Identification of extreme rainfall events and disasters triggered by rain in the city of Petrópolis-RJ

Identificação de eventos extremos de precipitação e desastres deflagrados por chuvas no município de Petrópolis-RJ

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ABSTRACT

The municipality of Petrópolis/RJ/Brazil is prone to extreme rainfall events that cause damage and direct and indirect economic losses. In order to verify the increase or not of these events, this study evaluates the temporal pattern of rainfall in the municipality (1976-2022), identifying whether the event that occurred in 2022 can be considered an extreme event, as well as the relationship between rainfall and impact intensity, in terms of damage and losses triggered. The accumulated rainfall over 24 hours (RX1), over 5 days (RX5), the 95th and 99th percentiles (R95 and R99), the Rainfall Anomaly Index (RAI) and trend analyses using the Mann-Kendall method, as well as loss and damage data were then calculated. The results did not indicate a trend towards an increase in precipitation extremes, although they did confirm the February 2022 event as an extreme event, which stood out as the largest within the historical series analysed.

Keywords: Precipitation extremes. Petrópolis-RJ. Rain-related disasters. Occurrence of disasters.

RESUMO

O município de Petrópolis-RJ, Brasil, está exposto a eventos extremos de precipitação, que resultam em danos e perdas econômicas diretas e indiretas. Para verificar o aumento ou não desses eventos, o objetivo foi avaliar o padrão temporal das chuvas no município (1976-2022), identificando se o evento ocorrido em 2022 pode ser considerado um evento extremo, bem como a relação entre pluviometria e intensidade do impacto, em termos dos danos e perdas deflagrados. Foram então calculados os acumulados de precipitação em 24 horas (RX1), em 5 dias (RX5), percentis 95 e 99 (R95 e R99), Índice de Anomalia de Chuvas (IAC) e análises de tendência pelo método Mann-Kendall, bem como dados de perdas e danos. Os resultados não indicaram viés de aumento dos extremos de precipitação, embora tenha confirmado o evento ocorrido em fevereiro de 2022 como um evento extremo, o qual se configurou como o maior da série histórica analisada.

Palavras-chave: Extremos de precipitação. Petrópolis-RJ. Desastres relacionados à chuva. Ocorrência de desastres.

1 INTRODUCTION

Since the 1990s, reports from the Intergovernmental Panel on Climate Change (IPCC) have been published regarding climate-related changes and expectations on a global scale, including significant alterations in the magnitude and frequency of extreme meteorological phenomena (IPCC, 2012, 2021). The most recent report also indicates an increased impact on ecosystems, populations, and settlements due to anthropogenic climate change (IPCC, 2022).

To comprehend the damages associated with extreme meteorological events, it is imperative first to recognise these occurrences. The World Meteorological Organization (WMO) defines them as meteorological events that deviate significantly from average conditions, considering a historical series of at least 20 years, and having the potential to pose hazards or significant impacts on human activities and the environment (IPCC, 2022).

Given the vulnerabilities inherent in the territory and the predisposition of exposed elements to suffer losses and damages, extreme meteorological events can trigger disasters of varying severity (COUTINHO *et al*., 2020; DEBORTOLI *et al*., 2017; IPCC, 2012; LAHSEN; RIBOT, 2020).

In tropical regions, there is evidence of an increasing frequency and intensity of heavy rainfall events, resulting in various impacts amplified by the limited adaptive capacity of developing countries (PRABHAKAR *et al*., 2009).

In Brazil, a significant portion of disaster occurrences is caused by phenomena triggered by rainfall, such as flash floods, inundations, and mass movements (PAINEL BRASILEIRO DE MUDANÇAS CLIMÁTICAS, 2014). Considering the projected rise in average air temperatures due to climate change, an expectation of more frequent extreme rainfall events emerges, thereby increasing the likelihood of disasters. To examine this hypothesis and formulate adaptation strategies for the country, it is essential to monitor extreme events within the territory.

The mountainous region of the state of Rio de Janeiro serves as an example of a city experiencing cascading effects from intense precipitation. In January 2011, a disaster resulted in damages and losses in at least seven municipalities, including Petrópolis, with an approximate toll of 947 casualties (DOURADO *et al*., 2012).

Petrópolis is recurrently affected by heavy rainfall and has records of disasters dating back to 1950 (ASSUMPÇÃO, 2015). More recently, between January and March 2022, three episodes of intense rainfall associated with Local Convective Storms caused severe impacts on the population. The most severe event occurred on February 15, resulting in the death of at least 234 people (ALCÂNTARA *et al.*, 2022; GRUBERTT, 2022).

Considering these alarming figures, inquiries arise regarding measures that could be undertaken to mitigate the risk of rainfall-triggered disasters in this region. Recognising that risk knowledge is one of the four fundamental pillars for disaster risk reduction, the objective of this study was to analyse the temporal pattern of extreme rainfall events (threat), determining whether the event in 2022 can indeed be classified as extreme, as well as exploring the relationship between rainfall and impact intensity in terms of damages and losses incurred in the municipality

2 MATERIALS AND METHODS

2.1 STUDY AREA

The municipality of Petrópolis is situated at the geographic coordinates of 22°30'17" South latitude and 43°10'42" West longitude, within the Serrana Region of the State of Rio de Janeiro. As indicated by the Geotechnical Suitability Map issued by the Geological Survey of the State of Rio de Janeiro, the combined area exhibiting moderate and high susceptibility to mass movements accounts for 64.06% of the municipality.

According to data from the year 2022, Petrópolis is estimated to harbour a population of 278,881 inhabitants, boasting a demographic density of 352.50 individuals per square kilometre (IBGE, 2022). Over the course of eight decades, the municipality has experienced a fourfold population increase, surging from 75.4 thousand inhabitants in 1940 to 278.881 thousand inhabitants in 2022 (IBGE, 1940, 2022).

As of the 2010 Census (the latest data available at the time of this publication), the population of Petrópolis stood at 295,917 individuals, of which 72,070 individuals (equivalent to 24.35%) resided within areas deemed prone to risks, distributed across 22,298 households (CEMADEN; IBGE, 2018). Despite this circumstance, the municipality displayed a Municipal Human Development Index (IDHM) of 0.745 (IBGE, 2010), signifying a level considered high and falling within the national average for Brazil, where the national HDI stood at 0.727. According to the Petrópolis municipal administration, the current IDHM for the locality has risen to 0.804, even in the face of adverse events encountered within the past decade, while the national figure for Brazil has declined to 0.724.

2.2 DATA

The rainfall data used in this work come from the automatic measurement station Xerém, belonging to the Inmet network, located in Duque de Caxias (-43° 30' 14.004" S, 22° 55' 33.996" W). This station is the closest to the study area (approximately 15 km) and has the longest historical series. In a complementary way, precipitation data from the São Sebastião station, belonging to the National Center for Monitoring and Alerts of Natural Disasters (Cemaden), located in the municipality of Petrópolis, were also used.

The analysis period of this study was established between 1976 and 2022 due to the availability of the largest amount of data in this interval. Although it is a long period, it is important to highlight that the data from the meteorological stations present some failures, which were corrected by using interpolated average rainfall values from the data of the Climate Hazards Group InfraRed Precipitation with Station data – Chirps (FUNK *et al*., 2015) and the Merge Product of the Center for Weather Forecasting and Climate Studies (MERGE; ROZANTE *et al*., 2010). These rainfall data sets have a spatial resolution of approximately 5 km and 10 km, respectively. A similar methodology was developed by Costa *et al*. (2019), who proposed to validate precipitation data in Brazil using Chirps data; Costa identified a compatibility of 95.4% between Inmet and Chirps data, which legitimises the use of these data to complete the gaps in the historical series selected for this study. Thus, from precipitation data from the meteorological stations of Xerém and São Sebastião and complemented by Chirps and Merge data, a time series of daily precipitation data from 1976 to 2022 was constructed.

2.3 METHODS

2.3.1 CLIMATE INDICES

The indices calculated to help understand the temporal pattern of precipitation in the municipality of Petrópolis and identify the extreme values were:

- Pt - Annual total precipitation
- Pmed - Annual average precipitation
- Ptri - Sum of the quarterly moving average
- R95 - Number of days when daily precipitation was greater than 95% of the precipitations of the period
- R99 - Number of days when daily precipitation was greater than 99% of the precipitations of the period
- RX1 - Maximum annual value in one day of precipitation
- RX5 - Maximum precipitation value in five consecutive days

2.3.2 RAINFALL ANOMALY INDEX

In addition to the indices presented, the Rainfall Anomaly Index (IAC) was also calculated, which considers the average of the ten highest rainfall events that occurred within the analysis period, as well as the average of the ten lowest, with positive anomalies being those above the average and negative anomalies being those below the average. The IAC is classified in terms of dry and wet periods, as proposed by Rooy (1965) and adapted by Freitas (2005). The anomalies can be expressed as follows:

Positive anomalies

$$IAC = 3\left[\frac{(N - \underline{N})}{(\underline{M} - \underline{N})}\right]$$

Negative Anomalies

$$IAC = -3\left[\frac{(N - \underline{N})}{(\underline{X} - \underline{N})}\right]$$

Where N is the monthly precipitation, _N is the average of the series, _M is the average of the ten highest precipitations, and _X is the average of the ten lowest precipitations. Still, according to the index, the rainfall classification varies from extremely rainy to extremely dry.

2.3.3 MANN-KENDALL TEST

The Mann-Kendall test (KENDALL, 1975; MANN, 1945) is a nonparametric test suggested by the World Meteorological Organization (WMO) to verify if the series have statistically significant temporal trends and has been used with great efficiency. Thus, for the trend to be confirmed, the p-value must be less than 0.05%, representing a confidence of 95%. Thus, the test was applied to identify possible trends in the temporal pattern of annual precipitation and the indices RX1, RX5 and IAC.

2.3.4 METHODOLOGIES USED TO CALCULATE LOSSES AND DAMAGES

After analysing the threat of extreme rainfall events, we performed analyses of the damage and losses caused by rain-related disasters in the municipality of Petrópolis. These analyses were based on data from the Integrated Disaster Information System (S2iD), which incorporates several products from the National Secretariat for Protection and Civil Defense – Sedec (BRAZIL, 2022). The historical series used corresponds to the period of data available for Petrópolis, 2001 - 2022. The typologies used in the classification of disasters in this database follow the Brazilian Disaster Coding – Cobrade. In S2iD, the impact data are grouped into four categories: human damage (DH), material damage (DM), public losses (PEPL) and private losses (PEPR), the same ones used in the present analysis. The DM, PEPL, and PEPR values received monetary correction in December 2022 and were synthesised in a single variable representing the total damage and losses (D&L: damage and losses in English), converted to US dollars. A summary of the methodological steps developed can be seen in Figure 1.

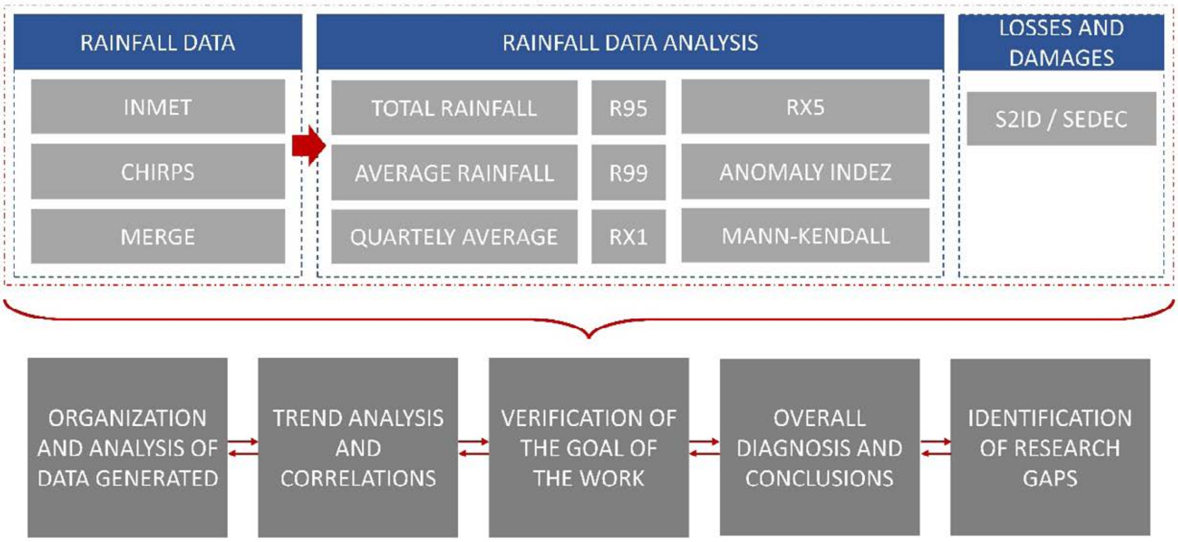

Figure 1 | Infographic with methodological steps

Source: The authors.

3 RESULTS AND DISCUSSION

3.1 ANALYSIS OF THE TEMPORAL PATTERN OF EXTREME PRECIPITATION EVENTS

In the period from 1976 to 2022, the average monthly rainfall remained more or less constant around the multi-year monthly average (Figure 2), in a standard deviation range of 77 mm, except for the year 1999, with a negative extreme of 5.5 mm (one time lower than the average) and 2022, with a positive extreme of 358.6 (three times the average).

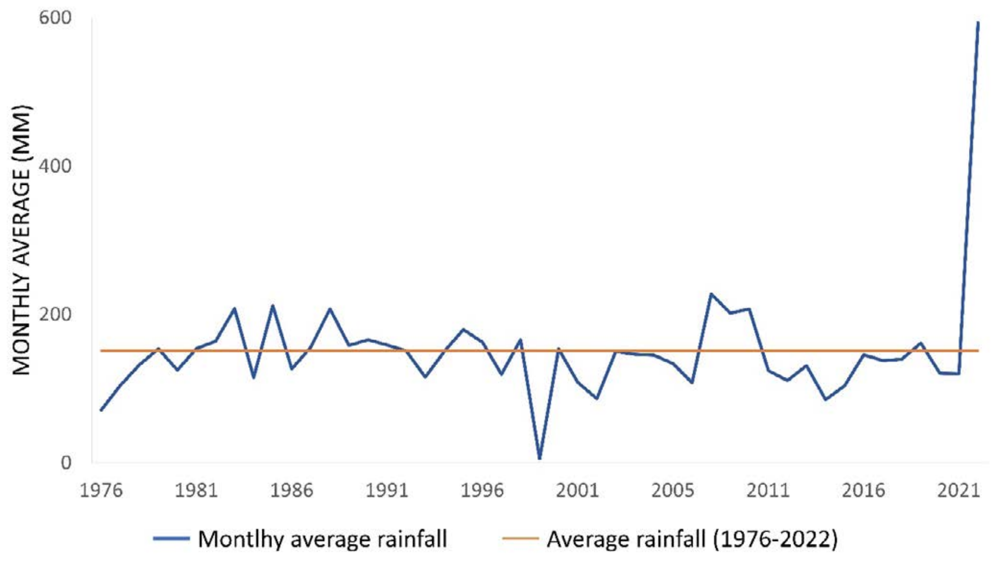

Figure 2 | Average monthly accumulated and multi-year monthly precipitation average in Petrópolis

Source: The authors.

The results of the Mann-Kendall test indicated a trend of reduction in rainfall volume over the period but did not show statistical significance. This result corroborates the analysis performed by Silva *et al*. (2023), who, when analysing the climatic trend of Petrópolis, did not find the presence of a trend by the Ljung-Box and Mann-Kendall tests and diverges from the analyses of Oscar Júnior (2021) that indicates that there is a statistically significant trend of increase in monthly rainfall in Petrópolis, although the authors used different time series.

The concentration of rain in certain periods of the year was also evaluated for the series. The analysis of quarterly moving averages of precipitation indicated that the quarter November - December - January had the highest monthly average of rainfall, followed by the quarter December - January - February, preceding the rainy season. In this season, the two events with the highest number of victims occurred: January 11, 2011, and February 15, 2022. According to Silva *et al*. (2020), rainfall accumulation between October and March occurs due to the meteorological system South Atlantic Convergence Zone, which acts strongly in the region, generating local storms. Although they are not conclusive about the motivation of the events, these results indicate that prevention and response actions to possible extreme precipitation events must precede the beginning of the rainy season in the region, in addition to requiring a greater focus on medium and long-term actions.

Beck (2023) points out that there are already actions in this direction under development in the municipality, such as a study for creating barriers to contain mass movements and the Municipal Risk Reduction Plan, both as part of a plan to make the city more resilient. Although extreme events have unique characteristics, they can be part of regional events or even be triggered by specific characteristics of the place, so it is necessary to have a consolidated diagnosis of the area that allows effective actions in favour of resilience and involving not only pluviometric analyses. In this sense, Alcântara *et al*. (2023) indicate that other factors, such as the removal of native vegetation, population growth in areas with slopes between 45-60º and lack of urban planning, contribute significantly to the occurrence of disasters in the municipality.

Still, regarding the analysis of precipitation data, the extremes of rainfall were also evaluated using the RX1 index, which returns the maximum precipitation values in 24 hours for each year (Figure 3). The highest rainfall volume of the entire time series occurred on March 21, 2022, with a total of 358.6 mm, followed by February 12, 1998, with 301.4 mm. The Mann-Kendall test did not show a significant change trend in the maximum rainfall value.

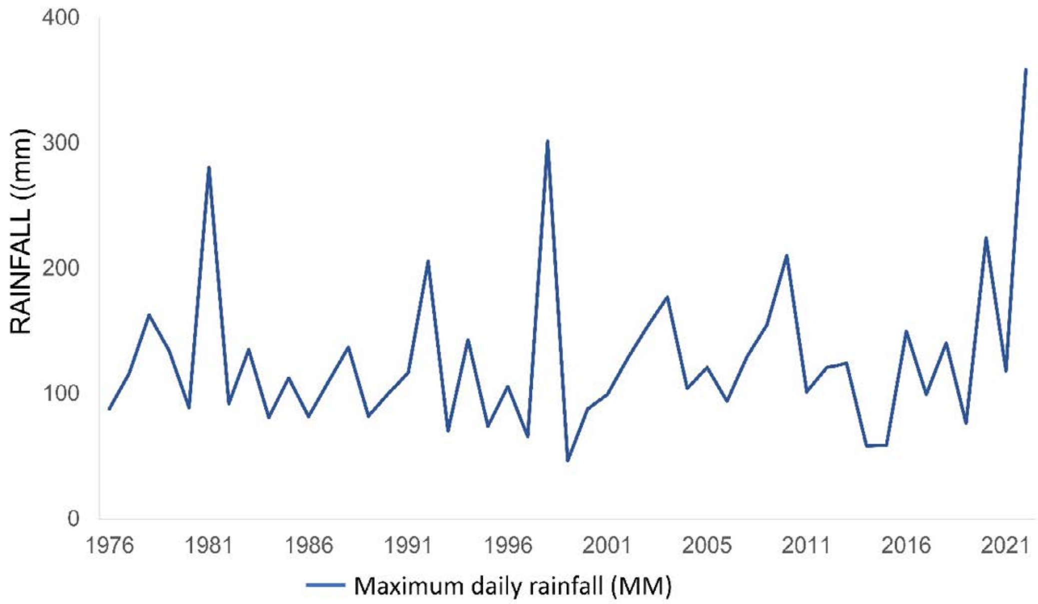

Figure 3 | Temporal evolution of the RX1 index for the municipality of Petrópolis

Source: The authors.

It should be noted that, concerning the daily data, the rain gauge installed by Cemaden in the São Sebastião neighbourhood, the main neighbourhood affected by the rains of 2022, recorded 260 mm of accumulated precipitation in two and a half hours on February 15, 2022, and 476.8 mm accumulated in 24 hours between March 20 and 21, while the rain gauge in the Quitandinha neighbourhood, about 3 km away, marked 200 mm, indicating that the event may have been extremely concentrated.

Unfortunately, due to the reduced number of rain gauges in the municipality, including a historical series of them, it is impossible to confirm whether this concentration existed or is recurrent, as the data indicate. Despite this, following this line, Oscar Júnior (2021) indicated a trend of reduction in the number of rainy days with an increase in the concentration of rainfall in daily events or up to five consecutive days for the municipality. Regarding the maximum volume of rainfall accumulated in five days (RX5), it was not possible to verify a trend of increase in the number of rainy days by the Mann-Kendall test. When analysing the 95th percentile of the historical series, an average of 17 rainy days per year above the average of the series is observed (Figure 4).

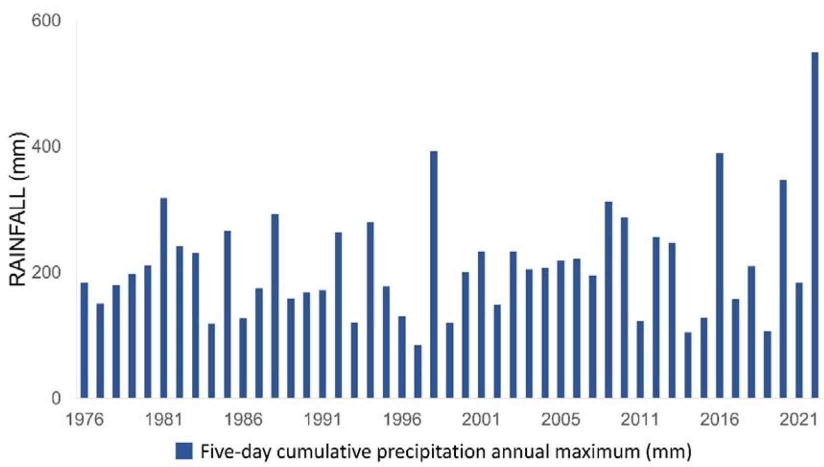

Figure 4 | Temporal (annual) distribution of the RX5 index in the city of Petrópolis

Source: The authors.

The 95th percentile for the maximum values of accumulated rainfall in five days (RX5) presents the value of 376.1 mm, and the 99th percentile shows 477.07 mm, both below the value of rainfall accumulated in five days in 2022, which in just one day the precipitation was 358.6 mm. This result confirms the exceptionality of the event in February 2022, which allows its classification as an extreme event.

Still aiming to understand the dynamics of rainfall distribution, the Rainfall Anomaly Index (IAC) calculated pointed out 26 extremely rainy, very rainy or rainy years, 26 dry and two very dry years (Figure 5). However, it was not possible to correlate whether the years with the highest positive anomalies resulted in a higher number of victims or even any trend (by the Mann-Kendall test) that the number of positive or negative anomalies is increasing, it was possible to observe that the year 2022 had the highest positive anomaly of the period, further confirming the exceptionality of the event.

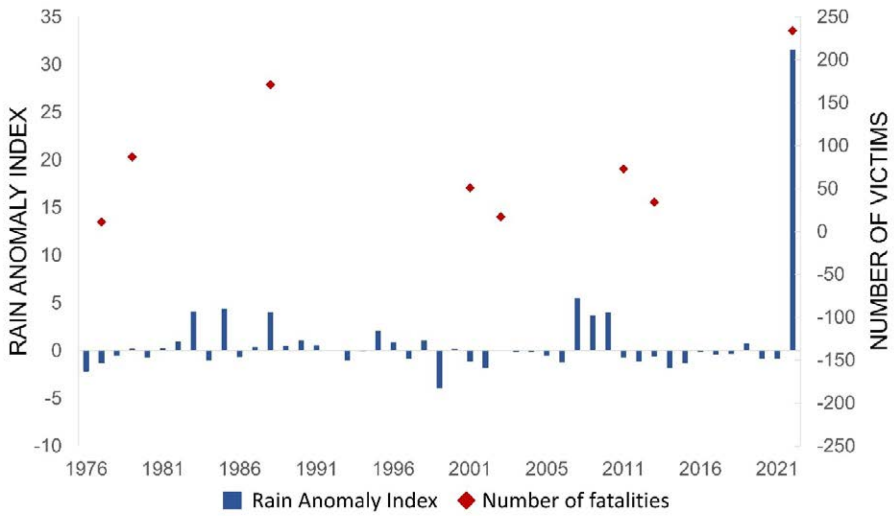

Figure 5 | Climate Anomaly Index (CAI) and years with fatalities in the city of Petrópolis

Source: The authors.

The occurrence of anomalies may be associated with the presence of other meteorological events, such as the South Atlantic Convergence Zone (SACZ) or even Frontal Systems, which enhance rainfall, causing river flooding, facilitating the occurrence of landslides and mass movements and, consequently, loss of lives (SILVA *et al*., 2020), recurrent events in the municipality of Petrópolis. In the specific case of the event in 2022, Alcântara *et al*. (2023) indicate that the SACZ was positioned over Rio de Janeiro, favouring atmospheric convection and consequent meteorological instability.

The data presented throughout the work corroborate studies that indicate that this region has undergone a change in the climatic scenario that, although it does not significantly affect the total annual rainfall amount, changes the distribution, leading to an increase in the probability of occurrence of extreme precipitation events, more specifically an increase in cases of large volumes of rain in a very short time (OSCAR JÚNIOR, 2021; SILVA *et al*., 2020; SILVA *et al*., 2023). With the present analysis, it was not possible to correlate whether the accumulated rainfall influenced the number of fatal victims, considering that susceptibility is the sum of several parameters and that Petrópolis presents a scenario of multiple hazards. However, it is possible to affirm that deaths occurred because of rainfall events. To perform this correlation, deepening the analyses and including other factors, such as slope, land use, and occupation, would be necessary. In this sense, Alcântara *et al*. (2023) affirm that the rates and the way urbanisation occurred in Petrópolis surpass climatic characteristics as inducers of landslides and, consequently, disasters since most of the constructions are in areas with slopes greater than 20%.

Urbanisation affects and is directly affected by the concentration of rainfall volume, influencing the definition of suitable places for housing, for example. Consequently, it generates concern regarding the municipality's capacity to respond to high rainfall concentrations in a short period. Although the Municipal Government of Petrópolis has implemented actions such as the Alert and Alarm System, according to the Municipal Risk Reduction Plan, no physical interventions were carried out to improve water drainage during rainy events (PREFEITURA MUNICIPAL DE PETRÓPOLIS, 2017), which enhances the negative effect of rainfall.

3.2 ANALYSIS OF DAMAGES AND LOSSES RELATED TO RAIN

Based on the historical series of disaster occurrences related to the municipality of Petrópolis, period 2001 - 2022, it is observed that the typologies of threats with the highest number of occurrences are soil/rock landslides, flash floods and heavy rains. The distribution of these events occurred between October (the beginning of the rainy season) and April (the end of the rainy season), coinciding with the months that returned higher rainfall indices in the analysis (Figure 6). The data corroborate a study by Torres *et al*. (2020), which indicates that the number of landslides has shown an increasing trend in the municipality of Petrópolis, directly related to high precipitation values, especially when the accumulated exceeds 48 or 72h.

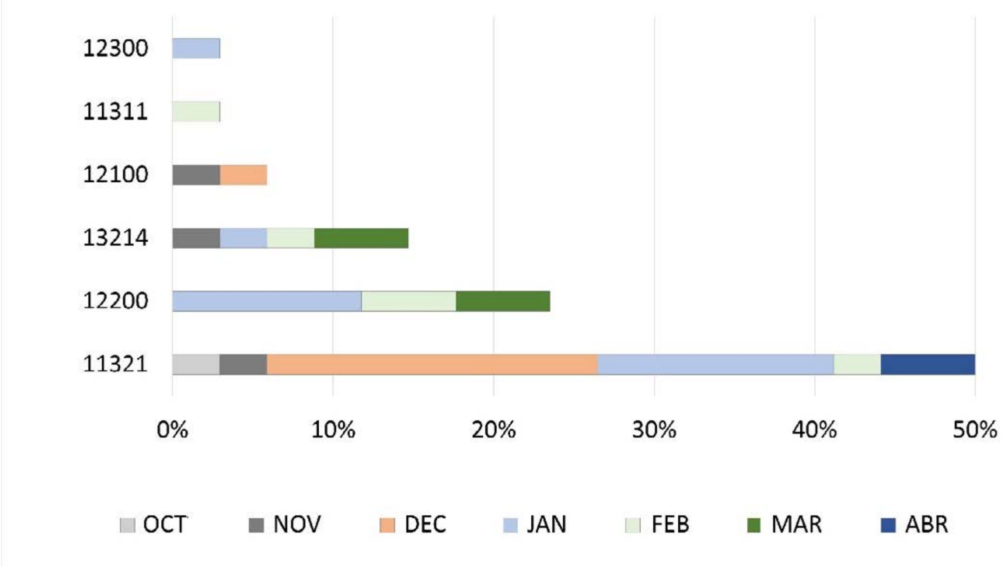

Figure 6 | Monthly distribution of disasters by threat typology in Petrópolis. 12300 Flooding (1); 11311 Rockfall (1); 12100 Inundation (2); 13214 Heavy Rain (5); 12200 Flash Flood (8); 11321 Soil and/or Rock Landslide (17).

Source: The authors.

Human damage (DH) refers to the impact on people; in the database, it is the number of deaths, injured, sick, homeless, displaced, missing and other affected. Table 1 shows that this last variable represents 97% of the DH, caused mainly by soil and/or rock landslides (45.6% of the events). The data show that, regardless of the type of damage, the number of people impacted is high, generating high costs recurrently. In addition, Acciari and Ribeiro (2022) indicate that, in the year 2021 alone, the estimated investment for disaster prevention was R$ 2 million reais. However, in addition to not being spent, the amount was less than half of what was expected to be spent on Christmas decorations (R$ 5.5 million), indicating a disregard for the historical situation of the municipality.

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Table 1 | Human Damage (HD) by typology of events present in the historical series of disaster occurrences in the municipality of Petrópolis, 2001 – 2022

COBRADE	*11321*	*12200*	*13214*	*12100*	*12300*	*11311*	*TOTAL*	
Total of human damages	373.959	95.623	348.561	1.119	40	15	819.317	100,00%
%	45.6	11.7	42.5	0.1	0.1	0.0	100.0	
Deaths	104	81	85	0	0	0	270	0.03%
Injured	530	16	356	0	0	0	902	0.11%
Sick	143	0	200	0	0	0	343	0.04%
Homeless	2287	2921	1629	0	0	0	6.837	0.83%
Displaced	6171	8605	660	19	8	15	15.478	1.89%
Missing [1]	23	0	203	0	0	0	226	0.03%
Other affected	364701	84000	345428	1100	32	0	795.261	97.06%

Source: The authors.

The historical average of DH shows an increase between 2001 and 2022. This average was exceeded in 2005, 2013 and 2022, with 2022 DH corresponding to 40.64% of the total for the period (Table 2), coinciding with the periods of higher precipitation. According to Cabral *et al*. (2023), the event that occurred in 2011 in the mountainous region of Rio (Petrópolis and Teresópolis) was the second-largest event in number of deaths caused by landslides in the history of Brazil.

Table 2 | Values of the annual distribution of Human Damage (HD) in Petrópolis

Year	*2001*	*2003*	*2004*	*2005*	*2007*	*2008*	*2009*	*2010*	*2011*	*2013*	*2015*	*2016*	*2018*	*2022*
Total of human damages	5773	1957	3847	130056	738	46906	22336	58544	48239	152292	0	0	15695	332934
%	0.70	0.24	0.47	15.87	0.09	5.73	2.73	7.15	5.89	18.59	0.00	0.00	1.92	40.64
Deaths	38	17	0	0	5	9	7	3	71	34	0	0	3	83
Injured	143	320	1	0	7	16	10	0	0	49	0	0	4	352
Sick	143	0	0	0	0	0	0	0	0	0	0	0	0	200
Homeless	812	88	89	0	223	81	29	7	2805	1074	0	0	0	1629
Displaced	4375	20	544	56	335	1800	90	33	6363	1135	0	0	260	467
Missing	22	0	0	0	0	0	0	1	0	0	0	0	0	203
Other affected	240	1512	3213	130000	168	45000	22200	58500	39000	150000	0	0	15428	330000

Source: The authors.

The monetary values of damage and losses (D&L) caused by flash floods in January 2011 represent 43% of the impact for Petrópolis in the period 2001 - 2022. In total, adding the percentages of other years (2001, 2008 and 2016), flash floods represent 52% of the D&L in the municipality and continue to reach very high figures (Table 3).

In this context, Cabral *et al*. (2023) state that the prospects for the municipality are not promising, considering the discontinuity of disaster prevention programs, such as the case of the alert program, which was not working during the 2022 rain.

Table 3 | Monetary values of damage and losses in Petrópolis: sum of material damage (MD), public losses (PL) and private losses (PRL)

YEAR	*COBRADE*	*D&L US$*	*%*
2001	11321	38,396,426.27	10
	12200	6,973,728.00	2
2003	11321	10,005,759.76	3
2004	11321	6,781,324.60	2
	12100	0.00	0
	12300	0.00	0
2005	11321	0.00	0
2007	11321	16,387,420.05	4
2008	12200	7,144,301.59	2
2009	11321	4,877,982.03	1
	12100	0.00	0
2010	11321	0.00	0
2011	12200	167,632,309.83	43%
2013	11311	6,211.18	0%
	11321	52,954,078.74	14%
2015	12200	4,216.85	0%
2016	12200	21,444,285.63	5%
	13214	2,052,260.06	1%
2018	12200	0.00	0%
	13214	2,234,802.67	1%
2022	13214	54,828,781.60	14%
2001 - 2022	**TOTAL US$**	**391,723,888.85**	**100%**

Source: The authors.

4 FINAL CONSIDERATIONS

With the analyses, it was possible to confirm that the event in 2022 was an extreme meteorological event, being the most severe of the last decades and associated with the highest human damage recorded in the municipality of Petrópolis. The study indicated that this event occurred, among other factors, due to rain concentrated in only one place, a point that needs further research.

The study did not find a significant change trend (positive or negative) for the monthly rainfall indices, RX1, RX5 or climatic anomalies for the municipality of Petrópolis. However, it is important to carry out additional studies to verify trends of extreme events, using time series of precipitation from other municipalities in the southeast region or considering other methodologies.

The analyses also identified that the event of 2022 was associated with the highest human damage recorded in Petrópolis. Regarding human damage, 2005 and 2013 can also be considered extreme since they greatly exceeded the annual average, all triggered by rainfall events.

Contrary to attributing the disaster only to the high rainfall volume, the study identified few indications of preventive actions that occurred prior to the rainy period or in the following months in favour of water drainage, reinforcing the need for improvement of governance related to disaster risk reduction in the short, medium and long term. However, this topic has not been deepened in the research in

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question. In addition, there is evidence of discontinuity of disaster risk reduction programs in the municipality that require more attention.

NOTES

1| The number of missing people usually turns into the number of deaths.

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