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Spatial analysis of daily rainfall concentration in Paraíba State, Brazil

Análise espacial da concentração das chuvas diárias no Estado da Paraíba, Brasil

Leonardo Caçadini Bizerra da Silva[*], Juliana Vilardo Mendes[**], Patrick do Nascimento da Silva[***], Núbia Beray Armond[****]

[*]Department of Geography, Federal University of Rio de Janeiro (UFRJ), leocacadini@gmail.com
[**]Department of Geography, Federal University of Rio de Janeiro (UFRJ), julianavilardo@outlook.com
[***]Department of Geography, Indiana University - Bloomington, padona@iu.edu
[****]Department of Geography, Indiana University - Bloomington, nuberay@iu.edu

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Abstract

Recent studies indicate a reduction of total rainfall and an increase of extreme rainfall events in the Brazilian Northeast region. It is crucial to understand the concentration of daily rainfall for environmental planning and land management. This study performs the analysis of the daily rainfall concentration for the Paraíba State in the period between 1970 and 2019, using data from 26 rainfall stations across the State. Additionally, to the total annual precipitation (PP), the following concentration indicators were applied: frequency of days with precipitation up to 20mm (R20MM), maximum daily rainfall (Rx1Day), maximum rainfall over 5 days (Rx5Day), frequency of days with precipitation in the 10^{th} (P10), 90^{th} (P90), 95^{th} (P95), and 99^{th} (P99) percentiles, number of rainy days (NRD), and the Concentration Index (CI), which estimates the contribution of daily rainfall to the annual total. The Mann-Kendall test and Sen's slope were applied to identify possible trends in the time series and its magnitude. Spatially, the highest concentration values were observed in the *Litoral* and *Brejo* regions, decreasing towards the State hinterland. Temporally, most indicators displayed negative trends, suggesting reductions in both annual rainfall totals and rainfall on isolated days or groups of days. However, the CI showed predominantly an upward trend, indicating increased rainfall concentration. P10 values also exhibited an increase tendency, suggesting that days with the lowest rainfall amounts are becoming more frequent.

Keywords:
Precipitation, Rainfall concentration, Concentration Index, Extreme events, Northeast Brazil.

Resumo

Estudos recentes evidenciam a redução dos totais pluviométricos e o aumento de eventos extremos de chuva no Nordeste brasileiro. Compreender a concentração da precipitação diária é crucial para o planejamento ambiental e a gestão territorial. Este artigo analisa a concentração diária da precipitação no Estado da Paraíba entre 1970 e 2019, utilizando dados de 26 postos

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pluviométricos. Foram avaliados indicadores como precipitação anual acumulada (PP), frequência de dias com precipitação até 20 mm (R20MM), chuva máxima diária (Rx1Day), chuva máxima em 5 dias (Rx5Day), e a frequência de dias com precipitação nos percentis 10 (P10), 90 (P90), 95 (P95) e 99 (P99). Também foram considerados o número de dias chuvosos (NDC) e o *Concentration Index* (CI), que estima o peso da precipitação diária em relação ao total anual. Aplicou-se o teste de Mann-Kendall e a declividade de Sen para identificar tendências na série temporal e sua magnitude. Espacialmente, os maiores valores de concentração foram encontrados nas regiões do Litoral e Brejo, diminuindo em direção ao interior. Temporalmente, a maioria dos indicadores mostrou tendências negativas, indicando redução tanto nos totais anuais de chuva quanto na precipitação isolada ou em agrupamentos de dias. No entanto, o CI mostrou uma tendência de aumento, sugerindo maior concentração das chuvas. Valores de P10 também mostraram tendência de aumento, indicando que os dias com menores valores de precipitação estão se tornando mais frequentes.
Palavras-chave:
Precipitação, Concentração pluviométrica, Índice de concentração, Eventos extremos, Nordeste brasileiro.

I. INTRODUCTION

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021) emphasizes significant shifts in rainfall patterns across various regions in the world, due to climate change. Although these changes vary regionally, there is a general trend towards an increase in frequency and intensity of extreme rainfall events worldwide.

In Northeast Brazil, the effects of climate change are already evident. An increase in the magnitude and frequency of extreme precipitation events occurred in parallel with a reduction in average rainfall. Studies, such as Spinoni et al. (2014), reported an increased aridity in NE Brazil from 1951 to 2010. Brito et al. (2018) also observed longer and more severe drought periods in the region, analyzing data from 1981 to 2016. Ferreira et al. (2017) also identified significant downward trends of rainfall in parts of the semiarid region within Pernambuco State, using data from 1963 to 2014. Further studies, including those by Santos and Manzi (2011) and Nóbrega et al. (2015), highlighted positive trends for extreme rainfall events in Ceará and Pernambuco States, respectively.

Climate projections suggest an increased likelihood of extreme events and prolonged drought in the region, with medium confidence, as indicated by the IPCC (2021). Marengo et al. (2017), using CMIP5 models, predicted a reduction in rainfall of approximately 0.3 mm/day under the RCP8.5 scenario. Specifically, during the rainy season (March-April-May), the reduction reached 0.5 mm/day, while during the austral winter and

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spring it was 1 mm/day. These projections underscore the need to reflect on strategies for adaptation and mitigation, as emphasized by Gutiérrez et al. (2014) and Kane (1998).

Former studies on these issues have focused on understanding rainfall patterns and anomalies in the region, particularly its impact on urban environments (MONTEIRO, 2022; WANDERLEY; NÓBREGA, 2022; MEDEIROS et al., 2021; WANDERLEY et al., 2021; PEREIRA et al., 2020; CAVALCANTE et al., 2019; WANDERLEY et al., 2018; LUCENA et al., 2016) In the Paraíba State, several studies analyzed the systems that generate rainfall (ALMEIDA; CABRAL JÚNIOR, 2014) and examined the distribution and frequency of rainfall on daily and hourly scales (SOUSA; LUCENA, 2023; PEREIRA, 2016). Simultaneously, climate and socio-environmental vulnerability dimensions have been widely studied (SILVA et al., 2021; SILVA et al., 2019; ARAUJO et al., 2018; MARQUES et al., 2018), particularly in the context of risk-reduction from climate-related disasters (MOURA et al., 2016; SERGIO et al., 2018; SILVA; MOURA, 2018; ARAÚJO et al., 2019; CUNICO et al., 2022). However, there is a notable lack of research related to the use of concentration indices to investigate the spatial distribution of precipitation and to the analysis of its tendencies over time. Such information is crucial for both the climatic characterization of specific regions (SERRANO-NOTIVOLI et al., 2017) and the identification of positive or negative precipitation trends on annual or seasonal scales, which can offer insights to changes of both rainfall patterns and global climate (ZHANG et al., 2019).

The literature presents several indices indicated to assess the rainfall spatial and temporal concentration, which are critical indicators for climate change studies. Notably, the Expert Team on Climate Change Detection and Indices (ETCCDI), part of the World Climate Research Program (WCRP) under the World Meteorological Organization (WMO), has developed widely used standard indices for the detection of climate change. This team created 27 indices that address both temperature and precipitation variables. Among the most relevant precipitation indices are Rx1day (maximum precipitation in one day), R5mm (days with rainfall equal to or above 5mm), R20mm (days with precipitation equal to or above 20mm), P95 (95^{th} percentile), and P99 (99^{th} percentile) (PETERSON et al., 2001; KARL et al., 1999). In addition to the ETCCDI indices, other ones gained prominence in the literature. They are considered as the key indicators of climate change, such as the Standardized Precipitation Index (SPI) (MCKEE et al., 1993) and the Precipitation Concentration Index (PCI) (OLIVER, 1980).

Using the normalization from the monthly precipitation, the SPI is calculated by a probability distribution function (CPTEC/INPE, 2022). It is widely applied for the detection and projection of drought periods (KOMUSCU, 1999; AGNEW, 2000; SILVA et al., 2023; OLIVEIRA-JÚNIOR et al., 2021; COSTA et al., 2020;

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SILVA et al., 2020; CUNHA et al., 2018; BRITO et al., 2017; AHMAD et al., 2016; MORADI et al., 2011; KHAN et al., 2008). In contrast, the PCI allows insights to the seasonal concentration of precipitation and is frequently used to assess the rainfall seasonality (BHATTACHARYYA; SREEKESH, 2022; AMIRI; GOCIC, 2021; LI et al., 2020; ZHANG et al., 2019; TOLIKA, 2018; PETKOVIC et al., 2017; SHI et al., 2015).

Furthermore, the Concentration Index (CI), introduced by Martín-Vide (2004), is one of the few indices that quantify the heterogeneity of daily precipitation throughout the year. It allows the analysis of the percentage contribution from high-magnitude rainfall events to the total precipitation amount. The CI evaluates the importance of individual daily precipitation volumes concerning the total accumulated precipitation. Its calculation is based on the Lorenz curve, which graphically represents the cumulative distribution of daily rainfall over the year. The curve plots the cumulative percentage of precipitation on the y-axis against the cumulative percentage of days with rainfall on the x-axis.

According to Núñez-Gonzalez (2020) and Caloiero (2014), the Concentration Index (CI) is a well-established and efficient tool for analysis, widely applied worldwide, including Spain (SERRANO-NOTIVOLI et al., 2017; MARTÍN-VÍDE, 2004), Irã (ALIJANI et al., 2007), China (HUANG et al., 2016; SHI et al., 2014, 2013; LI et al., 2010), Itália (COSCARELLI; CALOIOERO, 2012), Nova Zelândia (CALOIOERO, 2014), Malásia (SUSHAILA; JEMAIN, 2012), Índia (PATEL; SHETE, 2015), Peru (ZUBIETA et al., 2017), Rússia (VYSHKVARKOVA et al., 2018), among others. In Brazil, most studies using the CI are concentrated primarily in the southern region (BACK, 2022; BACK et al., 2020; PINHEIRO; MARTIN-VIDE, 2017). However, there are notable gaps in the literature regarding studies linking the CI to geographical factors as well as spatial and temporal climate trends. In this context, this article highlights the potential of the CI as an index that can significantly contribute to climate change studies.

The objective of this study is to perform a spatial-temporal analysis of daily rainfall concentration in Paraíba State. The following indicators are proposed: total annual precipitation (PP), number of rainy days (NRD), frequency of days with precipitation up to 5mm (R5MM), frequency of days with precipitation up to 20mm (R20MM), maximum daily rainfall (Rx1Day), frequency of days with precipitation within the 10^{th} percentile (P10), 90^{th} percentile (P90), 95^{th} percentile (P95), and 99^{th} percentile (P99), as well as the Concentration Index (CI), which estimates the contribution of daily precipitation relative to its total annual volume.

Daily rainfall data from 1970 to 2019 were collected in 26 rain gauges across the State, available at the HidroWeb Portal.

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To achieve these goals, the text is organized in five sections. The first section characterizes the study area, emphasizing its climate and the atmospheric systems responsible for the rainfall generation. The second section outlines the methodological procedures adopted and discusses the indices used, focusing on the Concentration Index. In the third section, the results obtained are presented on boxplots. Both, the rainfall patterns in the rainfall homogeneous regions of Paraíba and the frequency of its concentration indicators (CI), including R5MM, R20MM, Rx1Day, P10, P90, P95, P99, are analyzed. The CI assesses the contribution of daily rainfall to total precipitation. The fourth section analyzes the spatial distribution of these indicators, linking them to the dynamic and static characteristics of the State. Lastly, the fifth section provides a temporal analysis of the indicators, identifying potential trends in the time series and its magnitudes.

Study area

Located in NE Brazil, between latitudes S6° and S8° and longitudes W35° and W39°, the Paraiba State is located near the Equator. Covering an area of 56,467.242 km², it borders with Rio Grande do Norte State to the North, Pernambuco State to the South, the Atlantic Ocean to the East, and Ceará State to the west (IBGE, 2021). With altitudes ranging from sea level up to 1,192 meters, the relief varies significantly, featuring lowlands and coastal tablelands in the East, the *Borborema* Plateau in the center, and the *Sertaneja* Depression in the West. This topography influences its climate, contributing to semiarid regions characterized by water scarcity and high evaporation rates (PARAÍBA, 2006; IBGE, 2002).

According to IBGE (2002), Paraíba presents a variety of climates, including humid, semi-humid, and semiarid conditions. The thermal spectrum ranges from sub-humid (with an average temperature of 15°C to 18°C for at least one month) to hot (with average temperatures exceeding 18°C throughout the year). The humid climate dominates the coastal region, while the semi-humid climate prevails in the transition zone between the coast and interior, and the semiarid climate covers much of the remainder of the State.

Nimer (1989) posits that the climatology of the Brazilian Northeast is among the most complex in the world, primarily due to its diverse rainfall patterns and geographical position concerning various atmospheric circulation systems. Ferreira and Mello (2005) highlight factors such as variability modes, sea surface temperatures—especially in the Atlantic—the Intertropical Convergence Zone (ITCZ), Upper Tropospheric Cyclonic Vortices (UTCVs), and the influence of trade winds contribute to its climatic diversity, interacting with geographical features.

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Silva (1996) and Braga and Silva (1990) proposed a classification based on the municipal rainfall data, dividing Paraíba into six rainfall homogeneous regions. From East to West, they are: *Litoral, Brejo, Agreste*, *Cariri/Curimataú, Sertão, and Alto Sertão* (**Figure 1**).

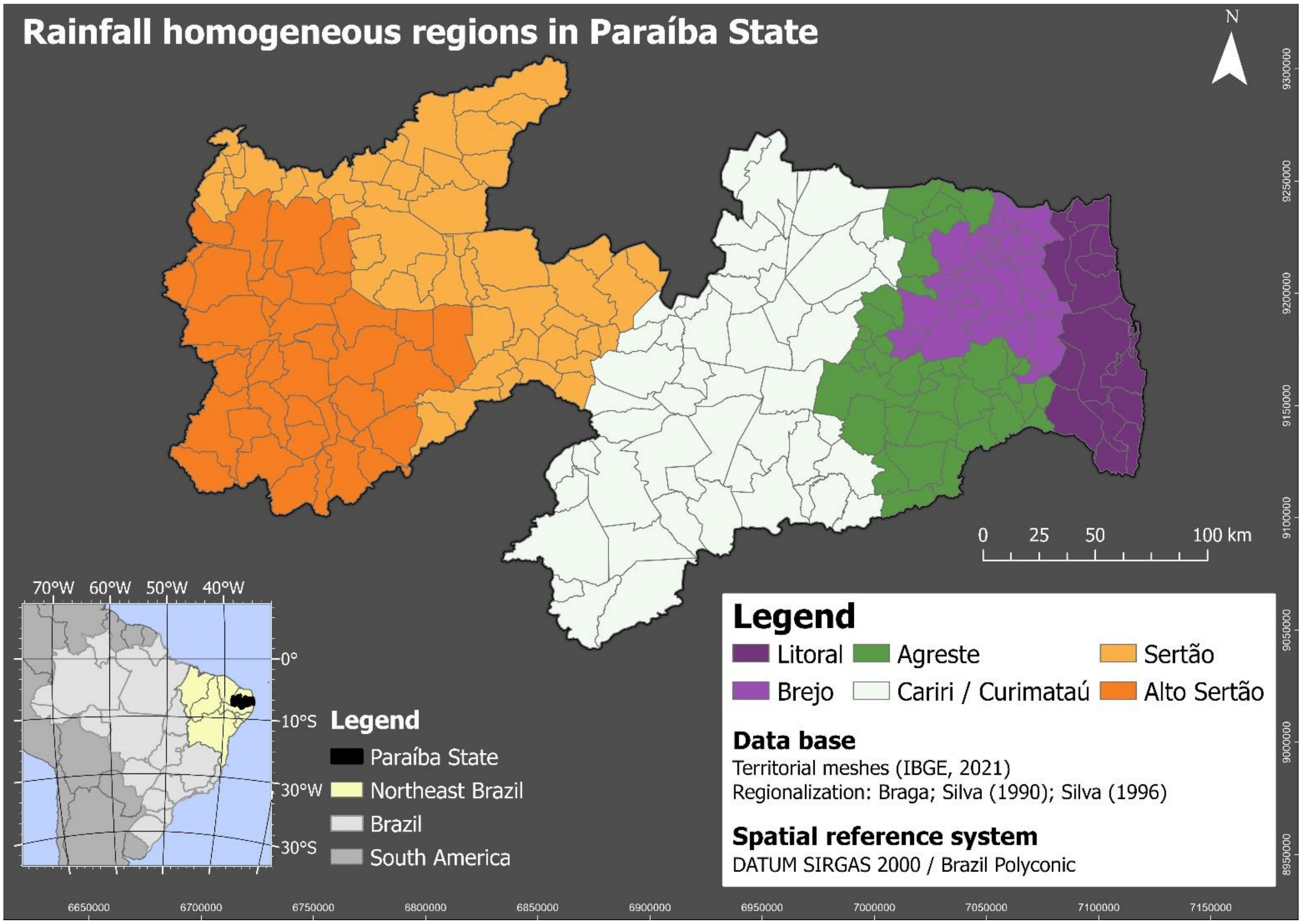

Figure 1 – Rainfall homogeneous regions in Paraíba State (Source: Authors).

Becker et al. (2011) made a climatic characterization of the rainfall homogeneous regions from Paraíba, reporting an average annual rainfall of 1510.8 mm for the coastal (*Litoral*) region, decreasing to 1082.7 mm in the *Brejo* area. Further inland, *Alto Sertão* receives an average of 878.5 mm, followed by 779.1 mm in the *Sertão*. The *Agreste* region averages 729 mm, and the *Cariri/Curimataú* region receives the least rainfall, with 482.7 mm annually.

The authors note that the *Litoral, Brejo*, and *Agreste* regions are influenced by the Intertropical Convergence Zone (ITCZ), Easterly Waves Disturbances (EWDs), and sea-land breeze interactions, which are the primary rain-generating systems. Almeida and Cabral Júnior (2014) also emphasize the ITCZ as important for the precipitation in the hinterland of Paraíba. They suggest that differences in the seasonal rainfall

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distribution between the interior and eastern regions are due to the timing of maximum convergence between trade winds and land breezes, which occur during the May-June-July quarter in the East of the sector. In contrast, the ITCZ and local convection influence predominantly the rainfall in the *Sertão* and *Alto Sertão* during the fall and winter months. Other atmospheric systems, such as Mesoscale Convective Complexes (MCC), Upper Tropospheric Cyclonic Vortices (UTCVs), and Lines of Instability (LoI), also play a significant role, contributing to the atmospheric stability and instability in the region (ALBUQUERQUE et al., 2013; ALVES et al., 2006; FERREIRA; MELO, 2005; FILHO et al., 1996).

II. MATERIALS AND METHODS

To characterize the spatial distribution of rainfall in Paraíba, daily rainfall data from rain gauges within the area (Figure 2) were used, obtained from the HidroWeb Portal of the National Water Agency (ANA). Initially, data from all operational stations (394) were downloaded. Afterwards, the collected data underwent a rigorous quality control. A filter was applied to select those stations with longer and more consistent historical records, ensuring a significant spatial coverage. The defined time space for the study period was 1970 to 2019. For this 50-year period, only those stations with less than 5% missing data (approximately 913 out of 18,261 days) were included. This process identified 26 rain gauges (Figure 2 and Table 1). It is important to note that, given the daily scale of the historical series considered for this study, no imputation techniques were applied to fill in the missing data.

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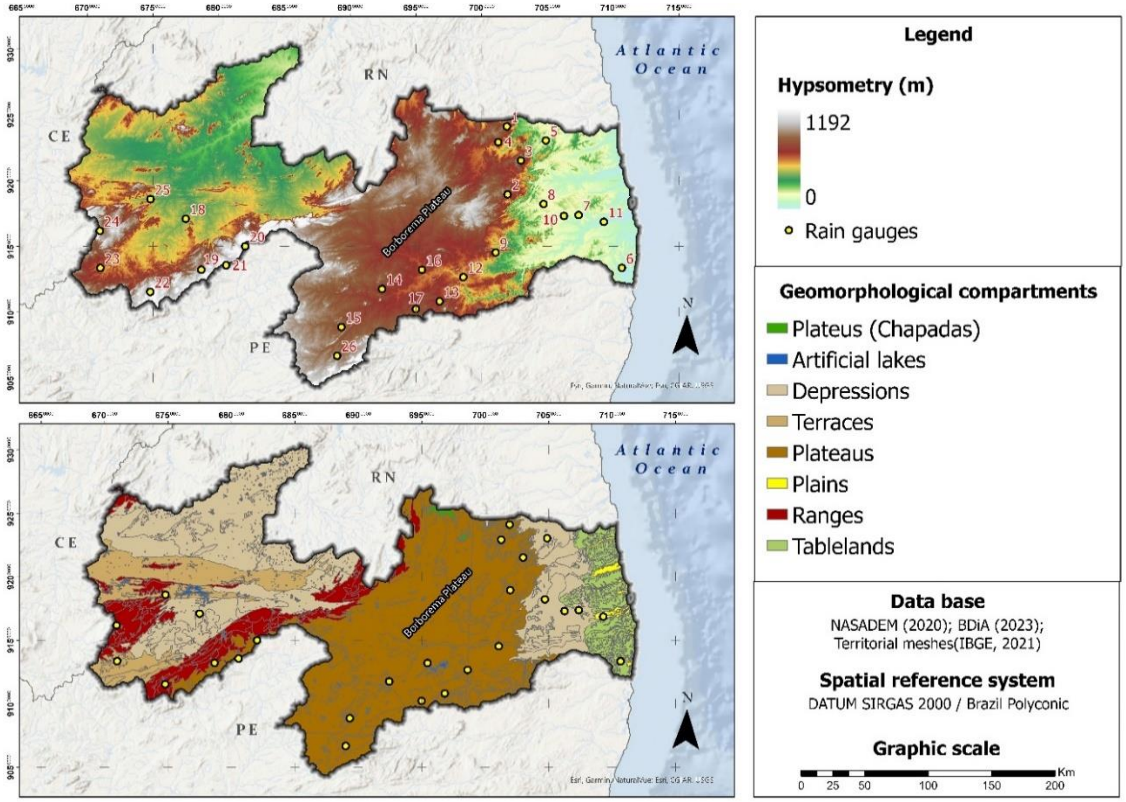

Figure 2 – Location of the study area (State of Paraíba), with a grid of rain gauges on the hypsometry and the geomorphological compartments (Source: Authors)

Table 1 - Rain gauges used

ID	COD	Name	Pluviom Region.	Latitude (S)	Longitude (W)	Altitude (m)
1	635028	Araruna	Agreste	-6.53	-35.74	580
2	635030	Areia	Brejo	-6.98	-35.72	445
3	635033	Bananeiras	Brejo	-6.75	-35.63	552
4	635037	Cacimba de Dentro	Agreste	-6.64	-35.80	460
5	635038	Caiçara	Brejo	-6.61	-35.47	185
6	734008	Alhandra	Litoral	-7.43	-34.91	49
7	735006	Sape	Brejo	-7.09	-35.22	125
8	735009	Mulungu	Brejo	-7.03	-35.47	100
9	735018	Fagundes	Agreste	-7.36	-35.78	520
10	735035	Caldas Branao	Agreste	-7.10	-35.32	146
11	735036	Ponte da Batalha	Litoral	-7.13	-35.05	18
12	735124	Bodocongo	Cariri/Curimataú	-7.53	-36.00	350
13	736013	Riacho Santo Antonio	Cariri/Curimataú	-7.69	-36.16	455
14	736017	Coxixola	Cariri/Curimataú	-7.63	-36.56	465
15	736021	Camalau	Cariri/Curimataú	-7.89	-36.83	565
16	736022	Cabaceiras	Cariri/Curimataú	-7.49	-36.29	390
17	736025	Barra de São Miguel	Cariri/Curimataú	-7.75	-36.32	520
18	737006	Pianco	Alto Sertão	-7.21	-37.93	250
19	737016	Juru	Alto Sertão	-7.55	-37.81	470

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20	737017	Imaculada	Sertão	-7.38	-37.51	750
21	737022	Agua Branca	Sertão	-7.51	-37.64	710
22	738015	Manaira	Alto Sertão	-7.71	-38.15	605
23	738020	Conceição	Alto Sertão	-7.56	-38.50	370
24	738022	Bonito de Santa Fé	Alto Sertão	-7.31	-38.51	575
25	738025	Aguiar	Alto Sertão	-7.09	-38.17	280
26	836000	São João do Tigre	Cariri/Curimataú	-8.08	-36.85	616

Source: National Water Agency - ANA (2022).

The data were imported into RStudio® to calculate all the indices. The average annual rainfall (PP) and the annual number of rainy days (NDC) were initially computed. A rainy day was defined as one with ≥ 0.2 mm of precipitation. To calculate the various indicators—annual total (PP), number of rainy days (NDC), frequency of days with rainfall up to 5mm (R5MM), frequency of days with rainfall up to 20mm (R20MM), maximum daily rainfall (Rx1Day), frequency of days within the 10th percentile (P10), 90th percentile (P90), 95th percentile (P95), 99th percentile (P99), and the Concentration Index (CI)—years with data missing for 50% or more of the days were excluded (as shown in Table 1). The Concentration Index (CI) for each station was generated using the Precintcon package (POVOA; NERY, 2016).

Maps of each rainfall variable were then created to support the analysis of the spatial and temporal distribution of rainfall concentration indicators, using the Spline with Barriers interpolation method from ArcGIS PRO® (FARIAS et al., 2017). The Concentration Index (CI) quantifies the relative impact from different classes of daily rainfall throughout the time series. This Index measures the weight of the most significant daily precipitation events, considering the relative contribution (in percentage) of progressively accumulated rainfall (Y) as a function of the accumulated percentage of wet days (X) when (Y) occurs. The CI values range from 0 to 1, with higher values indicating that rainfall is concentrated on fewer rainy days throughout the year and lower values indicating a more even distribution (CALOIERO, 2014).

To illustrate how the CI is calculated, the example of Martín-Víde (2004) was used: considering stations 736013 and 735009 as references. These stations represent the lowest and highest CI values among those analyzed, highlighting the distribution of daily precipitation throughout the year. The distance from the equi-distribution line indicates the degree of daily concentration or irregularity. As shown in Figure 3, station 735009 (CI = 0.64) exhibits a higher concentration or irregularity than station 736013 (CI = 0.53). At station 735009, a percentage of the wettest days accounts for a higher proportion of total annual rainfall than at station 736013.

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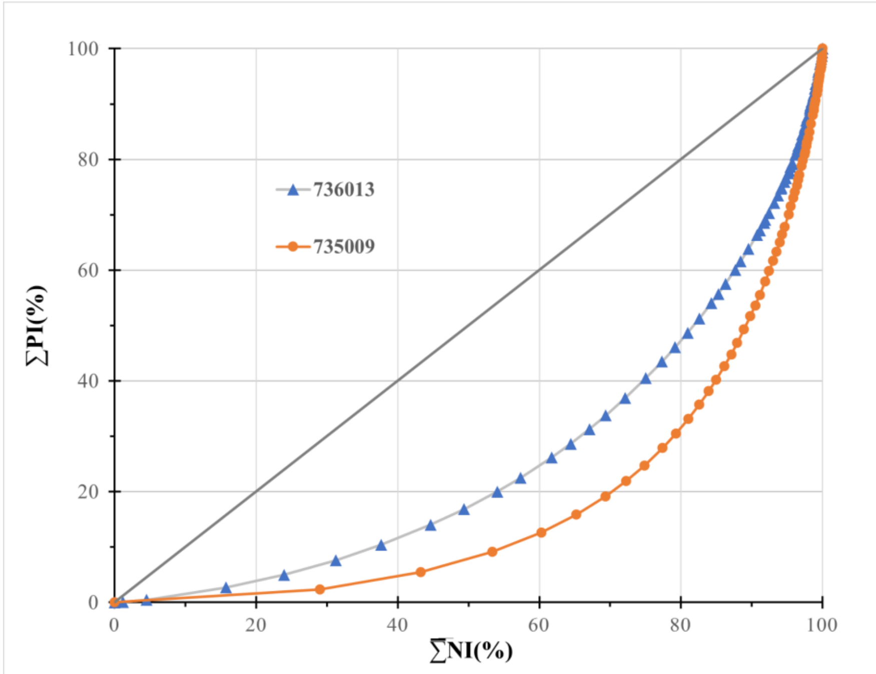

Figure 3 - Concentration curve of stations 736013 and 735009 (1970-2019) (Source: Authors).

Martín-Vide (2004) explain that we can improve the concentration curve by replacing the polygons with exponential curves. The Y=aX exp(bX) gives the exponential curve, where a and b are constants. The parameters a and b of the equation are given by Martin-Vide (2004):

$$a = \frac{\sum X_i^2 \sum \ln Y_i + \sum X_i \sum X_i \ln X_i - \sum X_i^2 \sum \ln X_i - \sum X_i \sum X_i \ln Y_i}{N \sum X_i^2 - \left(\sum X_i\right)^2} \quad (1)$$

$$b = \frac{N \sum X_i \ln Y_i + \sum X_i \sum \ln X_i - N \sum X_i \ln X_i - \sum X_i \sum \ln Y_i}{N \sum X_i^2 - \left(\sum X_i\right)^2} \quad (2)$$

After calculating the two constants, the concentration curve, plotted with both axes varying between 0 and 100, is given by the area A (MARTIN-VIDE, 2004):

$$A' = \left[\frac{a}{b} e^{bx} \left(x - \frac{1}{b}\right)\right]_0^{100} \quad (3)$$

Finally, the *Concentration Index* is calculated using the following formula (MARTIN-VIDE, 2004):

$$CI = \frac{5000 - A}{5000} \quad (4)$$

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According to the example, applying the equations to station 736013, we get a = 0.0958, b = 0.0229, and CI = 0.53.

III. RESULTS AND DISCUSSION

The rain gauges were analyzed concerning the rainfall regime during the historical series under investigation (1970–2019). A representative station from each rainfall homogeneous region was selected for detailed analysis using a boxplot graph (Figure 4). The analysis proceeds sequentially from the coastal region toward the State's interior.

At the *Litoral* region, represented by the *Ponte da Batalha* station, the rainfall regime shows monthly precipitation ranging from approximately 20 mm to 350 mm, with minimum as low as 0 mm and maximum reaching up to 450 mm. The months between January and July exhibit strong rainfall variability, as indicated by the broader interquartile ranges (significant dispersion). April, June, and July stand out for displaying particularly notable variability.

A crucial observation arises from the examination of the median (represented by the black line within the boxplot): in January, the median is close to the lower limit of the first quartile rather than centered in the boxplot (which would correspond to the average). The median's position below the mean suggests an asymmetrical distribution of rainfall data, indicating higher rainfall values during the analyzed month (positive asymmetry).

Outliers were identified every month, with the most frequent occurrences in September, November, and December. The most significant ones (farthest from the upper precipitation limits) occurred in April, July, and August.

In the *Brejo* region, represented by the *Areia* station, the seasonal pattern was similar to the one of the *Litoral* region, although the monthly rainfall totals were slightly lower. The rainfall regime showed monthly precipitation ranging from 0 to 300 mm, with maximum values reaching 400 mm. The period from January to July exhibited the most significant rainfall variability, as reflected by the wider interquartile ranges. July, April, March, and February stand out due to its substantial interquartile distances, suggesting considerable variability.

Median values across the months indicate a dynamic similar to that one observed in the coastal region. The median's position below the center of the boxplots (mean) suggests an asymmetrical distribution,

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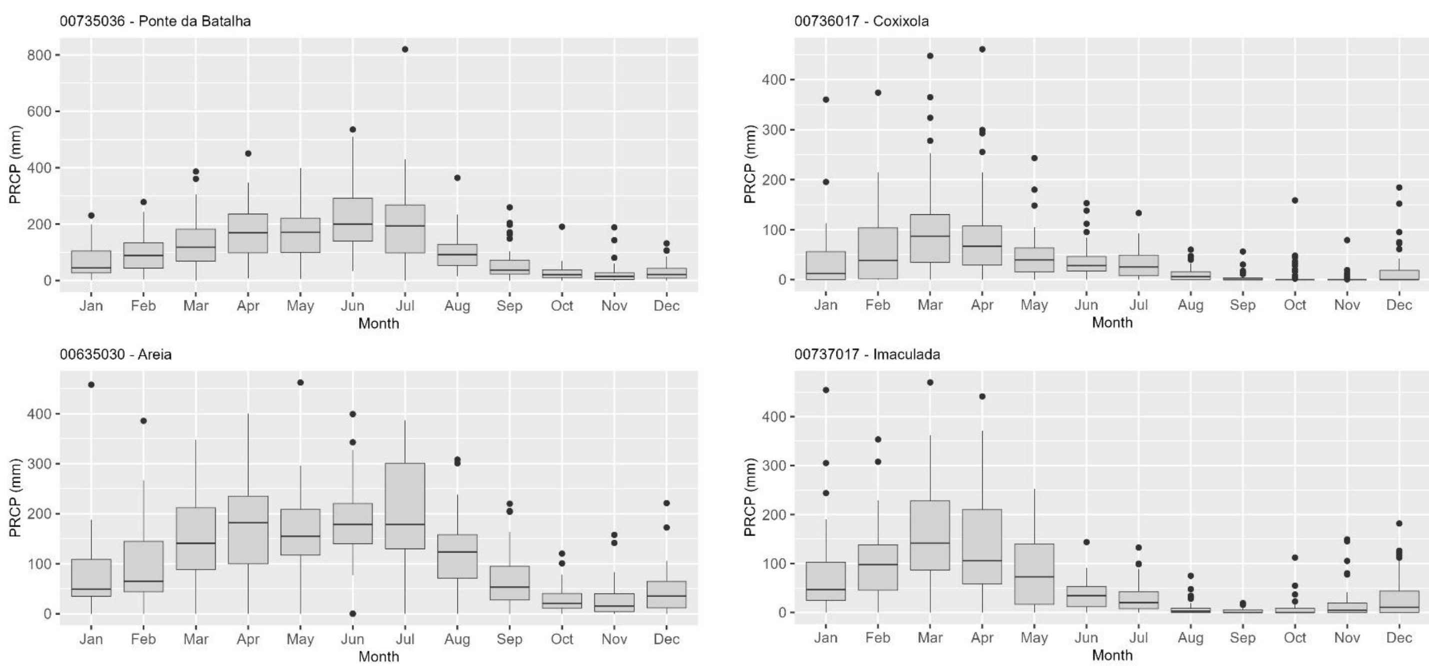
indicating more intense precipitation (positive asymmetry), particularly in January, February, July, October, and November. However, August displayed a slightly negative asymmetry pattern, suggesting a lower rainfall.

Regarding outliers, the positive ones predominate during almost all months, especially from August to December, except for June, which, despite showing two outliers, also indicates the occurrence of a negative outlier.

The *Agreste* region, represented by the *Cacimba de Dentro* station, exhibited lower rainfall than the previously analyzed regions. Rainfall ranged from 0 to approximately 150 mm, with maximum values reaching 300 mm in April. The wider interquartile ranges indicate a significant variability between February and August, representing substantial dispersion.

While most months showed median values close to the mean, February, October, and November displayed positive deviations. Additionally, positive outliers were more frequently observed during these months, suggesting an important variability and the occurrence of extreme rainfall episodes which can be considered as significant within these periods.



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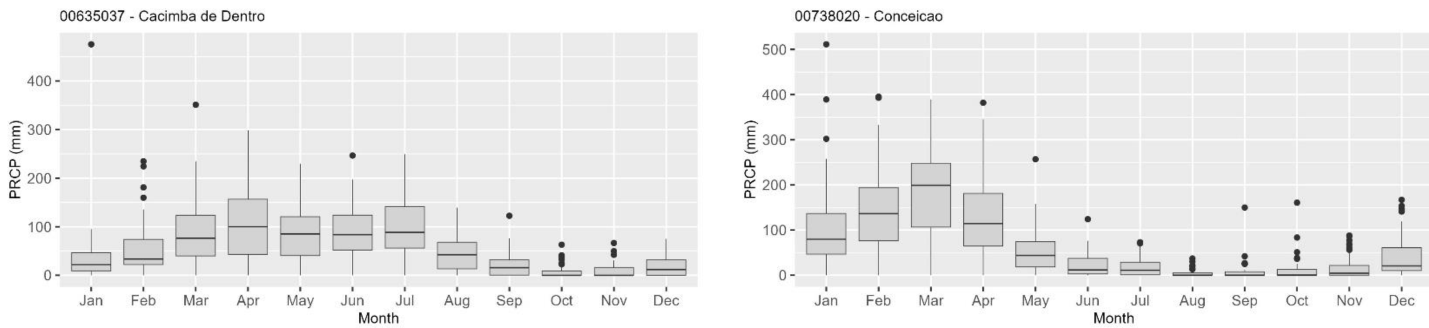

Figure 4 - *Boxplots* of rainfall, by the representative station for each rainfall homogeneous region: a) *Litoral - Ponte de Batalha, b) Brejo - Areia, c) Agreste - Cacimba de Dentro, d) Cariri/Curimataú - Coxixola, e) Sertão - Imaculada, f) Alto Sertão - Conceição*. (Source: Authors)

The *Cariri/Curimataú* region, represented by the *Coxixola* station, exhibited significantly lower rainfall values than the other three regions analyzed. The interquartile ranges generally varied from 0 to approximately 140 mm, with maximum values reaching 250 mm in March. A strong variability was observed, with significant data dispersion, particularly between January and July.

January, June, and December displayed positive deviations, with the median shifting from the mean toward the lower limit. This asymmetry indicates variability and suggests the occurrence of significant rainfall episodes. Compared to the others, a distinctive feature of this region is the more frequent presence of outliers throughout the year, primarily concentrated in the drier months between September and December.

Rainfall totals in the *Sertão* region, represented by the *Imaculada* station, slightly increased, although the variability remained significant. The interquartile ranges varied between 0 and 230 mm, with a maximum value of approximately 365 mm in April. March also recorded a maximum of around 350 mm with an upper limit of 230 mm. A significant variability was primarily observed between January and May.

Regarding deviations, January and the months from August to December exhibited positive deviations, with the median shifting toward the lower limit, indicating asymmetry. This pattern coincided with the months showing the highest occurrence of outliers, especially between August and December, suggesting a variability marked by intense rainfall events.

In the *Alto Sertão* region, represented by the *Conceição* station, the interquartile ranges varied from 0 to 250 mm, with maximum rainfall values close to 400 mm. Similarly to the *Sertão* region, the months between January and May displayed significant dispersion, as indicated by the interquartile range. Positive deviations were identified from June to January, although March showed a negative deviation, with the median shifting toward the upper limit. As in the previous region, the positive asymmetries were aligned with the months of the highest outlier occurrences.

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The monthly analysis of rainfall across the regions of Paraíba State, confirmed the rainfall gradient described in the literature, which decreases from the coastal area to the *Cariri/Curimataú* region and increases again from *Sertão* to *Alto Sertão*. These patterns are aligned with the influence of the ITCZ on rainfall generation, particularly during the maximum convergence of the trade winds with the land breeze in the May-June-July quarter for the *Litoral, Brejo*, and *Agreste* regions. In contrast, local convection combined with the ITCZ during the fall and winter month drives rainfall in the *Sertão* and *Alto Sertão* areas (ALMEIDA; CABRAL JÚNIOR, 2014; ALBUQUERQUE et al., 2013; ALVES et al., 2006; FERREIRA; MELLO, 2005; FILHO et al., 1996). Future studies on the rainfall genesis and climate dynamics would provide further insight on these phenomena.

Spatial analysis of rainfall concentration indicators

The rainfall homogeneous regions (Figure 1) were used as spatial references for the spatial distribution of indicators (Figure 5).

Regarding average annual rainfall (PP), the coastal region stands out as the wettest, particularly in its southernmost part, where rainfall ranges from 1951 to 2100 mm. As one moves further east-west or south-north, rainfall totals decrease, reaching 901 to 1050 mm in the northwest. The *Brejo* and *Agreste* regions show lower rainfall than the coast, with values ranging from 601 to 1350 mm, primarily following an East-West gradient, highlighting the role of the continental condition, reducing rainfall totals. Meanwhile, the *Cariri/Curimataú* region records rainfall ranging from 300 to 1200 mm, resulting in the lowest PP values of this region. The lowest values are found in the southernmost part of the Borborema Plateau, underscoring its role as a barrier to moisture entry.

In the *Sertão* and *Alto Sertão* regions, PP values range between 600 and 1050 mm, with a general East-West decrease that shifts when moving away from the Borborema Plateau. In this context, PP values tend to increase, particularly toward the northwest, suggesting the influence of topographic compartments, which interact with atmospheric systems such as the land breeze and the ITCZ.

The spatial distribution of the average number of rainy days (NDC) shows that the highest values are concentrated near the coast. Two significant gradients emerge: the NDC is highest in the southernmost part of the coast, ranging from 149 to 162 days, and gradually decreases toward the North, with values between 113 and 123 days. Further inland, the NDC also progressively decreases in the East-West direction.

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However, in the transition zone between the *Litoral* and *Brejo* regions, an increase in NDC is observed, with the highest average recorded in this area, ranging from 163 to 181 days, possibly due to topographic rainfall on the windward side of the Borborema Plateau.

In the southern part of the Cariri/Curimataú region, close to the plateau, the lowest NDC averages in the State are found, ranging from 26 to 38 rainy days. In contrast, the *Sertão* and *Alto Sertão* regions exhibit relatively homogeneous averages, ranging from 26 to 62 rainy days.

The spatial distribution patterns of Rx5day, Rx20Day, P10, P90, P95, and P99 are similar to those of PP and NDC.

Overall, the spatial distribution of rainfall in Paraíba appears to be strongly influenced by the geographical controls present in this State. Proximity to the coastline is a significant factor, as those areas close to the coast exhibit the highest average NDC and PP. This indicates that proximity to the coast is a crucial element in shaping the rainfall regime, with the influence of both breeze systems and Disturbances in the Easterlies (DEs), as documented in the literature.

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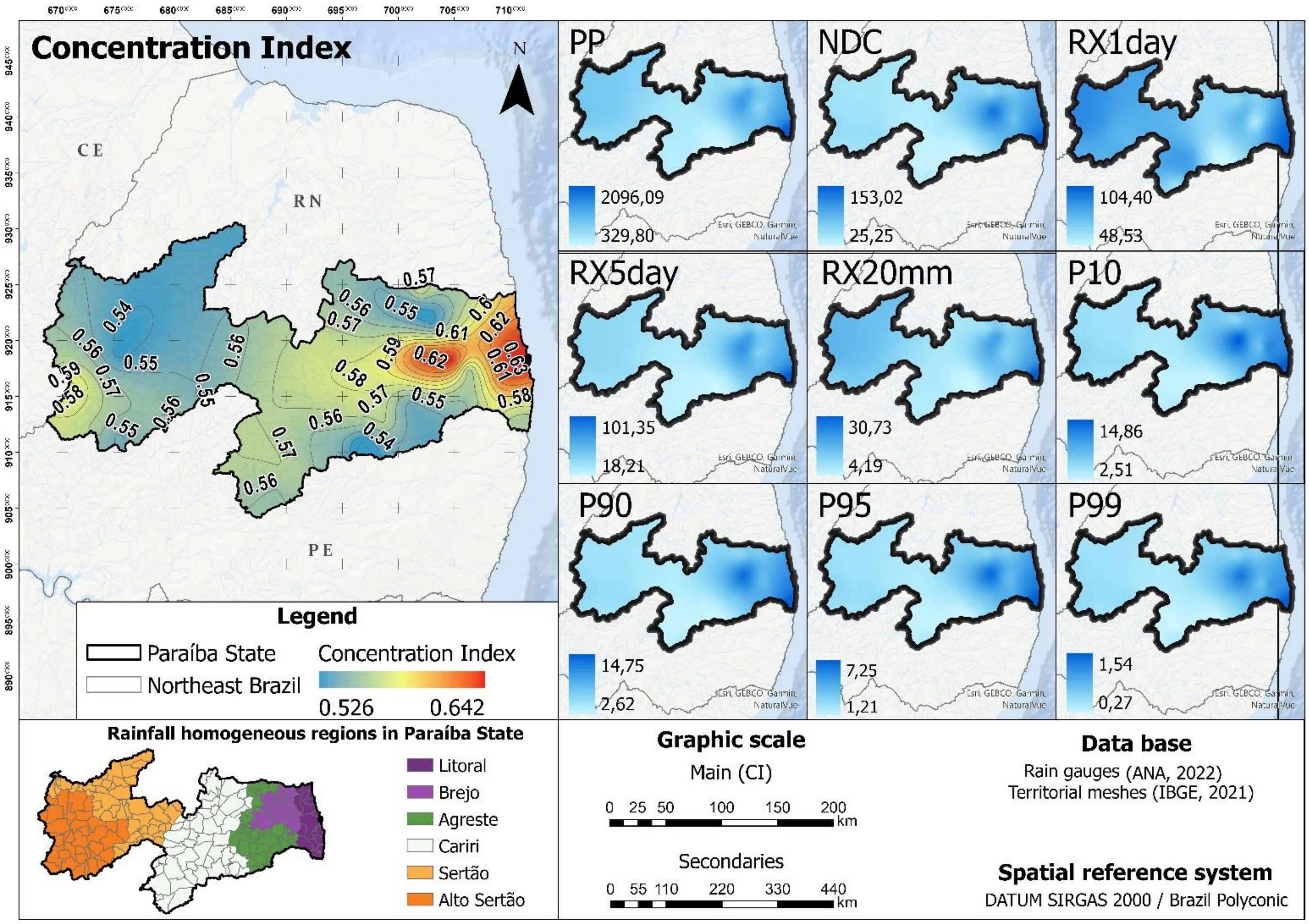

Figure 5 - Spatial distribution of rainfall concentration indicators, with emphasis on the Concentration Index (Source: Authors).

Additionally, the Borborema Plateau seems to play a crucial role as a barrier, affecting moisture flow between the coast and the State's interior. This influences directly the variation in the NDC, PP, Rx5day, Rx20Day, P10, P90, P95, and P99 averages. The eastern slopes are particularly humid, while the western slopes are drier, reflecting a pattern similar to that described by Sant'Anna Neto (2005) in his study of the role from relief in the spatial distribution of rainfall in southeastern Brazil.

Among the rainfall concentration indicators analyzed, the only one that deviated from the others was the Rx1Day variable, representing maximum rainfall within a 24-hour period. Its spatial distribution closely resembled that of the Concentration Index (CI). The highest Rx1Day values were recorded in the coastal region, peaking at 104.4 mm, particularly in the southernmost areas. Moving inland, these values decrease, increasing again in the southernmost part of the *Cariri/Curimataú* region, before slightly decreasing and increasing once more in the *Sertão* and *Alto Sertão* regions.

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Regarding the spatial distribution of the Concentration Index (CI), higher CI values indicate a more significant contribution of the rainiest days to the total annual rainfall. The extreme values observed ranged from 0.64 at station 735009, located in a transition area between *João Pessoa* and *Campina Grande* cities, on the windward side of the *Borborema* Plateau, to 0.53 at station 736013, located on the plateau in the *Campina Grande* region at an altitude of 455 meters.

When examining the spatial patterns, the *João Pessoa* region, especially along the coast, showed the highest CI values, ranging from 0.61 to 0.63 (except for the southern coast, where the CI is slightly lower, varying between 0.57 and 0.58). As the distance from the coast increases, CI values generally decrease, though they remain notably high in the central portion of the *Brejo* region, rising again near the plateau. This pattern reflects the influence of the Atlantic Ocean moisture and the existence of a gradient in an East-West direction, coupled with the effect of topography on precipitation—conversely, areas near the SE and NE slopes of the plateau exhibit lower CI values.

In the *Cariri/Curimataú* region, CI values are generally more moderate, decreasing outward as the distance from the central portion increases. This region also contains the lowest CI value in the State (0.53) and the lowest values for NDC, PP, Rx5day, Rx20Day, P10, P90, P95, and P99.

In the *Sertão* and *Alto Sertão* regions, CI values range between 0.54 and 0.59. In the extreme SW of the State, close to the border with *Ceará* State, CI values are higher. Further studies focused on broader regional areas of the Brazilian Northeast would be crucial for elucidating this process in more detail.

Temporal (Trend) Analysis of Rainfall Concentration Indicators

For the temporal analysis of rainfall concentration indicators, trend analysis (Mann-Kendall) and magnitude estimation (Sen's slope) were applied to all rain gauges within the study area. For each indicator, both statistically significant and non-significant trends (i.e., with a p-value above 0.05) and positive and negative magnitude values were considered (Figure 6).

The results indicated that accumulated annual rainfall (PP) exhibits a predominantly negative trend, suggesting reduced precipitation values. However, except for six rain gauges, the remaining stations did not show statistically significant trends ($p > 0.05$). Spatially, statistically significant negative trends were observed in the *Alto Sertão* (three stations), *Cariri/Curimataú* (two stations), and *Agreste* (one station) regions.

Only two stations displayed statistically significant negative trends regarding the number of rainy days (NDC). These stations are located in the *Alto Sertão* and *Cariri/Curimataú* regions. Most other stations showed non-significant trends, and many indicating a positive direction. When considering the PP and NDC results

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together, a decline is observed in both total annual accumulated rainfall and its distribution throughout the year.

The maximum 24-hour rainfall indicator (Rx1Day) revealed only two stations with statistically significant values: one in the *Alto Sertão* region, with a negative trend (a decrease in maximum daily rainfall), and another in the *Brejo* region, with a positive trend (an increase in maximum daily rain). Non-significant values mostly followed a negative pattern for Rx1Day, particularly along a coast-to-interior gradient.

For the maximum rainfall over five days (Rx5Day), six stations showed statistically significant negative values: one in the *Alto Sertão* region, three in the *Cariri/Curimataú* region, one in the *Agreste* region, and one in the *Litoral* region. The trend in the *Cariri/Curimataú* region clearly indicates a maximum rainfall reduction over five days. Non-significant results indicated similarly a negative trend.

The frequency of days with rainfall up to 20 mm (R20mm) exhibited patterns similar to the other indicators. Four stations had statistically significant negative values: two in the *Alto Sertão* region, one in the *Cariri/Curimataú* region, and one in the *Agreste* region. Non-significant trends in other stations also pointed to a primarily negative pattern.

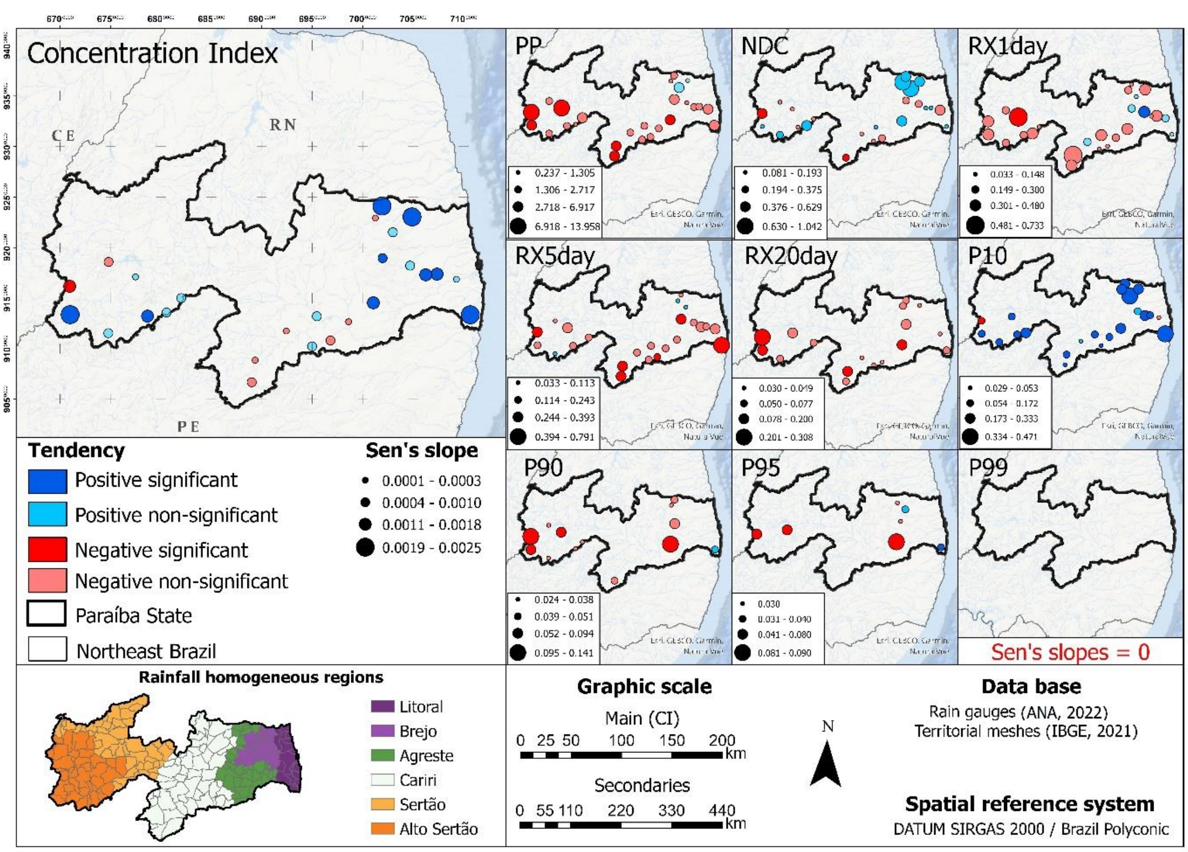

Figure 6 - Distribution of the trend and magnitude of rainfall concentration indicators, with emphasis on the Concentration Index (Source: Authors).

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The 10th percentile (P10) was one of the few indicators that exhibited considerable statistical significance in most stations. Nineteen stations demonstrated significant trends, with eighteen showing positive trends and only one displaying a negative trend. The station with the negative trend is located in the far west of the *Alto Sertão* region, while four stations with positive trends are also in this region. In the *Sertão* region, only one station indicated a positive trend, with additional positive trends found in the *Cariri/Curimataú*, *Brejo*, and *Litoral* regions. This result suggests that days with lower rainfall are becoming less frequent. In other words, over the historical series, there has been an increase in the number of days with minimal rainfall, potentially indicating more evenly distributed rainfall over time, particularly concerning the lowest rainfall days (corresponding to the 10% of days with the least precipitation). Although many stations showed a positive magnitude of less than 0.001 mm, the *Brejo* and *Litoral* regions exhibited higher magnitudes (>0.001 mm).

The results for the 90th percentile (P90) and 95th percentile (P95) followed similar patterns. Few stations showed statistically significant trends, particularly in the *Alto Sertão*, *Sertão*, and *Cariri/Curimataú* regions. The trends identified were negative, indicating a reduction in days with rainfall in the upper percentiles (the top 10% and 5% of the wettest days). No significant trends were observed for the 99th percentile (P99), representing the 1% wettest days, with trend values approaching zero.

Ten stations exhibited statistically significant trends regarding the Concentration Index (CI). Three of them were in the *Alto Sertão* region (one with a negative trend and two with positive trends), two in *Agreste* (both with positive trends), four in *Brejo* (all with positive trends), and one in *Litoral* (with a positive trend) region. The CI results are a synthesis of the other indicators, confirming their findings. For instance, the negative trends observed for PP (accumulated annual rainfall), NDC (number of rainy days), Rx1Day (maximum rainfall in 24 hours), Rx5Day (maximum rainfall in 5 days), and R20mm (days with rainfall up to 20 mm), combined with the positive trend for P10 (10% least rainy days), suggest an increase in rainfall concentration. However, it is essential to note that this concentration does not necessarily correlate with extreme rainfall events, nor imply consistent and sustained increases in high values sufficient to establish trends.

In particular, the *Bonito de Santa Fé* station in the *Alto Sertão* exhibited negative values across all metrics (except for P99 and Rx1Day). This specific case suggests a downward trend in both rainfall totals and distribution, reinforcing the consistency of the observed results for this station.

Finally, it is important to highlight that the indicators reflecting a higher concentration of rainfall (except for P10) are directly associated with the atmospheric mechanisms and systems generating weather

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instability. For the *Litoral, Brejo*, and *Agreste* regions, breeze systems, Easterly Wave Disturbances (EWDs) and Upper Tropospheric Cyclonic Vortices (UTCVs) are the primary drivers. At the same time, the ITCZ and local convection have been highlighted in the literature as significant contributors for the *Cariri/Curimataú*, *Sertão,* and *Alto Sertão* regions.

IV. Conclusions

The objective of this study was to analyze the spatial patterns of daily rainfall concentration in Paraíba using the Concentration Index (CI). In addition to the annual accumulated rainfall (PP), other indicators of daily rainfall concentration were applied, including the frequency of days with rainfall up to 20mm (R20MM), maximum daily rainfall (Rx1Day), maximum rainfall over five days (Rx5Day), frequency of days in the 10th percentile (P10), 90*th* percentile (P90), 95th percentile (P95), and 99th percentile (P99), as well as the number of rainy days (NDC).

The spatial distribution of CI values divides the Paraíba State into three large regions: the western portion, with the highest CI values (a maximum of 0.64, considered high); the central portion, where CI values are moderate for the study area; and the eastern sector, which has the lowest CI values (a minimum of 0.54, considered moderate).

The variables examined suggest a certain level of interrelationship. Areas with the highest rainfall totals (PP) also tend to exhibit higher values for the other indicators. In other words, regions with more total rainfall tend to experience more frequent rainfall throughout the year, with the wettest days contributing significantly to the overall rainfall totals. The exception is the Rx1Day indicator, which showed high values near the Coast and in the *Sertão* and *Alto Sertão* regions.

The spatial distribution of these indicator values suggests that geographical factors play a crucial role in the spatial variation for both total and concentrated rainfall.

Temporally, the indicators PP, NDC, Rx1Day, Rx5Day, R20MM, P90, and P95 showed declining trends, indicating that both annual rainfall totals and rainfall concentrated in groups of days (NDC, Rx5Day, R20MM) or within specific rainfall bands (Rx1Day, P90, P95) are decreasing. Conversely, the CI and P10 indicators showed increasing trends, suggesting that rainfall has become more concentrated over time (CI), while days with the lowest rainfall values have also slightly increased (P10).

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Future studies are recommended to explore these indicators further, particularly regarding the interactions between synoptic-scale atmospheric systems, modes of variability, and the context of climate change.

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