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Article

Analysis of Trends in Extreme Precipitation in the State of Minas Gerais

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Abstract

The study of the behavior of intense precipitation is extremely important in the management of disasters triggered by these events that culminate in environmental, social and economic damage throughout Brazil. The main objective of this work was to identify the trends and behavior of intense precipitation events in the State of Minas Gerais. Daily precipitation data from 309 rainfall stations managed by the National Water and Basic Sanitation Agency (ANA) were analyzed, corresponding to the period between 1978 and 2017. The quantile technique was used as a confidence interval (95%) in the trend analysis. The Mann-Kendall Test and the Sen Estimator estimated the trends and their magnitudes, respectively. Of the 309 stations analyzed, 20 stations showed a statistically significant trend (at the 95% level) in the intensity of events, with 8 stations showing an increasing trend and 12 stations showing a decreasing trend, in the States of Minas Gerais. Summer recorded the highest rate of intense rainfall (≥ 50%) throughout the State. An increase in extreme rain events was observed in some points in the north of Minas (increase of 0.20 mm/day/year) and a reduction in the Triângulo Mineiro region and central strip of Minas Gerais (reduction of 0.1 mm /day/year).

Keywords: extreme events, mann-kendall, magnitude.

Análise das Tendências de Precipitação Extrema no Estado de Minas Gerais

Resumo

O estudo do comportamento das precipitações intensas é de extrema importância no gerenciamento dos desastres deflagrados por estes eventos que culminam em danos ambientais, sociais e econômicos por todo o Brasil. O objetivo principal deste trabalho foi identificar as tendências e o comportamento dos eventos de precipitação intensa no Estado de Minas Gerais. Foram analisados dados diários de precipitação de 309 postos pluviométricos gerenciados pela Agência Nacional de Águas e Saneamento Básico (ANA), correspondentes ao período entre 1978 e 2017. A técnica dos quantis foi utilizada como intervalo de confiança (95%) na análise da tendência. O Teste de Mann-Kendall e o Estimador de Sen estimaram as tendências e suas magnitudes, respectivamente. Dos 309 postos analisados, 20 postos apresentaram tendência estatisticamente significativa (ao nível de 95%) na intensidade dos eventos, sendo 8 postos com tendência de aumento e 12 postos com tendência de diminuição, no Estados de Minas Gerais. O verão registrou a maior taxa de ocorrência de precipitações intensas (≥ 50%) em todo Estado. Observou-se um aumento de eventos extremos de chuva em alguns pontos no norte de Minas (aumento de 0,20 mm/dia/ano) e uma redução na região do Triângulo Mineiro e faixa central de Minas Gerais (redução de 0,1 mm/dia/ano).

Palavras-chave: eventos extremos, mann-kendall, magnitude.

1. Introduction

Extreme precipitation events each year have become more frequent and generated more environmental, social and economic damage. Studies such as those by Frich *et al.* (2002), Alexander *et al.* (2006), Donat *et al.* (2013) and Mudelsee (2019) showed that most regions of the world have been experiencing warmer temperatures over the years associated with high precipitation rates, which have been increasing exponentially since the 1950s and resulting in negative impacts on agricultural sectors. and in hydrological management (Avila-Diaz *et al.*, 2020).

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The State of Minas Gerais (MGS), located in the Southeast Region of Brazil (Rio de Janeiro, Minas Gerais, Espírito Santo and São Paulo), known for its extensive agriculture (as a producer of more than 50% of Brazilian coffee, as well as crops of corn, beans and soybeans), a strong industrial sector (mining and metallurgy) and an important contribution to the generation of electrical energy, from hydroelectric plants, each year it has become a vulnerable place to extreme precipitation events (Natividade *et al.*, 2017; Dalagnol *et al.*, 2021).

This vast region is located in an area defined by the South American Monsoon System (Zou and Lau, 1998; Gan *et al.*, 2004), responsible for determining a cycle of well-defined precipitation during the year, predominantly presenting the dry winter season and the rainy summer season, combined with the South Atlantic Convergence Zone, responsible for periods of intense and persistent precipitation (Nogués-Pagle and Mo, 1997), most of the time linked to natural disasters such as landslides and land and floods (Teixeira and Satyamurty, 2011; Brasiliense *et al.*, 2018).

Several studies have been developed at the MGS seeking to better understand climate extremes in the region and future scenarios (Natividade *et al*., 2017; Assis *et al.*, 2018; Abreu *et al.*, 2022; Avila-Diaz *et al.*, 2020; Reboita *et al.*, 2021; Garcia *et al*., 2023), which mostly concluded an increase in temperature and the number of hot nights, indicating more frequent dry days, highlighting impacts on the agricultural sector due to lack of water caused by droughts in the northern region of the state, leaving several municipalities in a state of water scarcity.

According to S2ID (2022), the MGS has the highest annual frequency of occurrence of natural disasters (associated with floods, floods and flooding) throughout the southeast region, with 52.7% of the total, with summer being the season that presented the highest frequency of disasters in the state, with 78.2% of the annual total (Carpenedo and Lima, 2022). Studies such as those by Santos *et al*. (2017), Natividade, Garcia and Torres (2017) and Reboita *et al.* (2018) report an increase in temperature over the state of Minas Gerais, which will consequently generate trends towards a reduction in cold nights and days (Sondermann *et al.*, 2022).

In view of the above, the main objective of this work will be to provide updated information on the trends of intense precipitation events in the MGS, seeking a better understanding of these extremes and their behavior. The results can contribute to future adaptation measures by governments and agencies to improve socioeconomic and environmental activities in different regions of the State, and promote a better adaptation strategy against the vulnerability of the population in the various exposed areas within the MGS, such as slopes and riverbanks.

2. Materials and Methods

2.1. Data

In this study, daily rainfall data were used, between 1978 and 2017, provided by the National Agency for Water and Basic Sanitation (ANA), and the stations that contained a maximum of 10% of failures were selected, as observed in Fig. 1. After discarding the erroneous data, 309 rainfall stations containing at least 30 years of data were used.

2.2. Methodology

The quantile technique was used in this study applied to the time series of daily precipitations. According to Pinkayan (1966), this technique represents the distribution, ordered in an increasing way, of a continuous sample series. According to the definition of Gouvea *et al.* (2018), a quantile of order p (determined for $0 < p < 1$) can be defined as a numerical value responsible for the division into two parts of numerical observations, presenting 100xp% of its elements located to the left of the sample quantile and the remaining 100 x (1 - p)%, to the right.

In this study, the quantile of order 0.95 (95% percentile) was determined to represent extreme values, defined as a confidence interval in the statistical analysis of the trend, already applied in studies such as those by Gouvea *et al.* (2018), Marrafon and Reboita (2021), Gomes Néto and Santos (2022) and Holender and Santos (2023). When values are greater than the adopted confidence limit (95% in this study), the trend is considered positive. The estimation of percentiles was based on precipitation records that contained values greater than 0 mm, thus excluding days without rain.

The statistical analysis of the linear trend in this work was carried out using the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975), where the statistically significant temporal trend in the data series was evaluated (Yue *et al.*, 2002). Subsequently, the Sen Estimator (Sen, 1968) was used to calculate the magnitude of the trend, both increase and decrease (Yue and Hashino, 2003), which is more robust than other tests due to its insensitivity to outliers and missing data, presenting greater rigor than the curvature of linear regression (Alcantara *et al.*, 2019).

Let be the observations x_1, x_2, …., x_n of a time series. In the Mann-Kendall test, one wishes to test the null hypothesis, (H_0) of no trend, that is, observations x_n are randomly ordered in time, against the alternative hypothesis, (H_1), in which there is a monotonic trend of increase or decrease. The test statistic is defined as follows:

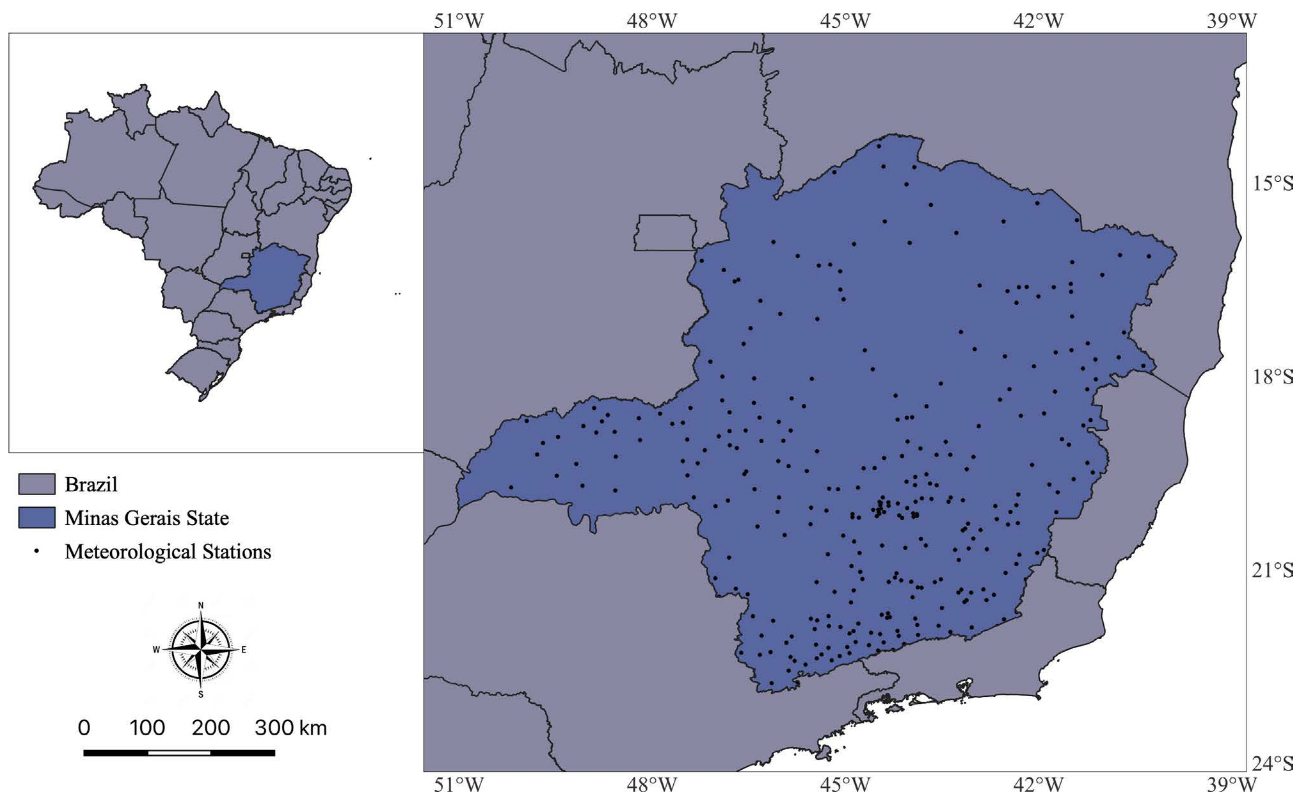

Figure 1 - Location of the State of Minas Gerais and the distribution of the 309 rainfall stations used in the study.

$$Z = \begin{cases} \frac{s-1}{\sigma}, \text{se } S > 0 \\ 0, \text{se } S = 0 \\ \frac{S+1}{\sigma}, \text{se } S < 0 \end{cases}, \quad (1)$$

where:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sinal } \left(x_j - x_k\right), \quad (2)$$

where x_j and x_k sequential values, n is the number of observations and the signal obtained as follows:

$$\text{sinal } (x_j - x_k) = \begin{cases} 1, \text{se } (x_j - x_k) > 0 \\ 0, \text{se } (x_j - x_k) = 0 \\ -1, \text{se } (x_j - x_k) < 0 \end{cases} \quad (3)$$

In a bilateral test, we do not reject the null hypothesis, (H_0), for a certain significance level α, if given the quantile value of a standard normal distribution we have. The sign of the Mann-Kendall statistic indicates whether the trend is increasing (greater than zero) or decreasing (less than zero). For this study, a significance level of 5% was considered $Z_{\frac{\alpha}{2}}|Z| \leq Z_{\frac{\alpha}{2}}$.

For the calculation of Sen's slope, Portela *et al.* (2011) and Tao *et al.* (2014) describe that:

$$Q_{ij} = \frac{X_j - X_i}{j - i} \text{ com } i < j, \quad (4)$$

where X_i and X_j represent the values of the variable under study in years i and j. Positive or negative value for Q indicates an increasing or decreasing trend, respectively. If there are n values in the analyzed series, then the number of estimated pairs of Q is given by $N = n\ (n - 1)/2$. The Sen slope estimator is the median of the N values of Q_{ij}.

All the data presented in this work came from the manipulation and statistical analysis of the R tool of programming language. The data presented in the spatial analysis were performed using the deterministic interpolation method Inverse Distance Weighting (IDW), with exponent equal to 2 ($p = 2$), through the QGIS Geographic Information System (version 3.30.0). This method indicates that each point will exert an influence inversely proportional to the square of the distance from the mesh node, therefore, the higher the value for the weight, the less influence will be exerted on the most distant points of the node (Mazzini and Schettini, 2009). Its formula is represented below:

$$F(x, y) = \sum_{k=1}^{N} W(x_k, y_k) F(x_k, y_k), \quad (5)$$

where, represents the value that was interpolated to the coordinate (x, y), N indicates the number of points observed in the vicinity of the interpolated site, $F(x_k, y_k)$ is the value at the point k that was observed, and $W(x_k, y_k)$ corresponds to the weights that were assigned to each of the regions.

3. Results and Discussion

3.1. Climatological characterization of precipitation in the State of Minas Gerais

The MGS is in the southeast region of Brazil, being the x largest State in the country, with 853 municipalities totaling an area of 586,514 km^2 and with approximately more than 20 million inhabitants (Abreu *et al.*, 2022; IBGE, 2023). The State is characterized by a Cwb/Cwa climate (dry winter and hot/temperate summer) in the southern, southeastern and high elevation portions according to the Köppen-Geiger classification, while the northern and western parts have an Aw/As climate (semi-arid summer and dry/dry winter), while a small portion in the extreme north has a BWh/BSh classification (semi-arid climate) (Alvares *et al.*, 2013).

Several systems operate in the MGS and predict the occurrence of extreme precipitation trends in the State. During winter, the region is influenced by the South Atlantic Anticyclone (ASAS), which acts as a rain inhibitor in eastern South America, providing a reduction in atmospheric humidity and being responsible for long periods of rainfall shortage in the MGS (Vianello and Maia, 1986). At this same time of year, in the opposite way, the formation of Cold Fronts stands out, responsible for 60% of the rains in the South of MGS, characterized in the region by their low intensity and long duration according to Mello *et al.* (2007).

Another phenomenon that plays a prominent role in the MGS is the South American Monsoon System (SMSA). The SMSA is known for its high rainfall in the summer and low rainfall in the winter. This system is associated with the formation of the South Atlantic Convergence Zone (ZCAS), a meteorological system fed by humidity from the Amazon that provides a band of cloudiness in the northwest-southeast direction, generating high rainfall levels throughout the MGS region (Kousky, 1988; Reboita *et al.*, 2010). The SMSA integrated with the ZCAS component promotes humidity in South America, which begins in September until its maturation in November, extending thereafter until the end of summer (Vera *et al.*, 2006). According to results from Bombardi and Carvalho (2008), the MGS has a rainy period of 165 days.

Furthermore, there is the El Nino Southern Oscillation (ENSO), which is another major influencer on the region's climate, being associated with Sea Surface Temperature (SST) anomalies that generate a drought process, while La Nina characterizes the occurrence of flooding over the MGS due to the transport of moisture to the region. Coelho (2001) in his work identified a reduction, during the La Nina summer, in rainfall in the MGS. Coelho *et al.* (1999), when studying strong, moderate and weak ENSO events, identified positive anomalies in the center of Minas Gerais and negative anomalies in the north of the State in strong/moderate events for the El Nino summer. In the spring in the center-north of Minas, negative anomalies were observed for strong/moderate El Nino events.

Finally, the South Atlantic Dipole (DAS) is observed, which, associated with SST variations, influences rainfall in the MGS. In its positive phase, there is an increase in rainfall in the state, while in its negative phase, when the waters of the South Atlantic are warmer, a reduction in rainfall can be observed, causing episodes of drought in Minas Gerais. Furthermore, DAS can be associated with extreme events, such as floods and prolonged droughts, impacting society and agriculture in the SMG, for example (Carpenedo and Lima, 2022).

In addition to the meteorological systems operating in the MGS, a large part of its population faces socio-environmental problems, occupying risky locations such as slopes and/or riverbanks, with precarious housing conditions, presenting a high vulnerability to the onset of natural disasters such as landslides. land and floods (Natividade *et al.*, 2017).

3.2. Annual analysis of intense precipitation events

The analysis of the values of the 95th percentiles (P95) of the precipitation time series and the average daily precipitation equal to or greater than the P95 (Fig. 2) shows that in a large part of the MGS the P95 values are between 40 and 50 mm/day, with only some cores showing values lower than 40 mm/day (P95), mainly located in the northeast of the State, which has a semi-arid climate, referring to the period from 1978 to 2017. This region is also where the lowest average rainfall is observed. equal to or greater than P95, with values below 50 mm/day.

Small cores that presented P95 values greater than 60 mm/day can also be observed in Fig. 2, located mainly in the Triângulo Mineiro, northwest of the MGS. In general, these regions with a more tropical climate also presented the highest rainfall averages equal to or greater than P95, with averages greater than 75 mm/day.

The values recorded in the MGS, in Fig. 2, are in agreement with the intense rainfall observed in the studies by Mello *et al.* (2007) and Mello and Viola (2013), who pointed out the northwest, east and central regions of the State, in addition to the Triângulo Mineiro, the highest occurrences of intense rainfall, while the northern, northeastern and southern regions of Minas Gerais presented lower precipitation values.

The trend of the intensity of intense precipitation events (mean precipitation $\geq$ P95) and the estimate of the magnitude of these trends, based on the annual average of

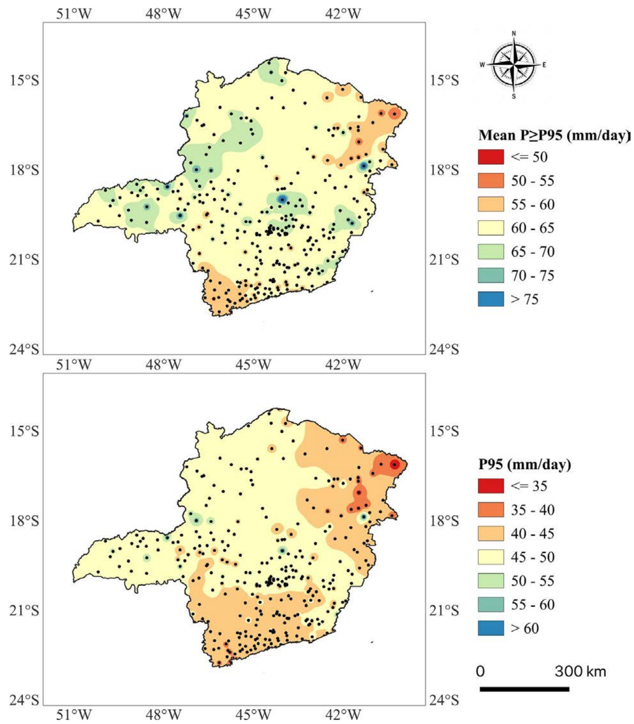

Figure 2 - Values for the period from 1978 to 2017 of the average rainfall equal to or greater than the 95th percentile (P ≥ P95, mm/day) (higher) and the values of the 95th percentiles (P95) of the daily precipitation time series (mm/day) (lower) for the State of Minas Gerais.

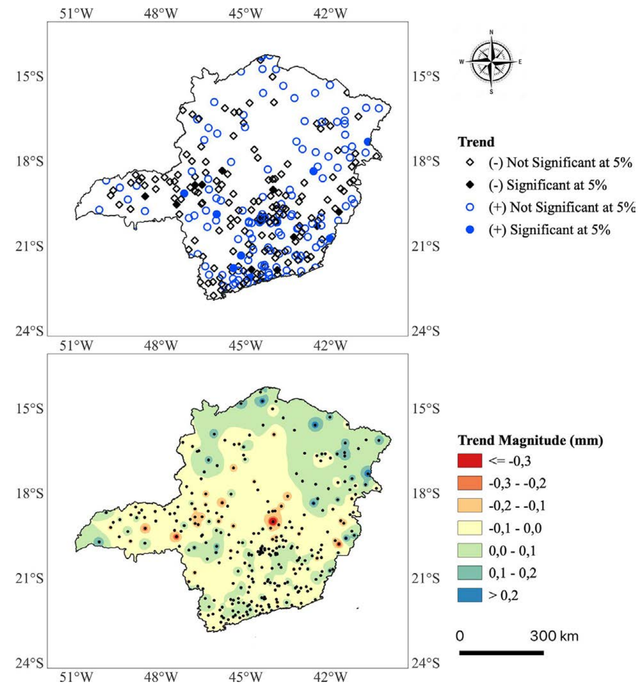

Figure 3 - Trend of the intensity of intense precipitation events (mean precipitation greater than or equal to P95) (higher) and the magnitude of the trend of intensity of intense precipitation events in the State of Minas Gerais (lower).

daily precipitation greater than or equal to P95 are observed in Fig. 3. Among the 309 rainfall stations analyzed, only 20 (~6.5% of the total) showed a statistically significant trend at the significance level of 5%. Of these 20 posts, 8 showed a significant positive trend and 12 showed a significant negative trend, representing 2.6% and 3.9% of the 309 posts analyzed, respectively.

These positive trends shown in Fig. 3 suggest an increase in the intensity of intense precipitation events and negative trends suggest a decrease in the intensity of events. The results of Santana *et al.* (2020) showed significant positive and negative trends (at the significance level of 5%) for the analysis of trends in the time series of annual precipitation over the Paraíba do Sul River basin (which covers part of the MGS), suggesting changes in the rainfall regime on a local scale, being in agreement with the results of this work.

A slight reduction in the trend can be observed in the central portion of the State and a slight increase in the southern sector, due to the displacement of the ZCAS over the southernmost region of the State, which features more persistent periods of rain. Regarding the magnitude of the trend (Fig. 3), the highest rates of increase (> 0.2 mm/day/year) were recorded mainly in the northern portion of Minas Gerais. Negative trends, with rates lower than -0.1 mm/day/year, were observed mainly in the Triângulo Mineiro and the central part of Minas Gerais.

Figure 4 shows the trend in the number of days with precipitation equal to or greater than P95 (intense precipitation). Of the 309 rainfall stations analyzed, 59 (~19.1% of the total) showed a statistically significant trend at the 5% significance level, mainly concentrated in the southern portion of the State. Of these, 6 showed a significant positive trend, suggesting an increase in the frequency of intense precipitation events. Therefore, of the total number of rainfall gauges analyzed (309), only 1.9% showed a significant upward trend. On the other hand, 53 stations (17.2% of the total) showed a statistically significant negative trend (decrease), located in the MGS.

In the magnitude of the trend of occurrence of intense precipitation events in the MGS (Fig. 4) it is shown that, in most of the number of days with rainfall greater than or equal to P95, the estimates were negative, suggesting a decrease in the occurrence of intense precipitation events. In the southeast of the MGS, rainfall stations were presented with positive estimates. These results corroborate the results presented in the analysis of statistically significant positive trends (Fig. 4) at the significance level of 5% for these regions.

3.3. Seasonal analysis of intense precipitation events

Figure 5 shows the number of occurrences (%) of intense precipitation events (precipitation greater than or equal to P95) per season. Among the events recorded during the study period, the highest occurrence was

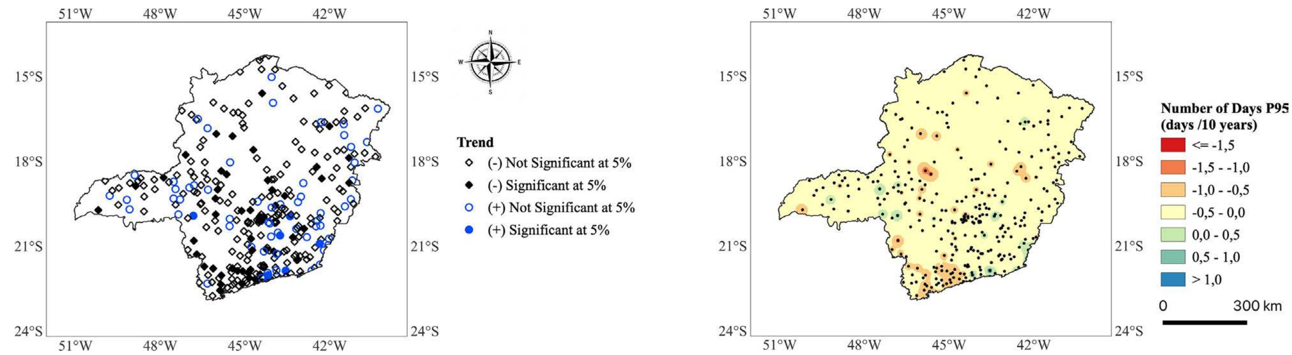

Figure 4 - Results of the trend of the number of days with precipitation equal to or greater than the 95th percentile (P ≥ P95) (left) and magnitude of the trend of occurrence of intense precipitation events (mean precipitation greater than or equal to P95) (right) in the State of Minas Gerais.

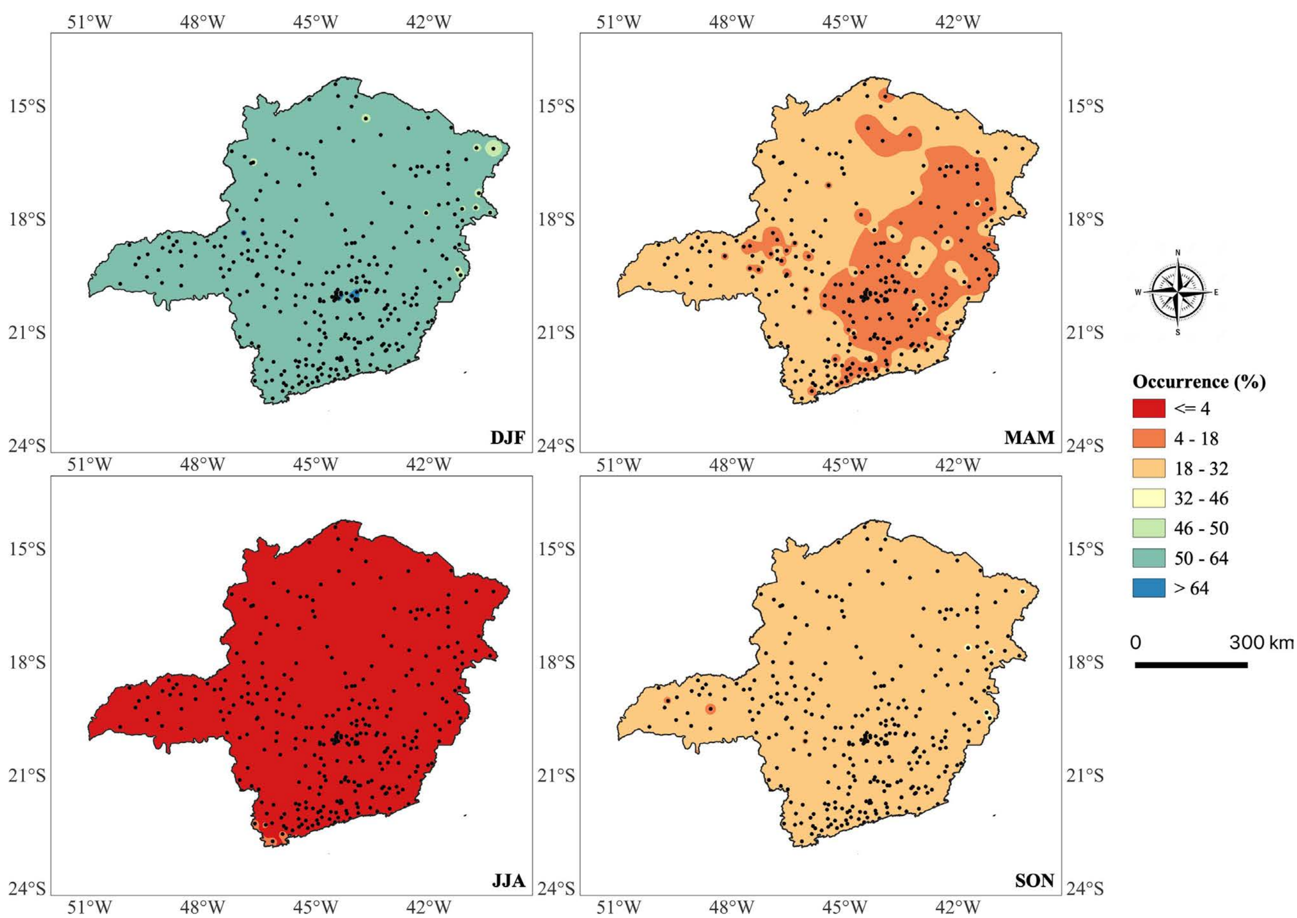

Figure 5 - Number of occurrences of intense precipitation events by season of the year in the State of Minas Gerais for summer (DJF), autumn (MAM), winter (JJA) and spring (SON).

observed in summer (December, January and February - DJF), exceeding 50% in practically all stations analyzed, with emphasis on the southern and central part of the State. Occurrences lower than 50% (presented in the summer) were found in stations located in the northeast of the State of Minas, with occurrence values between 46% and 50%.

During winter (June, July and August - JJA), the lowest occurrence records were observed (< 18%), with only 7 rainfall stations with an occurrence above 4%, found in the south of the State. The results of Siqueira *et al.* (2018) also indicated winter as the season corresponding to the dry period in the southwestern portion of Minas Gerais. In autumn (March, April, May - MAM) and spring (September, October, November - SON), the occurrence of events is mostly between 18 and 32% across the State, with some rainfall levels showing an occurrence of less than 18 %, located mainly in the central and southeastern portion of the State of Minas Gerais during the autumn months.

The northeast of the State of Minas during the summer presented the lowest intensity values (less than 60 mm/day), and the central region of the State in all seasons presented values above 70 mm/day, as consistent with intensity records of intense precipitation events pointed out by Holender and Santos (2023).

Figure 6 indicates the trend, by season of the year, of the number of days with precipitation equal to or greater than P95 (intense precipitation). In the summer (DJF), 39 rainfall stations showed a statistically significant trend at the significance level of 5%, corresponding to 12.6% of the 309 rainfall stations analyzed. Of these 39 posts, 5 showed a positive trend, suggesting an increase in the number of days of occurrence of intense precipitation events and 34 posts showed a negative trend, indicating that the frequency of these events is decreasing, more frequently in La Nina events.

In the autumn (MAM), the number of posts that showed a significant trend to the significance level of 5% was 30 (9.7% of the posts analyzed). Of these, 9 posts showed a positive trend, located mainly in the southern portion of Minas Gerais, and 21 posts showed a negative trend, also found in the southern portion of Minas Gerais.

During the winter (JJA), of the 15 rainfall stations that showed a significant trend at the significance level of 5% (4.8% of the stations analyzed), 14 showed a negative trend, located mostly in the central and southern portion of the State of Minas Gerais, due to the influence of ASAS and SMSA, and 1 showed a positive trend, located in the southeast of Minas Gerais.

In the spring (SON), of the 21 rainfall stations (6.8% of the total) that presented a statistically significant trend at the significance level of 5%, 18 presented a negative trend and 3 presented a positive trend (in view of the action of the SMSA), both of which can be observed in a more concentrated way in the south of the MGS.

Figure 7 represents the magnitude of the trend of occurrence of intense precipitation events by season of the year. It is observed that, during the summer (DJF), there is an estimated decrease of more than -0.2 day/10 years in several points scattered throughout the MGS. Meanwhile, in winter (JJA), spring (SON) and autumn (MAM), most

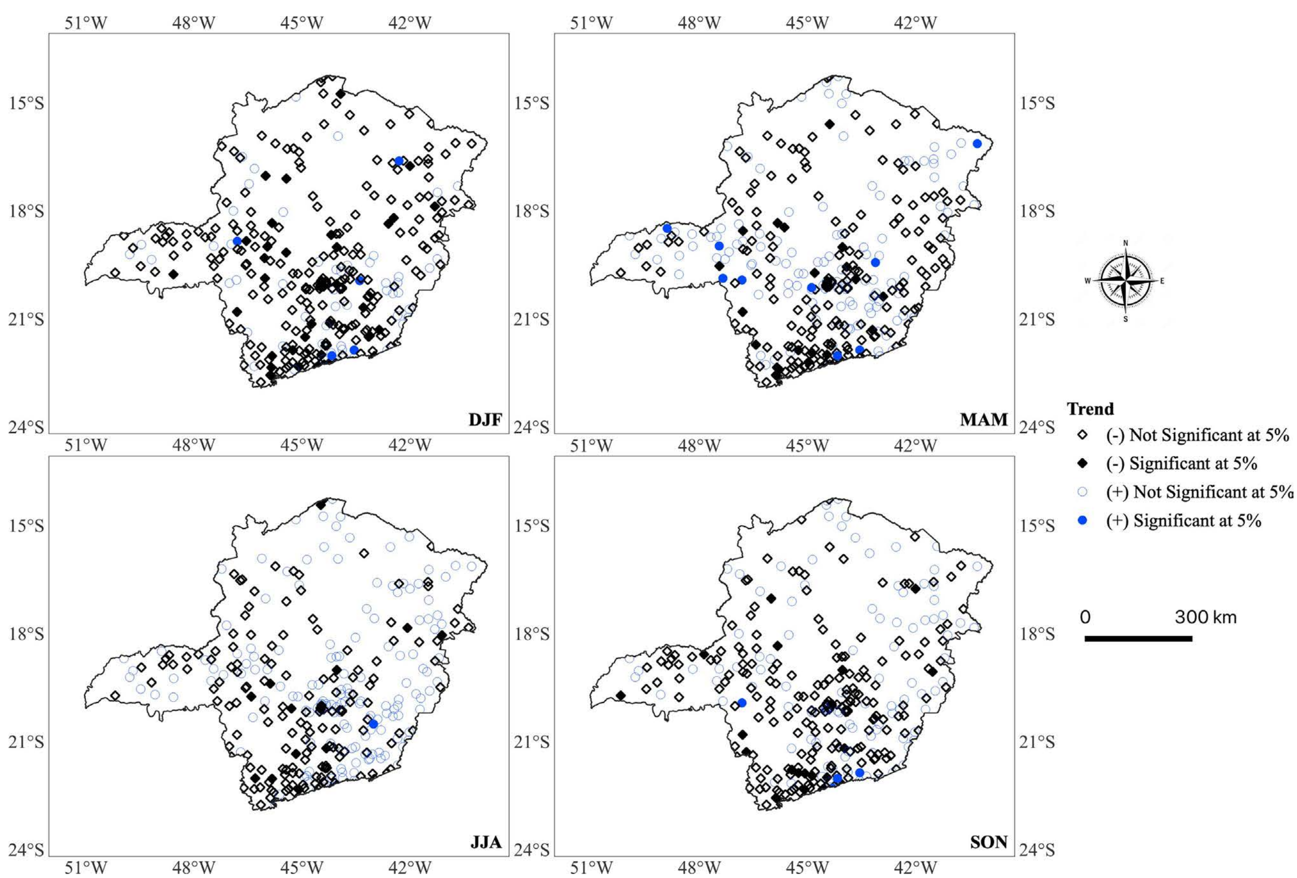

Figure 6 - Trend distribution of the number of days with precipitation equal to or greater than the 95th percentile (P ≥ P95) per season in the State of Minas Gerais: summer (DJF), autumn (MAM), winter (JJA) and spring (SON).

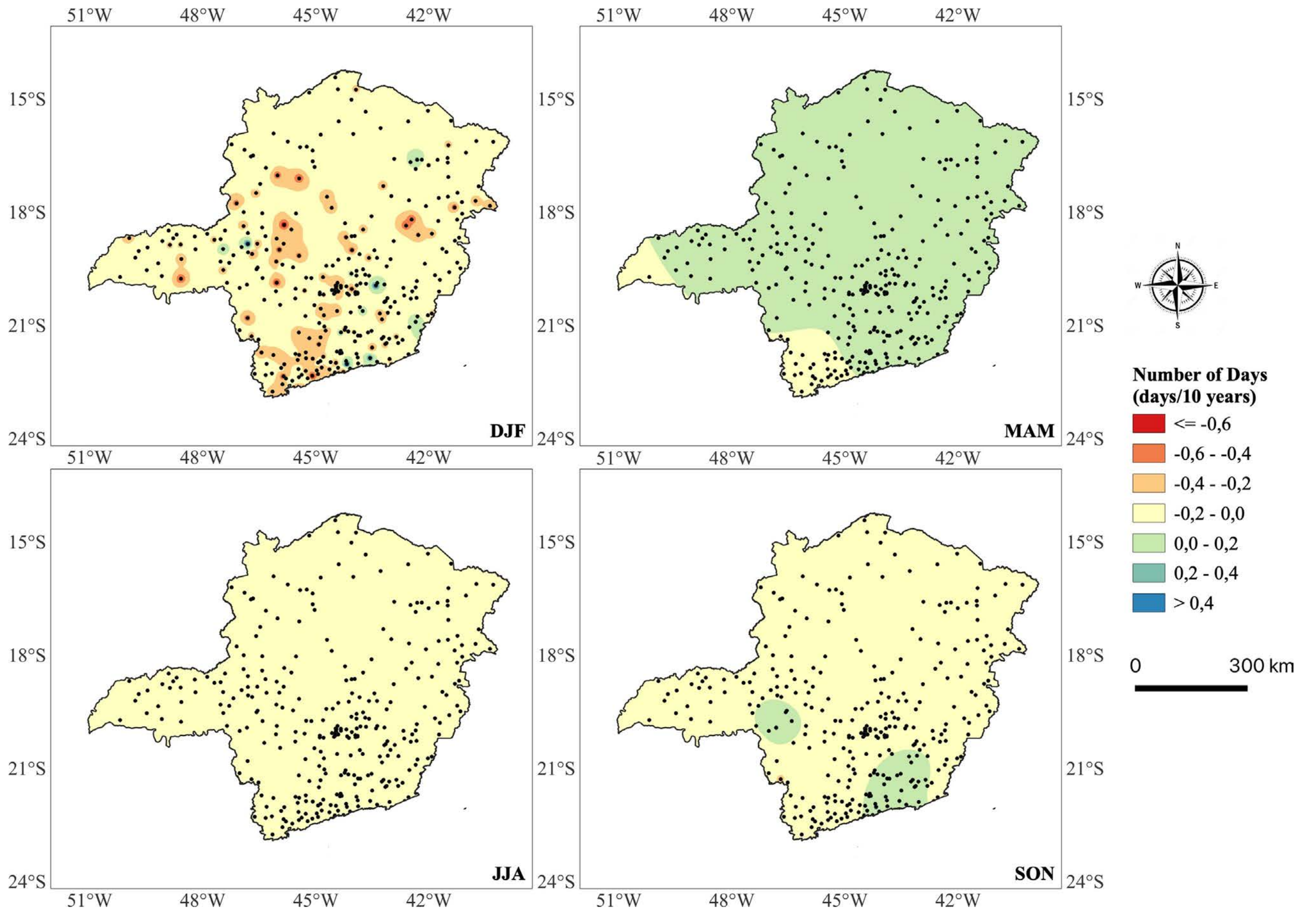

Figure 7 - Magnitude of the trend of occurrence of intense precipitation events (average precipitation greater than or equal to P95) by season of the year in the State of Minas Gerais: summer (DJF), autumn (MAM), winter (JJA) and spring (SON).

of the rainfall stations presented estimates between -0.2 and 0.2 day/10 years.

4. Conclusions

This research presents an updated analysis of the trend of intense daily precipitation in MGS, through daily precipitation data from 1978 to 2017 from 309 rainfall stations. The most intense values in relation to the 95th percentile of daily precipitation and the average precipitation equal to or higher than the 95th percentile were recorded in some small areas of the MGS.

Regarding the annual scale, the trend analysis of the intensity of intense precipitation events collected information from 6.5% of the rainfall stations (20 stations), which showed a statistically significant trend at the significance level of 5%, with 2.6% (8 posts) with an increasing trend and 3.9% (12 posts) with a decreasing trend.

The magnitude of the trend of intense precipitation events, on the annual scale, indicated negative trends with rates lower than -0.1 mm/day/year in some regions, mainly in the Triângulo Mineiro and central strip of Minas Gerais. While the highest rates of increase (> 0.20 mm/day/year) were observed mainly in the north of Minas Gerais. In most rainfall stations, the estimate of the magnitude of the trend was negative, suggesting a decrease in the occurrence of events up to 1 day/10 years in the MGS.

Entering the seasonal analysis, summer presented the highest frequency of occurrence of intense precipitation events, with occurrence predominantly higher than 50%. In the autumn and spring seasons, in its majority, the occurrences of the events were between 18 and 32%, followed by the winter, which presented occurrence of less than 4%, in much of the region.

For the analysis of the seasonal trend of the number of days with precipitation equal to or greater than the 95th percentile (occurrence), the results indicated that there was a significant trend at the significance level of 5% negative, for most of the posts, suggesting a decrease in the occurrence of intense precipitation events.

It can be concluded that there is a trend towards an increase in dry events throughout the State and a tendency towards a reduction in extreme precipitation in a large part of the MGS. The central and southeastern region of the State had the highest percentage increase in precipitation trends across the MGS. The northern region showed rates of increase in intense precipitation, resulting in a large concentration of heavy rains in short periods.

In this way, these results were able to contribute to a better understanding of the behavior of intense precipitation, pointing out the importance of better understanding this region and the most vulnerable points within the MGS. Through this information, it is expected to contribute to improving strategic planning and provide practical information that can help mainly in the civil defense and agriculture sectors.

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