Revista Brasileira de Geografia Física

ISSN:1984-2295

Homepage: https://periodicos.ufpe.br/revistas/rbgfe

The impacts of the spatial variation of south atlantic convergence zone on rainfall, flow and water quality in river doce, Brazil

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Artigo recebido em 24/01/2024 e aceito em 20/05/2024

A B S T R A C T

This study focuses on the Rio Doce basin in Minas Gerais, Brazil, analyzing the impact of geographic positions (patterns) of the South Atlantic Convergence Zone (SACZ) on the variability of precipitation, river flow, floods, and water quality. Despite its significance, the lack of studies considering different SACZ positions in defining precipitation thresholds for early warning in flood events and water quality parameters persists. The results highlight that distinct SACZ positions are associated with variations in the distribution of precipitation, river flow, and water quality. The Northern Pattern (NP) and Central Pattern (CP) contribute to higher accumulations of rainfall (≥18 mm/day) and river flow (80-800 m^3/s) in the basin. The Piracicaba and Santo António sub-basins record the highest number of extreme rainfall events, with 168 and 127, respectively. Most floods occur in the NP pattern, totaling 54 cases (28.63% causing substantial harm to the population). We identified that precipitation levels ≥43 mm/day are linked to floods in both NP and CP patterns, serving as a threshold for watershed committee decisions. Trend analysis indicates a decrease in rainfall and river flow across all patterns. Regarding water quality, the presence of SACZ primarily increases parameters such as turbidity and total suspended solids. This work contributes to integrating water-related criteria into policies and decisions, especially relevant in the Rio Doce basin following an environmental disaster caused by the rupture of a mining dam.

Key Words: SACZ, Extreme Events, Water Quality, Governance

Impactos da variação espacial da zona de convergência do atlântico sul na chuva, vazão e qualidade da água no rio doce, Brasil

R E S U M O

Este estudo foca na bacia do rio Doce em Minas Gerais, Brasil, analisando o impacto das posições (padrões) geográficas da Zona de Convergência do Atlântico Sul (ZCAS) na variabilidade da precipitação, vazão, inundações e qualidade da água. Apesar da ZCAS ser muito discutida, a falta de estudos considerando diferentes posições de atuação na definição de limiares de precipitação para alertas precoces em eventos de inundação e nos parâmetros da qualidade da água, persiste. Os resultados destacam que posições distintas da ZCAS estão associadas as variações na distribuição de precipitação, vazão e qualidade da água. Os padrões Norte (NP) e Central (CP) contribuem para maiores acumulados de chuva (≥18 mm/dia) e vazão (80-800 m^3/s) na bacia. As sub-bacias do Piracicaba e Santo António registram o maior número de eventos extremos de chuva, com 168 e 127, respectivamente. A maioria das inundações ocorre no padrão NP, totalizando 54 casos (28,63% com danos substanciais à população). Identificamos que precipitações ≥43 mm/dia estão associadas a inundações nos padrões NP e CP, sendo um limiar para decisões de comitês da bacia. Em relação a qualidade da água, a presença da ZCAS aumenta principalmente os parâmetros de turbidez e sólidos suspensos totais. Este trabalho contribui para integrar critérios relacionados à água em políticas e decisões, relevante na bacia do rio Doce após um desastre ambiental causado pelo rompimento de uma barragem de mineração. A análise de tendências indica uma diminuição na chuva e vazão em todos os padrões.

Palavras-chave: ZCAS, Eventos Extremos, Qualidade da Água, Governança

Introduction

In Brazil, extreme precipitation events severely impact water availability and can lead to floods, landslides, and natural disasters, affecting a large portion of the population (Laureanti et al.,2022).Water resource management faces significant challenges due to the uncertainties and risks associated with extreme hydrological events, such as intense rainfall and droughts, as discussed by Esmeria et al.(2003) and Marengo et al.(2009). In this study, we investigate how the different geographical positions of the spatial variation of the South Atlantic Convergence Zone (SACZ) influence precipitation patterns, flow, and water quality.

The central hypothesis of study, suggests that these distinct patterns of SACZ result in varied amounts of precipitation in the region, with a predominant pattern that impacts rainfall and flow variability. Furthermore, the research aims to identify a precipitation threshold capable of triggering extreme events, such as floods, and investigate how the seasonal nature of the SACZ affects water quality parameters in the study area. In essence, this study not only enriches our comprehension of SACZ regional impacts but also establishes a robust foundation for effective flood event alerts associated with its performance, thereby contributing valuable insights to both scientific discourse and practical applications. Understanding these variabilities is essential for improving water resource management strategies and mitigating the impacts of extreme hydrological events.

The SACZ is a crucial meteorological element in Brazil, profoundly influencing the spatial distribution of rainfall and significantly impacting vital economic sectors, including agriculture, energy, and transportation (António, 2020; Quadro, 1999; Wong et al.,2021). As a band of cloudiness extending from Northwest to Southeast South America (Quadro, 1999), the SACZ is intrinsically linked to meteorological events such as floods, landslides, and avalanches (Reboita & Veiga, 2017; Seluchi & Chou, 2009).

The mechanisms involving the formation of SACZ and the occurrence of associated extreme events have been explored in studies by Carvalho et al. (2002), Zilli et al. (2021), Zhou and Lau (2001). According to these authors, the formation of the SACZ incorporates several meteorological characteristics, including the convergence of moisture at low and mid-levels, the presence of a trough at 500 hPa over the eastern coast, incursions of frontal systems, the presence of an Upper-Level Cyclonic Vortex (ULCV) over Northeast Brazil, upper-level jets, and a strong potential temperature gradient. Given the significant socioeconomic impact of SACZ events and the uncertainties in their predictions, previous studies have focused on better understanding their intensity, duration, and impacts. Approximately 70% of SACZ episodes last around four days, while the remaining 30% persist for more than four days (Carvalho et al., 2004; Ambrizzi e Ferraz, 2015; Escobar et al. 2020; Lauriante et al., 2024). The SACZ exhibits considerable spatial and temporal variability, playing a critical role in regulating the intensity and total precipitation that affects millions of people in South America (António and Aravéquia, 2023; Escobar et al., 2022).

The duration of SACZ events is closely related to the occurrence of extreme precipitation events. Through the analysis of circulation fields and longwave radiation, De Souza (2022) and Verdan (2022) observed that longer SACZ events had a higher number of associated cyclones in their oceanic branch. However, it was not possible to determine the lifecycle duration of these associated cyclones. Another significant finding was that precipitation in the South-Central region of Brazil was higher when Low-Level Jets exhibited a northwest-southeast orientation during SACZ days.

The study conducted by Fialho et al. (2023) and Viana et al. (2021) investigated the mechanisms behind SACZ events lasting more than seven days and associated with extreme precipitation events, often leading to floods and landslides. The results indicated that these persistent SACZ events are typically preceded by a semi-stationary Rossby wave train of mid-latitude over the South Pacific. This phenomenon acquires a barotropic structure and moves towards the equator after crossing the subtropical latitudes of South America. These combined processes enhance low-level westerly winds on the equatorial edge of the SACZ, resulting in the expansion of the phenomenon over the continent and the formation of convective clouds that induce intense precipitation. These characteristics are supported by anomalous cyclonic circulation and an increased moisture transport towards the southeast in the region, as highlighted by Pezzi et al. (2022). This pattern leads to heightened convection over the continent, keeping the SACZ active for prolonged periods and impacting the affected areas with high accumulations of rainfall over several consecutive days. Despite shorter SACZ events, lasting around four days, also being associated with a mid-latitude wave train, their transient nature results in distinct coupling effects. These observations play a crucial role in forecasting long-duration SACZ events, as emphasized by Escobar et al. (2022).

Braga et al. (2024) investigated a spatial variation of precipitation associated with the SACZ. Utilizing data on zonal and horizontal wind components combined with longwave radiation, the study revealed that a strong westward tropical flow associated with SACZ allows for the propagation of Rossby waves through the Equatorial Atlantic Ocean. These waves have the capacity to modify precipitation patterns, generating systems that either inhibit or trigger intense rainfall, leading to extreme rainfall events. Laureanti et al. (2024) further highlighted that wind circulation changes induce variations in Sea Surface Temperature (SST), ultimately impacting the dynamics of meteorological systems and influencing the duration of extreme precipitation events during SACZ occurrences. In essence, the Southwest Atlantic Ocean emerges as a potential influencer modulating the persistence of extreme precipitation events in the Central-Eastern region of Brazil.

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Fernandes and Rodrigues (2017), analyzing intense precipitation in southern Brazil (Santa Catarina state) during the periods of 1979-1999 and 2000-2015, made insightful discoveries. They found that the frequency and intensity of extreme precipitation events during the austral spring were reduced during El Niño years and increased in neutral years in the second period compared to the first. Their studies indicated a significant association between the historical series of extreme precipitation events and the SACZ, alongside a low-level anticyclone in the Southwest Subtropical Atlantic during the latter period. Moreover, Montini et al. (2019) revealed that positive trends in precipitation and the occurrence of extreme precipitation events in southeastern South America between 1979 and 2016 were linked to increased moisture transport from the northwest Amazon region to the subtropics, a phenomenon influenced by the activity of the SACZ. The study by Jorgetti et al. (2014) addressed precipitation variability due to the SACZ positioning. The researchers classified SACZ-North events when the precipitation band is over central Brazil and SACZ-South when it is over the southern region. SACZ-North occurs when waters of the Tropical Atlantic are cooler, and SACZ-South is associated with warmer waters. During the SACZ-South period, the upper-level anticyclonic circulation shifts towards southeastern South America, with warmer waters in the Tropical Atlantic. Consequently, the modulation of SACZ activity is linked to Sea Surface Temperature (SST) anomalies through dynamic and thermodynamic mechanisms. However, in Antonio's study (2021) on SACZ dynamics, three geographical patterns of SACZ were observed: South (PS), Central (PC), and North (PN). According to the author, precipitation occurrence can vary depending on the pattern, resulting in non-uniform spatial distribution. This finding supports Jorgetti et al.'s (2014) study, which emphasized circulation dynamics.

The SACZ have been routinely studied from a regional perspective. For instance, notably, in the state of Minas Gerais, Brazil, empirical evidence from 1995 to 2016 attributes 126 landslides, 546 inundations, 688 floods, and 41 overflows to the SACZ's presence (Aguiar, 2018). The southeastern region of Brazil faces a substantial average probability of SACZ-induced disasters, reaching 24%. This risk amplifies differentially across Espírito Santo (60%), Minas Gerais (50%), Rio de Janeiro (40%), and São Paulo (31%), underscoring the region's susceptibility to heightened rainfall events and emphasizing the intricate interplay between territorial planning and risk management (Da Fonseca Aguiar & Cataldi, 2021; Carvalho et al., 2002; Fialho et al., 2023; António and Aravéquia 2024), unravels nuanced spatial dynamics, impacting Brazilian watersheds disparately (Aguiar, 2018; Fialho et al., 2023; Neto, 2010). Despite the acknowledgment of physical processes within hydrographic basins during extreme rainfall events such as erosion and weathering comprehensive assessments of SACZ's influence on flow, flooding, and water quality remain conspicuous by their absence.

This study seeks to bridge this gap by categorizing SACZ patterns into three distinct types, scrutinizing their defining characteristics, and discerning their differential impacts on precipitation, flow rates, flood occurrences and water quality. Focused on the Doce River Basin in the Southeast region of Brazil, a region distinguished by its rich biodiversity and the endangered Atlantic Forest biome this research immerses itself in unraveling the intricate interrelationships between SACZ patterns and extreme weather events. The catastrophic rupture of the Fundão dam in 2015, releasing millions of cubic meters of mining tailings into the Rio Doce, serves as a poignant reminder of the region's vulnerability to environmental disasters exacerbated by SACZ-induced heavy rainfall. This event inflicted dire consequences on the entire ecosystem, including physical devastation by mud transport, 17 human casualties, 2 missing individuals, extensive fish mortality, and significant damage to local flora (Neves, 2022).

Moreover, the ongoing flow of mud, exacerbated by heavy rainfall, continues to compromise water quality and the well-being of communities in the Doce River basin (Andrade et al., 2021; Hatje et al., 2017, Pacheco et al., 2022). Furthermore, SACZ's impacts on the Piranga sub-basin are characterized by extreme rainfall events, leading to a substantial increase in peak flow rates, while urban areas experience a slight reduction in peak flow rates (Camargo, 2014). These fluctuations in flow rates pose a threat to flood-prone areas, particularly those affected by long-term extreme rainfall events associated with the SACZ in the basin (Monteiro Cruz et al., 2015). Notably, in Minas Gerais state, extreme precipitation events linked to SACZ are marked by accumulated precipitation exceeding 55 mm/day (Silva et al., 2020).

Ferreira (2019) found a decrease in rainfall on humid days and an increase in dry days in the Doce River basin, with varying effects on maximum and minimum flow in different regions. Moreover, high rainfall totals are linked to increased sediment transport, deteriorating water quality (Jia et al., 2021; Jiang et al., 2023; Oliveira & Quaresma, 2017; Wang et al., 2022; Yang et al., 2021). Studies have shown that meteorological and hydrological factors influence water quality parameters such as nitrogen, phosphorus, turbidity, pH, and biochemical oxygen demand (Fan & Shibata, 2015; Xia et al., 2014). Despite advancements in understanding these factors, the relationship between SACZ and water quality parameters in the Doce basin remains largely unexplored.

The studies previously mentioned have identified SACZ events and characterized their formation, intensity, duration, and positioning. These studies have utilized methodologies that analyze not only the synoptic and dynamic characteristics of SACZ but also their impacts on precipitation extremes at both local and regional scales. This study aims to fill a gap in research by examining how different spatial patterns of the SACZ affect the distribution of precipitation, flow, and water quality in the Rio Doce basin.

Methodology

Data

The Rio Doce basin (Figure.1) watershed covers an area of 86,715 km², primarily in the state of Minas Gerais (86% of the basin area) and partly in Espirito Santo (14%). This region includes 230 municipalities with around 2,341,206 urban residents and 833,437 rural inhabitants . In terms of water usage, 51% of the total water extracted directly from the Doce River basin is used for irrigation, 22% for urban supply, 17% for industries, 7% for animal watering and 3% for rural supply.The basin is divided into six Water Resources Planning and Management Units (UPGRHs), corresponding to six sub-basins and their respective Hydrographic Basin Committees (CBHs): Piranga River (DO1), Piracicaba (DO2), Santo Antônio (DO3), Suaçuí River (DO4), Caratinga (DO5), and Manhuaçu River (DO6). All data access links are duly detailed in the supplementary material (https://github.com/NelsonMateus/SM.git).

Precipitation data were obtained from the CHIRPS (Climate Hazards Group InfraRed Precipitation). This dataset combines satellite precipitation estimates with weather station observations to provide nearly global precipitation coverage from 1981 to the present (Funk, C. et al., 2015). CHIRPS is highly detailed, with a daily temporal resolution and a spatial resolution of 0.05 degrees (~5.5 km). Additional data were obtained from six weather stations managed by the National Water Agency (ANA).

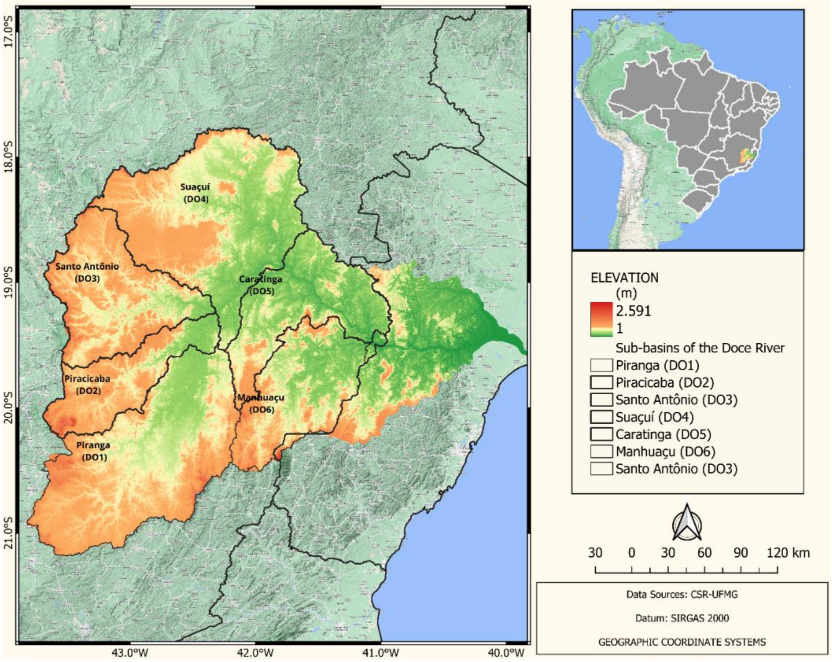


Figure 1 Representation of the study area and the Sub-basins to be evaluated.

Data from these stations used for the period from 1991 to 2020. The use of data from ANA stations aimed to complement and enrich the analysis conducted with CHIRPS data, providing validation and increasing the accuracy of the results. The CHIRPS precipitation data were integrated with the data from ANA stations to perform a detailed analysis of SACZ patterns. It was not necessary to apply any gap-filling techniques for the SACZ occurrence dates in each pattern, as the collected data were complete for the corresponding dates throughout the temporal series of the considered stations. For additional details on the source of each data point, refer to Table 1 in the supplementary material. The material can be accessed at the following repository: https://github.com/NelsonMateus/SM.git.

Spatial Segmentation and Classification of South Atlantic Convergence Zone (SACZ) Patterns

Our methodological approach begins with identifying the variation of SACZ over the basin, utilizing a time series from 1991 to 2020.

For this purpose, the spatial performance of the SACZ was segmented into three positions, referred to as patterns: North Pattern (NP), South Pattern (SP), and Central Pattern (CP), following the methodology adopted by António (2020). North Pattern (NP): Defined by the occurrence of negative Outgoing Longwave Radiation (OLR) anomalies located north of the climatological mean position of the SACZ. Central Pattern (CP): Serves as the baseline pattern, characterized by the climatological mean position of the SACZ with the most negative OLR anomalies centered around this mean. South Pattern (SP): Characterized by negative OLR anomalies situated south of the climatological mean position of the SACZ.

Selection of SACZ cases by default

To examine the extent to which different areas of the basin are affected by SACZ and how precipitation is distributed in the basin when the SACZ is in different geographical positions, we proceeded as follows:

A - The dates of occurrence of the SACZ were obtained from the study by António (2020) and from the bulletins of the National Institute for Space Research of Brazil (INPE), available at the link in Table 1 of the supplementary material (https://githu [b.com/NelsonMateus/SM.git](https://github.com/NelsonMateus/SM.git)). The dates of occurrence of the SACZ were separated on a daily time scale, covering the summer season (from November to April). We used the software R (version 4.3.2,R Core Team, 2022) and the Climate Data Operator (CDO) to build a filter capable of identifying each day of activity of the SACZ and the corresponding values of flow and precipitation for each pattern. All days with the occurrence of the SACZ were filtered, excluding the days without occurrence. We calculated the average of the selected values for each pattern: South Pattern (SP), North Pattern (NP) and Central Pattern (CP), obtaining the monthly average for the entire period evaluated.

B- After the separation dates of occurrence SACZ in the respective patterns, the average monthly precipitation of each pattern was elaborated. The purpose of this phase is to examine the extent to which the different areas of the basin are affected by SACZ and how the rain is distributed over the basin, when the SACZ is located in different geographical positions. Following, we evaluate the impact of each pattern on the monthly and annual flow of the six sub-basins of the Doce River.

Evaluation of extreme rainfall events and floods

We employed the percentile methodology to identify extreme precipitation events associated with flood events in the different positions of SACZ (CP, NP, SP). First, we calculated the 90th and 95th percentiles of the daily precipitation series for each of the six meteorological stations. We adopted the 95th percentile to identify extreme precipitation events. Thus, the precipitation values corresponding to this percentile were considered as thresholds to define extreme events in each SACZ pattern. The number of extreme precipitation events and flood events in the different SACZ pattern is presented in Table 3 of the supplementary material (https://github.com/NelsonMateus/SM.git).

The percentile methodology is widely used to identify extreme events (Bombardi et al., 2013; Dereczynski et al., 2009; Reboita & Veiga, 2017; Silva et al., 2020).

After defining the extreme precipitation events for each SACZ pattern, as described above, we proceeded to separate all flood dates and alert quotas from the time series. For this purpose, we used the alert and flood quota data from the National Water Agency (ANA) in collaboration with the Geological Survey of Brazil (CPRM). We evaluated seven municipalities in the Doce River basin: Ponte Nova, Nova Era, Mário Carvalho, Belo Oriente, Vila Matias, and Governador Valadares. Each municipality has a quota level for the occurrence of floods, available on the CPRM website (see Table 1 of the supplementary material). Thus, we used the SACZ occurrence dates in the 95th percentile as a reference to filter the flood and flood warning events that occurred on those same dates. It is worth noting that the alert quota represents the river level that indicates a high possibility of flooding, while the flood quota represents the first damage observed in the municipality. The objective is to evaluate the number of cases of floods in SACZ events when it acts in different positions (CP, NP, SP).

Statistical analysis

The Modified Mann-Kendall test was employed to identify significant trends (increasing or decreasing) in precipitation and flow time series for each SACZ pattern. A significance level (α) of 0.05 was chosen, meaning we reject the null hypothesis (no trend) if the test statistic (Z) is greater than the critical value for a 5% significance level. Positive Z values indicate statistically significant upward trends, while negative Z values indicate statistically significant downward trends. For further details on the test statistic and critical values, refer to Yue & Wang (2004).If a significant trend is identified, the linear trend component is removed from the time series to obtain a detrended (stationary) series. In MMK the trend part T_t of the new series X_t is linear then, trend part is removed to obtain the stationary series Y_t:

$$Y_t = X_t - T_t = X_t - B\ x\ T \quad \text{(eq.2)}$$

The variance (S) an test statistic Z is calculated of the trend statistic S of autocorrelation series is obtained as follows:

$$z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & S > 0 \\ 0, & S = 0 \\ \frac{S-1}{\sqrt{V(s)}}, & S < 0 \end{cases} \quad \text{(eq.3)}$$

Multiple Regression Model (MLR)

We employed multiple linear regression to assess the influence of rainfall on flow rates within each SACZ pattern (CP, NP, SP) across the Doce River sub-basins. This supervised learning technique identifies a linear relationship between a dependent variable (Y) and multiple independent variables (X) (Moore et al., 2006). In our case, the dependent variable (Y) is the monthly flow rate, and the independent variables (X) include monthly rainfall values for each SACZ pattern. This analysis aims to identify the SACZ pattern that has the strongest influence on flow rate variability in each sub-basin.The principle of linear regression is to model a quantitative dependent variable Y through a linear combination of p quantitative explanatory variables, X1, X2, ..., Xp. The deterministic model is written for observation i as follows:

$$y_i = \beta_0 + \sum_{j-1}^{p} \beta_j x_{ij} + \varepsilon_i \quad \text{(eq.4)}$$

where yi is the observed value for the dependent variable for observation i, xij is the value assumed by variable j for observation i, and ε_i is the random error.

Principal Component Analysis (PCA)

To investigate the influence of SACZ on water quality in the Doce River basin, we meticulously collected and analyzed a comprehensive dataset. This dataset encompassed daily precipitation and flow data for each of the six sub-basins within the basin, along with water quality data for various indicators. We chose a six-day window for accumulated rainfall and average flow to correspond with the typical duration of SACZ events. The water quality indicators we selected included pH, total suspended solids, water temperature, turbidity, dissolved oxygen, conductivity, total chloride, nitrate, biochemical oxygen demand, total phosphorus, total nitrogen, and total coliforms. These classic indicators have been consistently monitored at least quarterly for over ten years, providing a robust dataset for analysis.

To unravel the complex interplay of factors influencing water quality variability, we employed a powerful statistical technique called Principal Component Analysis (PCA). PCA excels at identifying underlying patterns in large datasets by reducing them into a smaller number of components that explain most of the data's variance. We performed four sequential PCA analyses, each focusing on a specific dimension or scale of water quality variation.

a) Seasonal Contrasts: The initial PCA was performed on the entire dataset to identify seasonal contrasts between dry winters and wet summers. This analysis revealed the most significant water quality parameters that drive seasonal spatial variations, aligning with the SACZ's seasonal influence.

b) Sub-basin Differences: Subsequently, we focused on the months during which the SACZ occurs (October to April) and conducted a second PCA analysis to identify the differences between the Doce River sub-basins. This analysis highlighted the unique water quality characteristics of each sub-basin, providing insights into the spatial variability of water quality within the basin.

c) Spatial and Temporal Influences: To isolate the influence of the spatial component, we performed a third PCA after standardizing the data by the mean and standard deviation for each sub-basin. This analysis revealed how water quality varies across the months, providing insights into the temporal dynamics of water quality within each sub-basin.

d) SACZ Impact: Finally, we standardized the data using both spatial (sub-basin) and temporal (monthly) dimensions to isolate these respective influences. This last analysis aimed to identify how the SACZ specifically affects water quality. This multi-layered statistical methodology highlights the complex interaction between climatic phenomena and river water quality, providing a unique understanding of environmental dynamics in the Doce River basin.

PCA reduces large sets of input variables into a reduced number of components. PCA can be used to indicate factors associated with water quality. At the seasonal level, the PCA obtains information on the most significant quality parameters of seasonal spatial variations, which is the time scale of the performance of the SACZ

(Olsen et al., 2012). The PCA steps are shown below:

1. Normalize the X mxn data matrix to matrix Y = $(Y_1, \ldots, Y_n)$
2. Calculation of the Z covariance matrix according to the following equation:

$$z = \frac{1}{m-1} \sum_{k=1}^{m} (Y_{ke\bar{u}} \bar{Y}_{eu}) \, (Y_{ke\bar{u}} - \bar{Y}_{eu}) \quad \text{(eq.5)}$$

3. Calculate the eigenvalues and eigenvectors of the covariance matrix Z. Cumulative percentages of the eigenvalues indicate their contribution to the main components, and the eigenvectors present the loads. The eigenvectors are multiplied with the original matrix to obtain the scores of the main components.

Results

Evaluation of the spatial pattern of the SACZ in the rainfall regime

In our analysis, we examined the trends and durations of SACZ events over the years, considering all observed patterns in the event averages (Figure 2a, 2b). It was observed that the average duration of SACZ events during the time series (1991 to 2020) was approximately 6.2 days, a duration consistent with findings in previous studies (Ambrizzi & Ferraz, 2015; Braga et al., 2022; de Oliveira Vieira et al., 2013; Pezzi et al., 2023). This finding solidifies the consistency of the observed duration of SACZ across different study periods.

The maximum number of days with SACZ occurrence in a year varied between 6 and 70 days (Figure 2b), and this variability was attributed to the influence of large-scale atmospheric systems, such as Bolivia High, Cyclonic Vortices at high levels, and local weather conditions in the region (Braga et al., 2022; Pezzi et al., 2023). These systems play a critical role in modulating the duration and intensity of SACZ events, contributing to the observed interannual variability.

It is also noted that the years 2000 and 2012 stood out with prolonged durations of SACZ events, exceeding an average of 12 days (Figure 2a and 2b). Recent studies corroborate these observations, suggesting that large-scale anomalous events, possibly related to phenomena such as El Niño and the Pacific Decadal Oscillation, can prolong the duration of SACZ events (Pezzi et al., 2023).On the other hand, a decreasing trend in event duration was observed in the time series from 2013 to 2015. This decrease may be associated with changes in climatic variability and possible alterations in large-scale atmospheric circulation. Recent works discuss that climate change may be influencing the frequency and duration of the large-scale systems affecting SACZ, suggesting an urgent need for more studies to understand these trends and their implications (Braga et al., 2022; Pezzi et al., 2023).

Notably, the years 2000 and 2012 stood out with extended SACZ event durations, exceeding an average of 12 days (Figure 2a and 2b). Nevertheless, a decreasing trend in event duration was observed in the time series from 2013 to 2015. There was also a growing trend in the number of events, with peaks in 1999 and between 2004 and 2016, followed by a declining trend from 2017 to 2020. Recent studies, such as those by Fonseca Aguiar & Cataldi (2021) and Reboita et al. (2021), affirm these trends and discuss the possible implications for regional hydrology and climate. This upward trend suggests a higher prevalence of SACZ patterns in the basin, potentially leading to increased flood risks due to rising water levels in the basin (Fonseca Aguiar & Cataldi, 2021; Gutjahr & Heinemann, 2012; Reboita & Veiga, 2017).

The spatial patterns SACZ are associated with different geographic regions, each impacting the Rio Doce basin differently. The North pattern (Figure. 3) is characterized by higher accumulated rainfall in the northern and central areas of the basin, with an average of approximately 13 to 18.26 mm/day, in contrast to the southern sector with less than or equal to 9.4 mm/day. Recent studies, including Mayta et al. (2022) and António et al. (2023), have illustrated similar spatial differentiation, highlighting the significance of precise regional climate assessments. Notably, the Suaçuí (DO4) and Santo António (DO3) sub-basins experienced the highest levels of rainfall, averaging 18 mm/day with a monthly total of 547 mm. On the other hand, the Piranga and Piracicaba basins received lower rainfall in this pattern.

The observed rainfall concentration in the southern sub-basins (Suaçuí, Santo António, Piracicaba, and Piranga) under the Central Pattern (CP), with up to 14 mm/day, aligns with the findings of Silva et al. (2019) and Gomes et al. (2019), who highlighted the influence of local topography and land-use changes on precipitation distribution in these areas. The lower rainfall in the northern sub-basins (Suaçuí, Caratinga, and Manhuaçu) under CP, as low as 9 mm/day, could be attributed to the rain shadow effect caused by the Espinhaço mountain range, as suggested by Zilli & Carvalho (2021).

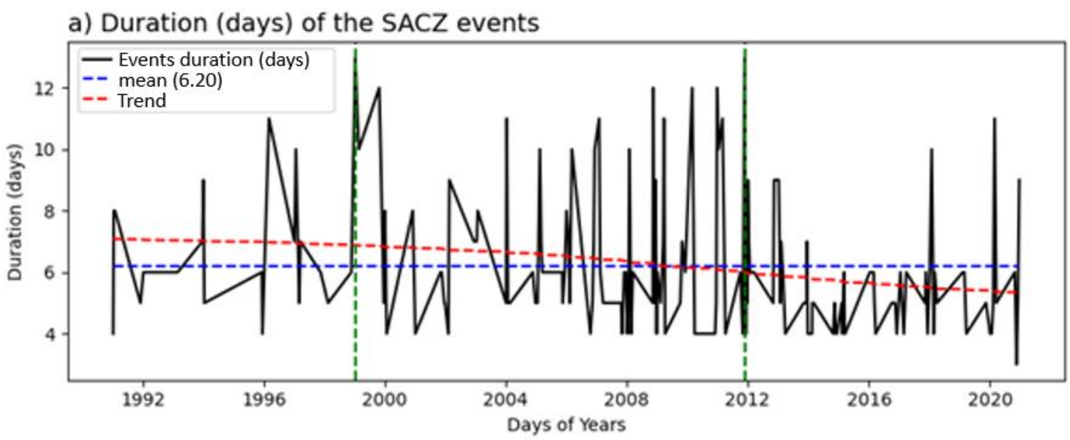
Similarly, the South Pattern (PS) reinforces this north-south rainfall gradient, with the Piracicaba, Piranga, and southern Santo António sub-basins receiving up to 14.90 mm/day, while the northern sub-basins experience less than 7 mm/day. This pattern is consistent with the findings by Escobar et al., (2023) and Zilli & Carvalho, 2021, who emphasized Synoptic patterns of SACZ enhancing convective activity and rainfall over the southern parts of southeastern Brazil during austral summer.

The North Position (NP), characterized by higher rainfall in the western and northern basin, is likely driven by the combined influence of the Bolivian High and Northeast trough, as documented by Barros et al. (2000) and Nogués-Paegle & Mo (1997). Recent work by Bombardi et al. (2023) has further elucidated the complex interactions between these systems and their modulation by the Madden-Julian Oscillation (MJO), leading to varying precipitation patterns across the basin.

The uneven distribution of rainfall in the Doce River basin is intrinsically linked to the spatial variability of meteorological systems (Silva et al., 2019; Gomes et al., 2019; Zilli & Carvalho, 2021). In the North Position (NP), the interaction of large-scale features like the Bolivian High and the Northeast trough plays a pivotal role (Nogués-Paegle & Mo, 1997; Barros et al., 2000). The work by Pezzi et al. (2023) has further elucidated how the Northeast trough, in conjunction with low-level moisture transport from the Amazon, fuels convective activity and concentrates rainfall in the western and northern parts of the basin.

The CP and SP patterns, on the other hand, exhibit distinct atmospheric behaviors (Refer to Figures 1 and 2 in the supplementary material: https://github.com/NelsonMateus/SM.git). In CP, the SACZ becomes more pronounced, enhancing convective activity and promoting rainfall over the southern regions of the basin. This is consistent with the findings of António (2020), who highlighted the importance of SACZ-related moisture transport for precipitation in the central and southern parts of southeastern Brazil.

The SP pattern, although less frequent, is often associated with the southward displacement of SACZ leading to increased rainfall in the southernmost region.



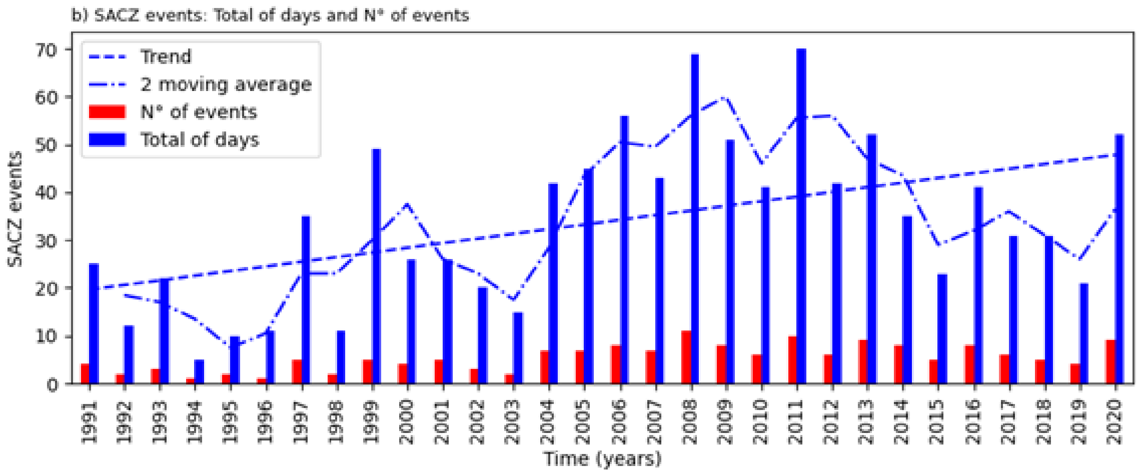


Figure. 2: a) Duration of days of SACZ events, b) Number of events and trend of events

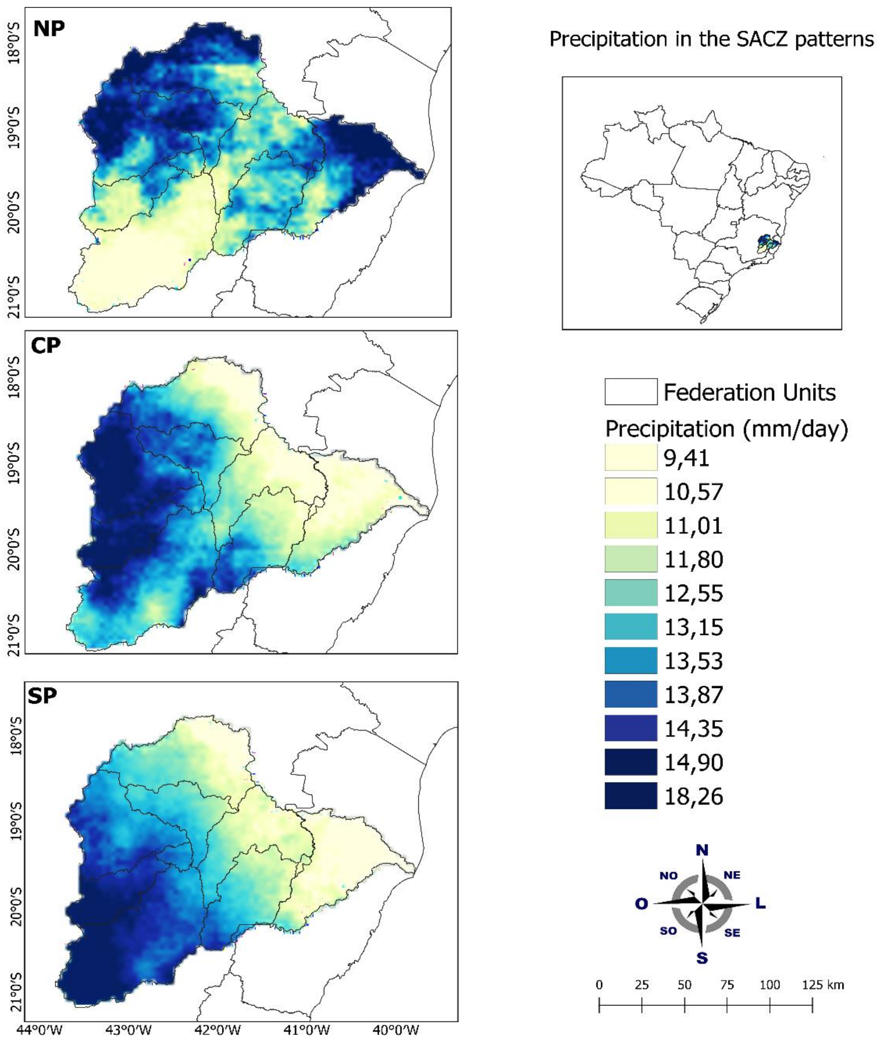


Figure 3 daily average precipitation for the patterns associated with SACZ (CP), (NP), (SP).

Monthly evaluation of SAZC patterns in precipitation and flow

In the Piranga, Piracicaba, Suaçuí, and Caratinga sub-basins, the highest monthly accumulated rainfall is primarily associated with the NP and CP patterns, ranging from 10.5 to 24.5 mm/day, equivalent to approximately 304 to 730 mm/month. This region typically experiences the highest rainfall from December to February, which are the months with the highest accumulated rainfall (Figure 4) (COSTA et al., 2022), with March, April, and November being the drier months. In the Manhuaçu and Suaçuí sub-basins, significant accumulated rainfall is also observed in the SP, resulting in monthly rainfall amounts that usually exceed the climatological monthly average (represented by the cyan dashed line in Figure 4).

The CP demonstrates consistently above-average precipitation across all months in the six sub-basins, peaking in December (up to 16 mm/day) and January (up to 24 mm/day) (Figure 4). Notably, the uninterrupted action of the South Atlantic Convergence Zone (SACZ) for an average of 6.2 days can amplify these accumulations to approximately 43 to 155 mm/day. Such elevated rainfall totals significantly exacerbate water resource uncertainty and increase the risk of flood events, as highlighted by Marengo (2004), Marengo et al. (1998), and Zilli & Carvalho (2021).

The consequences of heightened rainfall during SACZ events are particularly evident in Minas Gerais, where landslides and flooding are prevalent. Aguiar (2018) and da Fonseca Aguiar & Cataldi (2021) reported that 58% of rainy days associated with SACZ coincide with landslides, while 49% trigger flooding, and 47% and 46% result in floods and overflow, respectively. These findings underscore the critical need for proactive disaster risk reduction strategies in regions prone to SACZ influence.

The NP and CP patterns dominate the rainfall regime across the sub-basins, coinciding with high flow values ranging from 19 to 890 m^3/s, predominantly between December and February (Figure 4)This period of elevated flows aligns with the increased precipitation observed under these patterns, particularly during the austral summer months. Importantly, from January to April, both NP and CP consistently generate flow rates exceeding the normal climatological across all sub-basins (Figur 5).

This finding strongly reinforces the association of these patterns with heightened flood risk and the occurrence of extreme hydrological events. In stark contrast, the SP demonstrates significantly lower accumulated flow values (Figure 5). This suggests that the SP, despite potentially generating localized heavy rainfall events, does not contribute as substantially to the overall water balance and flood risk in the Doce River basin as the NP and CP patterns.

The heightened rainfall and subsequent peak flow rates associated with the North (NP) and Central (CP) patterns significantly elevate the likelihood of flooding in the Doce River basin. This finding underscores the critical role of these patterns in shaping the region's hydrological regime and flood risk. Notably, throughout the entire time series, there were no recorded instances of SACZ operating in either the NP or SP patterns during April across all analyzed sub-basins. This absence of SACZ activity in these patterns during April warrants further investigation to understand the underlying mechanisms and potential implications for water resource management.

Furthermore, the Suaçuí sub-basin exhibits a striking contrast in flow behavior under different patterns. The NP pattern generates exceptionally high flow values, reaching up to 800 m^3/s, while the accumulated flows under CP and SP remain below 200 m^3/s (Figure 5). This disparity highlights the unique vulnerability of the Suaçuí sub-basin to flooding under the NP pattern, emphasizing the need for tailored flood mitigation strategies in this specific area.

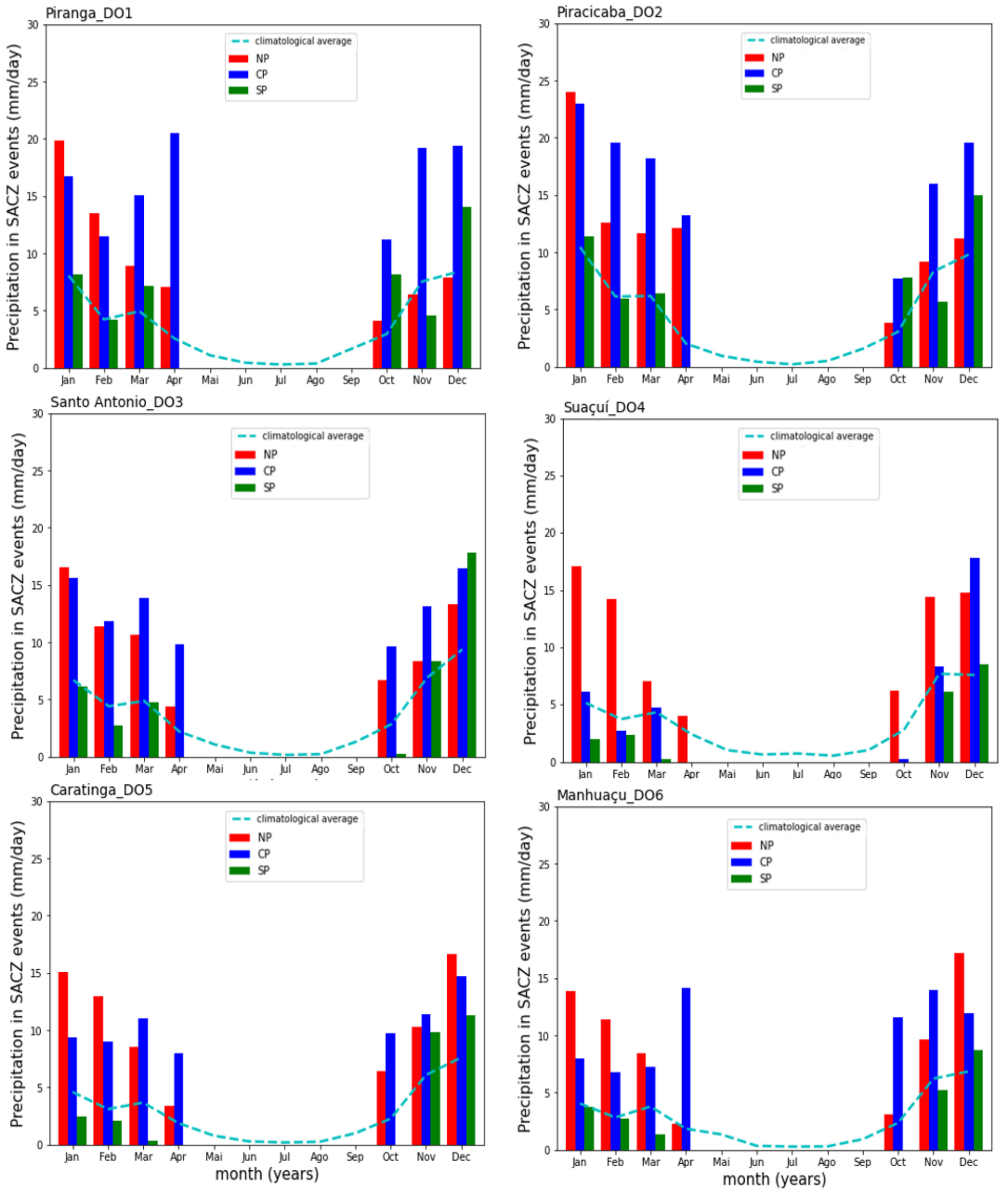


Figure 4: Monthly precipitation on SACZ days on the six sub-basins of the Doce river. NP- North Pattern, CP- Center Pattern, SP-South Pattern (1991 to 2020).

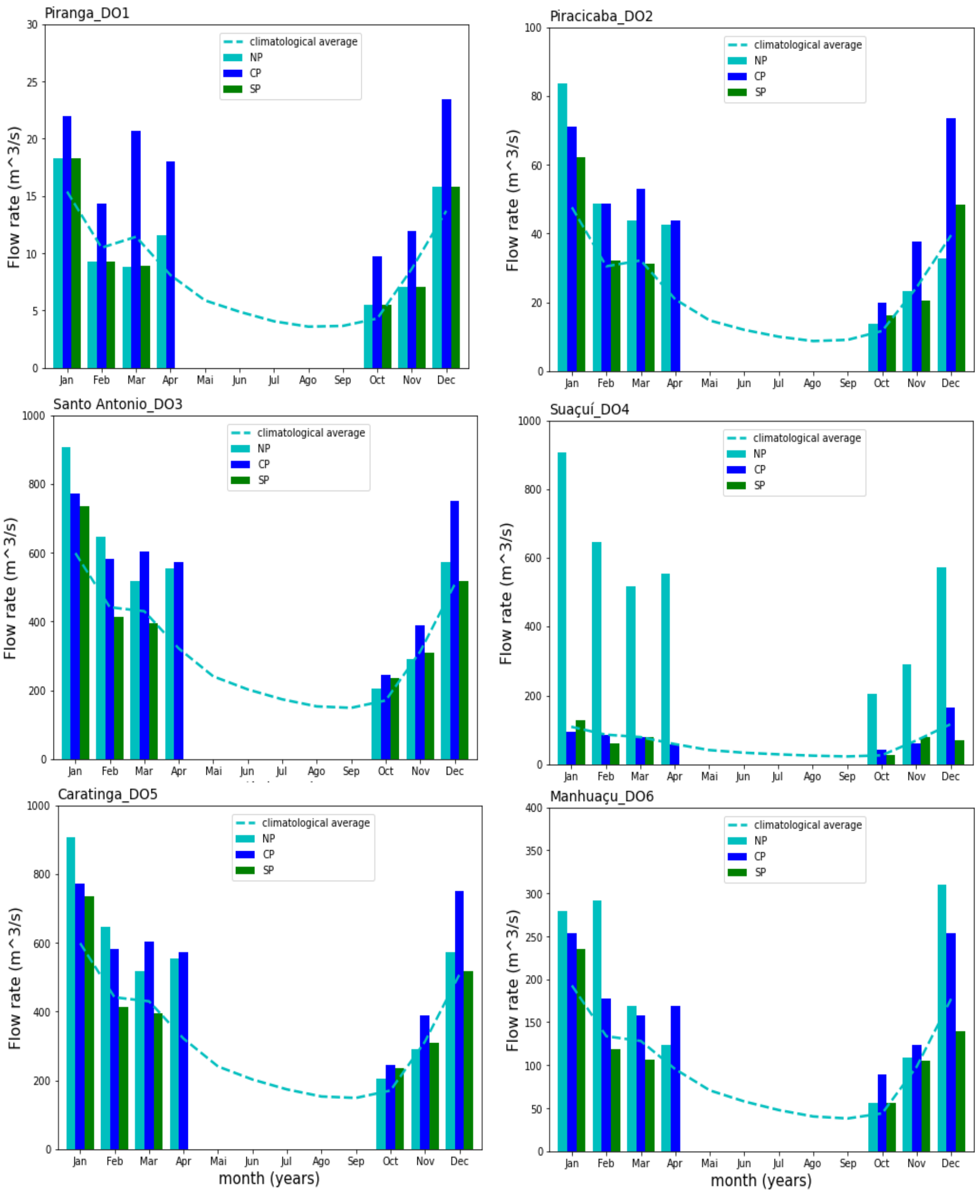


Figure.5: Monthly Variation of rainfall and Flow rates in SACZ events, for the six sub-basins of the Rio Doce. NP-North Pattern, CP- Center Pattern, SP-South

Trend analysis and statistics

The analysis utilizing the Modified Mann-Kendall Test (MMK) revealed a statistically significant ($p < 0.05$) decreasing trend in both precipitation and flow across all sub-basins (Table 1). This decline was particularly pronounced in the Northern and Central regions, aligning with recent studies that have documented a downward trend in precipitation and rising temperatures across Central and Northern Brazil (Barbosa et al., 2021; Costa et al., 2022). For instance, Barbosa et al. (2021) attributed the declining precipitation in the Central region to shifts in atmospheric circulation patterns, while Costa et al. (2022) linked the Northern trend to deforestation and land use changes.

The observation of these decreasing trends has significant implications for water resource management, especially in the affected sub-basins.

This analysis provides valuable insights for future decision-making, suggesting the need for adaptation strategies to address changes in hydrological conditions (Lima et al. 2005; and Coelho 2006). Furthermore, our findings echo the broader patterns observed in climate projections for the region (Shekhar et al., 2020). These projections suggest that continued warming and altered atmospheric patterns will likely exacerbate the decreasing precipitation trends. The observed decrease in flow across all sub-basins underscores the direct hydrological consequences of these climatic shifts.

Thus, while the influence of precipitation on flow variability is well-established (McCabe & Wolock, 2011; Barbosa et al. 2021; Costa eta al., 2022; Kabir, 2023), our analysis goes further by examining how precipitation within specific patterns impacts flow in each sub-basin.

Our multiple linear regression (MLR) model reveals that over 86% of flow variability across the six sub-basins can be explained by precipitation within the three SACZ patterns. Importantly, this analysis focuses on the relationship between monthly flow and monthly precipitation within each pattern. The statistical significance ($p < 0.05$) of the F statistic in our model confirms that these precipitation variables substantially improve our ability to predict flow variability compared to a simple average.

This finding reaffirms the substantial influence of precipitation within the SACZ patterns on the observed flow variability. Notably, our analysis reveals that precipitation within the NP pattern appears to be the most influential driver of flow variability across most sub-basins. This is evident in the MLR results (Table 1), where the NP pattern consistently demonstrates the strongest association with flow, except in the Santo Antônio sub-basin. In Santo Antônio, both the NP and South Pacific (SP) patterns play significant roles in explaining flow variability.

Extreme events and floods

The 95th percentile thresholds for daily rainfall vary across the SACZ patterns: 18.4 to 33.73 mm for the SP, 22.81 to 49.65 mm for the CP, and 32.57 to 56.30 mm/day for the NP Pattern. These thresholds, which define extreme rainfall events (Figure 6), represent the top 5% of daily rainfall values observed during each respective pattern.

Analysis of extreme events (Table V in SM) reveals distinct patterns across the sub-basins. The Piracicaba and Santo António sub-basins experienced a notably higher frequency of extreme precipitation events (168 and 127 events, respectively) primarily during the occurrence of the NP and CP patterns. Conversely, the Caratinga (58 events) and Manhuaçu (88 events) sub-basins exhibited fewer extreme events, likely due to the infrequent influence of the NP and CP patterns in those areas throughout the time series (Figure 6).

These episodes of extreme rainfall are often associated with river overflow within the Doce River basin, leading to floods and damage to properties (Nascimento, 2012; Silva et al., 2020). Therefore, considering the earlier average daily duration of SACZ episodes (6.2 days), extreme events linked to SACZ, occurring over this duration, can result in accumulated precipitation ranging from 114.08 to 394.32 mm.

While extreme rainfall events are a key factor, not all of them result in flooding. To gain a deeper understanding of the relationship between extreme rainfall and flooding during SACZ activity, we analyzed 54 flood events occurring during the northern SACZ position (NP), 13 during the central position (CP), and 33 during the southern position (SP).

Our analysis reveals that Governador Valadares, Ponte Nova, and Tumuritinga – municipalities previously identified as vulnerable to extreme hydrological events (Silva et al., 2023; Santos & Oliveira, 2022) were the most frequently impacted by floods during SACZ events, especially when was positioned further north. The average flood level during these events reached 432.98 cm, with a maximum of 552 cm (Figure 3 in Supplementary Material).

The NP pattern emerged as the most significant contributor to flood events, accounting for 28.63% of events with property damage and 23.91% without. The CP pattern followed, responsible for 6.32% of events with property damage and 11% without. The SP pattern contributed to approximately 6% of flood events (Figure 3 in SM).We also examined instances where flood warnings were issued but no damage occurred. Here, the NP pattern again dominated with 48 cases, followed by the CP pattern with 27 cases, and the SP pattern with 15 cases (Figure 6).

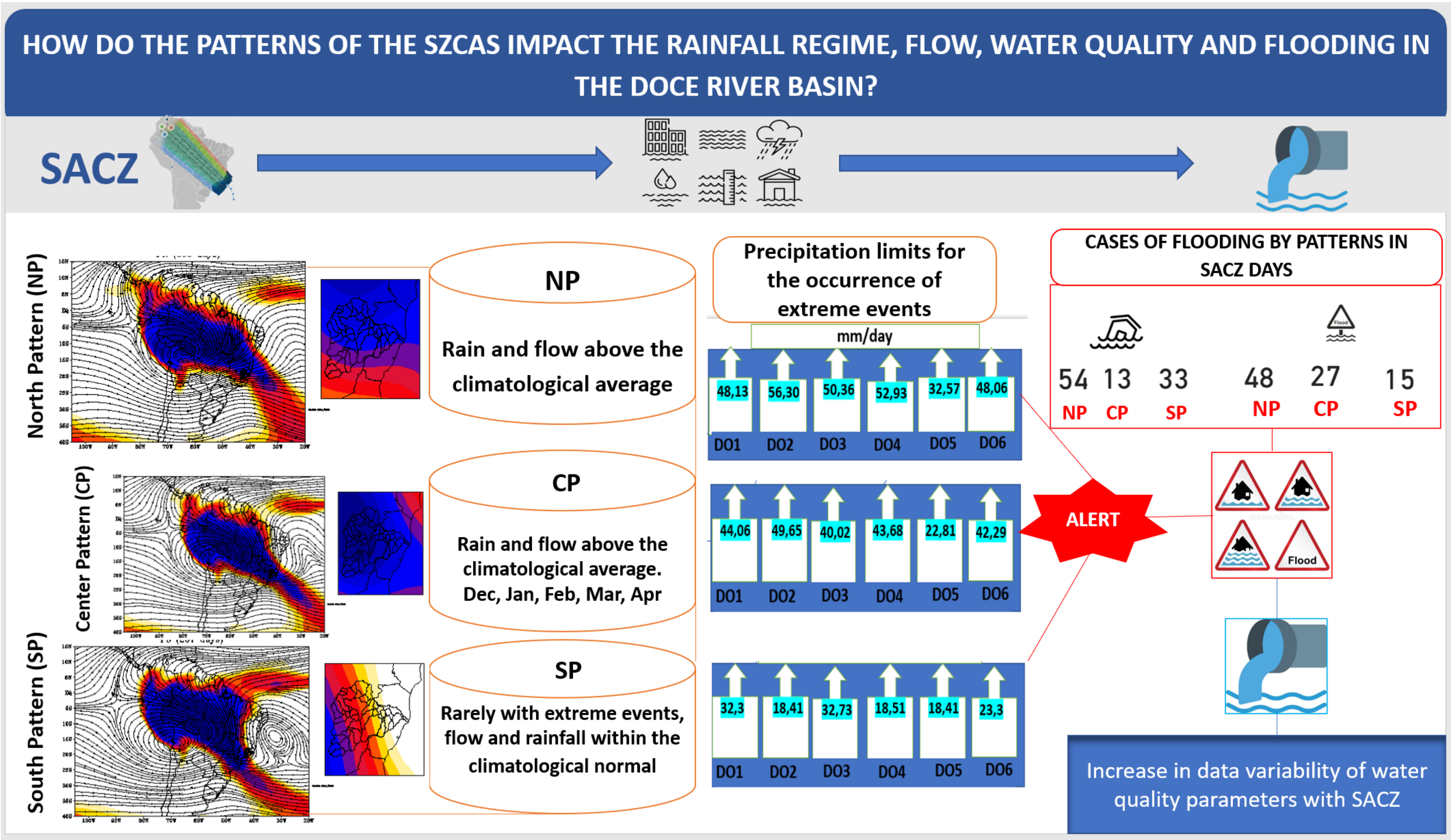


Figure 6 Summary of the effects of SACZ patterns on flooding. (I) Position of weather systems in the definition of each standard. (II) Precipitation limit to evaluate extreme events through the 95% percentile. (III) cases of flooding.

Table 1: Tau statistic values from the Mann−Kendall (MK) test values in the patterns of the SACZ. The highlighted in green lines indicate a significance level of 0.05. Results of the regression model, North Standard (NP), Center (CP), South (SP). Understanding the historical series from 1991 to 2020.

Basin	PN_Rainfall	PC_Rainfall	PS_Rainfall	R^2
Piranga	-0,019	-0,066	-0,049	0,88
Piracicaba	0,025	-0,058	0,006	0,91
Santo Antonio	0,011	-0,187	-0,049	0,86
Suaçuí	-0,04	-0,09	-0,02	0,87
Caratinga	-0,216	-0,263	0,001	0,97
Manhuaçu	-0,056	-0,141	-0,059	0,87
	PN_Flow	**PS_Flow**	**PC_Flow**	
Piranga	-0,233	-0,278	-0,114	
Piracicaba	-0,149	-0,190	-0,107	
Santo Antonio	0,001	-0,755	0,001	
Suaçuí	-0,196	-0,310	-0,273	
Caratinga	-0,155	-0,755	-0,241	
Manhuaçu	-0,111	-0,278	-0,114	

Impact of SACZ on water quality

Considering seasonal variation without filtering for SACZ events, our Principal Component Analysis (PCA) reveals that 45.30% of the variation in water quality parameters is explained by two primary components. The fact that neither set of principal components explains more than 50% of the variation suggests that other factors not considered in this analysis may be influencing water quality. Seasonal analysis indicates that the majority of variation occurs during the rainy season (summer) across all sub-basins. Monthly assessments further emphasize elevated levels of total solids and turbidity during months when SACZ is active.

Seasonality strongly influences water quality in the Doce River. The rainy season exhibits increased turbidity and total suspended solids, likely due to heightened erosion (Andrade et al., 2021; Cunha Richard et al., 2020; Olsen et al., 2012; Santana et al., 2021; Vaneli et al., 2022). Additionally, total coliforms, total phosphorus, and water temperature rise during this period, while dissolved oxygen increases during the dry winter months (Figure 7a).

Focusing on the months when SACZ is active, a second PCA highlights a stark contrast between the Caratinga sub-basin (DO5), with poorer water quality (higher conductivity, total chloride, ammonia, and biochemical oxygen demand), and the Santo Antônio sub-basin (DO3), which exhibits lower values for these variables and higher dissolved oxygen. The other four sub-basins fall between these extremes (Figures 7a-d). This disparity may be attributed to the impact of the dam rupture, which increased erosion and transport of contaminants during heavy rainfall, a phenomenon less pronounced in the Santo Antônio basin (Magalhães et al., 2022; Oliveira & Quaresma, 2017; Zorzal & Fernandes, 2021).

Standardizing the data within each sub-basin and distinguishing points by month (Figure 7a) reveals that December and March exhibit the highest levels of total phosphorus, total coliforms, total suspended solids, and turbidity. These months coincide with peak SACZ rainfall and flow. Finally, a fourth PCA, controlling for sub-basin and month effects, demonstrates that SACZ presence is associated with elevated levels of turbidity, total suspended solids, total phosphorus, total coliforms, ammonia nitrogen, and biochemical oxygen demand.

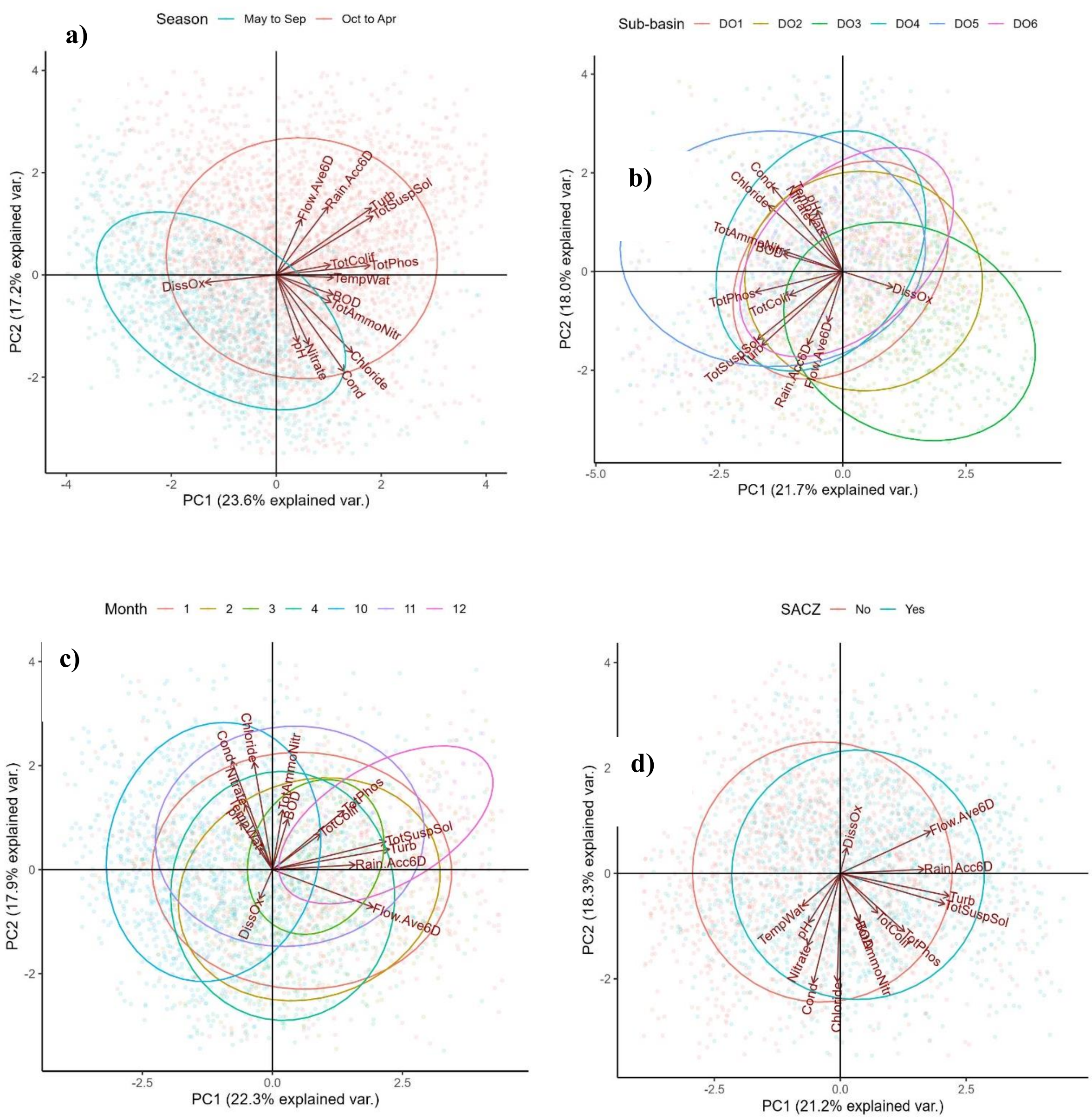


Figure.7: Graphical representation of the first two axes obtained from the first Principal Component Analysis (PCA) with all the available data. b) First two axes obtained from the second Principal Component Analysis (PCA) only with months of SACZ occurrence. C) First two axes obtained from the third Principal Component Analysis (PCA) only with months of SACZ occurrence and after applying standardization by sub-basin. d) First two axes obtained from the fourth Principal Component Analysis (PCA) only with months of SACZ occurrence and after standardization by sub-basin and by month of the year. The percentage of explanation of the total variance of each axis is specified in the title of the respective axis. Each point represents a sample from a site in a given campaign. The colors specify the dry and rainy seasons. The ellipses delimit the regions where approximately 68% of the group's values are concentrated (equivalent to 1 standard deviation of the bivariate normal distribution).

Acknowledgments

Acknowledgment to CAPES for granting the scholarship.

Conclusion

This study reveals that the relationship between extreme weather events, floods, and flood warnings is complex and varies depending on the position of the South Atlantic Convergence Zone (SACZ) in the Doce river basin. To mitigate flood risks, we established precipitation thresholds for extreme rainfall events: 43 mm for the northern (NP) and central (CP) positions, and 23 mm/day for the southern (SP) position. These thresholds are valuable information that can be utilized by weather centers to issue warnings of potential flooding in sub-basins.

Moreover, we identified that floods are more prevalent when the SACZ is in the northern position (NP), with 54 recorded cases, followed by 13 cases in the central position (CP) and 33 cases in the southern position (SP). The northern position (NP) of the SACZ is associated with the highest number of flood cases in the region, especially in the city of Governador Valadares. The central position (CP) also significantly contributes to flood cases, notably affecting the city of Ponte Nova.

With the identification of precipitation thresholds, we captured the positions of the main systems that define the SACZ patterns. This information is incomplete without knowing when each pattern occurs, as the SACZ patterns are defined by the meteorological systems that compose them. The northern position (NP) occurs when the Bolivian High (BH) extends zonally up to 40°W, and the Northeast trough (CN) extends from 30° to 20°W. The central position (CP) occurs when the BH ranges from 80° to 60°W, and CN from 30° to 20°W. In the southern position (SP), the zonal extension of the BH ranges from 90° to 60°W, and the High-Level Cyclonic Vortex (HLCV) can extend up to 30°W, with characteristics predominantly observed at high altitudes (300hPa). At lower altitudes, there is an anomalous cyclone located between 20°-40°S in NP, 30°-35°S and 15°-20°S in CP, and 25°-30°W in SP. These findings offer valuable insights for meteorological forecasting.

Temporal analysis revealed that, on average, an SACZ event lasts 6.2 days, with annual occurrences varying from 6 to 70 days. We observed an increasing trend in SACZ events during the 1990s, peaking in 1999, and another period of higher activity between 2004 and 2016, followed by a decreasing trend from 2017 to 2020. From 2004 to 2020, the number of events per year increased from 5 to 11, in contrast to the decade from 1991 to 2003, when there were fewer than 6 events per year. The northern and central positions of the SACZ consistently experienced higher levels of precipitation (>=18 mm/day) in all sub-basins.

Our monthly analysis of precipitation and flow patterns identified the NP and CP positions as the most influential, with accumulations exceeding 18 mm/day for precipitation and flow ranging from 80 to 800 m³/s. However, in April, the SP position was notably absent for both flow and precipitation, possibly due to its infrequent occurrence during this month. Using Multiple Linear Regression (MLR), we determined that all SACZ patterns significantly contribute to flow in all sub-basins, explaining more than 86% of the flow variability on SACZ days.

The analysis of water quality in the Doce River highlights seasonal influence, especially during the rainy season and events such as the SACZ. Monthly analysis highlights December and March, associated with higher values. The last PCA, by extracting the effects of both sub-basin and month, shows that the presence of SACZ is related to peaks, mainly in turbidity and total suspended solids, indicating the complexity in the dynamics of water quality in the Doce River. These findings have important implications for the management and preservation of this crucial resource.

Future Research Proposals

Acknowledging the limitations of our study, we propose the following directions for future research: Influence of Climate Change on SACZ: Investigate how climate change affects the dynamics and frequency of SACZ events, using long-term climate models to project future changes and their implications for precipitation, flooding, and flow patterns in the Doce river basin. Modeling Flow and SACZ Positions: Develop hydrological models that correlate SACZ positions with flow cases in the Doce river sub-basins, using simulations based on historical data and climate forecasts. Temporal and Spatial Analysis of SACZ: Expand temporal analysis to include long-term data and utilize spatial analysis techniques to understand SACZ displacement patterns and regional impacts, exploring interannual and decadal variability. Integration of Satellite Data and Remote Sensing: Use satellite data and remote sensing techniques to monitor and model SACZ in real-time, aiding in the creation of early warning systems and rapid response plans.

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