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Drought Events Analysis and Spatial Distribution for the states of Rio Grande do Norte and Paraiba, Brazil

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Abstract

The application of the Standardized Precipitation Index was established for 13 rain gauge stations selected in the catchment sub-basins of number 37 and 38, which correspond to the area of the states Rio Grande do Norte and Paraiba. The monthly rainfall data of the stations was analyzed, and the missing data was filled by simple linear regression. A 6-month time scale was adopted for the method; the data was organized in a moving cumulative distribution of precipitation and applied to the Standardized Precipitation Index (SPI). In the application of the method, the cumulative values are processed into a normal distribution with the mean zero and variance one. That way, a drought event begins when the cumulative precipitation in the historical data series reaches an SPI value smaller than or equal to -1.00. Between 22 and 26 events for the stations of the sub-basin 37, and between 18 and 22 events for the stations of sub-basin 38 were identified. Medium-term tendencies were observed, with the occurrence of events every year or two, proving certain seasonality. The obtained values were then transformed into a return period of 20 years, and an isohyetal map was developed with the purpose to show the spatial variation of the event precipitation. By the outlined map, becomes evident an area of higher precipitation rates, situated on the coast along the states, and a drier region, located in the inland territory.

Keywords: Drought; Standardized Precipitation Index; Water Resource Management

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1 Introduction

The randomness characteristic of natural hydrological phenomena motivated studies to focus on the concepts of Statistics and Probability. This way, a joint management with mathematical, statistical and operational researches is needed (SIBUT GOMIDE, 1976). For the estimation of flood, drought and rainfall frequencies, the likelihood of occurrence may be given by a frequency analysis (CHOW, 1964).

To achieve a good planning and management for water resources, minimum flow values are of major importance in the development of projects and studies of springs hydrological analysis, for water resources use grant systematics and drought control (KAVISKI, 1983). According to Gottschalk et al. (2013), the study of minimum flow and its relation to the ecosystems maintenance impacts the economy and due to its importance in climatic changes, is becoming increasingly important. Having a relatively smaller number of studies, comparing with the flood ones, manuscripts related to lower extremes seek a better fitting into distribution functions.

The Standardized Precipitation Index (SPI), developed by McKee, Doesken and Kleist (1993), is used for a classification of rainfall data as a standardized value, according to a rainfall occurrence probability (TEODORO et al., 2015). According to the World Meteorological Organization (WMO, 2012), data computation for a time series with at least 30 years is preferred. The Organization cites as benefits of the method the flexibility of calculation for different time scales, its spatial consistency, enabling the comparison among different locations, and its simplicity in the calculation.

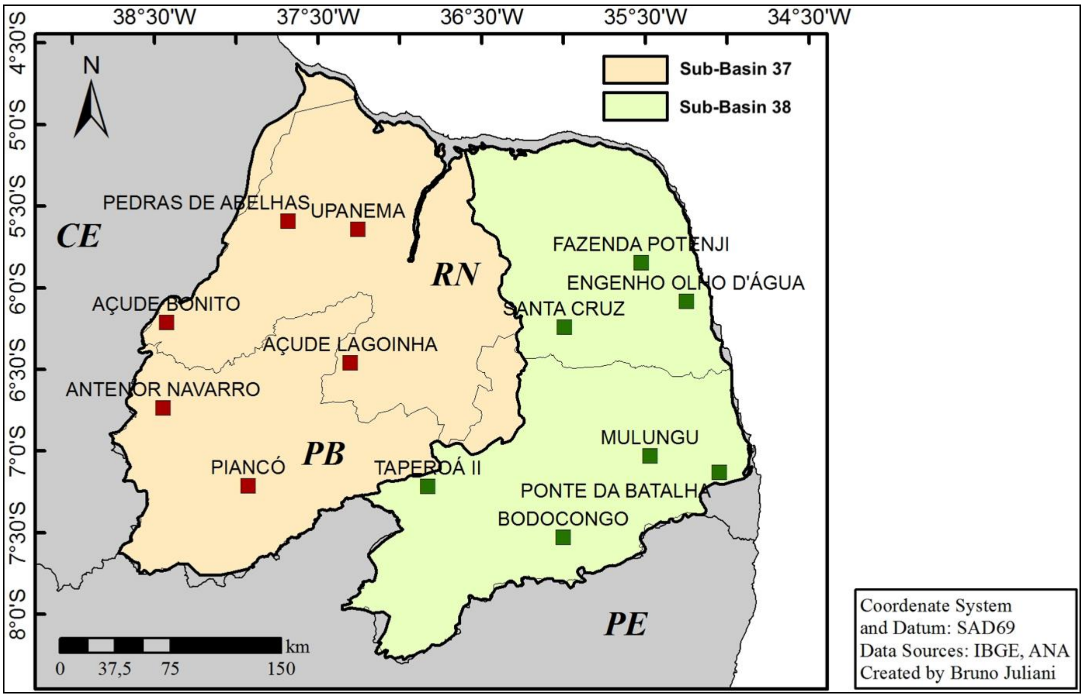
The Brazilian Northeast is characterized by three different climates: Humid Coastal, in its eastern border; Humid Tropical, occurring in part of the states of Bahia, Ceara, Maranhao and Piaui; and Semi-Arid Tropical, inland the continent, known in Portuguese as “sertao” (KAYANO and ANDREOLI, 2009). The region possesses high annual and seasonal variability of precipitation, influenced by Pacific and Tropical Atlantic oceans (MOURA and SHUKLA, 1981).

In face of the above, the present paper aims the application of the Standardized Precipitation Index in a defined area of Brazilian Northeast region for the identification of drought events in a given time series. By means of a statistical methodology, with the critical drought events values identified, a critical situation in a return period of 20 years will be calculated. For a better presentation of the results, an isohyetal map will be developed for a spatial observation of the obtained punctual results.

2 Materials and Methods

As selected area for the study, the Brazilian sub-catchment basins 37 (Apodi river, Piranhas river and others) and 38 (Paraiba river, Potenji river and others) have their boundaries similar to the boundaries of the states of Rio Grande do Norte and Paraiba. For the first sub-basin, six pluviometric stations were identified with a time series of 30 years, whereas for the second sub-basin, seven stations were selected. The pluviometric station information, as well as the precipitation data, were obtained through the Hydrological Information System Hydroweb, provided by Brazilian National Water Agency (ANA, 2017). The study area and the identification for the 13 selected stations, can be observed in Figure 1.

Figure 1 – Sub-catchment basins 37 and 38, and selected stations



Commonly used in Brazil, the Simple Linear Regression (LR) method was adopted in order to fill the missing data from the time series, as recommended by Brazilian National Water Agency (DESTRO; FARIAS; LIMA, 2013). The method consists in selecting in a neighbourhood near meteorological stations with sufficient and consistent data, in order to linearly correlate the monthly precipitation values observed. The neighbouring station with the best correlation coefficient is selected to fill the missing data using a linear regression equation.

The Standardized Precipitation Index methodology consists basically of a transformation of a precipitation time series into a standardized normal distribution (TSAKIRIS; PANGALOU; VANGELIS, 2007). A time scale should be selected, in other words, the cumulative period for comparison (WMO, 2012). For this present study, a 6-month time scale was selected, as it is effective in the comparison of precipitation among different stations and indicates medium-term tendencies, associated with outflows and water reservoirs levels.

Therefore, for each station, the cumulative 6-month precipitation for the entire time series was adjusted into Gamma Distribution. A density probability is applied, as shown in Equation (1):

$$g(x) = \frac{x^{\alpha-1} e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)} \quad (1)$$

Where: α is the shape parameter, β is the scale parameter, x is the cumulative precipitation value, and Γ(α) is the Gamma function, given by Equation (2):

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1}\, e^{-y} dy \quad (2)$$

The cumulative probability gamma distribution is given by the integral of the probability density function, as observed in Equation (3):

$$G(x) = \int_0^{x} g(x)\, dx = \int_0^{x} \frac{x^{\hat{\alpha}-1} e^{-x/\hat{\beta}}}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} dx \quad (3)$$

Where the parameters of the function G(x) are following the Equations (4), (5), and (6), n is the number of observations of precipitation, and $\bar{x}$ the sample data average.

$$\widehat{DZ} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad (4)$$

$$\hat{\beta} = \frac{\hat{x}}{\hat{a}} \quad (5)$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (6)$$

The resulting values of the Gamma cumulative probability distribution are related to values of a Normal probability distribution, with the mean zero and variance one. This relation results in the SPI values.

According to classification presented in Table 1, a drought event begins when the cumulative precipitation in the time series reaches a SPI value equal or below -1.00. The end of the event is considered when the SPI value becomes positive, meaning that the cumulative precipitation reached up a value higher than the historical average, compensating the event deficit (RAHMAT; JAYASURIYA; BHUIYAN, 2015). Rahmat, Jayasuriya and Bhuiyan mention that the cumulative precipitations related to a SPI smaller than -1.00 comprehend 15,8% of all data, these being the lowest observed values.

Table 1 – Classification of dry and wet periods according to SPI. Source: (MACEDO et al., 2010)

Classification of SPI	
≥ 2.00	Extreme rainfall
1.99 to 1.50	Severe rainfall
1.49 to 1.00	Moderate rainfall
0.99 to -0.99	Normal

Continue...

Continuation...

-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤ -2.00	Extreme drought

$$AD = \left(\sum_{i=1}^{N} \frac{(2i-1)}{N}\left[\ln F(Y_i) + \ln(1 - F(Y_{N+1-i}))\right]\right) - N \quad (7)$$

Where: F is the cumulative distribution function for the distribution; *i* is the position in ascending order of magnitude; and *N* is the number of data points. For the significance of the distribution at the level of 95% of confidence, the AD test result must be smaller than the critic value, obtained by Equation (8).

$$AD_{Cr} = \frac{0.752}{1+\frac{0.75}{N}+\frac{2.25}{N^2}} \quad (8)$$

The exceedance probabilities are transformed into return period according to the definition of equation (9):

$$\mathrm{EP} = \frac{1}{\mathrm{RP}} \text{ x } 100\mathrm{EP} = \frac{1}{\mathrm{TR}} \text{ x } 100 \quad (9)$$

Where: *EP* is the exceedance probability; and RP is the average recurrence interval (return period).

Therefore, the 6-month cumulative precipitation values correspondent to the drought events for each station are obtained for the desired return period. Due to the spatial variability of rainfalls, an isohyetal map design is aimed, as a visual and practical tool for the values visualization.

Isohyetal maps are designed by means of a spatial interpolation of punctual precipitation values, corresponding to each of the pluviometric stations selected. The map will be outlined using the software ArcGIS, by the Inverse Distance Weight technique, which consists of giving a greater weight to the points located spatially closer, and a lower weight to the farthest points.

The map presented in this paper will be plotted using the 6-month cumulative precipitation rates for an event with a return period of 20 years.

3 Results and Discussion

Applying the methodology of the Standardized Precipitation Index to the 13 selected pluviometric stations, values for the 6-month cumulative precipitation were found, relating to the classification presented in Table 1. The values referring to a SPI = -1.00, being these the 6-month cumulative precipitation considered the value at the beginning of a drought event, for all stations are presented in Table 2.

Table 2 – 6-month Cumulative Precipitation Values referring to the beginning of a drought event

Sub-Basin 37		Sub-Basin 38	
Station	**Reference Precipitation (mm)**	**Station**	**Reference Precipitation (mm)**
Pedra de Abelhas	79.8	Fazenda Potenji	178.3
Upanema	66.2	Engenho Olho D'Água	299.0
Açude Lagoinha	76.3	Santa Cruz	65.2
Antenor Navarro	99.1	Mulungu	197.2
Açude Bonito	133.7	Ponte da Batalha	276.0
Piancó	90.9	Bodocongo	84.2
		Taperoá II	75.8

The data presented in Table 2 show that, for different time series and for the same normal probability of occurrence of 15.8%, the reference precipitation vary considerably. For Sub-Catchment basin 37, the reference values vary from 66.2 mm to 133.7 mm among the stations. As for the Sub-Basin 38, the difference is even bigger, with values ranging from 65.2 mm to 299.0 mm. This variance confirms the rainfall spatial variability and demonstrates its occurrence in the study area.

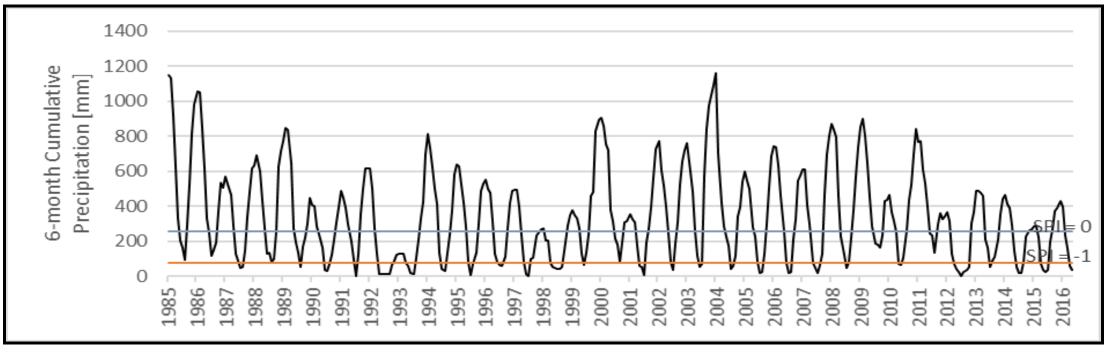
The identification of the drought events was performed according to the described methodology, with an event starting with a SPI equals to -1.00 and terminating when the SPI of the cumulative precipitations reaches a positive value. Therefore, events of different durations were identified for each station, varying from only one month of precipitation deficit, up to 19 months until the cumulative value overcomes the historical average. The number of events for each station is shown in Table 3.

Table 3 – Number of drought events identified

Sub-Basin 37		**Sub-Basin 38**	
Station	**Number of events**	**Station**	**Number of events**
Pedra de Abelhas	25	Fazenda Potenji	21
Upanema	22	Engenho Olho D'Água	22
Açude Lagoinha	26	Santa Cruz	18
Antenor Navarro	23	Mulungu	18
Açude Bonito	26	Ponte da Batalha	19
Piancó	24	Bodocongo	20
		Taperoá II	19

By the number of events observed in a 30 years time series, it shows that the adopted 6-month time scale allows the identification of medium-term tendencies in precipitation, with the existence of events every year or two, performing certain seasonality. This distribution of the events along the period analysed is exemplified for the station Pedra de Abelhas in Figure 2.

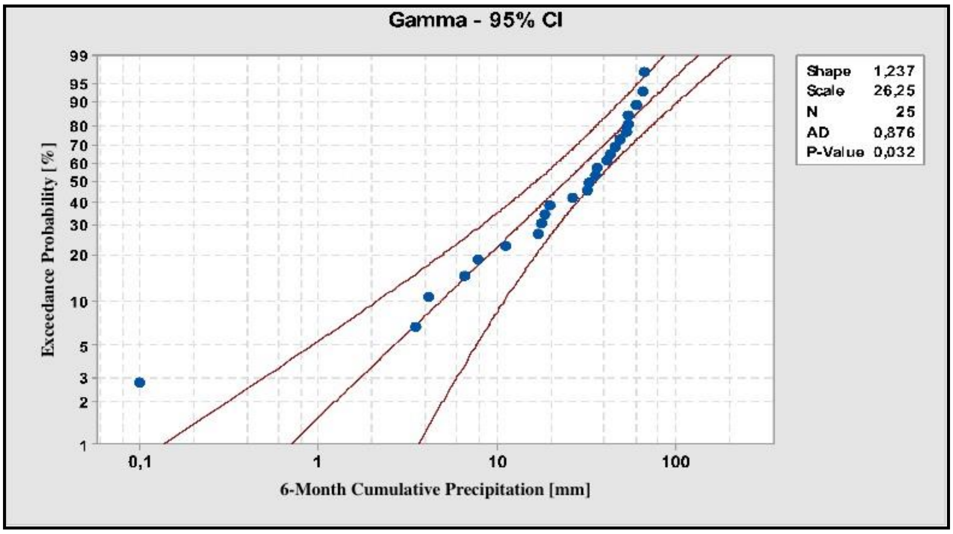
Figure 2 – 6-month Cumulative Precipitation following the time series for Pedra de Abelhas station



As observed in Figure 2, each event begins when the cumulative precipitation reaches the value corresponding to the SPI = -1.00, and ends when the series reaches the precipitation referent to the SPI = 0.00. According to this, for the station Pedra de Abelhas 25 events were identified. The characterization of each event is given by its minimum value, i.e. the minimum 6-month cumulative precipitation value within the duration of the event.

For each station, the identified events were ranked according to the magnitude (minimum values). With the values ranked from the lowest (most critical) to the highest, these values were then used as input for the software Minitab in a Gamma distribution in order to obtain the occurrence probabilities of drought events. The distribution for the station Pedra de Abelhas can be observed in Figure 3.

Figure 3 – Gamma distribution applied to the identified events for Pedra de Abelhas station



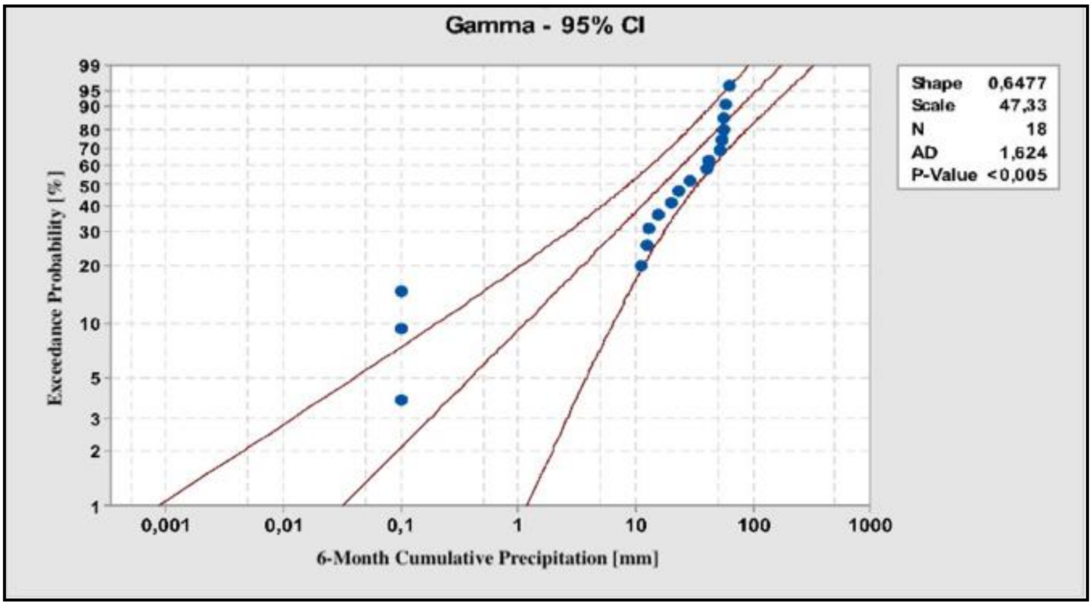
As observed in the distribution, the most critical event has the 6-month cumulative precipitation as 0,1 mm. This can be considered an event with no rainfall, representing a 6-month period without precipitation for one of the events in Pedra de Abelhas station. Having this dissonant value from the others, the Anderson-Darling fitting test was applied, according to the methodology. For the 25 events, the AD critic is 0.728, which is below the AD obtained for the distribution. Therefore, it is concluded that the Gamma distribution does not fit the critical values for the events of this station. The Anderson-Darling test results for the 13 studied stations are presented in Table 4.

Table 4 – Anderson-Darling test applied for the studied pluviometric stations

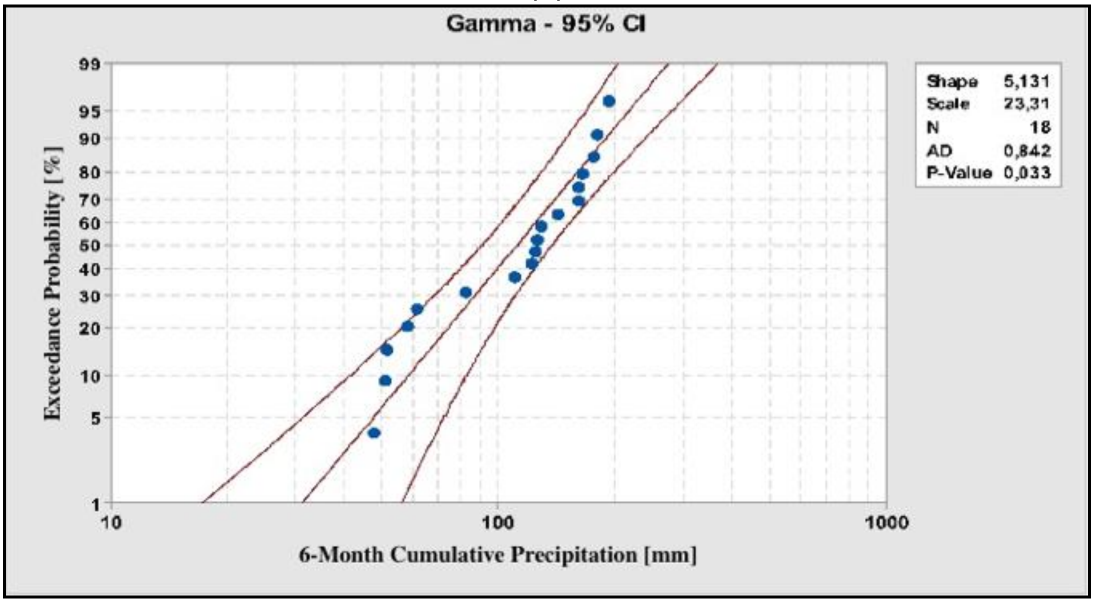
Sub-Basin 37			Sub-Basin 38		
Station	**AD**	**AD_{CR}**	**Station**	**AD**	**AD_{CR}**
Pedra de Abelhas	0.876	0.728	Fazenda Potenji	0.575	0.723
Upanema	0.525	0.724	Engenho Olho D'Água	0.355	0.724
Açude Lagoinha	0.603	0.729	Santa Cruz	1.624	0.717
Antenor Navarro	0.572	0.725	Mulungu	0.842	0.717
Açude Bonito	0.402	0.729	Ponte da Batalha	0.281	0.719
Piancó	0.567	0.726	Bodocongo	0.305	0.721
			Taperoá II	0.391	0.719

As observed in Table 4, besides Pedra de Abelhas station, another two stations did not fit their events data to the Gamma distribution. Santa Cruz station presented its three most critical events with no precipitation. Consequently, the first three points were dissonant from the others, resulting in a significant difference in the AD coefficient. The event values for the Mulungu station also do not fit to the Gamma Distribution. The Gamma distribution for the stations Santa Cruz and Mulungu are presented in Figure 4.

Figure 4 – Gamma distribution applied to the identified events for the stations (a) Santa Cruz; (b) Mulungu



(a)



(b)

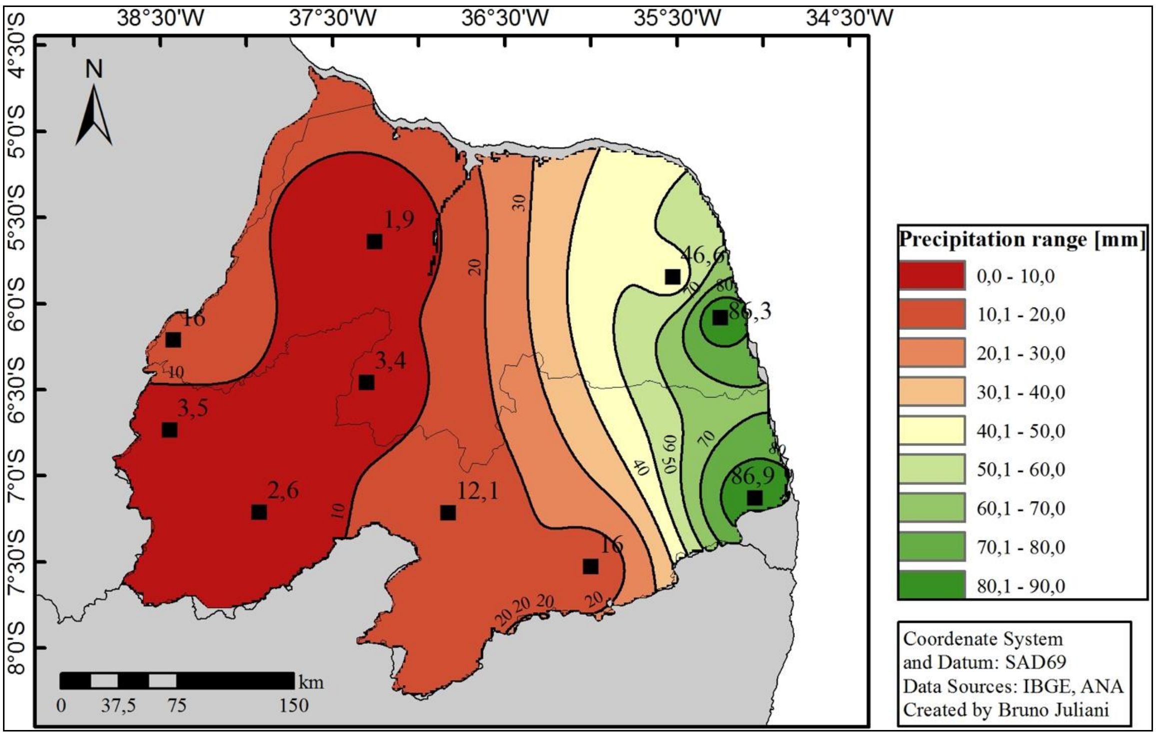
The other ten stations were fitted into the established limit for validation, therefore for these stations' data, a return period of 20 years was applied for the analysis. A return period of 20 years equals to a probability of 5% of being exceeded. In this study case, this represents a probability of 5% of occurrence for a 6-month period with precipitation equal or below the established. Table 5 presents the critical values of 6-month precipitation for the 10 validated stations.

Table 5 – 6-month Cumulative Precipitation for a 20 years return period

Sub-Basin 37		Sub-Basin 38	
Station	Precipitation [mm]	Station	Precipitation [mm]
Upanema	1.9	Fazenda Potenji	46.6
Açude Lagoinha	3.4	Engenho Olho D'Água	86.3
Antenor Navarro	3.5	Ponte da Batalha	86.9
Açude Bonito	16.0	Bodocongo	16.0
Piancó	2.6	Taperoá II	12.1

Applying the data presented in Table 5, an isohyetal map was outlined for the study area, aiming the transformation of data of punctual application to the application in areas where there are no pluviometric stations. Using the software ArcGIS and following the IDW method, the map of 6-month Cumulative Precipitation for drought events in a 20-year return period was designed for the study area, as observed in Figure 5.

Figure 5 – Spatial Analysis of 6-month Cumulative Precipitation of drought events with a return period of 20 years, for Sub-Catchment Basins 37 and 38



In the developed map, the variation for the 6-month cumulative precipitation expected for drought events in Sub-Basins 37 and 38 can be observed. The map shows a significant variation between the east coast region of the studied states and the further region inland. With a total rainfall for 6 months below 10.0 mm, the darker red region in the map nearly does not present any precipitation in the previous months before the drought event of a recurrence interval of 20 years. As for the eastern coastal area, the 6-month cumulative precipitation considered for the beginning of a drought event in a 20-year return period can be estimated around 80.0 mm. In face of this large variation indicated along the different regions, the existence of the spatial variation in precipitation intensities of drought events is proven for the study area.

This variation, shown in Figure 5 for the precipitation related to the drought events may also be highlighted by the reference precipitation data presented in Table 2. Based on these data, higher precipitations for the stations Fazenda Potenji, Engenho Olho D'Água, Mulungu and Ponte da Batalha can be noticed, when compared to the other stations.

As result, the obtained data shows the 6-month cumulative precipitation expected for a 20-year return period drought event. The identification of these values is important for reservoir water level control, water availability and planning control.

Since low values for the 6-month cumulative precipitation are expected in almost the entire sub-basin area, studies regarding water storage measures, population assistance, and also water level information are necessary, so that during the period of almost non-existent rainfall, problems such as the lack of water does not lead to worse consequences.

4 Concluding Remarks

In this present paper, drought events study for the sub-catchment basins 37 and 38 has proven to have a great importance. Bordered by similar territorial limits of the Brazilian states Rio Grande do Norte and Paraiba, the identification of the drought events and the spatial variability visualization of the data permit taking preventive measures against water shortage. Drought forecasting and its intensities can be crucial in hydrological and reservoirs management, especially in areas that present deficit on these factors.

The application of the Standardized Precipitation Index methodology has proved to be a useful in the identification of rainfall periods below the historic average, and in the identification of events of precipitation shortage. The method was applied in 13 selected stations located in the study area, resulting in the identification of regular events throughout the time series of all stations.

The precipitation values referring to each stations' events were applied to the Gamma Distribution, in order to determine the historical occurrence probability of drought events. The Gamma distribution obtained a good fit for 10 of the 13 studied stations. The failure of fitting for the stations Pedra de Abelhas, Santa Cruz and Mulungu was verified by Anderson-Darling test.

After converting the occurrence probabilities of the critical drought events precipitation values into different return periods, the plot of an isohyetal map related to droughts in a 20-year return period was aimed. The values presented on the map show the 6-month cumulative precipitation expected for the studied area in a critical event for a 20-year recurrence interval. The isohyetal map allows a simple identification of the expected values, being of an easy understanding for people without further knowledge in occurrence probabilities. Therefore, the isohyetal map turned up as a great tool for water resource management.

By means of the outlined map and the obtained data from the application of the Standardized Precipitation Index, the rainfall spatial distribution in the states of Rio Grande do Norte and Paraiba is clearly shown in the plotted map. The area of higher precipitation is located on the east coast of the states, while the drier region is located further inland.

As previously explained, in three of the selected stations, the obtained data did not fit into the Gamma statistical distribution. Thus, studies regarding other possible distributions may lead to better results, as well as increasing the number of sampling points for the isohyetal map development. A better analysis would also be possible with a higher number of stations with bigger time series. Therefore, further studies concerning this topic over the future years may lead to more accurate results.

Equivalent studies may be performed in areas in the surroundings of the study area. Besides gathering data for these new regions, these neighbour data would allow a better layout for the IDW isohyetal method, leading to even more precise results.

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