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Assessment of Drought Occurrence and Severity in the São Francisco River Basin between the years 1961 to 2019

Zoneamento e avaliação da severidade das estiagens entre os anos de 1961 até 2019 na Bacia Hidrográfica do Rio São Francisco com base em valores do Índice de Precipitação Padronizado

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Abstract: This research aimed to evaluate the impact of drought occurrences in the São Francisco River Basin and assess the severity of droughts that took place across the entire basin from 1961 to 2019. Additionally, the study sought to map the drought-prone areas within the basin. The Standardized Precipitation Index (SPI) was employed to determine the severity of droughts. Precipitation data from meteorological stations in the database of the National Institute of Meteorology (INMET) were utilized for the analysis. The results of this study revealed that the Upper São Francisco region exhibited significant values of accumulated precipitation but stood out regarding SPI3, indicating short-term droughts. In contrast, the Lower São Francisco region showed lower incidences of short-term droughts. However, long-duration droughts related to SPI12 and SPI24 were observed in the Submédio and Médio São Francisco regions. The application of Cluster Analysis unveiled similarities among rainfall stations located within different regions of the basin when considering drought-related variables.

Keywords: Standardized Precipitation Index; São Francisco River Basin; Droughts.

Resumo: Esta pesquisa buscou avaliar a ação do fenômeno da seca na Bacia Hidrográfica do Rio São Francisco e indicar a severidade das estiagens ocorridas em toda extensão territorial da Bacia entre os anos de 1961 até 2019, bem como mapear estas áreas de estiagens. Para a determinação da severidade das secas foi utilizado o Índice de Precipitação Padronizado (SPI). Foram utilizados os dados de precipitação das estações pluviométricas, do banco de dados do Instituto Nacional de Meteorologia (INMET). Para a realização do cálculo do índice de estiagem, foi utilizado um software de linguagem de programação. Os resultados desta pesquisa mostraram que embora a região do Alto São Francisco possua valores elevados de precipitação acumulada, ela se destaca quanto ao SPI3, secas de curto prazo, de forma contrária no Baixo São Francisco, que mostrou menores incidências de secas de curto prazo. De modo que as secas de longa duração, relacionadas ao SPI 12 e SPI24 foram observadas no Submédio e Médio São Francisco. Através da Análise de Cluster foi verificada a existência de similaridade entres postos pluviométricos alocados dentro de regiões distintas da bacia quando observadas nos parâmetros das variáveis da seca.

Palavras-chave: Índice de Precipitação Padronizado; Bacia do São Francisco; Secas.

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1. Introduction

The recurrent phenomena of drought rank among the world's most detrimental natural disasters, causing damage to crops, natural ecosystems, and water supply (ZHAO, T.; DAI, 2015). Drought is a natural phenomenon that can occur in diverse climatic zones (GONÇALVES et al., 2021). The nature of this phenomenon varies spatially and temporally, reflecting intrinsic climatic, meteorological, hydrological, and socioeconomic characteristics (GE; APURV; CAI, 2016). Droughts are known to be characterized based on their duration, severity, and geographical extent (AWAN; BAE, 2016).

Hydrographic basins have been widely impacted by drought events. One such example is the São Francisco River Basin, predominantly semi-arid, located in northeastern Brazil. This basin serves 70% of the population within its territory and accounts for approximately 13% of the Brazilian electrical demand. These indicators of function and representation demonstrate the catastrophic conditions of water scarcity in the basin. These drought events also result in short and long-term impacts, such as limited grazing for animals and reservoir water depletion, respectively (PAREDES TREJO et al., 2016).

In this context, drought indices are used by researchers in drought studies (DAS et al., 2016). Through these indices, it is possible to analyze the impacts and severity of droughts (ZHAO, Q. et al., 2018). Among these indices, the Standardized Precipitation Index (SPI), developed by Mckee et al. (1993), is commonly used to assess the severity of droughts using precipitation data.

Therefore, the objective of this study is to evaluate the impact of the drought phenomenon in the São Francisco River Basin and indicate the severity of drought occurrences across the entire basin from 1961 to 2019, through the calculation of SPI3, SPI12, and SPI24, as well as the mapping of these drought-prone areas.

In light of the need for scientific contributions regarding the mapping of drought-prone zones with SPI variations within hydrographic basins through regional analyses, and the indication of the severity of concentration and expansion of areas affected by this phenomenon through local clustering analyses, this work aims to address these aspects.

2. Methods and data

Study area

The São Francisco River Basin (Figure 1) has a drainage area of 639,219 km², equivalent to 7.5% of the country, with an average flow rate of 2,850 m³/s (CBHSF, 2021).

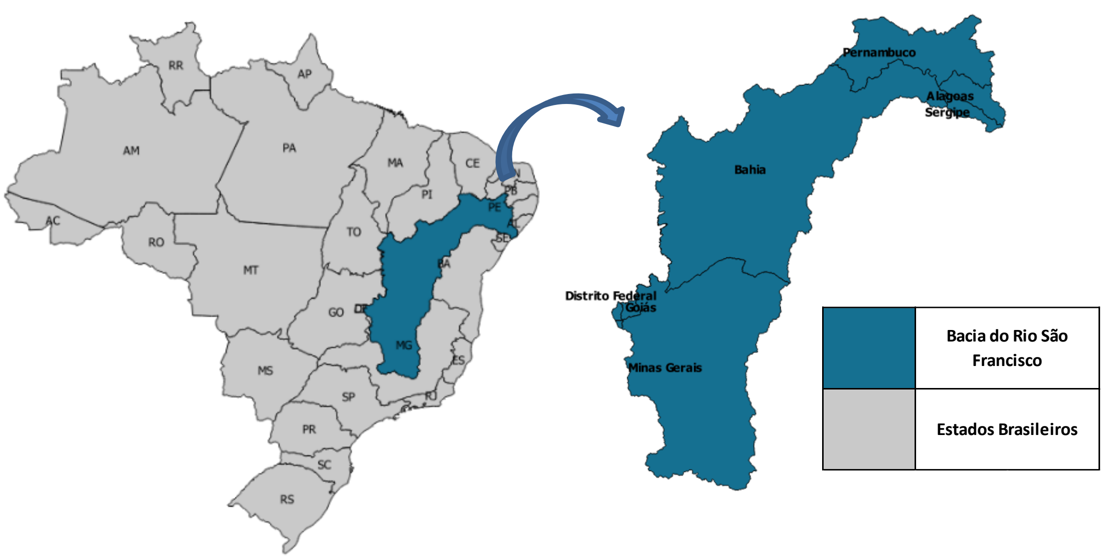

Figure 1 – São Francisco River Basin.
Source: Author (2022).

Part of the states is located within the basin area, namely Bahia (48.2%), Minas Gerais (36.8%), Pernambuco (10.9%), Alagoas (2.2%), Sergipe (1.2%), Goiás (0.5%), and the Federal District (0.2%). Additionally, it accommodates a total of 505 municipalities, approximately 9% of the total municipalities in the country. This basin is divided into four regions: Upper, Middle, Submiddle, and Lower São Francisco (Figure 2).

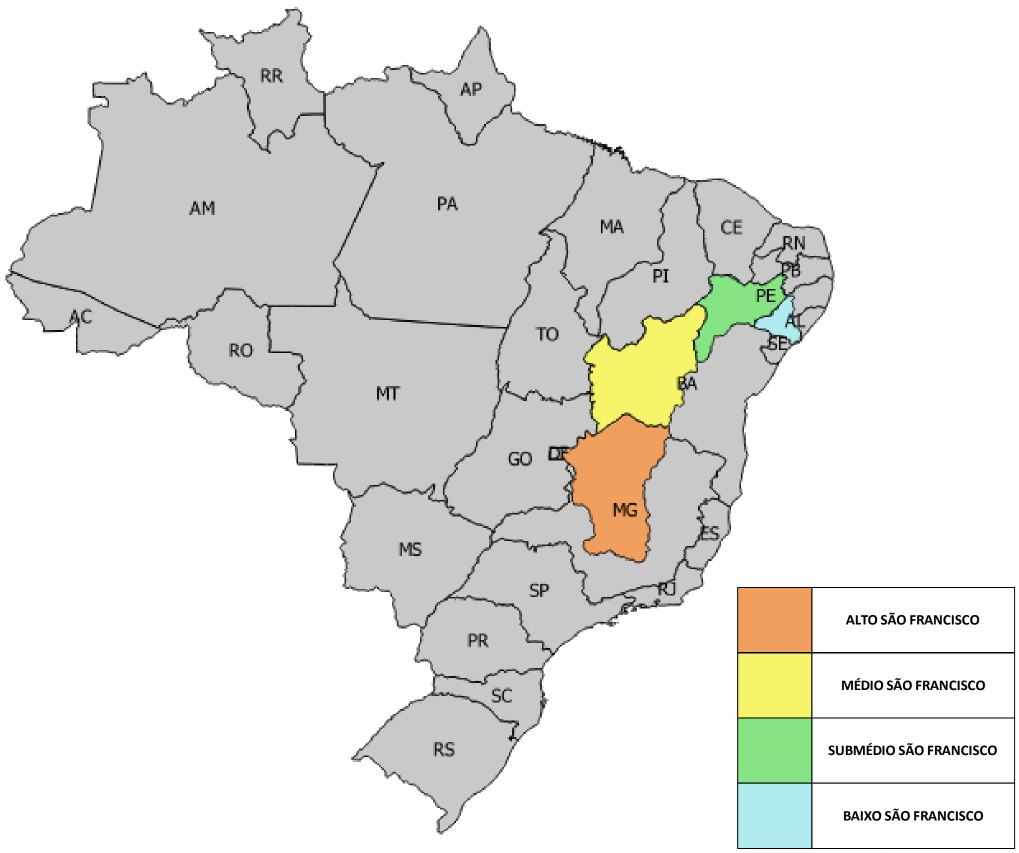

Figure 2 – Divisions of the São Francisco River Basin
Source: Author (2022).

The climate of the São Francisco River Basin exhibits variability between humid and arid, with an average annual temperature ranging from 18 to 27 ºC. It experiences an average annual rainfall of 1036 mm, with higher values at the river's source, around 1400 mm, and lower values between Sento Sé and Paulo Afonso, Bahia, reaching 350 mm. The trimester with the highest rainfall occurs from November to January, contributing to 55 to 60% of the annual precipitation, while the driest trimester is from June to August. The average evapotranspiration is 896 mm per year, with higher values in the south (approximately 1400 mm) and lower values in the north (around 840 mm) (CBHSF, 2021).

Data

The precipitation data from meteorological stations in the database of the National Institute of Meteorology (INMET) were utilized for this study. The data period covered the years from 1961 to 2019, selected to capture interdecadal rainy periods, which are periods of prolonged rainfall that can persist for over a decade. This choice aimed to verify the consistency and rationale behind phenomena associated with these periods.

17 rain gauges were used to ensure data representativeness and provide the necessary historical series for the index calculation. Figure 3 illustrates the accumulation of precipitation across the entire territorial extension of the basin from 1961 to 2019.

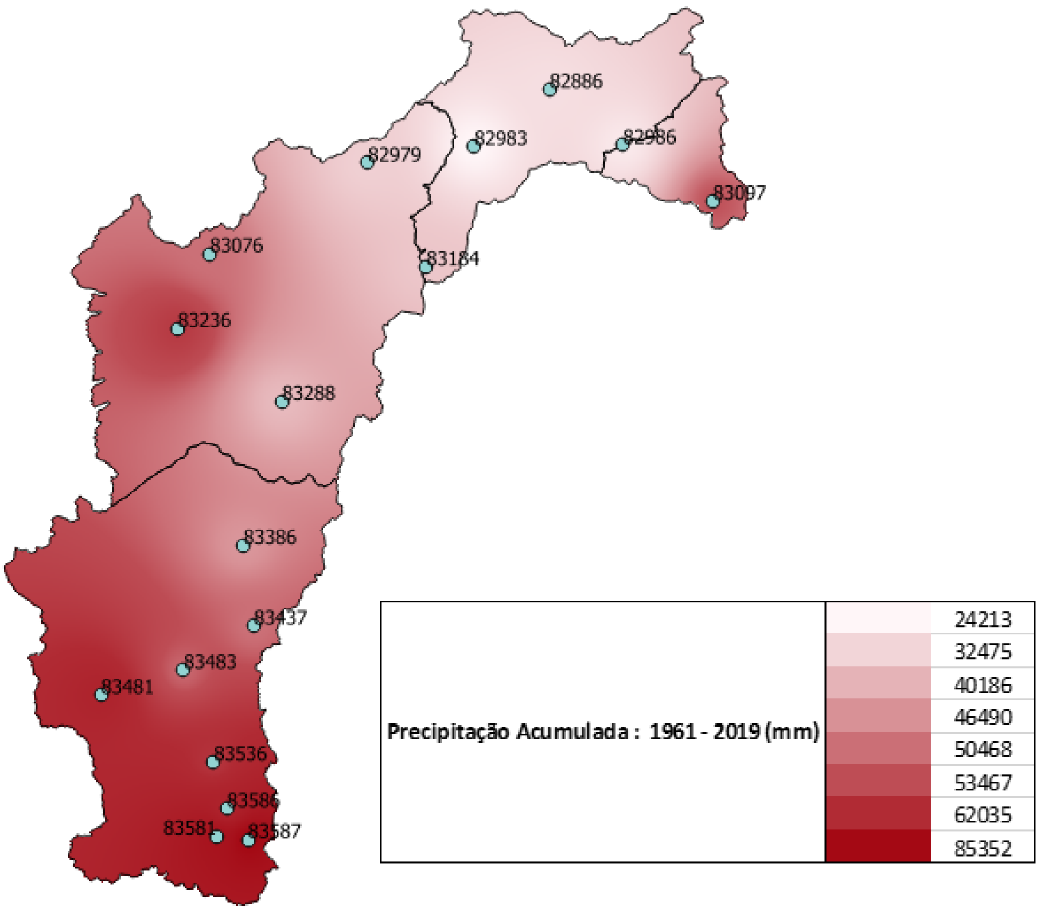

Figura 3 – Precipitação Acumulada
Source: Author (2022).

Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was proposed by Mckee et al. (1993) and serves as an operational tool for national or regional drought monitoring systems (MAHFOUZ et al., 2016). This index monitors droughts through the utilization of precipitation data and allows for the monitoring of wet and dry periods. It is calculated to assess water behavior in reservoirs, river flows, soil moisture, and groundwater (MCKEE et al., 1993).

The SPI is based on the premise that precipitation follows an asymmetric distribution rather than a normal distribution (YAN et al., 2017). The SPI value is derived from the inverse Gaussian cumulative distribution function applied to this probability (SOUSA et al., 2016). The occurrence of drought is indicated when the SPI remains continuously negative, and the drought event ceases when the SPI becomes positive (MCKEE et al., 1993). Table 1 below displays the drought classification based on SPI values.

Table 1 – Drought Classification based on SPI.

SPI Value	Drought classification
0 a -0,99	Mild
-1,00 a -1,49	Moderate
-1,50 a -1,99	Severe
≤ - 2,00	Extreme

Sourcet: Adapted from Mckee 1993.

Another important factor in SPI analysis is the time scale, as different types of droughts are directly associated with different SPI time scales, namely 3, 6, 9, 12, and 24 months. The SPI-3 reflects soil water conditions in the short and medium term, providing an estimate of seasonal precipitation. It is used to represent short-term droughts and to assess soil moisture sensitivity, water stress, and agricultural crop failure (ADARSH, 2018; ADNAN, 2021). The SPI-6 relates to river flow and water reservoir anomalies. The SPI-9 indicates precipitation patterns, considering that droughts can take a year or more to develop. The SPI-12 and SPI-24 are associated with water scarcity in terms of river flow and groundwater levels (VALTER et al., 2012). According to Mateus and Antonio (2020), the 12-month time scale is commonly used for analyzing meteorological and hydrological droughts. This time interval helps avoid interannual variations and allows the identification of key dry periods (MATEUS; ANTONIO, 2020).

Guerreiro et al. (2008) stated that the main dry periods can be identified by analyzing the SPI-24. The SPI with a 24-month time scale represents peaks, so by identifying peaks at this scale, SPI-3 and SPI-12 should also be calculated, as these peak values occur after a slight decrease in these SPI values (GUERREIRO; LAJINHA; ABREU, 2008).

Thus, based on the results obtained for the SPI-3, 12, and 24 months, drought maps are generated. These drought maps provide an overview of the respective dry points and an overview of the most affected areas (SPINONI, 2013). They are an essential component in drought risk management, allowing the display of regional differences in the severity of drought phenomena (BLAUHUT; GUDMUNDSSON; STAH, 2015).

Cluster analysis

Cluster analysis is a statistical technique used to classify elements into groups based on their shared characteristics (OLIVEIRA, 2020). The objective is to have elements within the same cluster that are similar while being distinct from other clusters. In cluster analysis, dendrograms are used, which are tree diagrams that display the groups formed through variable clustering at different levels of similarity. The vertical axis of the dendrogram represents the level of similarity or distance, while the horizontal axis represents the variables.

To visualize the similarity and distance of the station characteristics regarding SPI classification, dendrograms were created for these visualizations. The Ward method was employed to minimize within-cluster variation and maximize between-cluster variation. The Ward method is a hierarchical clustering technique where the similarity measure used to merge clusters is calculated as the sum of squares between the clusters over all variables. This method tends to result in clusters of approximately equal sizes due to the minimization of internal variation (SEIDEL et al., 2008).

3. Results and discussion

Analysis of SPI Regional Patterns - Drought Maps

By analyzing the drought maps for a short term (Figure 4), specifically for 3 months using SPI3, it was observed that even during decades of mild drought, the Upper São Francisco region still experienced drought occurrences, albeit in specific areas such as in Minas Gerais. The Upper São Francisco region had drought occurrences in all six decades studied. Throughout the decades, some points in the Middle São Francisco region showed low variations in precipitation, as seen in the maps around station 83288 located in Bahia, where drought did not occur. However, the Middle São Francisco region still experienced drought occurrences.

In a descending order of impact, the regions most affected by drought according to the SPI3 analysis were the Upper, Submiddle, Middle, and Lower São Francisco regions, respectively.

For the entire basin, the first two decades were marked by more severe drought events, between 1961 and 1980, with a predominance of moderate and severe droughts. After these initial two decades, a gradual decrease in drought occurrences was observed, starting with a prevalence of mild droughts and subsequently an increase in areas without drought occurrence, particularly in the fifth decade, where the drought phenomenon was milder. However, in the last decade under analysis, a return of water stress in the basin was observed, with occurrences of moderate and severe droughts.

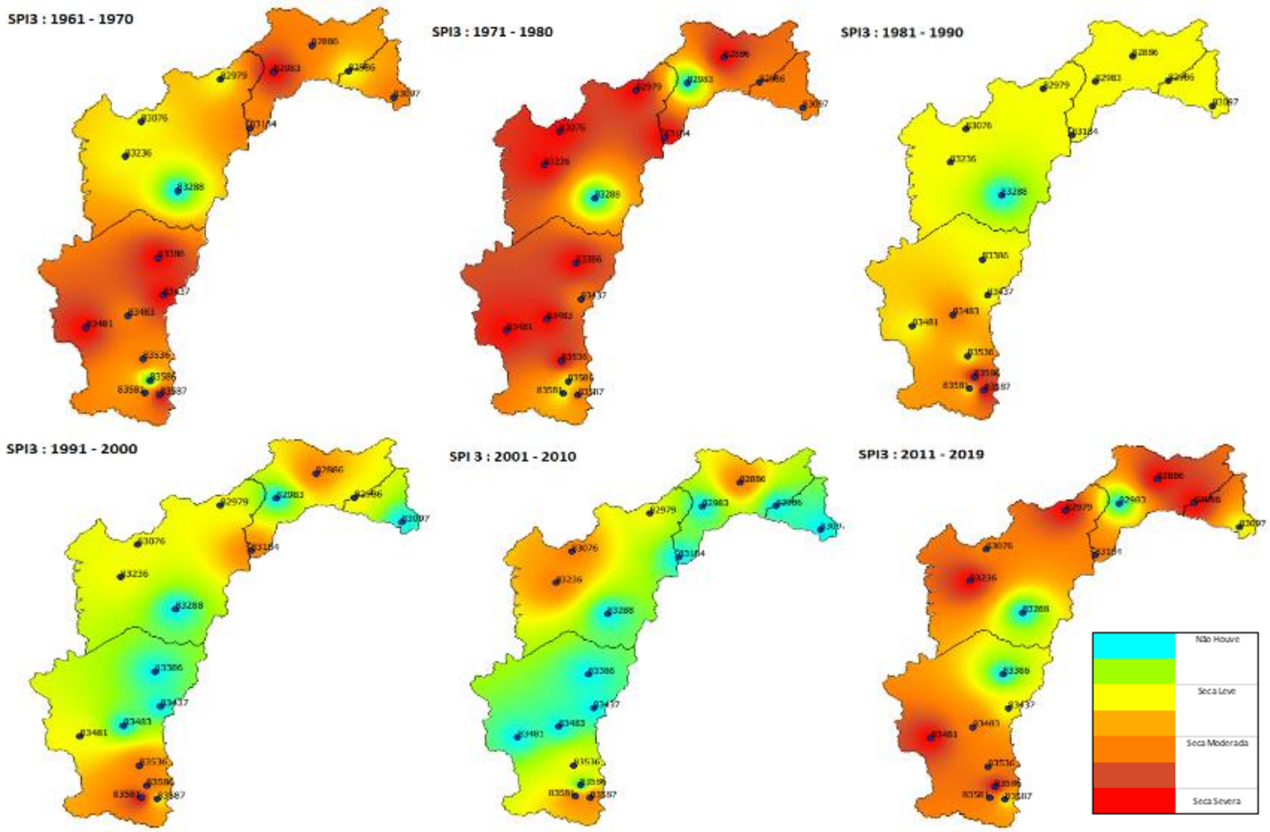

Figure 4 – Drought Maps: SPI3
Source: Author (2022).

Regarding the SPI12 drought maps (Figure 5), it can be observed that the first two decades were marked by more severe drought events, between 1961 and 1980, with a predominance of moderate and severe droughts in all regions. A smoothing of this phenomenon is evident in the two subsequent decades, between 1981 and 2000, except for long-term mild and moderate droughts occurring in the Upper and Submiddle São Francisco regions between these decades. The fifth decade, between 2001 and 2010, showed fewer drought events compared to the others, with only mild droughts intensifying in the Upper and Middle São Francisco regions. In the last decade under analysis, as shown by SPI3, there was a period with greater precipitation variations and drought events, specifically severe droughts in the Submiddle São Francisco and moderate droughts in the Upper São Francisco region.

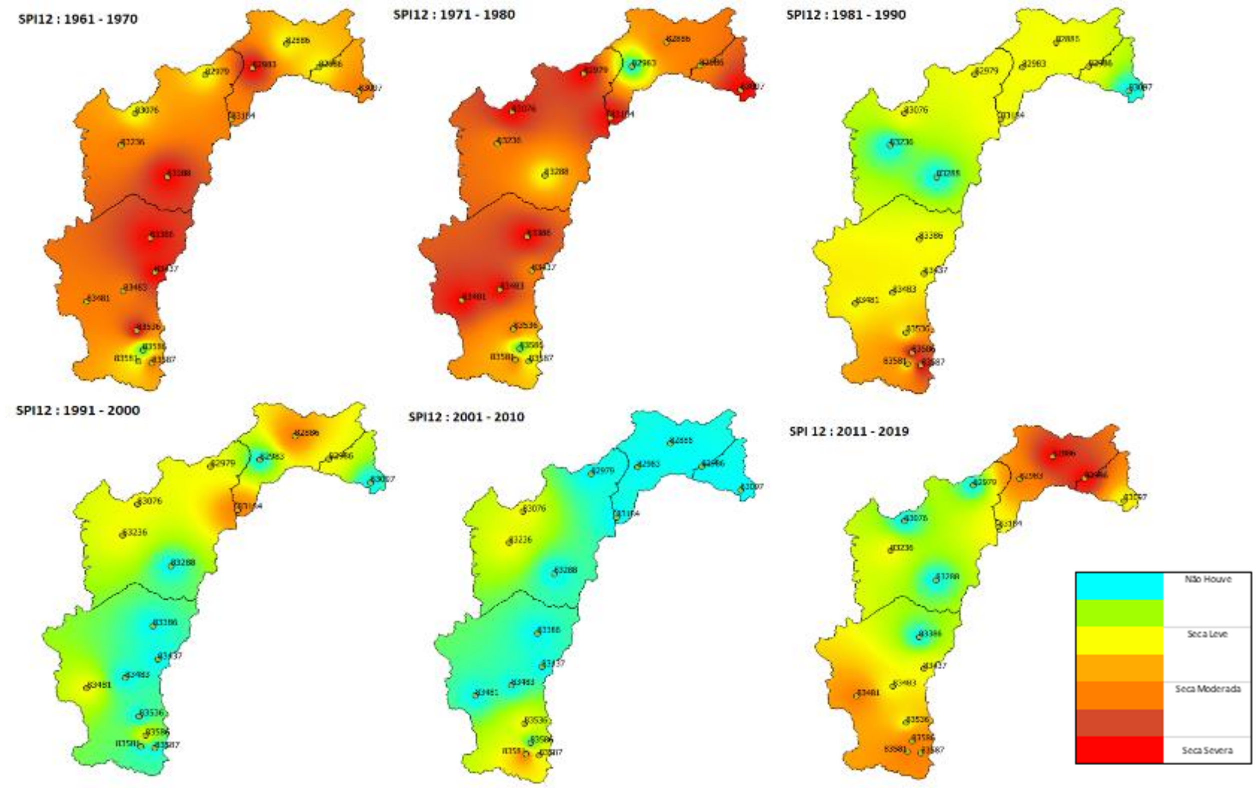

Figure 5 – Drought Maps: SPI12
Source: Author (2022).

In the SPI24 analysis (Figure 6), indications of long-term droughts ranging from moderate to severe are observed in the Upper, Middle, and Submiddle São Francisco regions in the first decade under analysis. Similarly, this pattern repeats in the second decade, with drought intensification in the Lower, Middle, and Upper São Francisco regions. According to the analysis, there is a trend of drought smoothing in the fourth and fifth decades, followed by a resurgence of drought incidence in the sixth decade.

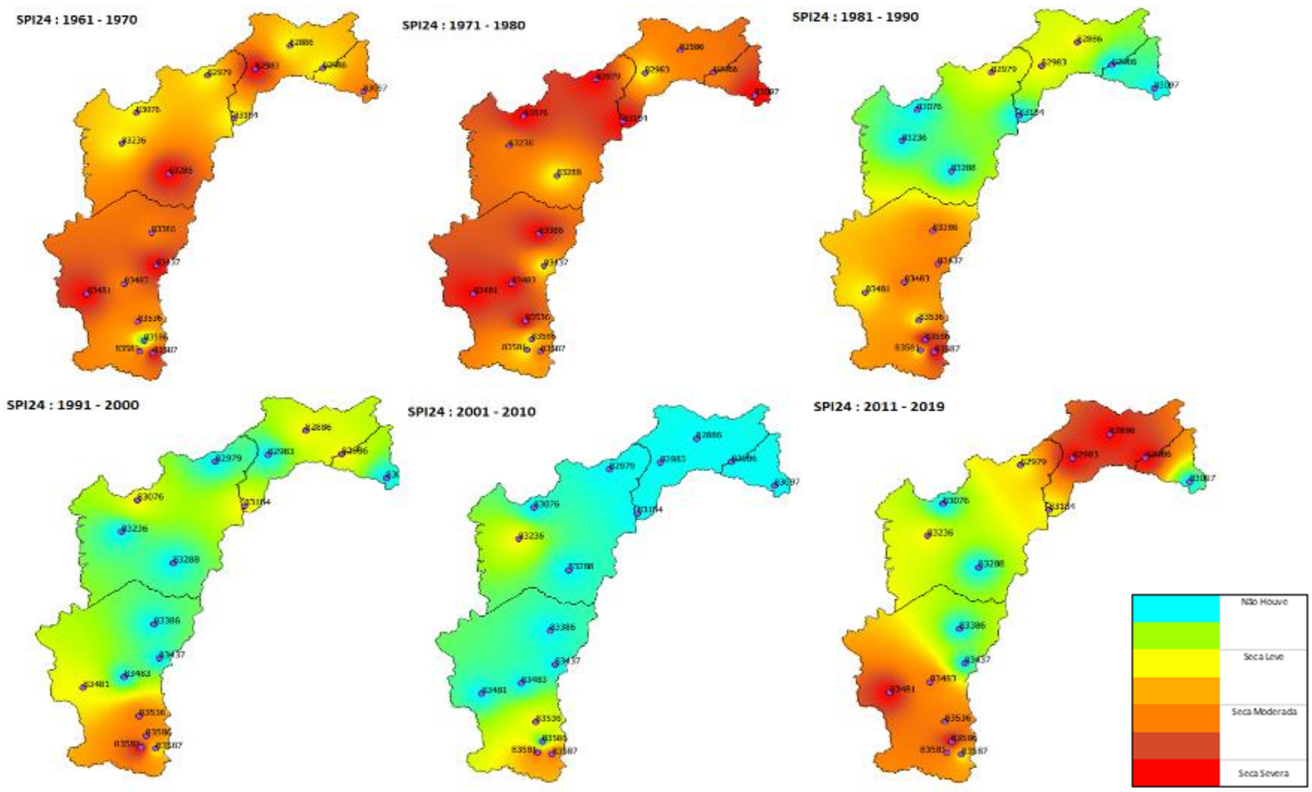

Figure 6 – Drought Maps: SPI24
Source: Author (2022).

Studies such as Paredes-Trejo (2021) also demonstrate the occurrence of drought in the last decades, indicating that drought events have increased along the basin. According to the author, these events are linked to distinct climatic systems modulated by El Niño-Southern Oscillation (ENSO), tropical Atlantic Sea Surface Temperature (SST) anomalies, and Pacific Decadal Oscillation, which have implications for the agricultural and hydropower sectors. The droughts that occurred between 1980 and 2015 coincided with the El Niño and Tropical Atlantic Anomalies (PAREDES-TREJO, 2021).

Gurjão (2012) also highlights in their study the relationship between droughts and rainfall variability in the semi-arid region of the São Francisco River Basin with El Niño. They also point out that atmospheric synoptic-scale systems such as high-level cyclonic vortices can substantially alter the impact of this phenomenon, either favouring or inhibiting the development of intense precipitation systems (GURJÃO, 2012).

In years of El Niño, there is an increase in precipitation in the Upper and Middle São Francisco regions, while the Lower São Francisco region experiences a reduction. Conversely, during La Niña events, these increases and reductions in precipitation occur in the opposite pattern (GALVÍNCIO; SOUSA, 2002; SILVA; GALVÍNCIO; NÓBREGA, 2009). Generally, El Niño years lead to drought in the semi-arid region of Northeast Brazil and the northeastern part of the basin, i.e., the Lower São Francisco region. On the other hand, La Niña years lead to drought events in the Upper and Middle São Francisco regions. It is observed that during El Niño years, the São Francisco River Basin produces more water than during La Niña years (GALVÍNCIO; SOUSA, 2002; SILVA; GALVÍNCIO; NÓBREGA, 2011).

According to Silva (2005), El Niño and La Niña phenomena significantly influence the region's climate, leading to periods of drought and irregularly occurring wet periods (SILVA, 2005).

Regarding the climatic characteristics of the basin regions, it is noteworthy that the Upper São Francisco region has a semi-humid and temperate tropical climate in some locations, the Middle São Francisco region has a semi-arid tropical climate with summer rains, the Submiddle region is typically semi-arid, and the Lower region has a semi-humid tropical climate. The average annual rainfall in the basin is 1,036 mm, with the highest precipitation values of around 1,400 mm occurring at the river's headwaters and the lowest, about 350 mm, between Sento Sé and Paulo Afonso, in Bahia. The wettest quarter is from November to January, contributing 55 to 60% of the annual precipitation, while the driest quarter is from June to August (CBHSF).

Dendrograms - SPI3/SPI12/SPI24

Within each group for the drought variables, it is possible to visualize the distances and levels of similarity between the stations.

Through the frequency dendrograms for SPI3, SPI12, and SPI24 (Figure 7), it is possible to observe the stations in each group that have similar numbers of drought events, as well as the groups of stations that have distinct drought frequencies.

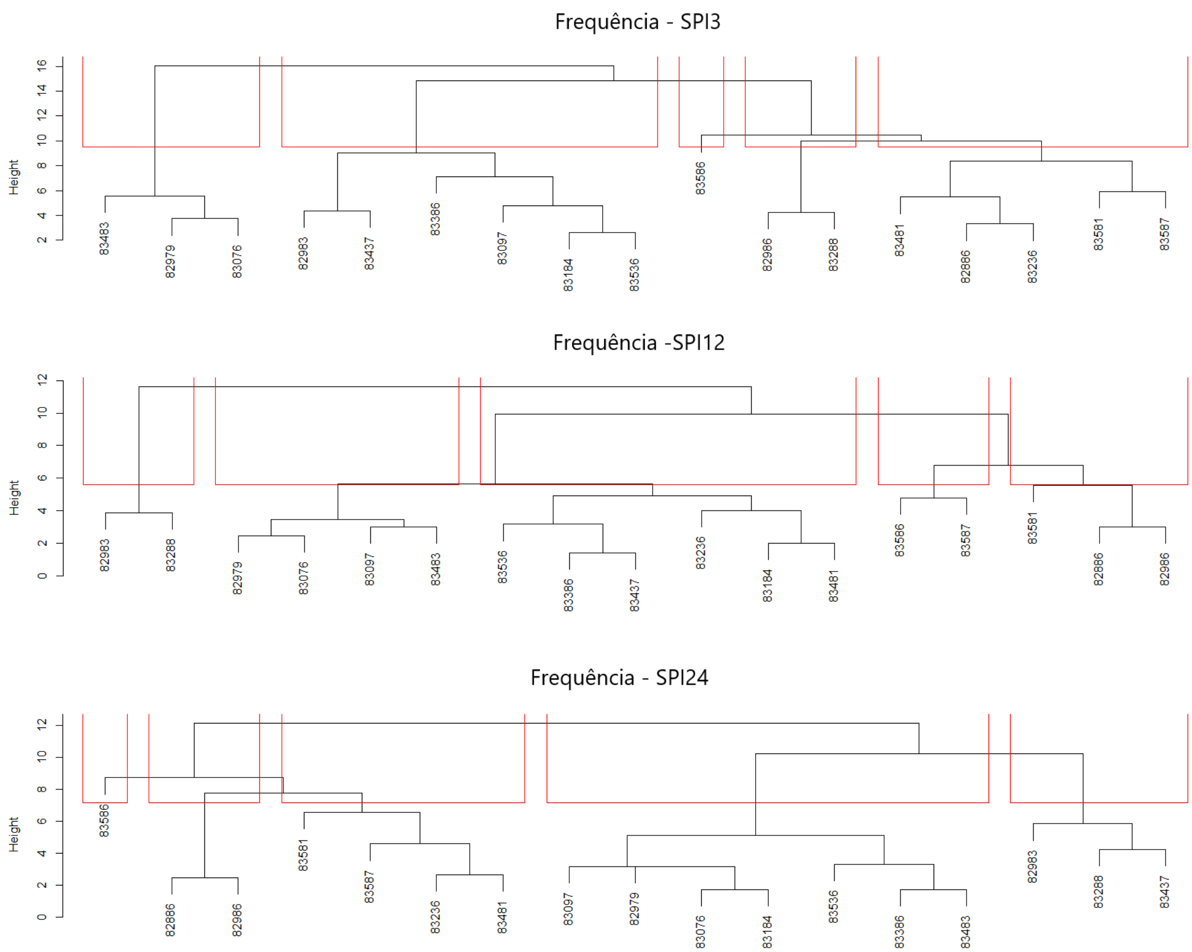

Figure 7 – Frequency Dendrograms
Source: Author (2022).

Through the duration dendrograms for SPI3, SPI12, and SPI24 (Figure 8), it is possible to observe the stations in each group that have similar durations of drought events, as well as the groups of stations that have distinct durations of drought events.

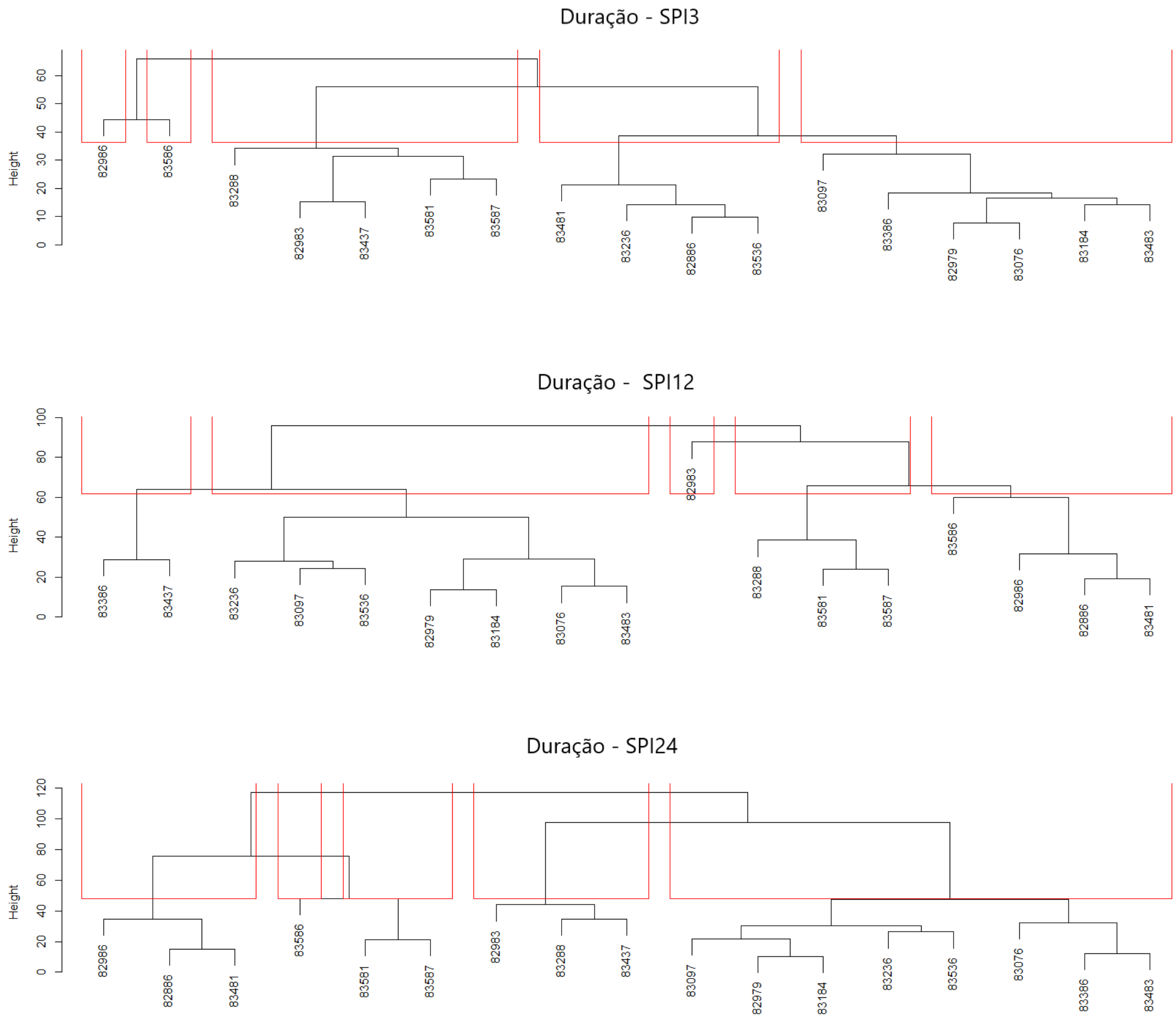

Figure 8 – Duration Dendrograms
Source: Author (2022).

Through the severity dendrograms for SPI3, SPI12, and SPI24 (Figure 9), it is possible to observe the stations in each group that have similar severity values of drought events, as well as the groups of stations that have distinct severity values of drought events.

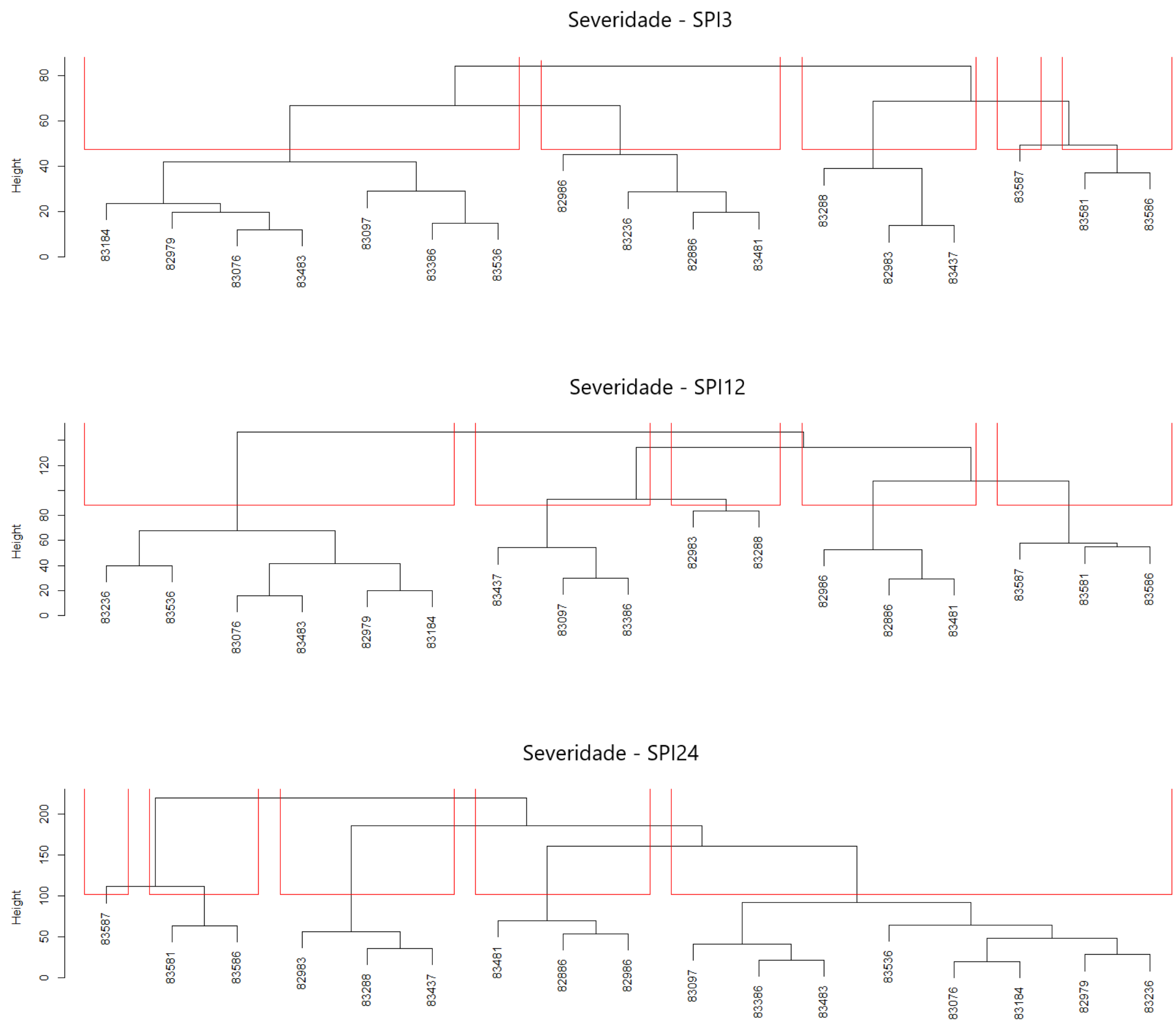

Figure 9 – Severity Dendrograms
Source: Author (2022).

4. Final remarks

Regarding the SPI3, it can be concluded that short-term droughts with impacts on precipitation variations and soil moisture occurred in decreasing order in the regions of Alto São Francisco, followed by Submédio, Médio, and finally the Baixo São Francisco region. The most critical decades for these short-term droughts were the first, second, and sixth decades, with significant mitigation of the phenomenon observed in the fifth decade. It is also noted that the second and sixth decades showed a greater intensification in the frequency and duration variables.

In the analysis of SPI12 and SPI24, the occurrence of hydrological droughts, long-term droughts, was observed throughout the first, second, and sixth decades. During these decades, drought occurrences were intensified lastingly in the regions of Alto, Médio, and Submédio São Francisco.

Although the Alto São Francisco region has high accumulated precipitation values, it stood out in SPI3, indicating a significant occurrence of short-term droughts in that region. It is also noteworthy that in the regions of Submédio and

Médio São Francisco, analyzed through SPI12 and SPI24, long-duration droughts are predominant. In these regions, the most recurrent droughts have a long duration. Although the Alto São Francisco region stood out in SPI3, the analysis of SPI12 and SPI24 also shows the occurrence of long-lasting droughts in this region, but with less intensity than those in SPI3, short-term droughts. These droughts are related to the conditions of climatic systems such as El-Niño and La Niña.

Thus, through the occurrence maps of drought events, it is evident that droughts in the studied basin occur predominantly in the regions of Alto, Médio, and Submédio São Francisco, with a particular emphasis on the Alto region due to its higher incidence. Through Cluster Analysis, as visualized by dendrograms, it is observed that rain gauge stations with similar characteristics do not necessarily belong to the same region of the SFRB. The formed clusters allow verification of groupings among rain gauge stations located in distinct regions within the basin.

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