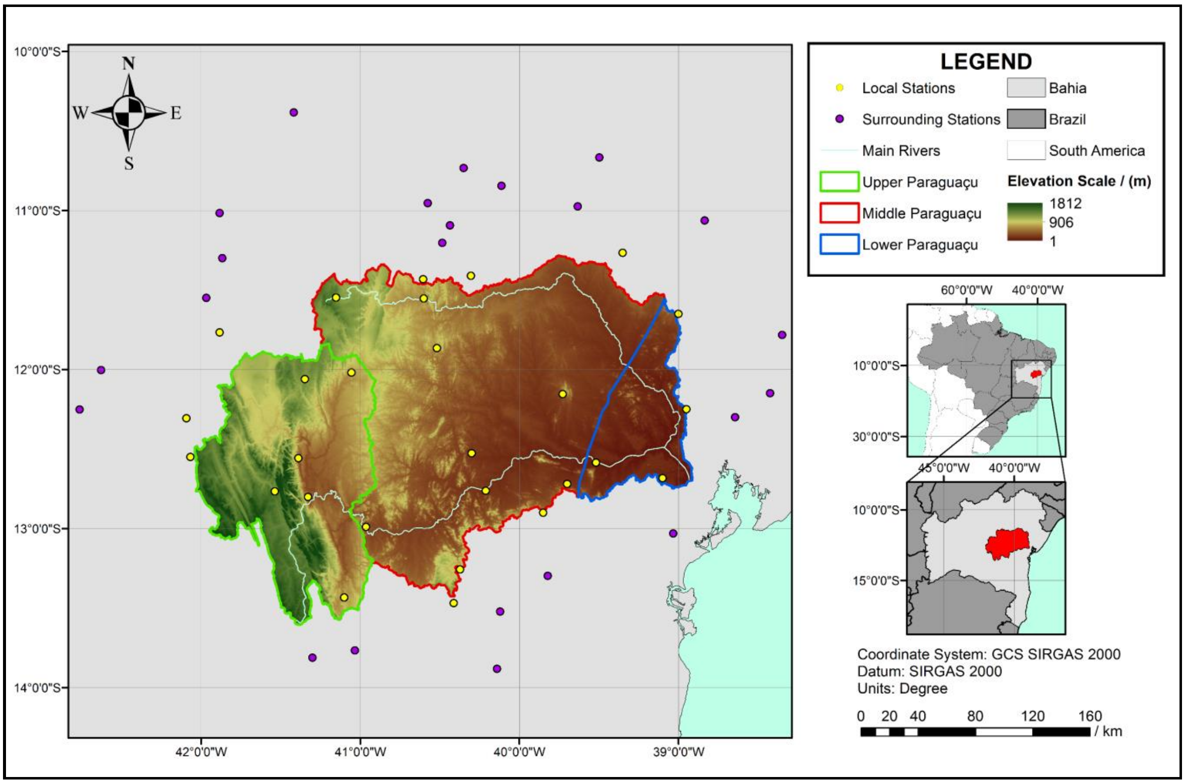
Methodology

Study Area

The hydrographic region of Paraguaçu (13° 36’ S to 11° 17’ S, 42° 2’ W to 38° 55’ W), represented in Figure 1, is located in the central-eastern region of the Bahia State. It has an area of 54322 km², covering 86 municipalities including Feira de Santana, the second largest in the state in terms of population. The main watercourse in the region is the Paraguaçu River (lower portion). The River lies entirely within Bahia and is born in Chapada Diamantina. It has the Jacuípe River (upper portion) as its main tributary course (GENZ, 2006).

The basin has three geographical divisions. In the upper Paraguaçu, in the Chapada Diamantina region, there is a predominance of dry sub-humid climate, with the occurrence of rupestrian fields. In the highest places of Chapada, rainfall is greater than 1000 mm, while in the plateaus of its base the annual rates vary between 800 mm and 1000 mm. In the middle Paraguaçu the climate is semi-arid, with predominance of typical Caatinga vegetation. The rainfall of this portion is lower, varying from 500 mm to 600 mm, due to the presence of mountain ranges that act as a barrier to the humid air masses. In the lower Paraguaçu, closer to the coast, the climate is humid to sub-humid, with vegetation remaining from the Atlantic Forest. In this portion, rainfall is abundant throughout the year, with rates exceeding 1300 mm annually (VALÉRIO, 2014; SOUSA et al., 2016).

Figure 1: Location, division, hydrography and elevation scale of the study area, together to the geographical distribution of the stations



Source: Authors, 2020.

The Paraguaçu has the most important river system in Bahia, which is why the region was chosen as a pilot area for the application of the second National Environment Program (BRASIL, 2004). The current licenses for the catchment of surface water are destined for irrigation (86 %), human supply (10 %) and industries (4 %), with Paraguaçu River being the source used for supplying the capital Salvador and its metropolitan region (SILVA et al., 2017).

Dataset

Data on rainfall were collected from the Hidroweb, an online platform of the National Water Agency (*ANA*). Such information includes monthly historical series collected by conventional climatic stations located within the hydrographic region of Paraguaçu and surroundings. A 30-year study period (from 1989 to 2018) was adopted, referring to 50 different municipalities, 27 of which belong to the hydrographic region. Data from the other 23 surrounding municipalities were used only for the purpose of spatial interpolation.

For series with missing data, filling in the gaps was performed using kriging, applied over the time series of the data. This technique is widely used in hydrology, including for estimating missing precipitation data (TEEGAVARAPU et al., 2018). This geostatistical method is based on the autocorrelations between the predicted variables, based on the variation functions, the semivariograms (HU et al., 2019). The limitation of this methodology is the adjustment of the ideal variogram model, essential for the determination of the standard parameters: sill, range and nugget effect (ADHIKARY et al., 2016).

For the historical series of each municipality, the experimental variograms were adjusted by eliminating the discrepant data, until the model with the highest spatial dependence index (s) was obtained. This index is given by Eq. 1 and adopts some of the standard parameters of the semivariogram, where C_0 represents the nugget effect, which corresponds to the value of the semivariance for the zero distance and C_1 is the structural variance.

$$s = \left(\frac{C_1}{C_0 + C_1}\right) \times 100 \qquad (1)$$

The spatial dependence index of each series was adjusted up to the classification of strong spatial dependence, that is, $s \geq 75\,\%$, according to Zimback (2001). The kriging estimation was performed using the Surfer, version 9, 2010. Table 1 shows the list of municipalities in which rainfall stations used were located and their main geographic information (altitude, latitude and longitude).

Table 1: Data from the 50 stations situated within and around of the Paraguaçu

Municipality	Altitude / (m)	Latitude	Longitude
Upper Paraguaçu			
Andaraí	330	12° 48' 06" S	41° 19' 39" W
Bonito	962	12° 03' 36" S	41° 20' 51" W
Canarana	693	11° 46' 00" S	41° 53' 00" W
Ibitiara	1098	12° 33' 00" S	42° 04' 00" W
Lençóis	439	12° 33' 26" S	41° 23' 19" W
Mucugê	870	12° 45' 59" S	41° 32' 10" W
Seabra	1033	12° 18' 22" S	42° 05' 31" W
Utinga	511	12° 01' 10" S	41° 03' 17" W
Middle Paraguaçu			
Iaçu	237	12° 45' 44" S	40° 12' 39" W
Ipirá	350	12° 09' 16" S	39° 43' 38" W
Iramaia	590	13° 26' 00" S	41° 06' 00" W
Itaberaba	250	12° 31' 36" S	40° 17' 59" W
Itatim	260	12° 43' 10" S	39° 41' 57" W
Itaetê	299	12° 59' 24" S	40° 57' 48" W
Maracás	677	13° 28' 08" S	40° 24' 44" W
Miguel Calmon	562	11° 25' 57" S	40° 36' 16" W
Milagres	395	12° 54' 00" S	39° 51' 00" W
Morro do Chapéu	1003	11° 32' 51" S	41° 09' 05" W
Mundo Novo	515	11° 51' 56" S	40° 31' 04" W
Piritiba	508	11° 33' 12" S	40° 36' 00" W
Planaltino	723	13° 15' 27" S	40° 22' 21" W
Santaluz	349	11° 16' 00" S	39° 21' 00" W
Serrolândia	380	11° 24' 38" S	40° 18' 13" W
Lower Paraguaçu			
Cruz das Almas	226	12° 41' 00" S	39° 06' 00" W
Feira de Santana	231	12° 15' 00" S	38° 57' 00" W
Rafael Jambeiro	159	12° 35' 06" S	39° 31' 06" W
Serrinha	360	11° 39' 00" S	39° 00' 00" W
Surrounding Paraguaçu			
Alagoinhas	131	12° 08' 56" S	38° 25' 27" W
Brotas de Macaúbas	837	12° 00' 13" S	42° 37' 42" W
Caém	500	11° 05' 39" S	40° 26' 06" W
Caldeirão Grande	348	10° 50' 40" S	40° 06' 42" W
Cansanção	359	10° 40' 00" S	39° 29' 48" W
Contendas do Sincorá	286	13° 46' 00" S	41° 02' 00" W
Ibititá	700	11° 33' 00" S	41° 58' 00" W
Inhambupe	158	11° 46' 58" S	38° 20' 53" W
Irecê	747	11° 18' 00" S	41° 52' 00" W
Itiruçu	756	13° 31' 21" S	40° 07' 15" W
Ituaçu	531	13° 48' 43" S	41° 18' 00" W
Jacobina	485	11° 12' 15" S	40° 29' 03" W
Jequié	199	13° 52' 56" S	40° 08' 25" W
Jussara	680	11° 01' 00" S	41° 53' 00" W
Mirangaba	930	10° 57' 14" S	40° 34' 31" W
Nazaré	35	13° 01' 51" S	39° 01' 56" W
Oliveira dos Brejinhos	440	12° 15' 07" S	42° 45' 46" W
Pindobaçu	600	10° 44' 00" S	40° 21' 00" W
Queimadas	279	10° 58' 27" S	39° 37' 58" W
Santa Inês	415	13° 17' 51" S	39° 49' 17" W
Sento Sé	950	10° 23' 00" S	41° 25' 00" W
Teodoro Sampaio	116	12° 18' 01" S	38° 38' 38" W
Tucano	153	11° 03' 47" S	38° 50' 07" W

Source: *ANA*, 2019. Organized by the authors, 2020.

In order to ensure better information reliability, a data homogenization procedure was adopted in all pluviometric stations. For this purpose, the RHtest package was used, programmed in R and developed by Wang (2008a, 2008b), where it is possible to verify the homogeneity of the historical series through statistical tests that assess the significance of the points of change. The series that presented significant noise were adjusted using the quantile correspondence, responsible for the seasonal discontinuity of the new data set (SI et al., 2018).

Rainfall Indices

Van Rooy (1965) developed the RAI, which indicates the frequency of dry and rainy periods in a given study area. This parameter serves as a basis for studying the severity of droughts, in addition to being popular and widely accepted (RANGARAJAN et al., 2018). For the Paraguaçu region, the annual RAI of each municipality was calculated, using Eq. 2 and Eq. 3, which present positive and negative anomalies, respectively.

$$RAI = 3 \times \left[\frac{(N - \bar{N})}{(\bar{M} - \bar{N})}\right] \quad (2)$$

$$RAI = -3 \times \left[\frac{(N - \bar{N})}{(\bar{X} - \bar{N})}\right] \quad (3)$$

The parameter N indicates the annual precipitation in mm, while $\bar{N}$ is the average precipitation of the historical series, $\bar{M}$ is the average of the ten largest annual precipitation in the series and $\bar{X}$ is the average of the ten lowest ones. Positive anomalies indicate years with precipitation above average, while negative anomalies indicate those below. The classification of rainfall intensity due to the RAI is shown on Table 2.

Table 2: Classification of the intensity of the dry and rainy years from the RAI

Variation of RAI	**Intensity Category**
Above 4	Extremely Rainy (ER)
2 to 4	Very Rainy (VR)
0 to 2	Rainy (R)
0 to -2	Dry (D)
-2 to -4	Very Dry (VD)
Below -4	Extremely Dry (ED)

Source: Van Rooy, 1965. Adapted by Freitas, 2005.

Another indicator of precipitation used was the PCI, proposed by Oliver (1980) to determine the degree of rainfall concentration, closely linked to the drought pattern of a locality, which in turn is aggravated the greater the heterogeneity of rainfall distribution (THOMAS; PRASANNAKUMAR, 2016; RANGARAJAN et al., 2018). Each station located in the Paraguaçu had its index estimated separately, using Eq. 4 for annual data and Eq. 5 for seasonal data, as described by De Luis et al. (2011).

$$PCI\ (annual) = 100 \times \frac{\sum_{i=1}^{12} pm_i{}^2}{(\sum_{i=1}^{12} pm_i)^2} \tag{4}$$

$$PCI\ (seasonal) = 25 \times \frac{\sum_{i=1}^{3} pm_i{}^2}{(\sum_{i=1}^{3} pm_i)^2} \tag{5}$$

In both equations, pm_i represents the monthly precipitation in the month i. The annual calculation counts all months of the year, while the seasonal calculation takes into account the months corresponding to the seasons of summer, autumn, spring and winter. The classification of rainfall regularity due to the PCI is shown on Table 3.

Table 3: Classification of rainfall regularity according to PCI

Variation of PCI	**Precipitation Distribution**
Below 10 %	Regular (R)
11 % to 15 %	Low Irregularity (LI)
16 % to 20 %	Medium Irregularity (MI)
Above 20 %	High Irregularity (HI)

Source: Oliver, 1980.

In order to characterize the spatial distribution, maps of the annual averages of rainfall and the anomaly and concentration of rain indexes were prepared. The input data were the geographical coordinates of the rainfall stations and the respective values of the annual variables. For the spatialization of these data, geostatistics was applied using ArcGIS, version 10.5, 2016.

The interpolation technique used was ordinary kriging with an exponential model, considered the most efficient among deterministic and stochastic techniques in estimating average annual precipitation, showing a satisfactory correlation between estimated and real values (CASTRO et al., 2010). The semivariogram model was optimized by the software for each spatialized variable, including disregarding anisotropy, since this condition can be assumed in rainfall data, with the purpose of simplifying procedures (CUNHA et al., 2013).

The performance validation of this interpolation method was performed using the Root Mean Square Error (RMSE), Eq. 6, where: N is the number of comparisons, p_i is the value estimated by the model, o_i is the value observed in the series. RMSE is a performance criterion widely adopted in gender studies (CHEN et al., 2017; GUNDOGDU, 2017; TEEGAVARAPU et al., 2018), because this metric is easy to understand, due to the maintenance of the unit of measurement of the quantities predicted in the model.

$$RMSE = \sqrt{\frac{1}{N} \times \sum_{i=1}^{N} (p_i - o_i)^2} \qquad (6)$$

Cluster Analysis

A cluster analysis was performed for the rainfall data, using the Ward (1963) method, which forms groups of individuals based on the homogeneity between the variables. In the present study, the aim was to confirm whether the groups formed are compatible with the previous characterization of rainfall in each geographical division of the region. In this case, the individuals were the municipalities situated in Paraguaçu, while the variables are their monthly rainfall in the 30-year series and the local altitudes, for a better geographical alignment.

The similarities between the data were attributed by means of the Euclidean distance (d_{ij}) between two objects (i and j) with values for p normalized variables, following Eq. 7. As this parameter is a measure of dissimilarity, the shorter the distance between the data, the greater the similarity between them (SILVA et al., 2018).

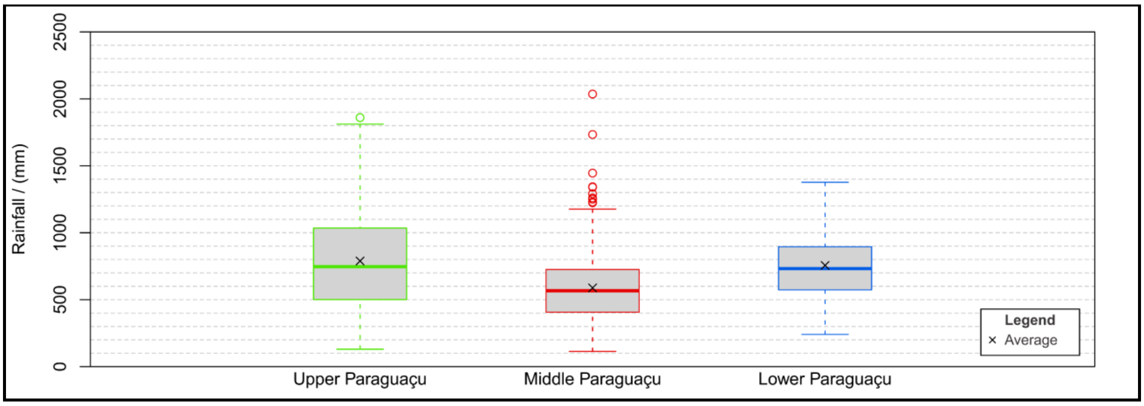
$$d_{ij} = \sqrt{\sum_{k=1}^{p} (x_{i,k} - x_{j,k})^2} \qquad (7)$$

The results of the cluster analysis were presented in two ways. One of them was the dendrogram, a graph that shows the grouping between similar individuals on one axis and the measure of similarity between variables on the other, performed using RStudio, version 1.1.463, 2018. The other was the zoning map, in which the Paraguaçu region was divided into the homogeneous groups formed, through the geostatistical model of kriging. This model has good precision in the spatialization of clusters according to Moral et al. (2016). For this, ArcGIS, version 10.5, 2016 was used.

Results and Discussion

Figure 2 shows the boxplot of the annual rainfall of each geographical division of Paraguaçu. They demonstrated that, during the study period, the annual averages of the lower and upper Paraguaçu were matched (756 mm and 789 mm, respectively), with the greatest dispersion occurring in the latter, which has the largest range of amplitude in the boxplot (500 mm and 1036 mm). The middle Paraguaçu, an area characterized by the Semiarid region, presented the lowest annual average (588 mm) and the smallest amplitude of the interquartile range (407 mm and 726 mm), configuring the lesser dispersion of the pluviometric indexes, in relation to the other divisions.

Figure 2: Boxplot of the annual rainfall for the divisions of the Paraguaçu hydrographic region

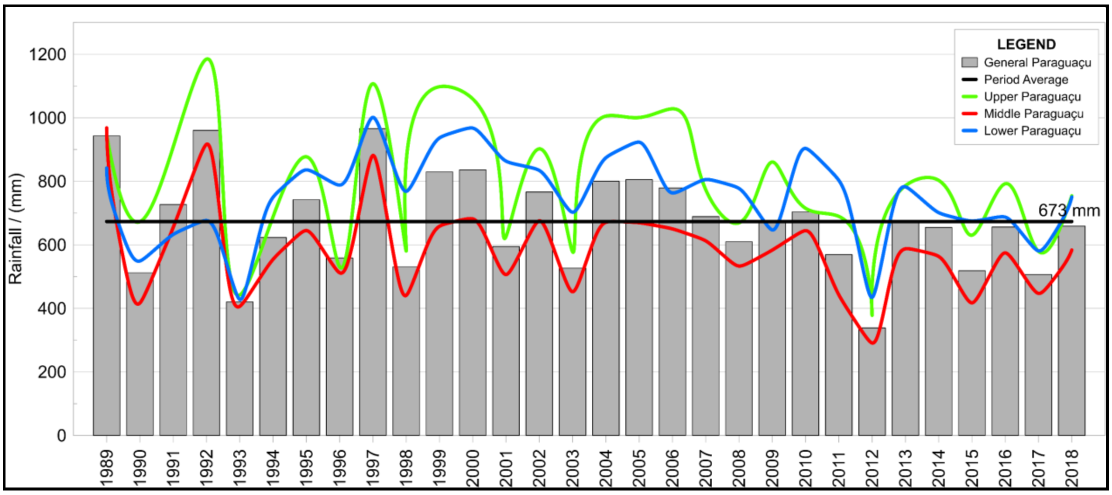


Source: Authors, 2020.

In the upper and middle Paraguaçu, the data showed the presence of outliers, behavior that is usual in historical series of pluviometric data, as verified in the studies by Wu and Qian (2017) and Phuong et al. (2019). These outliers are very common in rainfall time series, as the information comes from the measurement of a natural and random phenomenon, with the possibility of sudden large-scale events (PAUL et al., 2017).

The graph in Figure 3 demonstrates the interannual oscillation of total average rainfall for the Paraguaçu region and its geographical divisions, between 1989 and 2018. In general terms, the rainfall average for the period was 673 mm. 1997 presented the highest occurrences rainfall (average of 966 mm) and 2012 the lowest (average of 338 mm). For precisely 50 % of the period, the annual averages were below the general average, especially after 2010.

Figure 3: Variation annual of the average rainfall for the divisions of the Paraguaçu hydrographic region



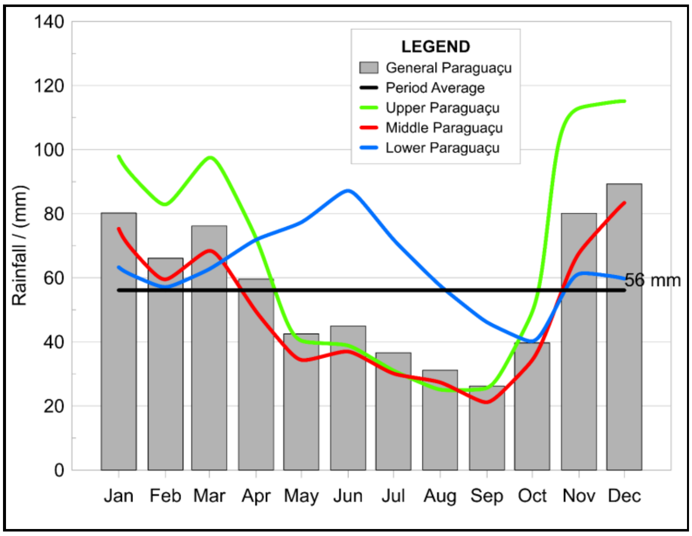
Source: Authors, 2020.

As for the geographic divisions, it is notable that the pluviometric precipitation was lower in the middle Paraguaçu, while the highest rainfall alternates between the high and low parts of the hydrographic region. The stations located in the lower Paraguaçu presented annual averages higher than the average of the hydrographic region for 80 % of the period. On the other hand, the annual indexes of the stations in the middle Paraguaçu were below this average for 83 % of the time. It is also observed that, although they have different amplitudes, the lines of average annual values, follow a similar oscillation pattern, particularly in the lower and middle Paraguaçu.

Figure 4 illustrates the monthly variation in rainfall. In general, the rainy season was between November and April. July (37 mm), August (31 mm), September (26 mm) and October (40 mm) presented the lowest rainfall averages for the period, characterizing the winter as a period of low rainfall. This result is compatible with the study by Sousa et al. (2016), who observed the period of greatest precipitated volume between November and March, in addition to average indices below 40 mm in the months of August, September and October, for the same hydrographic region.

The monthly rainfall of the upper and middle Paraguaçu follow the general oscillation of the region, with a well-defined rainy season between November and April. However, in the lower Paraguaçu there was a divergence, since the rain peaks were between April and July. Genz (2006), who compared rainfall data from the estuary (lower portion) and spring (upper portion) of the Paraguaçu River, pointed out this same divergence.

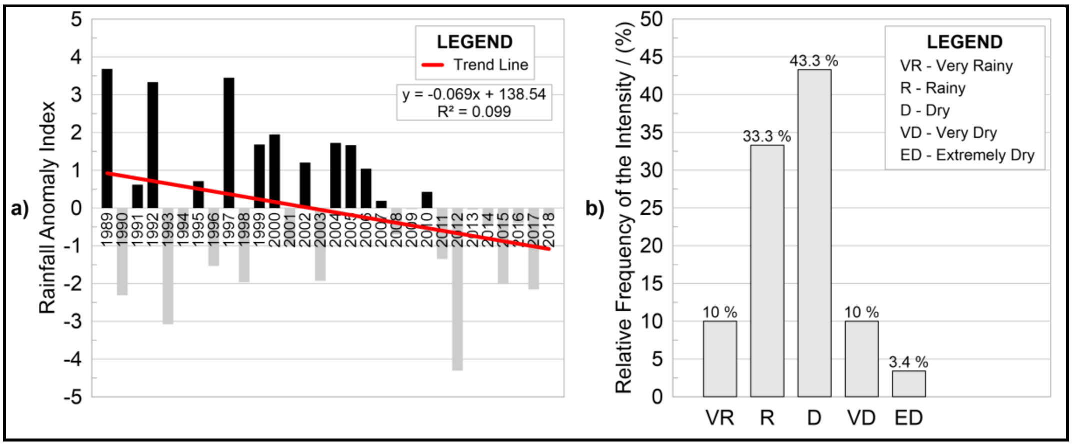
Figure 4: Variation monthly of the total average rainfall for the divisions of the Paraguaçu hydrographic region



Source: Authors, 2020.

The results associated with the RAI can be seen in Figure 5. As shown on Figure 5a, dry and rainy patterns were perceived throughout the historical series. Within the study period, the Paraguaçu region presented most of the average indexes classified as dry, very dry or extremely dry. The positive peaks of the RAI occurred in the years 1989 (+3.7), 1997 (+3.4) and 1992 (+3.3), noted by average annual rainfall rates greater than 940 mm.

Figure 5: Variation of the average annual of the RAI for the hydrographic region of Paraguaçu (a) and relative frequency by intensity category (b)



Source: Authors, 2020.

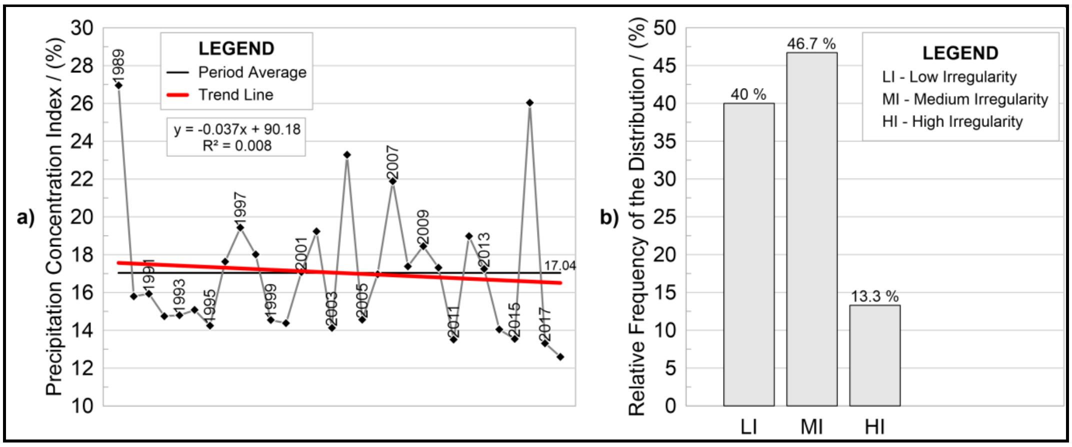
The main negative peaks were in the years 2012 (-4.3) and 1993 (-3.1), also marked by the lowest average precipitation records. In those same years, the maximum negative values of the RAI were found by Costa and Rodrigues (2017) in a basin in Ceará (state of the same region of Bahia), a fact explained by the occurrence of the El Niño phenomenon of strong intensity, responsible for the scarcity of rains in the Northeast of Brazil (NEB).

The trend line indicates that there was a decrease in RAI over the years. All the years after 2010 showed this negative index, which indicated the tendency of reduction of the precipitated volume. The coefficient of determination of the regression model was low and had an order of magnitude similar to the results obtained by Surendran et al. (2019) in another temporal analysis of RAI. This is due to the high interannual variability in rainfall, according to Asfaw et al. (2018).

According to Figure 5b, the dry, very dry and extremely dry years occurred with a relative frequency of 56.7 % within the analyzed historical series. According to Cerqueira et al. (2017), from this percentage, it is possible to infer that there is a greater probability that extreme drought events will be observed in the study area.

According to Figure 6a, the annual PCI varied between 26.95 % in 1989 and 12.60 % in 2018, assuming the historical average of 17.04 %, which classifies the distribution of rain in the region as medium irregularity. It was also possible to verify a slight tendency of reduction of the PCI in the period through the adjustment line, which was not significant enough to predict regular rain events in the short term.

Figure 6: Interannual variation of the average annual of the PCI for the hydrographic region of Paraguaçu (a) and relative frequency by distribution category (b)



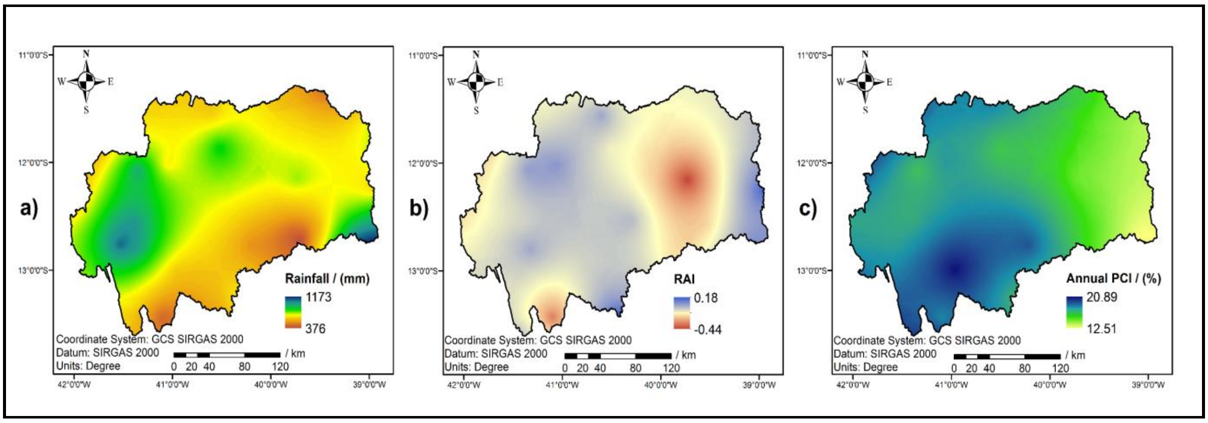
Source: Authors, 2020.

Of the 30 years evaluated, none showed a regular distribution (PCI < 10 %) of precipitation over the months. This may be associated with the fact that the average PCI of a region is significantly influenced by the spatial variability of the climate. Sangüesa et al. (2018), for example, attested that the annual PCI tends to decrease by up to 30 %, when it goes from an arid zone to a wet zone. According to Figure 6b, the average and the high irregularity of the distribution added up to a relative frequency of 60 % within the analyzed period.

The frequency of high values for PCI in the Paraguaçu region indicated that a greater part of the annual precipitation happened in some very rainy areas, which represents a potential risk for the occurrence of floods in these locations, as well as phenomena of extreme droughts in areas of naturally less occurrence of rainfall. According to Coscarelli and Caloiero (2012), high PCI values imply impacts on soil and human life, since concentrated rainfall leaves soils vulnerable to erosion and extreme droughts increase the possibility of desertification. These environmental risks affect economical activities, especially agricultural production.

Figure 7a shows the spatialization of average precipitation. It is possible to verify that the eastern and western extremes, practically corresponding to the lower and upper Paraguaçu, showed the highest rainfall rates, above 700 mm per year. On the other hand, it is noted that the center-south and center-north portions, which involve the semi-arid region, had a greater lack of high rainfall volumes, with annual rates below 400 mm. Sousa et al. (2016), found similar results for the same hydrographic region, with higher rainfall occurring close to the coast and in Chapada Diamantina.

Figure 7: Spatial distribution of the average annual precipitation (a), of the RAI (b) and the annual PCI



Source: Authors, 2020.

The spatialization of the RAI (Figure 7b) denotes that the points with the highest average rainfall tend to show positive values, because the RAI is a quantity that derives directly from the volume of rainfall. The highest indexes (between 0 and 0.18) occurred at the eastern end and in some points distributed from the central area to the west of the hydrographic region. Likewise, Costa and Rodrigues (2017) found higher RAI values in regions with high rainfall. On the other hand, the most critical negative indices were situated to the east of the middle Paraguaçu, which is influenced by the drier climate.

The annual spatial scale of the PCI (Figure 7c) can be described as highly irregular (more than 20 %) in the southern portion and moderately irregular (between 15 % and 20 %) in the other areas of the hydrographic region. Some points of low irregularity (between 12.51 % and 15 %) could be noted in the extreme east, probably due to the occurrence of a humid climate (SANGÜESA et al., 2018). It is important to note that these spatial patterns do not necessarily follow the patterns of rainfall behavior, as pointed out by De Luis et al. (2011), as places with high precipitation may have more or less irregular rainfall distributions.

The results of the performance evaluation of the spatial distribution by ordinary kriging with an exponential model are presented in Table 4. The RMSE for the average annual precipitation was around 193 mm, 80.8 % of the standard deviation of the data that was spatially distributed, which was equal to 239 mm. Kumari et al. (2016) evaluated this interpolator in the distribution of the same variable and found the similar percentage ratio of 88.2 %, for the 484 mm RMSE.

Table 4: Validation of interpolation performance through kriging with exponential model

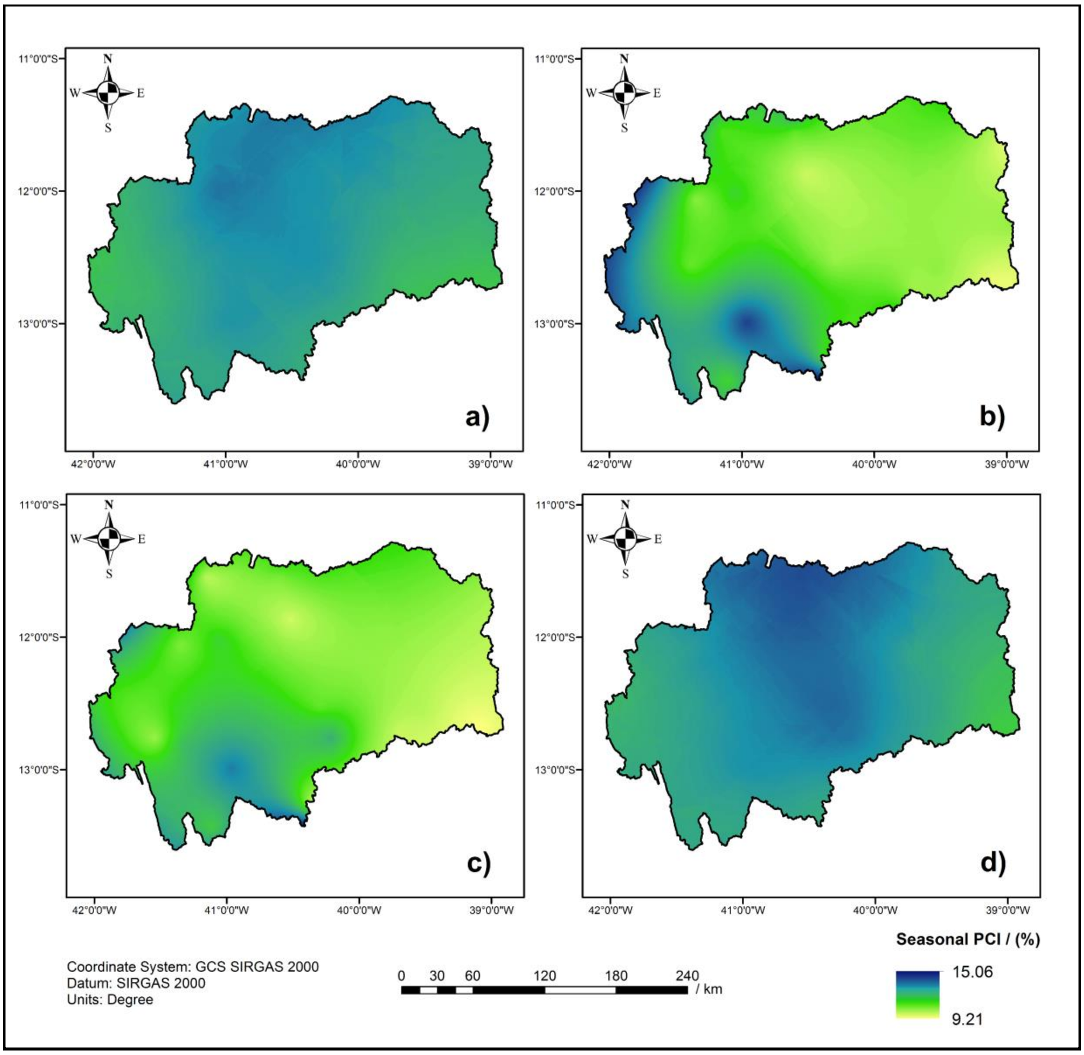
Variable	**RMSE**
Rainfall	193.16 mm
RAI	0.13
Annual PCI	3.41 %

Source: Authors, 2020.

As for the RAI and the annual PCI, the literature has not presented the performance of the models, and ordinary kriging is already used as a starting point for spatial distribution in Brazilian studies (COSTA; RODRIGUES, 2017; SIQUEIRA; NERY, 2018). Similar to the average annual precipitation, the values of the RMSE for the rainfall indexes were below the standard deviations of the initial data, equivalent to 0.14 for the RAI and 3.84 % for the annual PCI.

The spatialization of the seasonal PCI, shown in Figure 8, takes into account the distribution of rainfall in the period of each climatic season. There are few points in the hydrographic region that presented medium or high irregularity (PCI > 15 %), configuring a greater regularity of the intraseasonal distribution in relation to the annual distribution. In addition, it is observed that in the summer (Figure 8a) and spring (Figure 8d), seasons that coincide with the months with the highest precipitated volume, the rains tend to be more irregularly distributed in practically every hydrographic region, when compared to the autumn (Figure 8b) and winter (Figure 8c).

Figure 8: Spatial distribution, through kriging, of the seasonal PCI for the hydrographic region of Paraguaçu, considering the seasons: summer (a); autumn (b); winter (c); and spring (d)

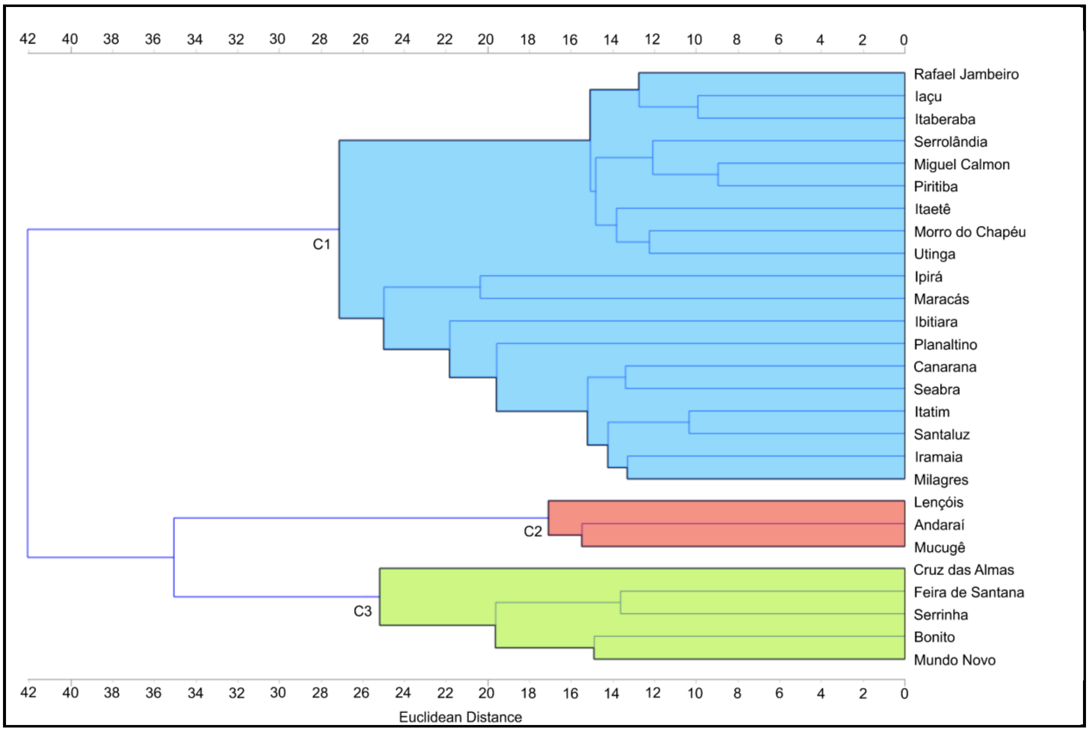


Source: Authors, 2020.

Similarly, De Luis et al. (2011) found points with more regularity in the distribution of precipitation, based on the assessment of the seasonal PCI to the detriment of the annual PCI. The same authors also found that this index rises with the increase in the concentration of rainfall, especially during the rainy seasons, while indications of more uniform precipitation begin to appear during the dry seasons.

Figure 9 shows the dendrogram representing the similarity between the precipitation of the stations effectively inserted in Paraguaçu. Considering that the level of similarity does not increase significantly for less variation in the Euclidean distance, the cut-off criterion was adopted where the number *n* of groups formed results from the greatest amplitude in relation to the subsequent *n+1*, the same criterion adopted by Singh et al. (2017) and Gebert et al. (2018). Thus, as the greatest amplitude of Euclidean distance was observed in the migration from three to four groups, three groupings were the quantity adopted.

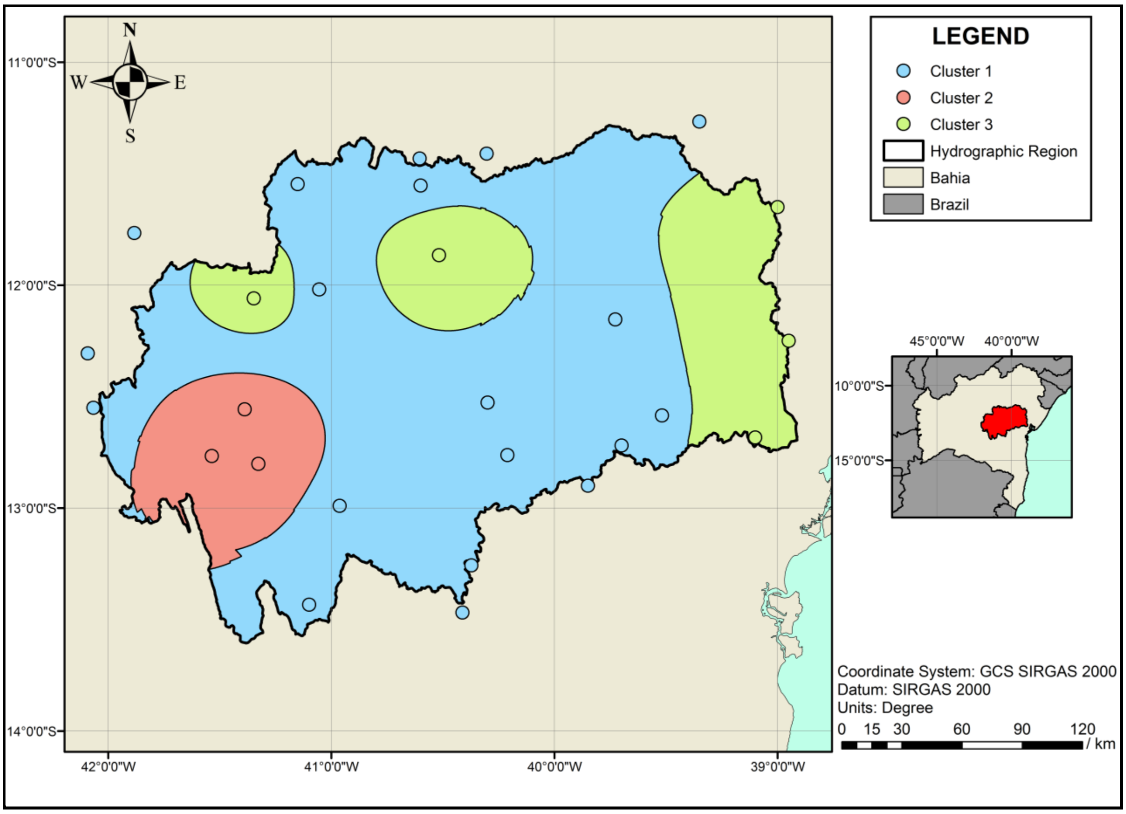
Figure 9: Dendrogram based on Euclidean Distance for the stations in the Paraguaçu



Source: Authors, 2020.

Based on the results of the dendrogram, the map of homogeneous zones was shown on Figure 10. It is possible to verify that the first group (C1) was the most general, covering 19 stations spread across the study area, which are located mainly in the middle, southwest of lower and in the northern and southern parts of the upper Paraguaçu. The second cluster (C2) has three stations located in the central portion of the upper Paraguaçu. The third group (C3) comprised the other five stations and is more concentrated in the lower Paraguaçu, with two isolated points in the middle and upper portions of the hydrographic region.

Figure 10: Homogeneous zones of monthly precipitation in the hydrographic region of Paraguaçu



Source: Authors, 2020.

It is worth noting that the geographic distribution of homogeneous zones was not fully compatible with the climatic characterization predicted by the geographical divisions of the region. However, it was still similar to the spatial distribution of annual rainfall. The areas with reduced rainfall (< 650 mm) were similar to the C1 cluster. The portion with the highest rainfall (> 890 mm), located to the west, corresponded to the C2 cluster. The areas of high or intermediate rainfall in the eastern portion and at specific points north of the hydrographic region, harmonized with the C3 cluster. This agreement between homogeneous zones and the annual rainfall distribution was also obtained by other authors (DOURADO et al., 2013; GEBERT et al., 2018).

Dourado et al. (2013) identified homogeneous rainfall zones for the entire state of Bahia, using an algorithm different from that of Ward (1963). Even so, the demarcation of the Paraguaçu hydrographic region presented points of three distinct groups. One encompassing the rainy municipalities on the coastal zone of the state. One with the driest municipalities in the Semiarid region. And finally, one in the transition region between the Semiarid and Cerrado, with high rainfall occurring due to the orographic effect.

Conclusions

The historical average annual rainfall in the hydrographic region of Paraguaçu was 673 mm, and in half of the analyzed period, the annual averages were below this value, especially in the latest years after 2010, a fact that indicated a possible tendency to reduce annual rainfall. The rainy period was well defined, between the months of November to April, with the exception of the lower Paraguaçu, which is influenced by maritime conditions and presented rain peaks between April and July.

The rainfall indices warned of two situations of different climatic extremes. The RAI classified most years as dry, very or extremely dry, in addition to presenting a downward trend, indicating a high probability of occurrence of extreme events drought. The annual PCI was not classified as regular in any year, indicating the possibility of occurrence of extreme events heavy rainfall, concentrated in short periods. The seasonal PCI indicated a greater regularity in the distribution of rainfall in autumn and winter.

Geographically, the eastern and western extremities, which correspond to the lower and upper Paraguaçu, showed the highest levels of rainfall, while the central-south and central-north portions, influenced by the semi-arid, presented the smallest levels. Through cluster analysis, the study area was divided into three homogeneous groups of monthly precipitation, and the geographical layout of the groups was compatible with the spatial distribution of annual precipitation.

This study has great local applicability, as there was a concern with hydrological extremes and their possible social and economic impacts. The spatio-temporal characterization of rainfall offered a compiled of information that works as planning tools for actions aimed at the adequate management of water resources, which prioritizes an optimized use, adapting the collection and storage systems to the variability of rainfall, reducing water scarcity.

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Authors

Tailan Santos de Souza – He has a degree in Civil Engineering and a Master's in Civil and Environmental Engineering from the *Universidade Estadual de Feira de Santana* (*UEFS*).

Address: Universidade Estadual de Feira de Santana, Av. Transnordestina, s/n, Novo Horizonte, Feira de Santana – BA – CEP: 44036-900.

Patricia dos Santos Nascimento – She has a degree in Agronomic Engineering from the *Universidade Federal do Recôncavo da Bahia* (*UFRB*), a Master's Degree in Agrarian Sciences from the *Universidade Federal do Recôncavo da Bahia* (*UFRB*) and a PhD in Agronomy from the *Universidade Estadual Paulista "Júlio de Mesquita Filho"* (*UNESP*). She is currently an Adjunct Professor at the *Universidade Estadual de Feira de Santana* (*UEFS*).

Address: Universidade Estadual de Feira de Santana, Av. Transnordestina, s/n, Novo Horizonte, Feira de Santana – BA – CEP: 44036-900.

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