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(REVIEW ARTICLE)

Quantitative analysis of rainfall events for potential rapid landslides and flashfloods in brazilian municipalities

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Abstract

This study examines rainfall events in Brazil, with emphasis on their potential to induce geo-hydrological hazards, like landslides and flash floods. Utilizing the CHIRPS dataset and rainfall thresholds for landslides, we quantify and analyze climatic hazards at a national level, providing perspective into the relationship between precipitation patterns and geo-hydrological risks. Our findings aim to contribute to a holistic understanding of climatic risk, guiding strategic decisions for disaster risk reduction and climate change adaptation.

Keywords: Landslides; Flash floods; Rainfall; Geo-hydrological risk; CHIRPS

1. Introduction

Natural disasters that cause the most deaths are related to precipitation, either its absence or excess, which resulted in 1.3 million fatalities between 1970 and 2020 [1]. Landslides, that can be caused by heavy rains, are more widespread than any other geological event [2]. In the Brazilian context, landslides caused 4,146 deaths between 1988 and 2022 [3]. This number considers only 16 (out of 26) states and 269 (out of 5,568) municipalities in Brazil. Therefore, this number is certainly underestimated regarding the country's real value, which is uncertain. Underestimation of landslides has already been reported with data of the International Disaster Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters. Kirschbaum et al. (2015) [4] showed underestimation of the number of fatal landslides by 1400% and 331% of deaths, while Petley(2012) [5] estimated 2000% and 430%, respectively.

The probability of certain meteorological or climatic events occurring, which can lead to other physical processes that cause impacts on both human and natural systems, is referred as "climatic hazard", or as “risk” in case of landslides.

The risk of landslides depends fundamentally, among other characteristics, on the geological-geotechnical and geomorphological conditions (slope, hillside amplitude, soil thickness, soil type, mechanical properties, lithology, among others), as well as the level of human interference at the local level. These characteristics vary for each location. The combination of these features results in different levels of slope susceptibility, which can lead to movement when specific volumes of rainfall on the soil, infiltration, and, once certain threshold conditions are exceeded, lead to its rupture, causing landslides (or other types of mass movements).

Thus, for a better representation of the climatic risk related to landslides, it is recommended that the information provided regarding the "climatic hazard" be combined with other dimensions that compose the risk. Besides susceptibility, these dimensions may also include the level of population exposure (the number of people living in areas

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with high and/or very high susceptibility), their vulnerabilities, and, depending on the approach, their capacity for coping and/or adapting to climate change.

In order to access the country's rainfall data, and thus comparing with landslides, we used the CHIRPS dataset. The Climate Hazards Group InfraRed Precipitation with Station data [6] is a 35+ year quasi-global rainfall data set, with 0.05° resolution satellite imagery. This dataset incorporates climatological satellite-based precipitation and estimates derived from Cold Cloud Duration (CDD) infrared observations, along with surface precipitation observations collected by rain gauges through an intelligent interpolation algorithm.

Many international papers have used CHIRPS for studying extreme climatological events [7-9]. Throughout the country, studies have also been employing CHIRPS data for climate variability, allowing for a better understanding of nationally precipitation patterns and climate change. These data are valuable for decision-makers, enabling them to implement disaster risk reduction policies and climate adaptation measures more effectively.

For instance, Marengo et al. (2017)[7] used CHIRPS data to analyze the characteristics of extreme precipitation events in the southeast region of Brazil and their relation to large-scale atmospheric circulation patterns. Palharini et al. (2022)[10] utilized various precipitation products, including CHIRPS, to identify and analyze extreme rainfall events in different regions of the country, such as the South, Southeast, and Northeast, and how these extreme events are linked to natural disasters caused by flash floods and landslides. Among other findings, the authors showed that extreme rainfall events are becoming more frequent in some regions of Brazil, especially in the Northeast.

In addition to applications in evaluating extremes related to extreme rainfall, CHIRPS is also used to assess precipitation deficit events. For example, Melo et al. (2018)[11] analyzed droughts in the Northeast of Brazil using the Standardized Precipitation Index (SPI), suggesting that the region has experienced an increase in the intensity and frequency of droughts in recent years, potentially linked to climate change.

Objective

This study aimed to provide a national-level database regarding precipitation events with the potential to trigger landslides, to guide subsequent analyses concerning the climatic risks in Brazilian territory and, eventually, support decision-making related to disaster risk reduction actions and climate change adaptation measures.

Scope

The focus of this study is to present a database with quantitative information on rainfall events that have the potential to trigger landslides. This database is organized for all Brazilian municipalities and serves to complement the studies presented by this subcomponent in the first and second year of INCT-II. The term "potential" is used because this type of information reflects only the climatic dimension related to the risk of landslides. It expresses the probability of occurrence of heavy and/or intense rainfall events, which theoretically have a higher statistical relationship with landslides.

In the literature, the climatic dimension of “risk” is also referred to as "climatic hazard," expressing the probability of certain meteorological/climatic events occurring, considering different magnitudes, which can lead to other physical processes (in this case, landslides) that cause impacts on human and/or natural systems.

However, the risk of landslides depends fundamentally on other characteristics, especially the geological-geotechnical and geomorphological conditions (slope, hillside amplitude, soil thickness, soil type, mechanical properties, lithology, among others), as well as the level of human interference at the local level. These characteristics vary for each location but will not be directly addressed in this study. The combination of these features results in different levels of slope susceptibility, which can lead to movement when specific volumes of rainfall on the soil, infiltration, and, once certain threshold conditions are exceeded, lead to its rupture, causing landslides (or other types of mass movements).

Thus, for a better representation of the climatic risk related to landslides, it is recommended that the information provided regarding the "climatic hazard" be combined with other dimensions that compose the risk. Besides susceptibility, these dimensions may also include the level of population exposure (the number of people living in areas with high and/or very high susceptibility), their vulnerabilities, and, depending on the approach, their capacity for coping and/or adapting to climate change.

2. Methodology and Data

2.1. Observational Precipitation Data

The database used for quantifying rainfall events with the potential to trigger landslides was the CHIRPS[6]. This product is a collection of over 40 years of precipitation data covering nearly the entire globe, with daily temporal resolution from 1981 to the present, and a spatial resolution of 0.05° (approximately 5 km). This dataset incorporates climatological satellite-based precipitation estimates derived from Cold Cloud Duration (CDD) infrared observations, along with surface precipitation observations collected by rain gauges through an intelligent interpolation algorithm.

CHIRPS has been employed to study climate variability throughout the country, allowing for a better understanding of precipitation patterns and climate change. These data are valuable for decision-makers, enabling them to implement disaster risk reduction policies and climate adaptation measures more effectively.

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2.2. Rainfall Thresholds for Landslides

In general terms, thresholds can be defined as pre-known values of rainfall volumes within a specific time window (1 hour, 6 hours, 24 hours, 48 hours, etc.) that, once surpassed, represent significant probabilities of landslides occurrence in a particular region. In Brazil, several studies have been conducted since the 1960s with the objective of finding thresholds related to landslide triggering, with notable researchers like Pichler (1957)[12], Vargas (1971)[13], Barata (1969)[14], among others, as highlighted by Guidicini & Iwasa (1977)[15] and Tatizana et al. (1987a)[16].

Later, Tatizana et al. (1987a, b)[16,17] assessed the numerical relationship between accumulated rainfall and hourly intensity that triggers these processes using the same logic of finding correlations between precipitation events, occurrences, and non-occurrences of landslides. They conducted retroanalysis studies of landslide events in the Serra do Mar region, Cubatão-SP. The studies presented by Tatizana et al. (1987a, b)[16,17] was fundamental references for other works in different regions of Brazil, attempting to find the relationships between precipitation intensity (mm/h) and/or daily precipitation (24h) concerning the antecedent accumulated rainfall before landslide occurrences. Notable works include those carried out by Coutinho (2002)[18], for the municipality of Blumenau (SC), Ide (2005)[19], for the municipality of Campinas (SP), Castro (2006)[6], for the municipality of Ouro Preto (MG), Bandeira (2010)[8], for the Metropolitan Region of Recife (PE), Parizzi et al. (2010)[20] for the municipality of Belo Horizonte (MG), Mendes et al. (2015)[21], for the municipality of São José dos Campos (SP), Soares (2015)[22], for the municipality of João Pessoa (PB), Metodiev et al. (2018)[23], for the Baixada Santista and Litoral Norte of the state of São Paulo, among others.

2.3. Assumptions

There are many thresholds for different Brazilian regions, but the method applied in this study accounted for events that historically exceeded the threshold of 50mm in 24 hours for all Brazilian municipalities. The choice of this specific threshold is based on several theoretical and empirical factors. Firstly, critical thresholds are not known for all Brazilian municipalities, necessitating an estimation that could represent, albeit preliminarily, the spatial variability of locations with a higher frequency of events potentially triggering landslides.

Although most Brazilian municipalities with a previous register of landslide-related disasters have operational thresholds higher than 50 mm/24h, there are several landslide occurrences recorded by Cemaden (REINDESC - Records of Flood and Landslide Events from Cemaden) in situations of rainfall around 50 mm, especially in cases where these rains were intense and concentrated in shorter periods (30 minutes, 1 hour, 2 hours, etc.). However, these events would not be possible to identify through the observed precipitation database (CHIRPS) because its available temporal resolution (daily, values in 24 hours). This allegation is also supported by several studies, notably the one by Tatizana et. al (1987a), which identifies this value (50mm) as the lower limit for triggering induced landslides (where there is human interference), provided that the rains are of high intensity (greater than 35 mm in 30 minutes).

Furthermore, the observed precipitation database used as a reference typically has limitations that tend to underestimate the measured rainfall values in a large part of the Brazilian territory, except for the extreme South (Palharini et. al, 2022). For this reason, the good quality of results could be compromised if higher thresholds were used, as many potentially landslide-triggering events would not be accounted for in practice

Therefore, it is understood that the number of days exceeding the value of 50 mm in 24 hours is a good representative to express the influence of the climatic dimension in the composition of the risk associated with landslides. As an additional contribution, the quantities of days exceeding higher thresholds, such as 100 mm and 150 mm in 24 hours, are also presented, but they were not used for the validation stage due to the limitations of CHIRPS data in estimating higher (extreme) rainfall values (i.e., high associated uncertainty).

2.4. Quantification of events that exceeded the thresholds

CHIRPS data was processed in its original format (.netcdf) at a resolution of 0.05º (approximately 5 km), covering the period from 1992 to the end of 2022, resulting in a 30-year historical series (over 10,950 days) that encompasses the entire Brazilian territory.

Using developed scripts, new fields were generated to quantify the total number of days when the total precipitation value exceeded the thresholds of 50mm, 100mm, and 150mm, for all original CHIRPS grid points.

The results were converted into spatial matrix (GEOTIFF format), which were subsequently transformed into vectors, generating point shapefiles. Each point representing the spatial location of the centroid of each original CHIRPS grid point.

Due to the high spatial resolution of the data (5 km), practically all Brazilian municipalities had more than one point within their political territory. This could lead to different results regarding the number of potentially triggering landslide events, especially for municipalities with large territorial extensions. To address this, the method used to obtain a single unique result per municipality was to use the urban area as a spatial reference and apply the Spatial Join function of the ArcGIS® software, using the "Average" Merge Rule.

The results are shown in the following table for the 40 municipalities with the highest number of occurrences, under the column "Days with rainfall above 50mm," displaying the absolute values found in the historical series between 1992-2022 (see Table 1). Additionally, the average per year (total divided by 30 years) is also provided. Finally, information about the number of days exceeding 100mm and 150mm is included, calculated in the same manner as the 50 mm threshold, as described above (previously). In sequence, it was developed a map using the same information about days with rainfall above 50mm, presented in Figure 1.

2.5. Trend analysis for individual cases

In addition to the steps described above, analyses were also conducted regarding the observed trend during the evaluated period (1992-2022) for some Brazilian municipalities. The analysis evaluated big Brazilian cities in different regions of the country, aiming to provide preliminary information about ongoing climate change and their influence on the occurrence of intense rainfall events, particularly those exceeding 50 mm/24h. The cities chosen for these analyses were Blumenau (SC), São Paulo (SP), São Luís (MA), Salvador (BA), Maceió (AL), and Manaus (AM).

For the graph's elaboration, the CHIRPS grid point from which the rainfall data were extracted was the one with the highest number of days above 50 mm within the municipal domain. The graphs were generated without any type of smoothing, and the trend line follows the linear method, automatically generated by Microsoft Excel.

The percentage increase values displayed on the graphs, accompanied by an arrow, were calculated by dividing the value obtained from the trend line formula in 2022 (x=30) by the value in 1992 (x=0), suggesting the current average increment compared to the beginning of the historical series (1992). For instance, a value of +30% represents that in recent years, on average, there has been a 30% higher frequency of days with rainfall exceeding 50mm when comparing the data from the early 1990s. The arrows in yellow, orange, and red represent the intensity of discreet, moderate, and high increases, respectively.

3. Results and Discussions

This item presents the results obtained after applying the methods described previously and the associated discussions.

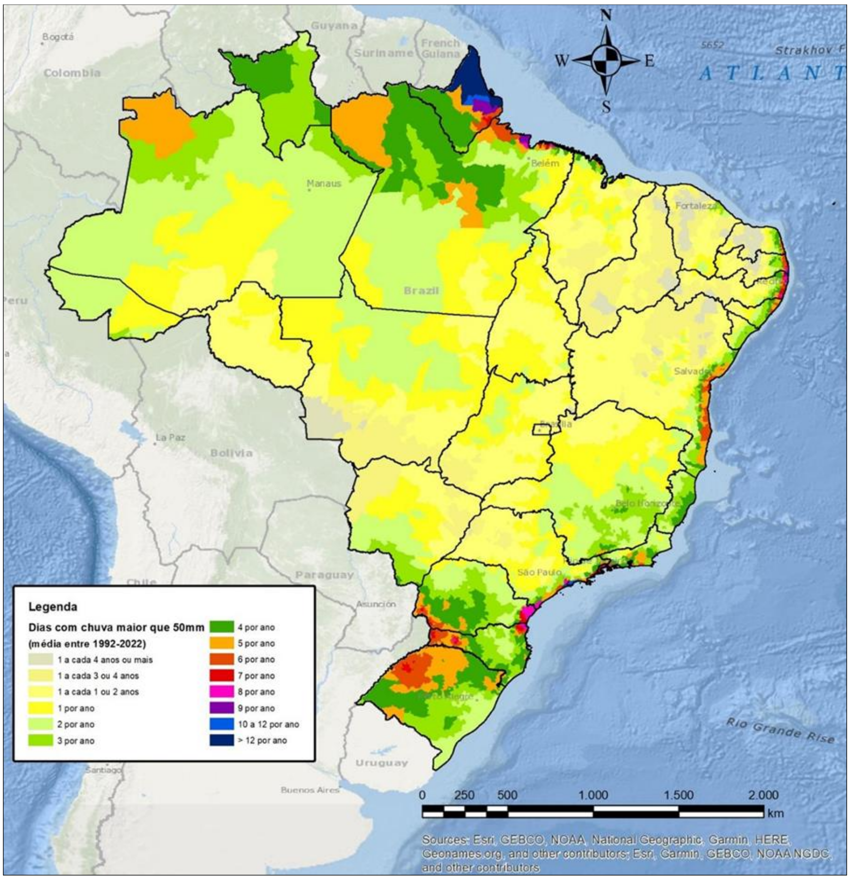

Figure 1 Map of annual average of Quantity of days with rainfall above 50 mm for all Brazilian municipalities. Source of original rainfall data: CHIRPS

Table 1 List of 40 municipalities with highest number of daily rainfalls above 50mm between 1992-2022. Source of original rainfall data: CHIRPS

State	Municipality	Days with rainfall above 50mm (1991-2022)	Average days per year with rainfall above 50mm	Days with rainfall above 100mm (1991-2022)	Days with rainfall above 150mm (1991-2022)
AP	Calçoene	510	17.0	62	12
AP	Oiapoque	423	14.1	53	12
AP	Amapá	394	13.1	37	6
SP	Cubatão	383	12.8	38	4
SP	Guarujá	379	12.6	40	6
SP	São Vicente	377	12.6	48	4
SP	Santos	374	12.5	39	3
SP	Bertioga	365	12.2	30	3
AP	Pracuúba	353	11.8	32	5

SP	Praia Grande	350	11.7	45	4
PB	Pitimbu	387	9.6	116	61
PB	Caaporã	287	9.6	100	56
SP	Mongaguá	286	9.5	36	2
PA	Soure	277	9.2	13	0
AP	Tanarugalzinho	276	9.2	17	2
SC	Itapoá	275	9.2	30	6
PE	Olinda	268	8.9	99	51
PE	Recife	261	8.7	98	55
PA	Salinópolis	261	8.7	16	2
AP	Cutias	258	8.6	11	1
PE	Goiana	256	8.5	90	48
PB	Cabedelo	252	8.4	97	52
PR	Paranaguá	252	8.4	28	4
PE	Ilha de Itamaracá	251	8.4	103	54
PR	Pontal do Paraná	251	8.4	31	4
PE	Tamandaré	249	8.3	94	48
SC	São Francisco do Sul	249	8.3	23	4
PE	Itapissuma	240	8.0	88	52
RJ	Angra dos Reis	237	7.9	26	3
SP	Cananéia	236	7.9	26	3
PE	Rio Formoso	236	7.9	24	3
PA	São João de Piribas	236	7.9	11	0
PB	Conde	235	7.8	87	46
PE	Paulista	234	7.8	99	48
SP	São Bernardo do Campo	234	7.8	17	2
PB	Alhandra	233	7.8	85	40
SC	Xanxerê	232	7.7	10	0

In summary, the results from Figure 1 and Table 1 indicate that certain regions of Brazil stand out for their high frequency of events exceeding 50 mm compared to others, such as:

- The extreme North of Brazil, particularly the State of Amapá;
- Part of the eastern Southeast region, especially the North Shore of São Paulo State and the Southern Coast of Rio de Janeiro State;
- The eastern portion of the Northeast of Brazil, particularly the coastal areas of Pernambuco and Paraíba States.

Although some municipalities in the State of Amapá have recorded the highest quantities of intense rainfall events, this region does not have a high susceptibility to landslides, nor does it have a significant number of people exposed and vulnerable to this type of disaster. However, the results could be important to show the propensity of this region be impacted by quick hydrological process, like flashfloods.

On the other hand, the coastal areas of the States of São Paulo and Rio de Janeiro are regions with many cities experiencing urban expansion towards the steep slopes of the Serra do Mar, creating high-risk scenarios. This combination of extreme “climatic hazard”, high local susceptibility, and a large population exposed and vulnerable is reflected in the recurring disasters during the last decades, highlighting the São Sebastião disaster in 2023, where the highest 24-hour rainfall in the history of Brazil was recorded in the neighboring municipality of Bertioga-SP. Other recent notable disasters have also occurred in Santos-SP, São Vicente-SP, Cubatão-SP, Guarujá-SP, and Angra dos Reis-RJ, which appear among the top 10 municipalities with the highest number of events in Table 1.

Other areas with high recurrence of daily rainfall above 50mm include the western regions of the States of Santa Catarina and Paraná; the coastal strip between the northeastern part of Santa Catarina, the eastern of Paraná, the southern coast of São Paulo; and the entire southern coast of Bahia and the Recôncavo Baiano. All of these regions also have a history of landslide-related disasters and, together with the previously mentioned ones, constitute the most impacted regions in Brazil by landslides caused by intense rainfall. The only regions that do not appear prominently in the results (both in Table 1 and in the Map of Figure 1), but have a considerable history of landslide-related disasters, are the Rio de Janeiro Mountain Region and the Metropolitan Regions of Belo Horizonte (MG), Vitória (ES), and Manaus (AM).

Although these areas do not have several occurrences of intense rainfall events recorded by CHIRPS, the results indicate that, on average, there are 4 rainfall events above 50 mm/24h per year, which represents an intermediate situation compared to all the results found for Brazil. Therefore, it is possible that the large number of previous disasters in these regions is more strongly linked to the high susceptibility of landslides and the high exposure of vulnerable population living in the slopes. In these cases, non-climatic conditioning factors are likely to be more representative in explaining the disasters of recent decades than the climate hazard. Another possibility is that the CHIRPS data may be underestimating the rainfall data, which requires further in-depth evaluations to test this hypothesis.

Figure 2 presents the results of trend analysis for Blumenau (SC), São Paulo (SP), São Luís (MA), Salvador (BA), Maceió (AL), and Manaus (AM).

The individual analyzes presented in Figure 2 indicates a pattern of increasing in daily rainfall events higher than 50mm. For Blumenau-SC and São Paulo-SP, the trend is discrete and there is little evidence of a systematic change in historical patterns of extreme events. However, it should be noted that the trend increasing is greatly influenced by some years that recorded values much higher than the average, with emphasis on some years in the period between 2006 and 2011, in both cases. During this period, two strong La Nina events occurred, which may be related to the increase in recorded extreme events. One of the explanations is that La Nina favors the passage of stronger cold fronts in these regions, which are responsible for causing massive and intense rainfall events, especially during the summer and in regions that are affected by the orographic effect.

For the other regions, the trend of increasing in extreme events is more evident, although there is high interannual variability. In these cases (São Luis-MA; Salvador-BA; Maceió-AL and Manaus-AM), it is likely that global climate changes may already be directly favoring the intensification of extreme rainfall events. This type of evidence requires special attention, given that these locations have complex scenarios of geo-hydrological risks established in their territories and a systematic increase in extreme rainfall events may indicate an exponential increase in economic and human losses.

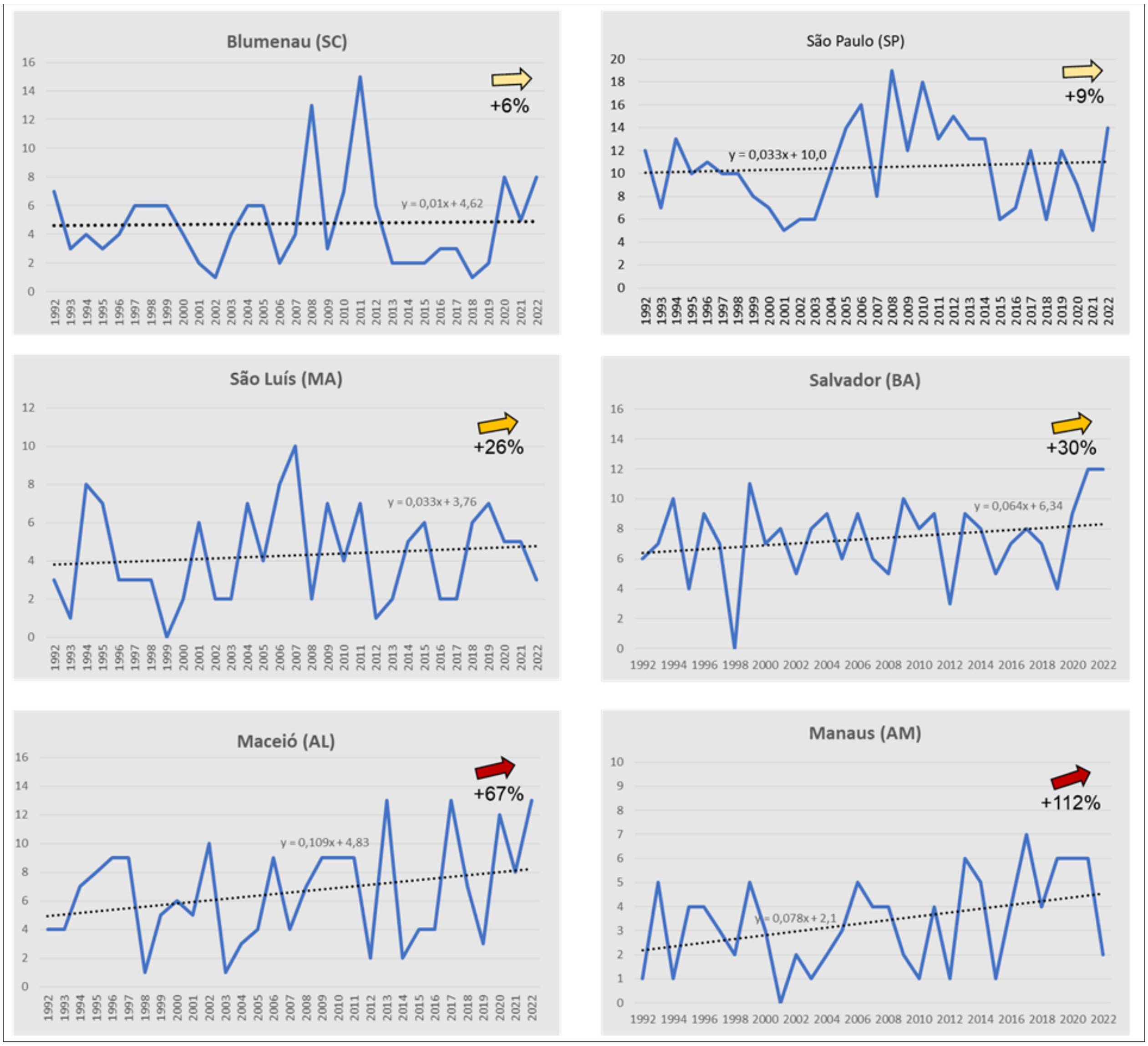

Figure 2 Graphs of temporal distribution of the number of days above 50 mm between 1992-2022 and linear trend line. The arrows in yellow, orange, and red represent the intensity of discreet, moderate, and high increasing, respectively

4. Conclusion

This study has systematically analyzed rainfall events across Brazilian municipalities, highlighting their potential to trigger landslides and flash floods. By employing the CHIRPS dataset and established a simple rainfall thresholds, we have provided a comprehensive overview of climatic hazards associated with geo-hydrological risks on a national scale The results indicate Brazilian regions that are more likely to be impacted by intense and heavy rainfall events, highlighting the western portion of the South Region (states of Rio Grande do Sul, Santa Catarina, and Paraná), the eastern portion stretching from Santa Catarina to Rio de Janeiro, especially coastal cities; as well as much of the eastern coast of the Northeast Region (Bahia, Alagoas, Pernambuco, and Paraíba) and the extreme North of the country, especially in the states of Pará and Amapá. With the exception of locations in the state of Amapá, all these regions have a vast history of geo-hydrometeorological-related disasters, which underscores the high vulnerability of municipalities in these regions, as well as their low cope capacity, emphasizing the urgent need for localized disaster risk reduction strategies and climate change adaptation measures. Importantly, the study reveals an increasing trend in extreme rainfall events in several municipalities, demanding enhanced monitoring and preparedness to mitigate potential impacts. This research contributes to a better understanding of the relationship between rainfall events and geo-hydrological risks, ultimately aiding in the development of more effective disaster management and climate resilience strategies. As such, it offers valuable insights for policymakers, urban planners, and communities, guiding efforts towards safeguarding lives and properties against the backdrop of changing climate patterns and their associated risks.

Compliance with ethical standards

Disclosure of conflict of interest

The author declare that she has no competing interests.

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