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Evaluation of the daily rainfall concentration index in Brazil

Avaliação do índice de concentração de precipitação diária no Brasil

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ABSTRACT

The concentration of rain in short periods can trigger erosion processes and natural disasters such as floods and landslides. In order to investigate the spatial and temporal distribution of daily precipitation throughout the Brazilian territory, the Concentration Index (CI) of daily precipitation was used. 1,402 daily rainfall series were used based on regular records from 1991 to 2020. The results of the annual CI allowed the identification of five climatic zones: 0.7% of the Brazilian territory with CI <0.54 located in the state of Mato Grasso do Sul; 29.4% with CI values between 0.54 and 0.56 located in the central-west region, and in small portions of the south, southeast and north regions; 48.1% with CI values between 0.56 and 0.58 distributed in the south, southeast, north and northeast regions of the Brazilian territory; 14.7% with a CI between 0.58 and 0.60 in the northeast region, and in interior portions of the south and southeast regions; 7.1% with CI values between 0.60 and 0.70 characterized by coastal regions from the north of the state of Santa Catarina to the state of Rio Grande do Norte.

Keywords: Spatial distribution; Variability; Seasonal IC;

RESUMO

A concentração das chuvas em curtos períodos podem desencadear processos erosivos e desastres naturais como inundações e deslizamento de terra. Com intuito de investigar a distribuição espacial e temporal da precipitação diária em todo o território brasileiro foi utilizado o Índice de Concentração (IC) de precipitação diária. Foram utilizados 1.402 séries de precipitação pluviométrica diária com base em registros regulares no período de 1991 a 2020. Os resultados do IC anual permitiram a identificação de cinco zonas climáticas: 0,7% do território brasileiro com IC <0,54 localizado no estado de Mato Grasso do Sul; 29,4% com valores de IC entre 0,54 a 0,56 localizado na região centro-oeste, e em pequenas porções das regiões sul, sudeste e norte; 48,1% com valores de IC entre 0,56 a 0,58 distribuído nas regiões sul, sudeste, norte e nordeste do território brasileiro; 14,7% com IC entre 0,58 a 0,60 na região nordeste, e em porções interiores da região sul e sudeste; 7,1% com valores de IC entre 0,60 a 0,70 caracterizado por regiões litorâneas desde o norte do estado de Santa Catarina ao estado do Rio Grande do Norte.

Palavras-chave: Distribuição espacial; Variabilidade; IC sazonal;

INTRODUCTION

Precipitation is one of the variables that directly affects the availability of water resources, being considered a climatic element and hydrological parameter of greatest importance for understanding the response of hydrology to climate change (Zamani et al., 2017).

The variability and concentration of rainfall precipitation considering climate change have caused extreme droughts and flood conditions in several regions of the world (Pawar et al., 2022). In recent decades, extreme rainfall events have increased around the world. Rains tend to become more anda more concentrated over time, where the highest percentages of total annual precipitation occurred on very rainy days (Ghenim and Megnounif, 2016). In the literature, several studies are found that deal with the variability of precipitation carried out in different regions of the world using different indices to investigate changes in forecast patterns and trends of extreme events (Rajah et al., 2014; Ghenim and Megnounif, 2016).

Serrano-Notivoli et al. (2018) describe that precipitation concentration can complement other common variables, such as annual precipitation and seasonal factors, being used to investigate risks of extreme precipitation events. Martin-Vide (2004) proposed the Concentration Index (CI) to quantify the daily heterogeneity of precipitation throughout a year, allowing to correlate the magnitude of precipitation events with the moment of their occurrence. The CI helps to understand precipitation variations on different time scales and its correlation is important, since precipitation concentration represents the potential for floods and landslides to occur.

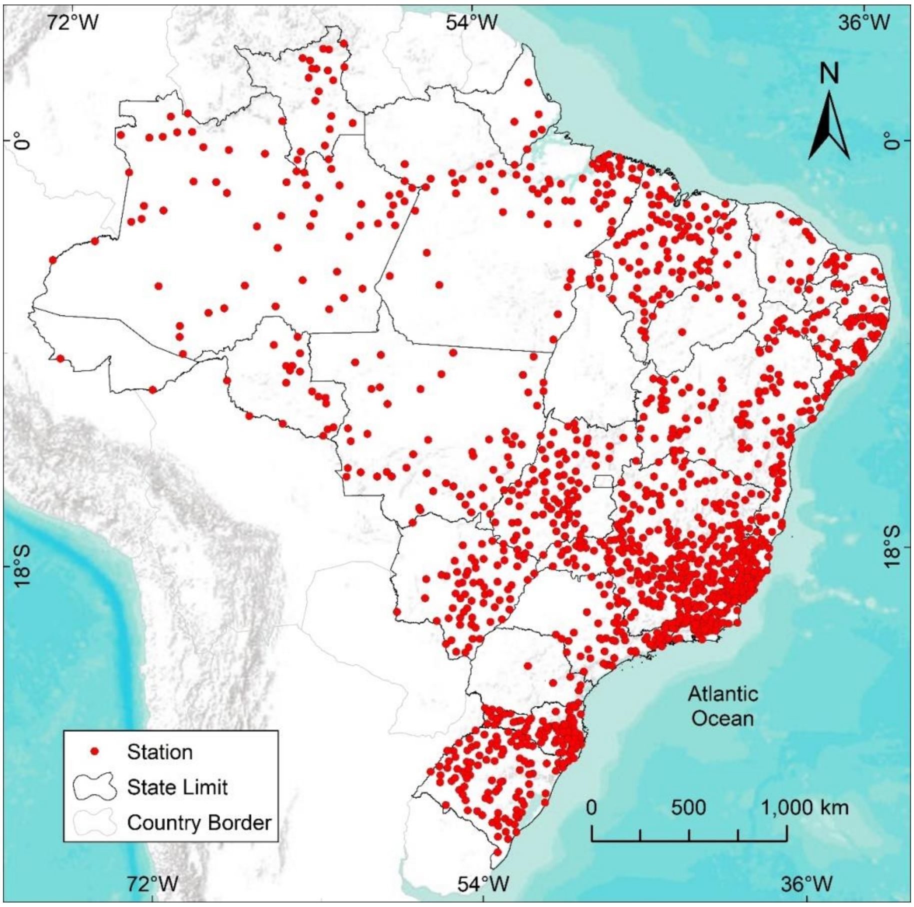
In this context, it appears that the Concentration Index (CI) of daily precipitation has been used to investigate and detect the spatial and temporal heterogeneity of rainfall distribution in many regions of the world, such as in Iran (Alijani et al., 2008), in Spain (Serrano-Notivoli et al., 2018), in European territories (Cortesi et al., 2012), in China (Zhang et al., 2009; Huang et al., 2016), in North Africa (Benhamrouche et al., 2015), in South America (Llano, 2017), in the USA (Roye and Martin-Vide, 2017) and in southern Russia (Vyshkvarkova et al., 2018).

This article seeks to investigate the spatial and temporal relationships of Concentration Index (CI) patterns using a set of daily precipitation data obtained from 1,402 rainfall stations spread across the territory of Brazil. The results obtained can corroborate important effects on the management of water resources and environmental phenomena

MATERIALS AND METHODS

The rainfall stations from the National Agency of Water and Basic Sanitation (ANA) were used with data from 1991 to 2022. The criterion used was to consider the stations that had failures of less than 5% of the data, with 1,402 rainfall stations being selected (Figure 1).

Figure 1 - Distribution of rainfall stations used in the study



Source: Back; Souza; Galatto (2024).

To calculate the Concentration Index (CI) values, the methodology proposed by Martin-Vide (2004) was used, which consists of determining the relative contributions of daily precipitation. A frequency distribution was determined in classes with an interval of 1.0 mm, determining the accumulated percentages of precipitation (X) that contributed with the accumulated percentages of days (Y).

The CI can be defined by Equation 1, while the constant A (Equation 2) defined by the coefficients of the model adjusted to the observed frequencies.

$$\mathrm{IC} = \frac{5000 - A}{5000} \quad (1)$$

Where:

$$A = \left[\frac{a}{b} e^{bx}\left(x - \frac{1}{b}\right)\right]_0^{100} \quad (2)$$

Being a and b adjusted model coefficients based on observed frequencies; x is percentage of rainy days. The CI value found can be classified according to Table 1.

Table 1 -Concentration index classification.

IC	Classification
≤ 0.50	Low
0.50 a 0.60	Medium
0.60 a 0.70	High
≥ 0.70	Very high

Source: Martin-Vide (2004).

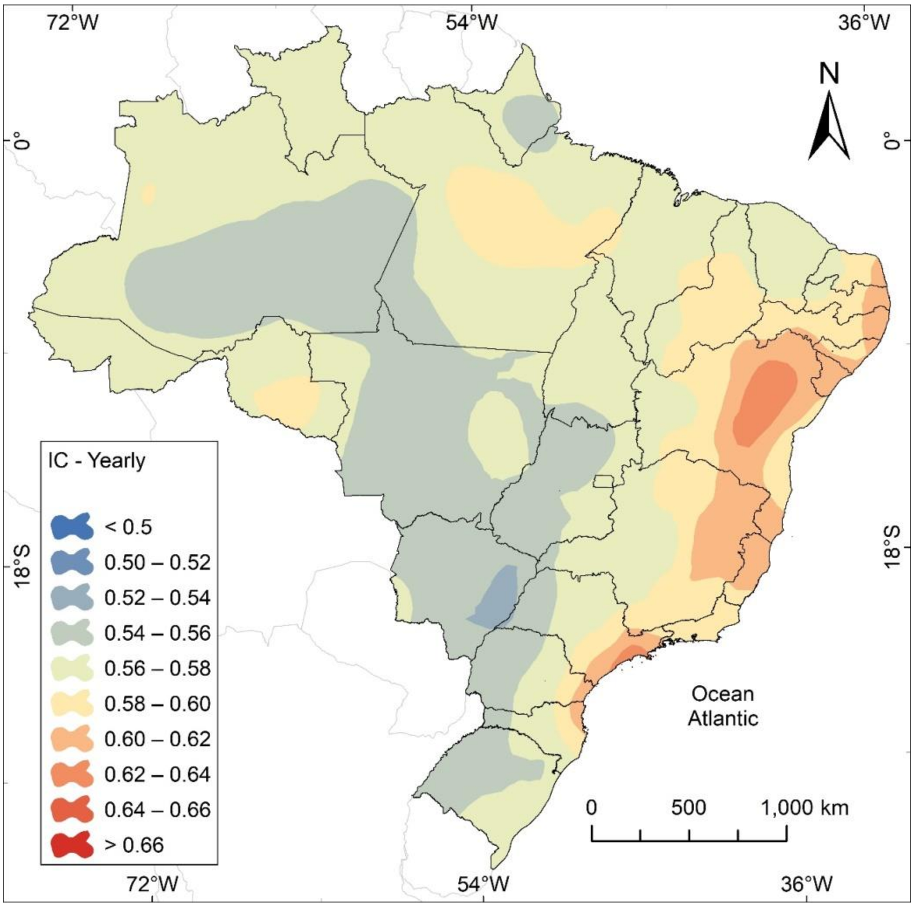
The annual CI values were determined, as well as the values for each quarter of the year. The precipitation values corresponding to the 25% of the rainiest days (PP25) were also determined.

For the spatialization and application of geostatistical interpolation, the geographic information system (GIS) ArcGis 10.8 (Esri, 2019) was used. Through the software, it was possible to spatialize the information and apply the geostatistical kriging method to estimate the concentration index values for deprived locations. Kriging has been constantly used in studies involving the area of hydrology and the like, and is also the most suitable for estimating variables for larger areas.

RESULTS AND DISCUSSIONS

In Figure 2 one can see the variation in CI for the Brazilian territory, with values between 0.50 and 0.65, classified as medium or high risk. These values are in agreement with those obtained by Back et al. (2020), who analyzed data from 208 rainfall stations located in the Southern Region of Brazil, and found that CI values ranged from 0.50 to 0.60. Also Nery et al. (2017), analyzing data from 180 stations in the Southeast Region of Brazil, found CI values between 0.54 and 0.60.

Figure 2 - Annual concentration index for the Brazilian territory



Source: Back; Souza; Galatto (2024).

Siqueira and Nery (2021) found that 56% of the 82 rainfall series in the Northeast region of Brazil have a CI greater than 0.60, indicating that the region has a high rainfall concentration. Studies carried out in other countries also corroborate these observations, such as the work of Bessaklia et al. (2018), who used rainfall data from Algeria and found CI ranging from 0.54 to 0.64, and highlighted that daily CI values are noticeably higher in places where the amount of total precipitation is low. Peng et al. (2014), estimating the concentration of daily precipitation in the Huai River, in China, found that the concentration is high, with CI values ranging from 0.64 to 0.72. Wang et al. (2019), working with data from 71 weather stations in China, cite CI values ranging from 0.69 to 0.76.

Theoretically, high IC values are located in regions with a high daily concentration of precipitation and, therefore, where precipitation has the potential to generate impacts such as landslides and flood risk (Back et al., 2020; Back et al., 2024). When the CI value exceeds 0.61 it means that 25% of the rainiest days contribute almost

70% of the total rainfall (Martin-Vide, 2004). In this condition, in places with high precipitation, this rain is capable of producing erosion, especially if the natural vegetation cover has been removed for other uses without soil protection. If the CI value reaches 0.70, the area must be classified as high risk for certain uses and, in some cases, protected and restored.

The CI allows analyzing the distribution of rainy days. Therefore, by analyzing Figure 2, it is observed that the highest concentrations of daily precipitation are distributed in the center of the state of Bahia, on the coast of the state of São Paulo and partly in the states of Minas Gerais, Espírito Santo, Sergipe and the coastal strip of the northeastern states, oscillating between 0.60 and 0.65.

Galatto et al. (2023) had already pointed out erosive potential in this region, justifying this with the observations of Baecheler and Bravo (2019), who highlighted that in recent times the scientific community has become interested in the hydrological processes that occur in arid zones, as these are characterized by be fragile and sensitive to plant and soil degradation. Convective storms in arid areas generate erosion processes, which are slow, recurrent, progressive and irreversible. Erosive processes can be grouped into energy and resistance factors, where the first is associated with the aggressiveness of rainfall.

The CI values (Figure 2) were also observed by Siqueira and Nery (2021). According to the authors, in the coastal strip of the northeastern states, the daily concentration of rainfall has resulted in few rainy days, which has led to a high percentage of annual precipitation. The origin of precipitation in the northeast is linked to the orography and climate dynamics in the region, influenced by polar masses to the south, sea breezes on the coast and the dynamics associated with the Intertropical Convergence Zone to the north. The lowest values observed in Figure 2 are distributed in part of the southern, southeastern, central-western and northern regions of Brazil, recording values between 0.50 and 0.58 concentration.

The distribution of rainfall throughout the year is the main factor that influences the values of rainfall coefficients (Panagos et al., 2015). In the river basins that make up the Brazilian territory, according to studies by Trindade et al. (2016), the average annual precipitation values varied from 1,107 mm (monthly maximum of 222 mm in December and minimum of 10 mm in August) in the basin of the São Francisco River, this region being partly inserted in the Northeastern Semiarid at 2,143 mm in the Amazon basin (minimum average rainfall of 80 mm in August and maximum of 281 mm in March).

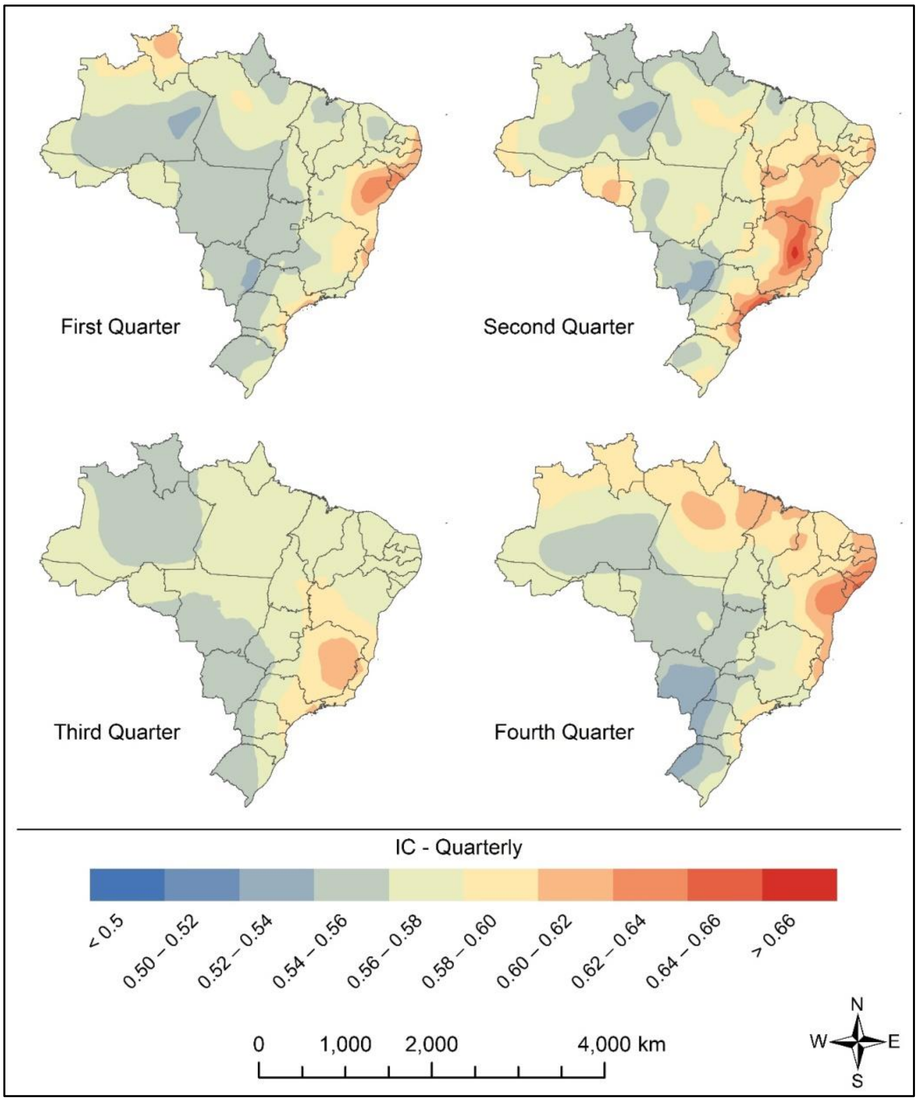
While the lowest monthly precipitation values were found in the Tocantins-Araguaia River basin (Trindade et al., 2016), with an average of 4.22 mm in July and the highest recorded value of 279 mm in January, but with an average annual value of 1571 mm.

In general, the classification of the annual CI allowed the identification of five climatic zones in the Brazilian territory: 0.7% with CI <0.54 located in the center-west, more precisely in the state of Mato Grasso do Sul; 29.4% with a CI between 0.54 and 0.56 in the center-west region, and in small regions of the south, southeast and north; 48.1% with CI between 0.56 and 0.58 distributed in the south, southeast, north and northeast regions; 14.7% with a CI between 0.58 and 0.60 in the northeast region, and in small interior regions of the south and southeast; and 7.1% with CI values between 0.60 and 0.70 in coastal regions from the north of the state of Santa Catarina to the state of Rio Grande do Norte.

Figure 3 shows the in CI variation per quarter for the Brazilian territory. In the first trimester, CI values range from 0.50 to 0.64, classified as medium to high risk. In the northern region of the states of Bahia and Roraima and in almost the entire territory of the state of Sergipe, CI values reach 0.66, classified as high. A similar situation was found in Bangi Knowledge City (western Peninsular Malaysia) with CI ranging between 0.54 and 0.58 (Hamzah, et al., 2016).

In the second quarter, the states of Minas Gerais (CI >0.54 to CI <0.70) and Bahia (CI >0.54 to CI <0.66) stand out, corroborating the results of Siqueira and Nery (2021), with CI >0.60 for the northeast region. On the coast of the states of São Paulo, Espírito Santo, Paraná and Santa Catarina, CI values (>0.54 to <0.68) are classified as medium to high. The CI values found in Mina Gerais and on the coast of São Paulo are considered high risk, as daily precipitation has the potential to cause landslides, high-intensity erosion, and flooding. A similar situation was found in Bangi in Malaysia (Hamzah et al., 2016), in Biska, Algeria (Benhamrouche et al., 2015) and in the west of the Amur River Basin (CI = 0.736 to 0.747), on the Hulun Buir Plateau (Wang et al., 2019).

Figure 3 - Quarterly IC values for Brazilian territory



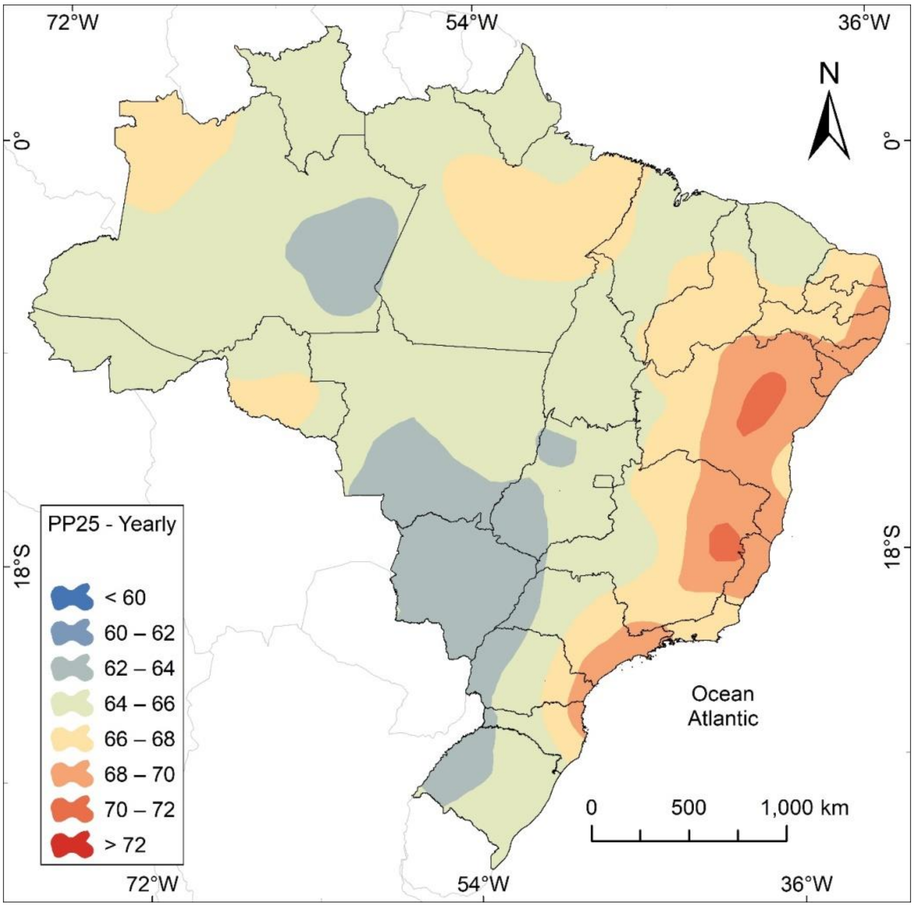
Source: Back; Souza; Galatto (2024).

In the third trimester there is a uniform distribution across almost the entire Brazilian territory, with CI values varying between <0.52 and >0.62. In the fourth quarter, a higher concentration of CI (>0.58 to <0.68) was again observed in the north of the state of Espírito Santo, and on the northeast coast, highlighting the northern region of Bahia and the states of Sergipe, Alagoas and part of Pernambuco. CI values reaching the range of 0.62 are still observed in some regions of the states of Paraíba, Rio Grande do Norte, Maranhão and Pará. In general, the increase in CI contributes negatively to the environment, with sudden floods and soil erosion events, which can harm soil and water conservation management.

The results on a seasonal scale allow inferring that the highest CI values are in the coastal regions of Bahia, Sergipe, Paraíba and Pernambuco, and that, on the other hand, they have lower monthly and annual rainfall rates, such as those found in the São Francisco River basin region, partly in the Northeastern Semiarid. Furthermore, high CI values were found in the southeastern coastal region, mainly due to the influence of topography on the local circulation atmosphere. The air masses that come from the Atlantic Ocean end up resulting in orographic rainfall, which is very abundant in the southeast region.

Figure 4 shows the PP25 values for the Brazilian territory, with values varying between 0.60 and 0.75, indicating that the 25% (PP25) of the rainiest days contribute 60% to 75% of the precipitation.

Figure 4 - Annual concentration index (PP25) for the Brazilian territory.



Source: Back; Souza; Galatto (2024).

The highest values are observed in the state of Bahia and in places in the state of Minas Gerais. Most of the Brazilian territory has PP25 in the range of 65 to 70%. The lowest values (60 to 65%) were observed in 39% of the territory, including the western region of the states of Rio Grande do Sul, Santa Catarina, Paraná and São Paulo, and a large part of the Central-West region, and part of the states of Amazonas, Roraima and Pará, and in a small area in the northern state of Rondônia.

These results are in line with other studies in the southern region of Brazil. Siqueira and Nery (2019), analyzing data from the state of Paraná, found PP25 values ranging from 60.9 to 75%. Nery et al. (2017), analyzing data from 120 rainfall stations in the Southeast region of Brazil, found PP25 values ranging from 31.9 to 69.9%.

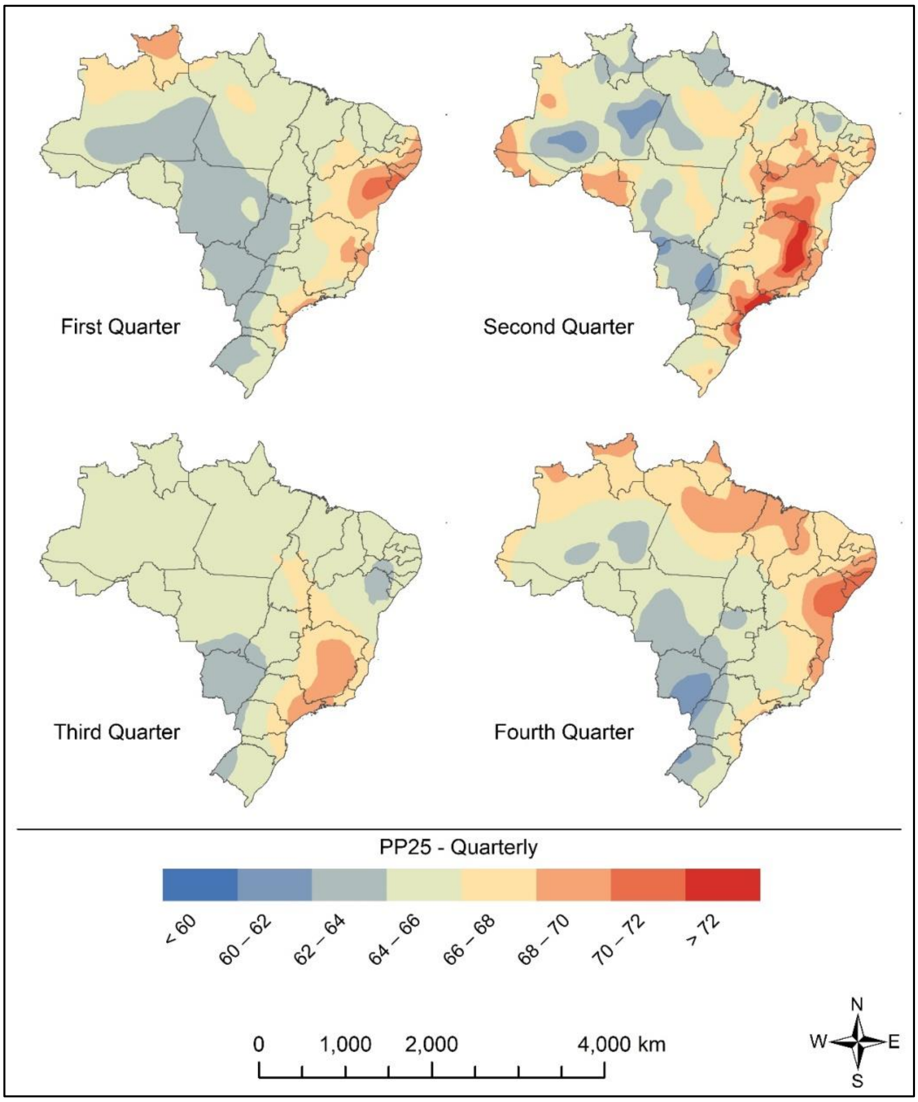
Figure 5 shows the quarterly CI values (PP25) for the Brazilian territory. In the first quarter, CI values (PP25) were between 0.60 and 0.65, corresponding to 45% of the Brazilian territory, while 54% of the territory with CI in the range of 0.65 to 0.70. In the second and fourth quarters, the CI values (PP25) had very similar behavior (around 39.3% in the range of 0.60 to 0.65; and 56.3% to 58.7 with CI values between 0.65 to 0.70). In the third quarter, 59.5% of the Brazilian territory had CI values between 0.60 and 0.65, and 40.5% in the CI range of 0.65 to 0.70. It was observed that the CI exceeds the value of 0.60 in several rainfall series, reaching above 0.70 in some points, reflecting that on some very rainy days, there is a high contribution to the annual precipitation value (25% of the hottest days). rainy season contributes 75% of total rainfall).

The use of daily precipitation data allowed us to increase knowledge of the temporal and spatial structure of daily precipitation with a more detailed resolution. Martin-Vide (2004) found that the CI allows evaluating the contribution of very rainy days to the total value, as some daily events produce a high percentage of the total monthly, seasonal or annual precipitation. The author concluded that a CI value of up to 0.7 indicates that more than 80% of all precipitation falls on 25% of heavy precipitation days.

For Lu et al. (2019), the occurrence or lack of intense rainfall on a daily basis can change the structure of rainfall in any month, season or year. According to the authors, the CI can be used to evaluate the distribution pattern of daily precipitation. Therefore, the higher the CI value, the greater the contribution of intense precipitation to total precipitation; therefore, more rain will be concentrated on fewer days.

It was found that changes in latitude indirectly influence the distribution of rainfall, mainly affected by atmospheric circulation. Altitude determines the vertical distribution of energy and water, possibly affecting regional precipitation change (Zhang et al., 2019). Another factor is the topography that can influence the distribution and quantity of rainfall, which, to a certain extent, was found in the differences in IC values in the Brazilian territory.

Figure 5 - Quarterly CI values (PP25) for the Brazilian territory.



Source: Back; Souza; Galatto (2024).

The concentration of precipitation in Brazil can be described as highly irregular in the coastal regions of the southern and southeastern states and in parts of the northeastern states. The regularity of the annual precipitation pattern decreases in the first and third quarters. IC changes appear to be complex and possibly related to regional atmospheric characteristics as well as geographic factors (latitude, longitude and altitude). In general, the results presented in this study indicate that CI is a fundamental characteristic in predicting risks associated with floods and droughts and in planning water resources.

CI analyzes (annual and quarterly) made it possible to identify regions with a higher incidence of drought and flood events. It should be noted that rainfall observation stations are scarce in the north and center-west regions of the country, and in some states in the northeast and southeast. Therefore, in these regions there may be some uncertainties in the IC values due to data interpolation.

The analysis of the precipitation concentration index throughout the year is extremely important due to its high impact on environmental phenomena. Thus, this study helps decision makers make more informed decisions about water resources management and economic development planning.

CONLCUSIONS

The daily rainfall concentration is a climatic variable of great interest to express the irregularity of precipitation, mainly the concentration or accumulation in a few rainy days. The CI is a useful indicator of the erosive capacity of rainfall, the danger of flooding and torrential rain. Therefore, studying the patterns and mechanisms of precipitation variations is important to assess the risks of floods and droughts and ensure the sustainable use of water.

In the current context of climatic events that Brazil has been going through, such as the drought in the Amazon Basin and the torrential rains with floods in the southern states of Brazil, adaptations to prevent and minimize climate impacts on water resources require researchers to run rainfall analysis at a detailed level.

In this study, the spatial and temporal characteristics of daily precipitation, with the use of CI, were analyzed from 1991 to 2020 on the annual and quarterly scales, and corresponding to the 25% of the rainiest days (PP25).

The annual CI values were determined and also for each quarter of the year. The precipitation values corresponding to the 25% of the rainiest days (PP25) in Brazilian territory were also determined. The calculated CI results made it possible to classify the Brazilian territory into five distinct regions. The coastal regions of the south, southeast and northeast are those that deserve the most attention, as they presented CI values between 0.60 and 0.70, classified as medium to high risk.

Therefore, accurately understanding the CI of daily precipitation allows it to be corroborated as an important reference in the prevention and control of natural catastrophes, in addition to assisting in future research on agricultural production and water resources management. In addition to these benefits, the CI can be useful in identifying areas of rainfall, hydrological and geomorphological risk, particularly those with risks arising from aggressive rainfall and soil erosion.

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