GEOVANE JUNQUEIRA ALVES

DAILY RAINFALL EROSIVITY AS AN INDICATOR OF NATURAL DISASTERS APPLIED TO THE MOUNTAINOUS REGION OF RIO DE JANEIRO, BRAZIL: CURRENT SCENARIO AND FUTURE PROJECTIONS

LAVRAS – MG
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Prof. Dr. Carlos Rogério de Mello
Orientador

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EROSIVIDADE DA PRECIPITAÇÃO DIÁRIA COMO UM INDICADOR DE DESASTRES NATURAIS APLICADO NA REGIÃO SERRANA DO ESTADO DO RIO DE JANEIRO, BRASIL: CENÁRIO ATUAL E PROJEÇÕES FUTURAS

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutor.

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RESUMO

Desastres naturais são definidos como decorrência de eventos naturais extremos que causam impactos significativos no equilíbrio social, econômico e ambiental. Assim, índices de alerta para prevenir ou minimizar os impactos causados por desastres naturais têm se tornando um dos grandes desafios do século XXI. Nesse contexto, e considerando que alguns índices baseados apenas na precipitação têm-se mostrados ineficientes, a erosividade da chuva, calculada como função da energia dissipada pelo impacto de gotas sobre a superfície, tem grande potencial para aplicação em estudos relacionados a deslizamentos de encostas e inundações. Assim, a erosividade de chuvas diárias (R_{dia}) é um índice promissor de ser aplicado como alerta de ocorrência de desastres naturais permitindo também analisar o comportamento destes eventos frente às mudanças climáticas. Neste aspecto, os objetivos deste estudo foram: i) modelar o R_{dia} através de um modelo sazonal para a Região Serrana do Estado do Rio de Janeiro (RSERJ), que tem sido uma das regiões mais afetadas por desastres naturais no Brasil; ii) adequar, com base em eventos catastróficos ocorridos nas últimas duas décadas, limiares do índice R_{dia} que classificam os eventos de acordo com os respectivos impactos observados; iii) aplicar o modelo sazonal ajustado para a estimativa de R_{dia} considerando dois cenários de emissão de gases de efeito estufa (RCP 4.5 e 8.5) e o modelo climático HadGEM2-ES regionalizado para a escala de 5 km ao longo do século XXI; iv) mapear a erosividade máxima diária (R_{maxdia}) para avaliar a susceptibilidade da região, conforme os limiares estabelecidos, ao longo do século e; v) analisar espacialmente a frequência de ocorrência dos valores de R_{dia} causadores de desastres naturais considerando as projeções futuras. O modelo ajustado apresentou resultado satisfatório, permitindo sua aplicação como estimador da sazonalidade do R_{dia} na RSERJ. Eventos que resultaram em R_{dia} > 1.500 $MJ.ha^{-1}.mm.h^{-1}.dia^{-1}$ foram aqueles com o maior número de óbitos nesta região. O mapeamento do R_{maxdia} demonstrou que toda a RSERJ apresentou nos últimos 30 anos valores classificados como causadores de grandes desastres naturais e ainda é altamente susceptível à ocorrência destes grandes desastres ao longo do século XXI, com intensificação no período de 2040-2071. As áreas urbanas de Nova Friburgo e Petrópolis foram as que apresentaram maior frequência de eventos na faixa $1.000 < R_{maxdia} < 1.500$ $MJ.ha^{-1}.mm.h^{-1}.dia^{-1}$. O período de 2011-2040 é o que apresentou a menor frequência de eventos, com concentração de $R_{maxdia} <$ 1.000 $MJ.ha^{-1}.mm.h^{-1}.dia^{-1}$. Os índices R_{dia} se mostraram promissores como indicadores de desastres naturais, sendo mais efetivo do que os usualmente utilizados, os quais são baseados somente em quantidade (mm) e intensidade ($mm.h^{-1}$) da chuva.

Palavras-chave: Erosividade diária. Desastres naturais. Regiões serranas brasileiras. Índices de alertas de precipitação. Mudanças climáticas.

ABSTRACT

Natural disasters result from extreme natural events that cause significant impacts on the social, economic, and environmental balance. Thus, alert indices to prevent or minimize the impacts caused by natural disasters have become one of the most significant challenges of the twenty-first century. In this context and considering that some indices based only on precipitation have been shown to be inefficient, the rainfall erosivity, calculated as a function of the energy dissipated by the impact of drops on the surface, has great potential for application in studies related to landslides and floods. Thus, daily rainfall erosivity (R_{day}) are promising indices to be applied as alerts of the occurrence of natural disasters, also allowing us to analyze the behavior of these events in the face of climate change. Therefore, this study aimed to i) model the R_{day} through a seasonal model for the mountainous region of the state of Rio de Janeiro (RSERJ), one of the regions most affected by natural disasters in Brazil; ii) adapt thresholds of the R_{day} indices that classify the events according to their observed impacts based on catastrophic events that have occurred in the last two decades; iii) apply the adjusted seasonal model to calculate R_{day} considering two greenhouse gas emission scenarios (RCP 4.5 and 8.5) and the regionalized HadGEM2-ES climate model for the 5 km scale throughout the twenty-first century; iv) map the maximum daily rainfall erosivity (R_{maxdia}) to evaluate the susceptibility of the region, according to the established thresholds throughout the century; and v) spatially analyze the frequency of occurrence of R_{day} values causes of natural disasters considering future projections. The adjusted model showed a satisfactory result, allowing its application as an estimator of the seasonality of the R_{day} at RSERJ. Events that resulted in R_{day} > 1,500 MJ.ha^{-1}. mm. h^{-1}. day^{-1} presented this region's highest number of deaths. The mapping of R_{maxdia} showed that the entire RSERJ presented values classified as causing major natural disasters in the last 30 years and is still highly susceptible to the occurrence of major natural disasters throughout the twenty-first century, with intensification from 2040 to 2071. The urban areas of Nova Friburgo and Petrópolis showed the highest frequency of events in the range 1,000 < R_{maxdia} < 1,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1}. The period between 2011 and 2040 presented the lowest frequency of events, with a concentration of R_{maxdia} < 1,000 MJ.ha^{-1}.mm.h^{-1}.day^{-1}. The R_{day} indices were promising indicators of natural disasters, being more effective than those generally used, based only on rainfall quantity (mm) and intensity (mm.h^{-1}).

Keywords: Daily rainfall erosivity. Natural disasters. Brazilian mountainous regions. Rainfall warning system. Climate change.

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1ST CHAPTER – GENERAL INTRODUCTION

1 GENERAL INTRODUCTION

Natural disasters are defined as the result of extreme natural events which cause negative impacts on the society, economy, and environment (ALEXANDER, 2018). Among the natural disasters that most affect the people, floods and landslides caused by intense rainfall are responsible for thousands of deaths worldwide.

The increase in the frequency and intensity of extreme rainfall in Brazil, combined with the high degree of susceptibility of the population in risk areas has triggered disasters, such as landslides and floods (FERNANDES and RODRIGUES, 2018; AMORIM and CHAFFE, 2019; MELLO et al., 2020). Within this context, one of the regions more affected by landslides and floods is the mountainous region of the state of Rio de Janeiro (MRRJ), which is one of the most vulnerable areas to the natural disasters in Brazil (BRASIL, 2012; FREITAS et al., 2012; BITAR, 2014; OLIVEIRA et al., 2016). In addition, in this region the influence of the South Atlantic Convergence Zone (SACZ) and the orographic influence coexist, resulting in frequent extreme rainfall events (BRITO et al., 2016; ANDRÉ et al., 2008). Thus, it can be said that, besides the higher frequency of extreme events, they can potentially affect regions more vulnerable to these natural disasters, leading to more significant consequences.

Landslides were triggered by extreme rainfall events between January 11 and 12, 2011, causing the so-called "mega disaster" in the MRRJ, where seven municipalities declared situation of public emergency (VASSOLER, 2013; CARDOZO and MONTEIRO, 2019). This event is considered the worst natural disaster in Brazil's history (CASTILHO et al., 2012; CARDOZO and MONTEIRO, 2019), not only because of the number of deaths, but also the significant damages in the economy and infrastructure. In Nova Friburgo, for example, the total number of fatalities related to landslides was 434 (205 women and 228 men) (CARDOZO et al., 2018; CARDOZO and MONTEIRO, 2019; OLIVEIRA et al., 2016). This represents more than 47% of the fatalities in the "mega disaster".

Although the "mega disaster" generated the most destructive landslides ever observed in Brazil, events with similar characteristics have already occurred at Rio de Janeiro state in the years of 1966, 1967, 1988 and 1996 (MEIS and SILVA, 1968; BARATA, 1969; JONES, 1973; LACERDA, 1997, 2007).

In view of the above-mentioned, some authors have assessed the efficiency of Early Warning System (EWS) indicators in reducing risks in the region, mainly related to economic impacts and fatalities (WEBSTER, 2013; ALVALÁ et al., 2019). Guzzetti et al. (2007) studied indicators that identify vulnerability to natural disasters, claiming that a good indicator should be based on the total precipitation amount, the rainfall intensity, the antecedent soil moisture, and the characteristics of the slopes.

However, despite the difficulty in obtaining all the above-mentioned variables (geological, geomorphological, climatic and hydrological) and gathering them in a single value as an alert index that can be used as an EWS, indexes have been applied to relate extreme precipitation events (accumulated and intensity) with the human and material damages caused (XU et al., 2014; CALVELLO et al., 2015; OLIVEIRA et al., 2016) since it is known that precipitation is the factor that triggers the most of natural disasters (GUZZETTI et al., 2007). In addition, the forecasting of precipitation can be made 48 or even 72 hours before the occurrence of the event (OLIVEIRA et al., 2016), which is enough time for the authorities to assess the characteristics of the event and warn the population of imminent risks.

Some indexes have been widely used in Brazil and in the world, such as the accumulated precipitation in the last 24, 48, 72 and 96 hours (SILVA et al., 2020), the precipitation intensity (mm/h), or even such variables evaluated simultaneously. However, some of these indicators have shown to be inefficient.

In this context, rainfall erosivity when applied in a daily scale, seems to be a good index for natural disasters as it encompasses the impacts caused by the impact of raindrops and the energy dissipated by them on the soil surface (MELLO et al. 2020). It was proposed and defined by Wischmeier and Smith (1958) as the product between the kinetic energy of raindrops and the maximum rainfall intensity in 30 consecutive minutes (I_{30}), designated as EI_{30}.

The original method for calculating EI_{30} for a given rainfall event ($Ec \times I_{30}$) requires rainfall records with a temporal resolution $\leq$ 15-min (WISCHMEIER and SMITH, 1978). However, such records are difficult to access and obtain, usually due to an insufficient number of stations (MELLO et al., 2020; XIE et al., 2016).

To apply a model for estimating daily rainfall erosivity based on daily rainfall data (since is much more accessible and spatially distributed) is essential to better understand the role of extreme precipitation events on natural disasters (MELLO et al., 2020). Therefore, Yu and Rosewell (1996) proposed a mathematically approach to estimate daily rainfall erosivity.

This approach is capable of estimating the daily erosivity considering the seasonality of the rainfall erosivity throughout the year. Furthermore, this approach using daily rainfall data makes it possible to evaluate the behavior of daily erosivity influenced by climate change, since the regionalized data by Eta model is capable of estimate rainfall in daily time resolution.

Climate change and its impacts on the magnitude and frequency of natural disasters are still uncertain, especially in regions with significant orographic influences (CHOU et al. 2014). In the last decades, it has been observed that natural disasters mostly landslides and floods have become more frequent and severe (CEPED, 2013), mainly in mountainous regions of Brazil (MELLO et al. 2020). These impacts are due to the evident increase in the intensity and frequency of extreme rainfall events (IPCC, 2013), together with the rapid population, economic and disordered urban growth.

The most important factor influenced by climate change which will affect a region's vulnerability to the natural disasters, are changes in the rainfall pattern. In tropical and subtropical regions, for example, a possible increase in the amount of precipitation is expected for specific periods of the year throughout the 21st century (MELLO et al. 2015).

Some studies have assessed the influence of climate change in erosivity on monthly and annual scales (NEARING 2001; ZHANG et al., 2010; SEGURA et al., 2014; MELLO et al., 2015; RIQUETTI et al., 2020), but none has evaluated these changes based on daily scale (R_{day}).

Therefore, two articles were developed to compose the present thesis that has as general objective to study the daily rainfall erosivity as a tool for natural disasters in mountain regions.

The first article is entitled *"Natural disaster in the mountainous region of Rio de Janeiro state, Brazil: Assessment of the daily rainfall erosivity as an early warning index"*, and its purpose is to model the daily rainfall erosivity index (R_{day}) using a seasonal model for the MRRJ. Based on this index, the other objective was to improve an indicator, which could be applied as an Early Warning System (EWS) for natural disasters in this region. This index is capable of to identify areas that are vulnerable to natural disasters, being more sensitive than others that are associate with only the total precipitation and the mean rainfall intensity. Finally, it was compared to other indexes that have been used by government warning systems aiming to demonstrate that R_{day} has great potential to be applied instead.

The second article, entitled *" Rainfall disasters under the changing climate: a case study for the Rio de Janeiro mountainous region"*, objectives: i) to apply a R_{day} seasonal model for the Mountain Region of Rio de Janeiro (MRRJ) throughout the 21st century, applying data simulated by the MCG HadGEM2-ES, regionalized by the ETA-CPTEC model on the spatial scale of 5 km, considering the RCP4.5 and 8.5 IPCC (2013) scenarios; ii) map the maximum daily rainfall erosivity (R_{maxday}) to assess, based on the R_{day} indice, the most vulnerable regions throughout the present century and; iii) spatially the frequency of occurrence of R_{maxday} values throughout the 21st century.

Thus, it is essential to note that this study highlights two pioneer aspects: i) the study of climate change and its influence on the values of R_{day}; and ii) use of the rainfall erosivity as an index of extreme events and their variations due to climate changes throughout the 21st century.

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2ND CHAPTER - ARTICLES

ARTICLE 1 - NATURAL DISASTER IN THE MOUNTAINOUS REGION OF RIO DE JANEIRO STATE, BRAZIL: ASSESSMENT OF THE DAILY RAINFALL EROSIVITY AS AN EARLY WARNING INDEX

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Natural disaster in the mountainous region of Rio de Janeiro state, Brazil: assessment of the daily rainfall erosivity as an early warning index

Abstract

Rainfall erosivity is defined as the potential of rain to cause erosion. It has great potential for application in studies related to natural disasters, in addition to water erosion. The objectives of this study were: i) to model the R_{day} using a seasonal model for the Mountainous Region of the State of Rio de Janeiro (MRRJ); ii) to adjust thresholds of the R_{day} index based on catastrophic events which occurred in the last two decades; and iii) to map the maximum daily rainfall erosivity (R_{maxday}) to assess the region's susceptibility to rainfall hazards according to the established R_{day} limits. The fitted R_{day} model presented a satisfactory result, thereby enabling its application as a R_{day} estimate in MRRJ. Events that resulted in R_{day} > 1,500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ were those with the highest number of fatalities. The spatial distribution of R_{maxday} showed that the entire MRRJ has presented values that can cause major rainfall. The R_{day} index proved to be a promising indicator of rainfall disasters, which is more effective than those normally used that are only based on quantity (mm) and/or intensity ($mm.h^{-1}$) of the rain.

Keywords: Daily rainfall erosivity; rainfall hazards; Brazilian mountainous regions; rainfall warning system.

1 INTRODUCTION

Rainfall erosivity is an index that encompasses the impacts caused by the raindrops impact and the energy dissipated on the soil surface. It was proposed and defined by Wischmeier and Smith (1958) as the product between the kinetic energy of raindrops and the maximum rainfall intensity in 30 consecutive minutes (I_{30}), designated as EI_{30}. Its calculation requires rainfall data recorded with a temporal resolution ≤ 15-min. However, such records are difficult to access and obtain, usually due to an insufficient number of stations in developing countries (Mello et al., 2015).

To develop a model for estimating daily rainfall erosivity (R_{day}) based on daily rainfall data is essential to better understand the role of extreme rainfall on natural disasters (Mello et al., 2020) since daily rainfall data is much more accessible and spatially distributed than those with temporal resolutions ≤ 15-minute. Therefore, a model to estimate R_{day} was initially proposed by Richardson et al. (1983), with the inconvenience of having to fit different models for each month. In addition, these models tend to underestimate the R_{day} (Angulo-Martinez and Beguería, 2009). To overcome these limitations, Yu and Rosewell (1996) proposed a mathematically more advanced approach by introducing a sinusoidal function to model the seasonality of rainfall erosivity. This approach can estimate R_{day} considering the period of the year (biweekly or monthly periods). This is a hypothesis that considers that the same precipitation can generate different R_{day} according to the period of year, which is relevant in regions with a seasonal climate.

The increase in the frequency and intensity of extreme rainfall in Brazil, combined with the high degree of susceptibility of the population in risk areas has triggered rainfall disasters (Fernandes and Rodrigues, 2018; Amorim and Chaffe, 2019; Mello et al., 2020), with a high number of fatalities (CEPED, 2013). The geomorphological and pedological characteristics associated with changes in land use (especially deforestation of the Atlantic

Forest) (Freitas et al., 2012) and the high intensity of the rainfall (Brito et al., 2016) are the key factors to rainfall disasters in mountainous regions in Brazil (Mello et al., 2020).

One of the regions most affected by rainfall disasters is the mountainous region of the Rio de Janeiro state (MRRJ) (Brasil, 2012; Freitas et al., 2012; Oliveira et al., 2016). In January/2011, landslides were triggered by extreme rainfalls, causing the so-called "mega-disaster" in this region. A total of 23 municipalities were affected, and seven of these were declared in a emergency situation (Cardozo and Monteiro, 2019). Petrópolis, Teresópolis, and Nova Friburgo municipalities recorded the highest number of victims. The most significant impacts in Nova Friburgo occurred in the urban area, whereas the rural areas were the most affected in the other two municipalities (Busch and Amorim, 2011; Cardozo and Monteiro, 2019). Official reports indicated 918 fatalities, 22,604 displaced, and 8,795 homeless across the region (Freitas et al., 2012). This event was the worst natural disaster in Brazil's history (Cardozo and Monteiro, 2019).

Some authors have assessed the efficiency of the early warning system (EWS) indexes in reducing risks from rainfall. However, due to the difficulty in obtaining and combine all the variables involved with landslides in an index that can be used as an early warning, indexes have been applied focusing on the extreme rainfall and the human and material damages (Xu et al., 2014; Calvello et al., 2015; Oliveira et al., 2016). Some indexes have been widely used in Brazil and the world, such as the accumulated rainfall in the last 24, 48, 72, and 96 hours, rainfall intensity (mm h^{-1}), or even such variables evaluated simultaneously. Nevertheless, some of these indexes have shown to be inefficient. An example of this was the rainfall disasters in Campus do Jordão county in Serra da Mantiqueira (southeastern Brazil) in the year 2000. This event was caused by an accumulation of rain below the limit previously established in 72 hours (Mendes et al., 2018). Another example, it was the index used by the

Alerta-Rio, as 20 false alerts were issued for the four warning zones of the city between 2010 and 2013.

Mello et al. (2020) proposed the use of R_{day} as a rainfall index as EWS for the Serra da Mantiqueira region (SMR), in Minas Gerais state (Southeast Brazil). Although this index has shown efficiency, it lacks a complementary spatial analysis using data from several stations with rain records every 15-minute, as they used data from only one station with this characteristic. This aspect makes it possible to better understand the genesis of extreme events in regions with a strong orographic influence, which the researchers did not properly characterize. In this direction, the purpose of this study is to fit a seasonal R_{day} model for the MRRJ. Based on this index, the main objective was to improve R_{day} as an index, which could be applied coupled with the EWS for rainfall disasters in this region in Brazil.

2. MATERIAL AND METHODS

2.1 The mountainous region of Rio de Janeiro state (MRRJ)

The MRRJ is located in Serra do Mar region, in southeast Brazil. In geomorphological terms, it is inserted in the Reverse Plateau unit (Garcia and Francisco, 2013), characterized by mountainous and steep relief, with altitudes ranging from 400 to 2350 meters (Figure 1). The predominant soils are the Cambisols, which are shallow, moderately permeable, with a high silt/clay ratio, low natural fertility, and with the formation of crusts that constraints the infiltration if the vegetation cover is scarce or absent (Pinto et al., 2018).

The geographical location of the three municipalities severely impacted by rainfall hazards is in Figure 1, as well as the location of the Brazilian National Water Agency (ANA) rain gauge stations and the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN) automatic rain gauges used in this study.

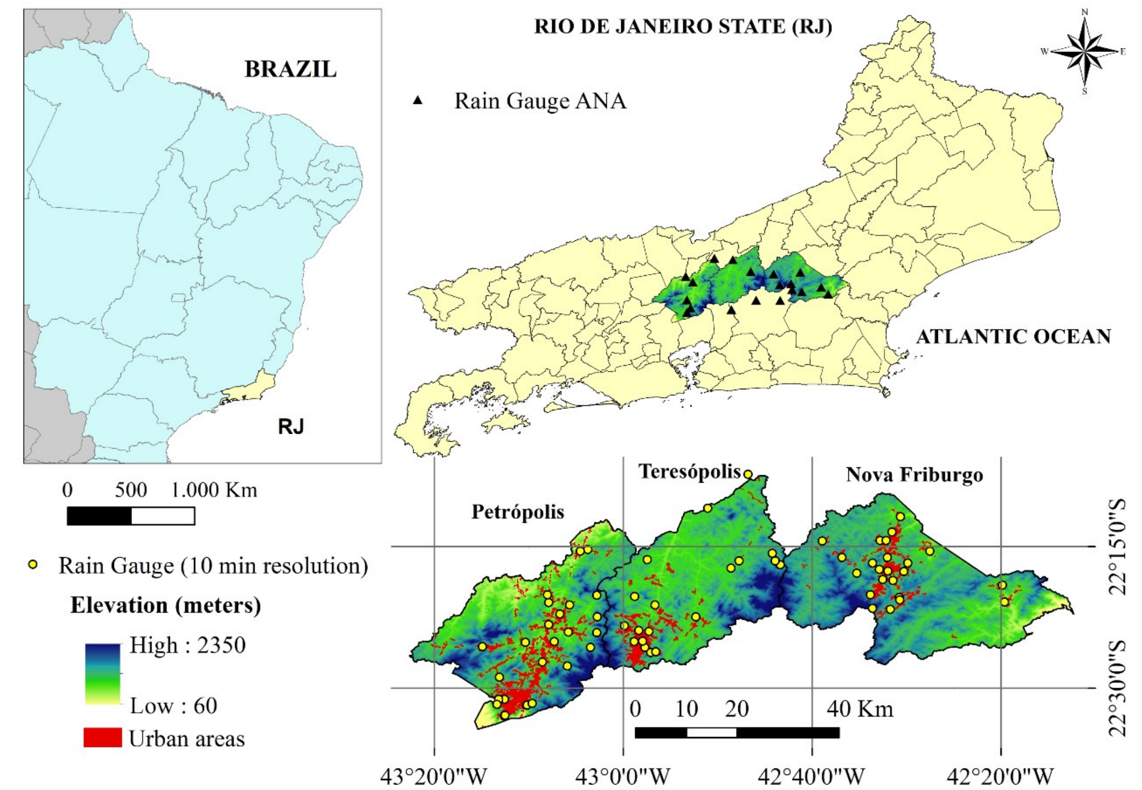

Figure 1. Geograpical location of MRRJ, highlighting Nova Friburgo, Petrópolis, and Teresópolis municipalities, the CEMADEN automatic rain gauges, and the ANA rain gauges.

The municipalities of Petrópolis (792 km²), Teresópolis (773 km²) and Nova Friburgo (936 km²) were focused in this study because they are the most representative municipalities in the population, and they were more prone to rainfall hazards in recent decades (Coelho Netto et al., 2013). The population of these three municipalities is predominantly urban (approximately 90%), totaling approximately 645,000 inhabitants (296,000, 166,000 and 183,000 in Petrópolis, Teresópolis, and Nova Friburgo, respectively) (IBGE, 2010; Coelho Netto et al., 2013; Cardozo and Monteiro, 2019). Its economy is geared towards industry, agriculture, and tourism (Coelho Netto et al., 2013).

The MRRJ climate is generally characterized as Cwb (according to the Köppen climate classification), with dry winters and rainy summers. The annual average temperatures are around 16°C (Coelho Netto et al., 2013) and the summer accounts for 70% of the rainfall between October and March. The winters are cool and dry (Dourado et al., 2012). The rainfall pattern in the MRRJ is driven by frontal systems; convective rains in the summer; South Atlantic Convergence Zone (SACZ); orographic effects; tropical and subtropical cyclones; surface water temperature of the Subtropical Atlantic Ocean; and maritimity (Reboita et al., 2010).

Nova Friburgo has been hit by the highest rainfall amount throughout the state of Rio de Janeiro, with an annual average of 2,500 mm in the highest areas, decreasing progressively towards the north (N) as the altitudes decrease (Coelho Netto et al., 2013; Cardozo and Monteiro, 2019). The average annual rainfall in Teresópolis also varies in the North-South direction (from 2200 to 1500 mm), and in Petrópolis (from 1900 to 1000 mm). The rainiest period occurs between December and February, when the monthly average rainfall varies between 340 and 240 mm in the highest altitudes in the southern MRRJ, and between 240 and 150 mm in the northern (Coelho Netto et al., 2013).

2.2 Rainfall erosivity calculation (EI_{30})

Datasets of rainfall from 68 automatic rain gauges provided by CEMADEN with a 10-minute temporal resolution (Figure 1) were used to calculate EI_{30}, using the available period between 2014 and 2020. The following equations were used to calculate EI_{30}:

$$ke_d = 0.29 \cdot [1 - 0.72 \cdot exp(-0.082 \cdot i_d)] \quad (1)$$

$$E_d = Ke_d \cdot P_d \quad (2)$$

$$\mathrm{KE} = (\textstyle\sum_{d=1}^{n} E_d) \quad (3)$$

$$EI_{30} = KE \cdot I_{30} \quad (4)$$

Equation 1 allows calculating the kinetic energy per mm of rain (ke_d) per time interval “d” ($MJ.ha^{-1}.mm^{-1}$), in which i_d is the rainfall intensity ($mm.h^{-1}$) (McGregor and Mutchler, 1976). In equation 2, E_d is the kinetic energy ($MJ.ha^{-1}$), and P_d is rainfall depth (mm), both in the "d" time interval. Thus, the kinetic energy of the event is obtained by the sum of the kinetic energy (E_d) calculated for each time interval (KE, $MJ.ha^{-1}$) (Equation 3), where "n" corresponds to the number of the time interval "d". Finally, the EI_{30} calculation for the event ($MJ.ha^{-1}.mm.h^{-1}$) (Equation 4) is made by multiplying KE by the 30-minute maximum rainfall intensity (I_{30}) ($mm.h^{-1}$).

Two conditions were considered to separate individual erosive events: $KE > 3.6$ $MJ.ha^{-1}$ (De Maria, 1994); and $I_{30} \geq 13.3$ $mm.h^{-1}$ (Xie et al., 2002). Nevertheless, EI_{30} is not necessarily synonymous with R_{day}, since a single rain event can have a duration greater than one day, or more than one erosive event may occur on the same day. Therefore, three situations are possible to define R_{day} (Xie et al., 2016; Mello et al., 2020):

Type I: a day with only one rain event (R_{day} = EI_{30} of the event);

Type II: a day with multiple rain events separated by > 6 hours (R_{day} = sum of the EI_{30} of each event in the day); and

Type III: a day with rainfall event that lasts over 24 hours (R_{day} = KE considering the 24-hour interval with the highest total rainfall multiplied by the highest I_{30} for their calculation).

2.3 Seasonal model for estimating R_{day}

A seasonal R_{day} model was fitted based on the study by Yu and Rosewell (1996):

$$R_{day} = \alpha \cdot [1 + \eta \cos(2\pi f j - \omega)] \cdot {P_{day}}^{\beta} \quad (5)$$

In which j is the fortnight of the year (ranging from 1 to 24); f = 1/24; η, α, ω *and* β are the fitted parameters. The η parameter is related to the amplitude in the variation of the α parameter; ω is the parameter related to the fortnight with the highest accumulated rainfall erosivity; β is a parameter considered for modeling the non-linearity of daily rainfall and respective erosivity (Richardson et al. 1983). In the MRRJ, the first half of January has the highest accumulated total erosivity (based on seven years of recording); $\omega = \pi/6$.

The model parameters were estimated using the least squares method considering the R_{day} and the respective daily rainfall observed in the 68 automatic rain gauges. For this, we split the dataset (rainfall erosive events) into two groups: one for fitting the daily rainfall erovisity model (equation 5) and the other for analyzing the model's performance. For the latter, approximately 37% of the data were used, being randomly chosen according to the number of erosive events distributed in daily rainfall classes (< 15 mm; 16-20 mm; 21-30; 31-40 mm; 41-50 mm; 51-75 mm; 76-100; > 101 mm).

Two precision statistics were adopted (Angulo-Martinez and Beguería, 2009):

i) Nash-Sutcliffe Efficiency Coefficient (C_{NS}) (Nash and Sutcliffe, 1970):

$$C_{NS} = 1 - \frac{\sum_{i=1}^{N}(E_{oi} - E_{ei})^2}{\sum_{i=1}^{N}(E_{oi} - \overline{E_o})^2} \quad (6)$$

ii) P_{bias} that measures the trend of estimates, and is calculated by:

$$P_{bias} = \frac{\sum_{i=1}^{N}(E_{oi} - E_{ei})}{N} \quad (7)$$

2.4 Natural disaster rainfall-based alert indexes

2.4.1 Previous rainfall indexes

Brooks and Stensrud (2000) defined that a rainfall event is classified as intense when the precipitation intensity is ≥ 25.4 mm/h. Groisman et al. (2001) established that intense and very intense rainfall can be separated using a fixed threshold of 50.8 and 101.6 mm/day, respectively, or the values corresponding to the 90th and 99th percentiles. In investigating the occurrence of extreme events in the United States, Groisman et al. (2012) considered four classes of precipitation: moderately intense (12.7-25.4 mm/day), intense (25.4-76.2 mm/day), very intense (76.2-154.9 mm/day), and extreme intense (> 154.9 mm/day); the latter is related to floods, property damage, accidents, and fatalities.

Dolif and Nobre (2012) defined an extreme event for the city of Rio de Janeiro as one that causes a precipitated accumulation > 50 mm in any interval of 24 hours. This threshold is the one used by the World Meteorological Organization (WMO) in the "Severe Weather Information Centre" (http://severe.worldweather.org/rain/), applied in intense precipitation prediction models (Pristo et al., 2018). Still, regarding the city of Rio de Janeiro, a system called *Alerta-Rio* has been applied since April/2010. However, despite its good performance in predicting extreme events and alerting the population to these, its implementation cost is high since it is based on rain intensity data derived from meteorological radars.

Despite the difficulty of establishing a single value as an alert index, it is known that precipitation is one of the factors that most triggers natural disasters (Guzzetti et al., 2007). In addition, the forecast of this variable can be made 48 or even 72 hours in advance (Oliveira et al., 2016), providing enough time for the authorities to assess the event and warn the population of imminent risks. Thus, precipitation has been used to compose the majority of EWS.

2.4.2 Application of the R_{day} as an EWS

R_{day} thresholds are proposed as an index to be used in the EWS. These thresholds were established through the joint analysis of the R_{day} values, which concomitantly caused rainfall hazards with the respective consequences observed in eight events that hit the MRRJ in the last two decades.

Maximum daily rainfall erosivity (R_{maxday}) (Mello et al., 2020) map was developed to identify areas more vulnerable to rainfall hazards. It is based on the maximum daily rainfall observed in at least 22 years since it is the minimum period to characterize the rainfall erosivity pattern for a given region (Wischmeier and Smith, 1978). Its mapping was developed by means kriging techniques, considering the highest rainfall values observed in the MRRJ in the last three decades (1990-2019).

The R_{day} index definition is based on (Mello et al., 2020): i) detailed survey of the events which caused natural disasters, characterizing, in this order, fatalities, homeless, and damage in the infrastructure; ii) other indexes were used for comparative purposes when establishing R_{day} thresholds. Thus, R_{day} intervals were proposed for MRRJ according to the occurrences and the respective R_{day}, linking these intervals to the consequences registered, and comparing them with other existing indexes.

The indexes used in this study for comparison purposes are those used by *Alerta-Rio*, operated by the Geotechnical Foundation of the municipality of Rio de Janeiro (*GEO-Rio*), and those presented by Oliveira et al. (2016), who studied the precipitation thresholds that caused rainfall hazards in the Nova Friburgo municipality (Table 1). The established indexes can be based on a relationship between rainfall and landslides or through statistical analysis (Calvello et al., 2015). The intervals that consider a period of 24 and 72 hours is presented in Table 1. Both indexes consider the rainfall duration; Alerta Rio one hour, 24 hours, and 72 hours, while Oliveira et al. (2006) 24 hours, 48 hours, and 72 hours. Besides, both indexes proposed a classification warning according to the magnitude of the rain; Alerta Rio defined "Mean," "High," and "Very High" warning, linking them to the respective duration and an interval of the rainfall depth. Oliveira et al. (2006) created three levels, A, B, and C, which are associated with the respective duration and rainfall depth. Similar to Alerta Rio, these levels indicate the concern with the rainfall impact, increasing from A to C.

Table 1. *Precipitation limits currently adopted as warning indexes in Rio de Janeiro state.*

Duration (hours)	**Alert level according to accumulated rainfall (mm) – Alerta Rio**		
	Mean	**High**	**Very high**
1	25-50	50-80	>80
24	85-140	140-220	>220
72	140-220	220-300	>300
Criteria	**Accumulated rainfall (mm) (Oliveira et al. 2016)**		
	24h	**48h**	**72h**
A	50	60	100
B	50	75	120
C	75	120	150

3. RESULTS

3.1 Daily rainfall erosivity modeling in the MRRJ

Based on 68 CEMADEN stations, 5,101 rainfall events with $I_{30} \geq 13.3$ mm.h^{-1} (the first step for split rainfall erosivity events) were identified between 2014 and 2019 in MRRJ, with the lowest observed amount of 6.7 mm. However, some of these events are not erosive according to the kinetic energy (KE > 3.6 MJ ha^{-1}). Therefore, the second step consisted of separating those that are erosive. From the 5,101 events, 3,698 were classified as erosive events, i.e., KE > 3.6 MJ.ha^{-1}, corresponding to 72.5% of the studied events. The number of erosive and non-erosive events and the frequency and respective class of R_{day} in MRRJ are presented, respectively, in Figures 2(a) and (b).

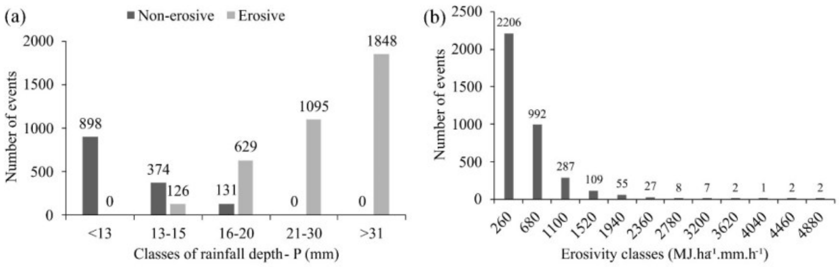

Figure 2. The number of erosive and non-erosive events (2014 to 2019) per rainfall classes (a) and frequency of R_{day} observed in MRRJ (b).

Table 2 shows the number and percentage of erosive events, the percentage of observed erosivity, and the average I_{30} ($mm.h^{-1}$) for each rainfall class.

Table 2. Percentage of erosive events and total erosivity for different rainfall classes.

Rainfall (mm)	**Nº. of events**	**% of Events**	**% of accumulated EI_{30} ($MJ.ha^{-1}.mm.h^{-1}$)**	**Average I_{30} ($mm.h^{-1}$)**
<15	126	3.4	0.5	26.1
16-20	629	17.0	5.2	25.6
21-30	1095	29.6	15.7	29.0
31-40	679	18.4	16.1	34.5
41-50	428	11.6	14.9	39.6
51-75	497	13.4	24.3	42.5
76-100	125	3.4	10.2	45.6
>101	119	3.2	13.1	46.2

The classification of erosive events in terms of their type is: 83% Type I; 11.6% Type II; and 5.4% Type III.

To apply the R_{day} model, it is fundamental to establish a minimum daily rainfall that potentially can triggers a rainfall erosive event. Figure 2a shows that all 898 events < 13 mm were not classified as erosive. However, 126 events in the 13 - 15 mm interval (25.2%) were erosive, which allows us to infer that the minimum precipitation depth to be considered erosive is within this interval, bearing in mind that some 13 mm events were erosives.

Erosive events had the following characteristics: i) they are generated by rainfall ≥ 13 mm; ii) all rainfall events ≥ 22 mm are erosive; iii) approximately half of the erosive events (1848 out of 3698 events) occur for rainfall ≥ 31 mm; and iv) despite representing approximately 50% of the total number of erosive events, rainfall ≥ 31 mm corresponds to 78.6% of the total observed rainfall erosivity over MRRJ.

3.2 Seasonal R_{day} model for MRRJ

The fitted seasonal model for MRRJ presented the following structure:

$$R_{day} = 3.3888 \cdot \left[1 + 0.4659 \cdot cos\left(\frac{2 \cdot \pi \cdot j}{24} - \frac{\pi}{6}\right)\right] \cdot Pday^{1.2028} \quad (8)$$

This model describes the inter-daily annual seasonality of R_{day} by estimating the parameters "α", "η" and "β" (3.3888; 0.4659; 1.2028; respectively). An important detail is that the fitted parameters spatially represent the MRRJ since it was determined based on data from 68 rain gauge stations with precipitation data recorded every 10 minutes.

The precision statistics associated with calibration (C_{NS} = 0.51; P_{bias} = -0.56) and validation (C_{NS} = 0.50; P_{bias} = -2.22) demonstrate satisfactory results for the R_{day} model, especially when considering that this estimate is made based only on daily rainfall and the period of the year.

Figures 3a and 3b represent the fitted model applied to the events (1,368 events) separated exclusively for validation. The regression in Figure 3a means a relationship between estimated R_{day} values by the fitted model in function of rainfall depth (red triangles). Through this fitting, one can observe that the model could capture the seasonality effect on daily rainfall erosivity, i.e., different Rday values were estimated with the same precipitation depth, meaning that these events occurred in different seasons of the year.

In Figure 3b, it is possible to verify that the estimated R_{day} values fitted reasonably well to the observed ones. However, overestimation and understation values can be seen, respectively, for the lowest and the highest values.

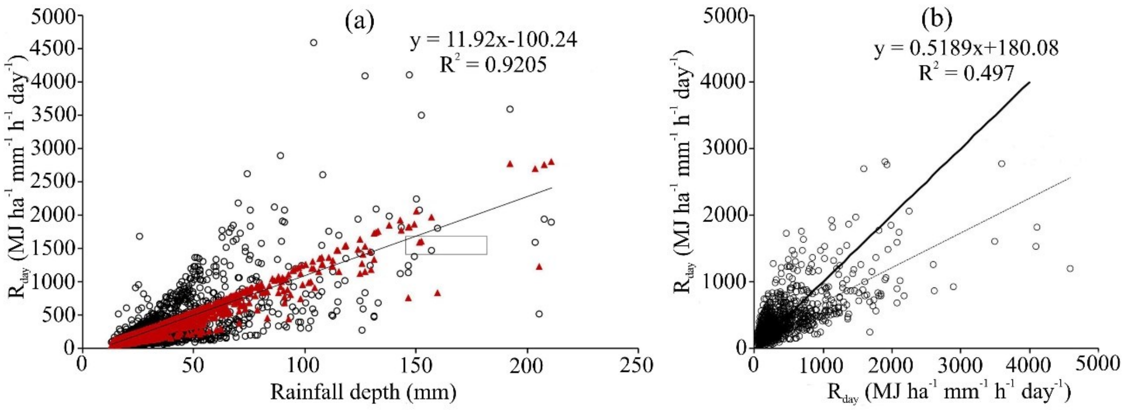

Figure 3. Behavior of the R_{day} by the seasonal model applied to the validation data.

Figure 4 shows the model fitting graphs for MRRJ considering different classes of I_{30}. It can be seen in Figure 4a that the model tends to overestimate R_{day} for I_{30} < 25 mm.h^{-1}. On the other hand, the model's performance is superior for the I_{30} between 25 and 50 mm.h^{-1} (Figure 4b), and between 51 and 75 mm.h^{-1} (Figure 4c), with good precision. However, the model underestimates R_{day} for the greatest I_{30} class (Figure 4d).

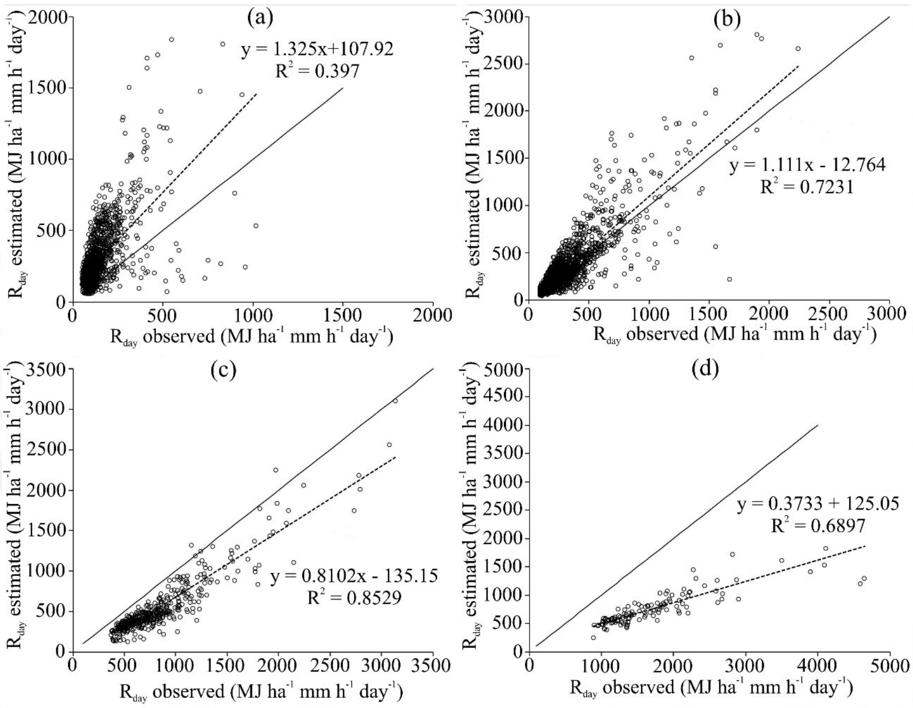

Figure 4. Model fitting for different I_{30} classes (a. $I_{30} < 25$; b. $25 \leq I_{30} \leq 50$; c. $51 \leq I_{30} \leq 75$; and d. $I_{30} > 75$).

3.3 Relation between R_{day} and rainfall hazards in MRRJ

To relate R_{day} values and the most significant rainfall hazards provoked by rainfall in MRRJ, maps of it were developed (Figure 5 – left colunm). For comparing purposes, a map using the EWS developed by *Alerta-Rio* was also developed (Figure 5 – right column), which allows observing how Rday is more sensitive and complete than the previous alert index.

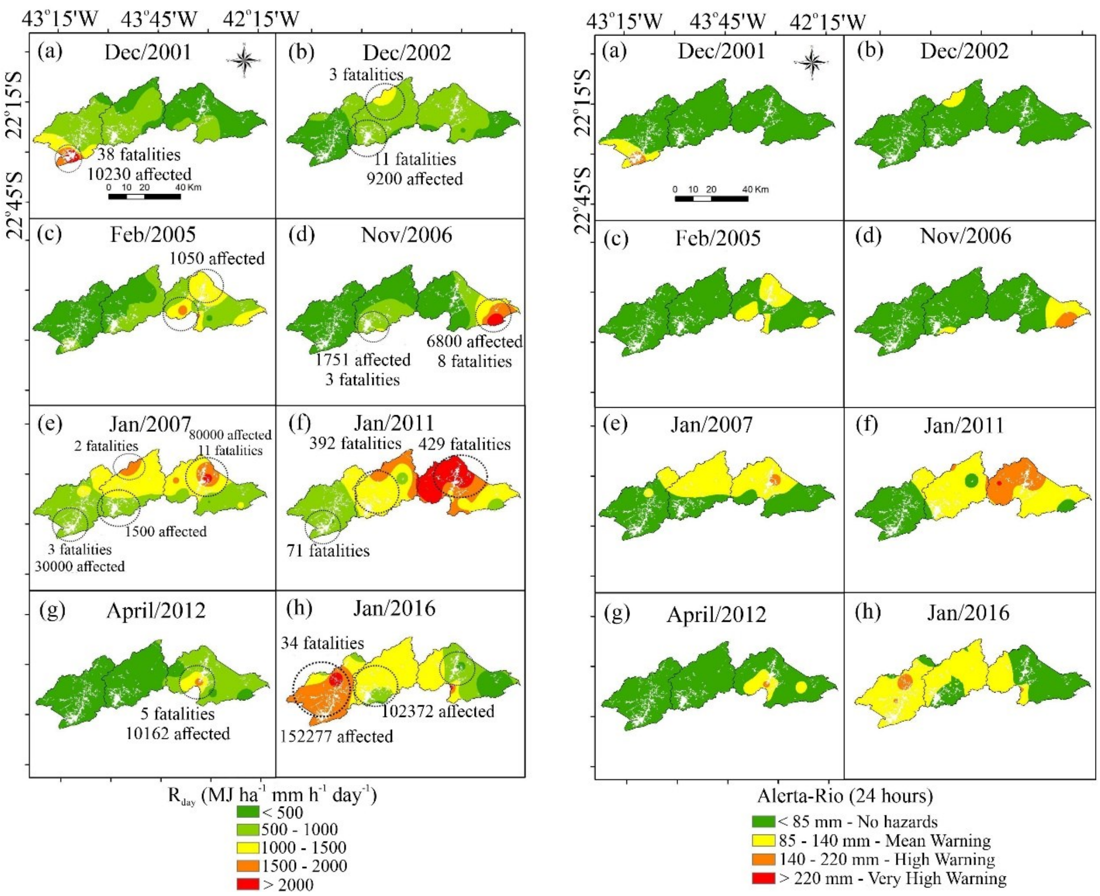

Figure 5. Maps of the most severe rainfall hazards in MRRJ (see Table 3) and respective R_{day} values (maps in left column) and using *Alerta-Rio* (maps in right column).

All three municipalities had R_{day} > 1,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1} at some point, and these events have always been linked to disasters that culminated in thousands of people affected (fatalities, displaced, homeless, injured people), as further depicted in Table 3. This table has as purpose of presenting the most impacting rainfall hazards in MRRJ between 2001 and 2016, respective impacts and risk classification (EWS) according to *Alerta-Rio*, taking the greatest precipitation in 24 hours or 72 hours, i.e., the worst situation (Table 1). Also, the disasters were presented according to the most affected (urban or rural), and the respective R_{day} was calculated using the fitted model.

Table 3. Summary of the rainfall hazards observed in the MRRJ in the last two decades and respective estimated R_{day}.

Date (DD/MM/Year)	Municipality	Displaced	Fatalities	Number of affected	R_{day} (MJ ha^{-1} $mm.h^{-1}$ day^{-1})	Area**	P24(mm)	P72(mm)	*Alerta-Rio*
24/12/2001	Petrópolis	5017	38	10230	3125.4	Urban	220.1	220.1	Very high
18/12/2002	Teresópolis	253	14	9200	1293.5	Rural	105.7	171.6	Mean
04/02/2005	Nova Friburgo	249	0	1050	1788.9	Rural	134.6	170	Mean
29/11/2006	Teresópolis	248	3	1751	1198.7	Urban	110.5	169.6	Mean
29/11/2006	Nova Friburgo	545	8	6800	2578.2	Rural	208.8	223	High
04/01/2007	Petrópolis	525	3	30000	1133.9	Rural	92.2	163.6	Mean
04/01/2007	Nova Friburgo	4196	11	80000	2238.4	Rural	162.3	395.9	High
04/01/2007	Teresópolis	229	2	1500	1851.3	Rural	138.6	160.1	Mean
12/01/2011	Petrópolis	7144	71	*	900.1	Rural	76.1	80.3	No hazards
12/01/2011	Nova Friburgo	5317	429	*	2594.6	Urban	183.5	201.8	High
12/01/2011	Teresópolis	15837	392	*	1962.8	Rural	145.5	249.8	High
06/04/2012	Nova Friburgo	2371	5	10162	1875.1	Urban	173	176.5	High
15/01/2016	Petrópolis	523	34	152277	1682.4	Urban	128.2	221.4	Mean
15/01/2016	Teresópolis	144	0	102372	1016.7	Rural	84.2	130.5	No hazards

* Official sources did not account for an approximate number per municipality, but it is known that more than 1,000,000 people were affected across the region. ** Areas more impacted (urban and rural).

The R_{day} estimates can be useful to analyze whether a given region can be hit by R_{day} that causes rainfall hazards. In addition, the development of R_{maxday} maps can be used as a tool to identify the most vulnerable areas to rainfall hazards. These maps can also be helpful in planning and managing the reduction of impacts caused by very erosive rains, which occur in mountainous regions of southeastern Brazil. The spatial distribution of R_{maxday} in MRRJ is presented in Figure 6 and was prepared using the maximum daily precipitation observed in the last 30 years (1990-2019).

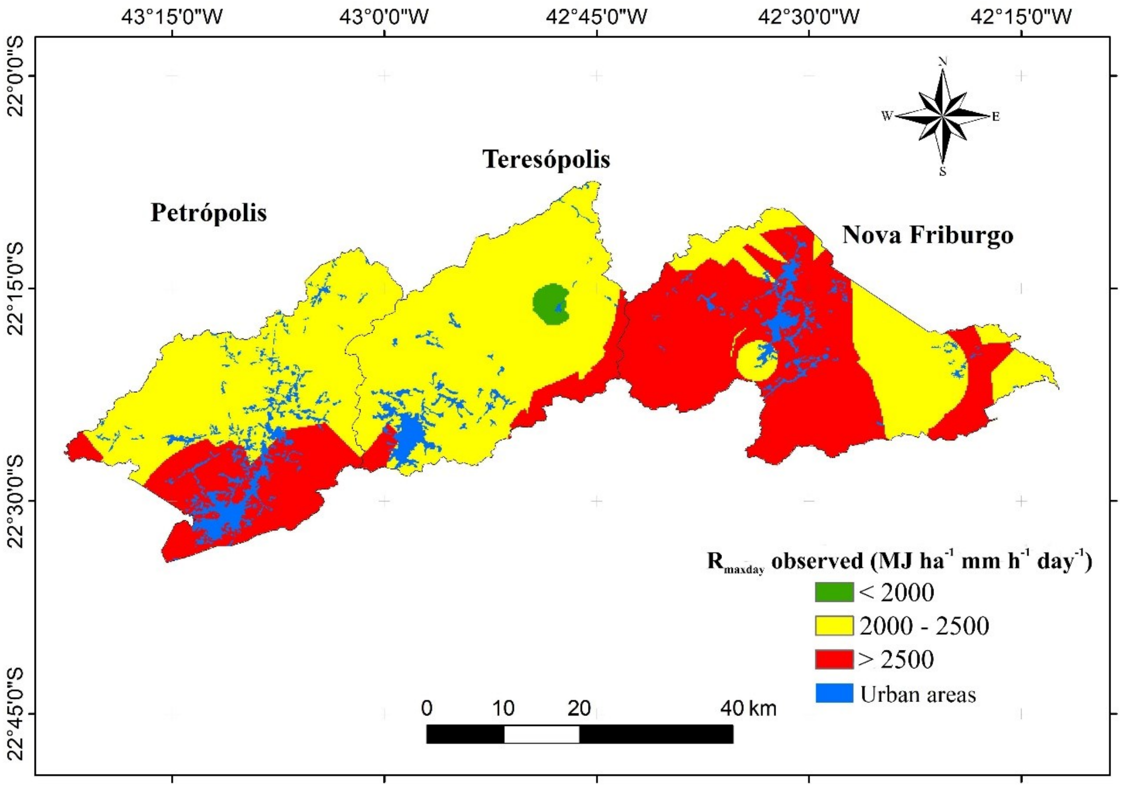

Figure 6. R_{maxday} mapping for the MRRJ considering the last three decades.

The highest R_{maxday} values ($\geq$ 2,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1}) were estimated in southern Petrópolis, eastern Teresópolis, and the largest part of the Nova Friburgo, matching with the highest altitudes. The urban areas of Petrópolis and Nova Friburgo are inserted in these regions, and Teresópolis is in a region where 2,000 < R_{maxday} < 2,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1}. These high values are explained based on the combination of the effects of orographic rainfall events due to altitude and proximity to the Atlantic Ocean. Therefore, these are the most vulnerable areas to rainfall hazards in MRRJ.

Nova Friburgo is the municipality with the highest R_{maxday} values. Thus, it is the most vulnerable to fatalities, damage to infrastructure, economy, and society in general. On the other hand, it is observed that practically all of the MRRJ presented R_{maxday} values > 2,000 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$, which is higher than the previously established index (1,500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$), allowing classifying this region as very vulnerable to fatalities, homelessness, and infrastructure damages.

4. DISCUSSION

4.1 General aspects of R_{day} in MRRJ

Despite the lower frequency of erosive events in the last three precipitation classes (Table 2; P ≥ 51 mm), these are the most expressive events in terms of erosivity, representing 47.6% of the total rainfall erosivity for the region. This fact demonstrates that only an erosive rain event can easily trigger natural disasters in the region. Thus, the study of these events is essential for analyzing the occurrence of natural disasters and a more practical index for issuing warning signs for natural disasters.

In MRRJ, there is a predominance of type I events due to the fact that the Serra do Mar is close to the Atlantic Ocean, increasing the presence of air humidity, leading to orographic and convective rains, which are generally of short to medium duration. Mello et al. (2020) for Mantiqueira Range region, southeast Brazil, also observed the dominance of type I, which is linked with the pattern of rainfall in tropical regions in summer. Most erosive events are associated with convective rains, characterized as local events of short duration and high intensity, increasing the *KE* values, as well as the maximum values for I_{30}. These rains are common in the summer, justifying the predominance of Type I. Despite the high magnitude of the total precipitation, events classified as Type III generally present lower I_{30} values since they come from high-duration frontal systems and less intensity than convective rains. However, several rainfall hazards are associated with this type of event since they are responsible for soil saturation, increasing the susceptibility to landslides and floods. It is also known that the variability in precipitation intensity during these frontal events is small, so that Type III events do not tend to overestimate R_{day} even with a higher amount of precipitation (Xie et al., 2016). Also, the South Atlantic Convergence Zone (SACZ) can hit the Southeast Brazil in summer, being responsible for several consecutive rainy days, and can therefore be highlighted as a potential source for types II and III.

Because a rainfall of 13 mm generated some erosive rains, this value is considered more appropriate as a threshold for erosive rainfall in MRRJ. This value is similar to those suggested by Xie et al. (2002), who conducted a study to characterize the erosive thresholds of the rains (from 11.9 to 12.8 mm), as well as Xie et al. (2016), who considered 12.0 mm as the most appropriate for eastern China, and Wischmeier & Smith (1978) suggested 12.7 mm for the United States. Mello et al. (2020) observed that none of the studied events smaller than 12 mm was erosive, while some events with precipitation equal to 13 mm were classified as erosive in the Mantiqueira Range region.

4.2 Seasonal R_{day} model for MRRJ

Mello et al. (2020) fitted values of *"α", "η"* and *"β"* for Mantiqueira range region equal to 1.8524, 0.2827, and 1.2950, respectively. Comparing these values with those fitted for the MRRJ, it seems that the *"α"* parameter, which is responsible for the R_{day} annual variation, is intrinsic to each region and did not show any similarity. *"β"* models the non-linearity variation between rainfall and rainfall erosivity (Yang and Yu, 2015; Wang et al., 2017), and therefore the value for MRRJ is similar to that for Mantiqueira range region. It is directly related to the rainfall patterns. Finally, *"η"* is the parameter that models the amplitude of the interannual variation of *"α"* and is not similar to the value for the Mantiqueira range region. Yu and Rosewell (1996) and Xie et al. (2016) fitted this model for eastern China and Australia, respectively, and found values equal to 0.2686, 0.5412 and 1.7265; and 0.535, 0.306 and 1.46 for *"α", "η"* and *"β"*, respectively, as mean parameters of the respective studied regions. Wang et al. (2017) also fitted a similar model in a subtropical region of China and found *"α"* varying from 1.04 to 3.12, *"η"* from 0.13 to 0.74, and *"β"* from 1.16 to 1.46. Therefore, it is recommended that each geographical region has its own fitted model since the parameters are associated with the respective rainfall pattern.

The behavior of the fitted model for MRRJ is similar to those found by Xie et al. (2016) and Mello et al. (2020), who found that this model shows an overestimation behavior for the lowest R_{day} values and produces better results for more intense rainfall events, which generate higher erosivity values. Despite the similarity of the results, Xie et al. (2016) and Mello et al. (2020) did not relate the model's performance to I_{30} behavior. In general, the model fits reasonably well to MRRJ, since the predominant I_{30} class in the region is 25 - 75 mm h^{-1} (Figure 4).

4.3 R_{day} and rainfall hazards in MRRJ: application of R_{day} and comparison with previous indexes

In this section, it is highlighted the main impacts of the rainfall hazards and respective R_{day}, which enable us to propose thresholds for R_{day} in MRRJ (Table 3), and to compare it with the previous existent. Petrópolis county was hit by a rainfall event in 2001 (220.1 mm in 24 hours) impacting the urban area, causing 38 fatalities (R_{day} > 3,000 MJ ha^{-1} mm h^{-1} day^{-1}). Similarly, the Teresópolis county was hit by rainfall in 2002 that resulted in R_{day} ranging from 500 to 1,000 MJ.ha^{-1}.mm.h^{-1}.day^{-1} in most part of its area. These events led to 11 fatalities and more than 9200 habitants affected. In the northern area, R_{day} reached 1,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1} and caused people to be buried by landslides. The R_{day} values in the urban area of Nova Friburgo in 2005 ranged from 500 to 1,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1} affecting 1050 inhabitants, and leaving 249 homeless. The R_{day} values in the rural area were between 1,500 and 2,000 MJ.ha^{-1}.mm.h^{-1}.day^{-1}. The municipalities of Nova Friburgo (545 homeless and eight fatalities), and Teresópolis (with 248 homeless and three fatalities) were severely affected again in 2006. In this year, the R_{day} values covered all the classes, with the highest values > 2,000 MJ.ha^{-1}.mm.h^{-1}.day^{-1}. The years of 2007 and 2011 had the highest R_{day} values and the greatest spatial coverage, resulting in 16 fatalities and 111,500 inhabitants affected.

The rainfall disaster that occurred in 2011 deserves special attention, since it was the worst observed in Brazil (Cardozo and Monteiro, 2019). This disaster not only caused a high number of fatalities, but also significant economic losses and damages. Petrópolis, Teresópolis and Nova Friburgo recorded the highest number of victims in MRRJ. The greatest impact in Nova Friburgo was observed predominantly in the urban area, while in the other two municipalities were on the rural areas (Busch and Amorim, 2011; Cardozo and Monteiro, 2019). The R_{day} values in Nova Friburgo exceeded 2,500 MJ.ha^{-1}.mm.h^{-1}.day^{-1}, and the entire urban area presented values varying from 1,500 to > 2,000 MJ.ha^{-1}.mm.h^{-1}.day^{-1}, which resulted in 434 fatalities (47% overall) (Cardozo et al., 2017, 2018; Cardozo and Monteiro, 2019). On the same day, the total number of homeless in Teresópolis reached 15,837 inhabitants, and it is estimated that more than 1 million people were affected in the three municipalities.

Nova Friburgo was again affected by similar natural disasters in 2012, however, unlike in 2011, they impacted the region in a more isolated way. R_{day} values ranged from 500 to 2,000 MJ.ha^{-1}.mm.h^{-1}.day^{-1}, resulting in five fatalities, 2,371 homeless and more than 10,000 affected inhabitants. In analyzing the year 2016 (Figure 5), it is observed that there was a considerable spatial range of the R_{day} values, with emphasis on the municipality of Petrópolis (34 fatalities, 523 displaced people, and 152,277 inhabitants affected). The fact that the number of victims decreased after the 2011 disaster compared to the number of victims in the years 2012 and 2016 indicates that the public policies, mainly the creation of structures such as CEMADEN, the Technical Support and Emergency Task Force at the National Secretariat for Civil Defense and the National Force of Brazilian Health System (SUS) had a positive effect on the protocols associated with natural disaster management.

Based on these data, it is possible to suggest some thresholds and possible impacts related to them. However, such thresholds do not necessarily mean that impacts, especially fatalities, may occur, since the system for protecting the population from these events is currently more structured than in the past. Therefore, we have: (i) R_{day} > 1,500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ presents a "very high" possibility of fatalities; "very high" number of homeless people; and "very high" possibility of social, economic and infrastructure damages. In these cases, the alert system must be activated immediately and the rescue teams must be properly prepared; (ii) 1,000 < R_{day} <1,500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ shows "high" possibility of fatalities, "very high" possibility for homeless people, and "high" possibility of causing damage to infrastructure and economy; (iii) 500 < R_{day} <1,000 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ "medium" possibility of fatalities in the urban area and "low" possibility in the rural area, "medium" impact in terms of homelessness, and "medium to low" possibility of causing damage to the infrastructure and economy; (iv) R_{day} < 500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ shows "very low" possibility of fatalities, "low" number of homeless people, and "low" possibility of economic and infrastructure losses.

According to the classification presented by *Alerta-Rio*, only one event of all the eight extreme events which caused great human and economic losses, or 14 if the municipalities are considered separately (Table 3), could be classified as "very high" risk, five as "high", six as "medium" and two were not classified, meaning they were not considered as causing natural disasters.

Among these events, the 3rd largest rainfall accumulated in 24 hours (183.5 mm) was the cause of the "mega-disaster" observed in MRRJ. According to the *Alerta-Rio* classification, this event would be classified as "high" risk (not "very high" risk as R_{day}). Although this event was the 3rd largest in terms of precipitation accumulated in 24 hours, it presented the 2nd highest R_{day} value (2,594 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$). This demonstrates how the proposed index is more comprehensive as a warning of natural disasters.

Considering the two events that were not classified by the *Alerta-Rio* since the accumulated precipitation in 24 hours was below 85 mm, it is observed that these events had R_{day} values close to 1,000 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$, which caused 71 fatalities. The other event, although no fatality was observed, affected more than 100 thousand inhabitants and left 144 families homeless. The alert system would have been triggered when applying R_{day}, and much of the impact would have been minimized.

Among the three criteria studied by Oliveira et al. (2016), criterion A is the least restrictive. Of the events presented in Table 3, only one (occurred on Jan-12, 2011) in the municipality of Petrópolis is not considered to cause landslides, when the precipitation accumulated in 72 hours is analyzed. The same result is obtained for criterion B.

Criterion C constraints the occurrence of landslides. The event that hit Petrópolis in 12/01/2011 was discarded as a cause of landslides in criteria A and B, as well as the event of Jan-15, 2016) in Teresópolis. These two events are the same that are not classified by *Alerta-Rio*, and together they affected thousands of people. Oliveira et al. (2016) emphasize that thresholds established for the most restrictive criteria do not separate events with landslides from those without landslides but are identified together with multiple disasters.

Comparing both early warning indexes (Figure 5) spatially, one can observe a sensitivity of the Rday index, especially in the rainfall hazards in which fatalities were observed. Examples are the events of 2001, 2006, 2007, 2011, and 2016. The *Alerta-Rio* index would emit a “high” warning in all these years, while Rday displays an “every high” warning for fatalities. Call attention 2011 event, the most severe rainfall hazard in Brazil. In this case, only a tiny spot would be warned as a “very high” warning, being the most significant part of the most affected area receiving a “high” warning. Otherwise, Rday would emit a “very high” possibility for fatalities in most of this area. We can see that more than 400 people died because of this event. In this direction, the event of 2016 would be understood as a “mean” warning using *Alerta-Rio*, whereas Rday would emit a “very high” warning (34 fatalities + more than 150,000 people displaced). Therefore, proposing Rday as a new early warning index proved to be more sensitive and more accurate with the impacts provoked by the rainfall because this index encompasses more information regarding the nature of heavy rainfall. Besides, it is easy to calculate and apply as a warning index for the MRRJ.

It should be noted that the occurrence of natural disasters in a region is inevitable since they depend on climatic variables. However, the consequences caused by these events not only depend on climatic factors, but also on political, social, and economic factors. Thus, an effective EWS must comprise four main components: knowledge of risk, monitoring, communication structures and efficient alerts, and lastly precautions, all of which need application of efficient public policies.

5. CONCLUSIONS

R_{day} addresses fundamental physical aspects associated with precipitation, its energy, as well as the mean and maximum intensities over a 30-minute time interval, being more sensitive than those which have been used in Brazil. Considering warning indices based only on the total rainfall or intensity of rainfall has not been shown to be sufficient to understand the complex dynamics of an extreme rainfall event, as its consequences are not only caused by water accumulation, but mainly by the dissipation of accumulated energy. R_{day} values can integrate national databases on the most vulnerable areas and specify risk management strategies and disaster response approaches, especially in places with the highest concentrations of exposed people. Further conclusions are:

a) The R_{day} model had superior performance of other studies with the same model and can be applied to additional studies related to rainfall disasters in Brazil.
b) All events with R_{day} > 1,500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ would fatally impact the region, and therefore areas historically affected by these events should be considered more prone to natural disasters.
c) Using the fitted model for R_{day} estimates, it was found that the municipality of Nova Friburgo, and the south of the municipality of Petrópolis are very vulnerable to natural disasters from the climatic point of view, with the highest R_{maxday} values.
d) January was historically the period with the highest daily erosivity values, in which all precipitation events used for developing the R_{maxday} map occurred in the first or second half of this month.

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ARTICLE 2 - RAINFALL DISASTERS UNDER THE CHANGING CLIMATE: A CASE STUDY FOR THE RIO DE JANEIRO MOUNTAINOUS REGION

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Rainfall disasters under the changing climate: a case study for the Rio de Janeiro mountainous region

Rainfall disasters under the changing climate: a case study for the Rio de Janeiro mountainous region

Abstract

Climate change impacts the erosive power of rain, influencing mountainous landscapes' vulnerability to natural disasters. This study evaluated the spatiotemporal projections of daily rainfall erosivity (R_{day}), an efficient warning index for rainfall disasters, under climate change. The objectives of this study were to project spatially R_{day} across the Mountain Region of the Rio de Janeiro State (MRRJ), one of the most vulnerable regions to rainfall disasters in Brazil, and to analyze the frequencies of R_{day} values throughout the 21st century. Two greenhouse gas emission scenarios (RCP 4.5 and 8.5), approximating the current status in South America, and a high-resolution climate model (the HadGEM2-ES physically downscaled to 5 km resolution by the Eta/CPTEC model) were applied to estimate daily rainfall values over the MRRJ. The mapping of the maximum R_{day} values in 30 years (R_{maxday}) showed that the entire MRRJ is highly susceptible to rainfall disasters throughout the 21st century, with intensification around 2040-2071. Urban areas, where fatalities have been recorded, have been the most vulnerable due to the high frequency of heavy rainfall. The projections for the 21st century indicated that 17 (under RCP4.5) and 15 (under RCP8.5) events like the "mega-disaster" could hit the study region. Thus, public policy efforts should focus on effective stormwater management actions to mitigate the impacts caused by such disastrous events in this century.

Keywords: daily rainfall erosivity; natural disasters; mountainous region; climate change Brazil.

Introduction

Natural disasters are the consequences of extreme events that cause significant impacts on the social, economic, environmental, or even psychological balance of people (Alexander et al., 2021). For example, floods and landslides caused by heavy rainfall are the most frequent natural disasters that affect humanity, causing thousands of deaths annually worldwide (Alexander et al., 2021).

Based on several studies worldwide, Lukic et al. (2013) reported that natural hazards have increased over time. From an economic point of view, the damages caused by natural hazards increased from several tens of billion dollars in the first seven decades of the last century to 380 billion dollars in 2011. The same was observed for fatalities, which globally impacted more than 24,000 lives per year between 1977 and 1997 to over 70,000 in 2011. Analyzing statistics published by Lukic et al. (2013), in America continent, 63% of the hazards are due to hydrological and meteorological events, such as severe storms, floods, and landslides. In Asia and Africa, 80% and 36% of natural hazards have occurred because of hydrological and meteorological events. In Europe and Oceania, natural hazards are considerably lower, 12% and 8%, from hydrological and meteorological causes.

Significant impacts of climate change have been observed in extreme heat, droughts, coastal flooding, erosion, wildfires, floods, and landslides. In South America, these drivers impact agricultural production, water availability, desertification of tropical biomes, and mass change in glaciers, which increase floods, soil erosion, and landslides (IPCC, 2022).

Natural disasters have hit South America, increasing the trends in climatic variability and extreme events, such as rainfall and droughts. In some regions of South America, especially in the southeast, a trend in precipitation has been observed. Projects from RCP4.5 and RCP8.4 scenarios indicate an increase of 25% in this region of South America (IPCC, 2022), which can potentially increase the occurrence of rainfall hazards in several regions, like the mountains of southeast Brazil, where Rio de Janeiro is located. It is essential to highlight the magnitude and frequency of extreme rainfall in South America and its projections. Chou et al. (2014a) projected a decrease in heavy rainfall considering an increase of 1.5ºC; however, Imbach et al. (2018) projected an increase in the frequency of the R50mm, i.e., an increase in the number of days with rainfall greater than 50 mm for global warming of 2ºC and 4ºC.

In Brazil, landslides and floods are the main ones responsible for the greatest impacts from natural hazards with a number of fatalities (CEPED, 2012). These hazards are triggered by extreme rainfall, leading to many fatalities in this country every year, especially in areas geomorphological prone to landslides, such as the mountains region of southeast Brazil. Thus, the increase in the frequency and intensity of extreme rainfall, in combination with the high degree of susceptibility of the population in risk areas, has triggered these disasters in the country, especially in mountainous regions with high geological risk (Fernandes and Rodrigues, 2018; Amorim and Chaffe, 2019). Some mountainous regions of Brazil are places where geomorphological features, deforestation of the Atlantic Forest, recurrent heavy rainfall (Freitas et al. 2012), and the uncontrolled growth of urban areas potentiate the consequences arising from natural disasters (Mello et al. 2020). One of the regions most affected by extreme rainfalls is the Mountain Region of the Rio de Janeiro State (MRRJ), which is one of the most vulnerable to rainfall disasters in the country (Freitas et al., 2012; Brasil, 2012; Bitar, 2014; Oliveira et al. 2016). This region suffered many events that resulted in several fatalities, such as the so-called "mega-disaster" in 2011 (Alves et al. 2022). The most recent hit the city of Petropolis in February 2022, causing the death of 231 people (Alcântara et al., 2022). This event, in meteorological terms, was extraordinary, bringing 252 mm of rain in three hours.

Determining indexes applied to alert/warning systems to mitigate the impacts caused by rainfall disasters is always challenging. The document of the World Conference for Disaster Reduction in Japan in 2005 warns of the need to develop indicator systems at different levels of scope to enable a better diagnosis and response to risk situations and vulnerability by decision-makers (Silva et al. 2016). In this sense, some studies have evaluated the efficiency of the Monitoring and Alert System (MAS) ("Early Warning System") indicators in reducing risks related to economic impacts, in addition to the risks of fatalities (Webster, 2013; Alvalá et al. 2019). As intense rainfalls trigger these events in Brazil, indexes are used as an early warning based on their temporal behavior. Weather forecasting can be reliable if made up to 72 hours in advance (Oliveira et al. 2016). Thus, rainfall (accumulated and its intensity) composes most of the MASs (Calvello et al., 2015; Mello et al., 2020; Alves et al., 2022).

Some indexes are widely used in Brazil and the world, such as the accumulated rainfall in the last 24, 48, 72, and 96 hours, the rainfall intensity (mm/h), or their combinations (Oliveira et al. 2016; Calvello et al. 2015; Silva et al. 2020). Some studies also used rainfall erosivity and other rainfall indexes to identify areas more prone to landslides in Europe. Lukic et al. (2021) applied the Angot Precipitation Index to study rainfall erosivity behavior in the Vojvodina region, Serbia and observed a good performance of this index to identify the aggressiveness of rainfall and its correlation with soil water erosion. Ponjiger et al. (2021) applied the daily rainfall erosivity and respective density erosivity to identify areas more susceptible to water erosion in the Pannonian Basin, Central Europe. Although they applied the model and respective parameters proposed by Zhang et al. (2002) to China, they identified the seasons in which rainfall erosivity has been marked, enhancing the assessment of the aggressiveness of rainfall erosivity in southern Europe. Morar et al. (2021) also studied rainfall erosivity as a predictor for natural hazards in the Ciuperca region, Romania, using monthly rainfall data. Besides rainfall erosivity, they applied the Precipitation Concentration Index (PCI) and Modified Fournier Index (MFI), both good indexes related to the aggressiveness of rainfall. In another study carried out in Belgrade, Serbia, Lukic et al. (2018) also applied the PCI and MFI and observed a moderate aggressiveness of rainfall, which, together with the geological features, demonstrated the vulnerability of the studied region to natural hazards triggered by rainfall.

However, these indexes may be inefficient in some cases (Calvello et al., 2015; Mello et al., 2020). Thus, Mello et al. (2020) established an alert climate index (R_{day}) related to the maximum daily rainfall erosivity for the Mantiqueira range region (Southeast Brazil) based on the impact of the rain, rainfall amount, and rainfall intensity. This index is based on rainfall erosivity, a climatic index that portrays the impacts of energy dissipated by raindrops on the surface. Thus, it is a more comprehensive index than the others to predict hazards, especially fatalities. This concept was initially proposed and defined by Wischmeier and Smith (1958) as the product between the kinetic energy of raindrops (Ek) and the maximum rainfall intensity in 30 consecutive minutes (I_{30}), designated as EI_{30}. When applied on a daily scale, it can help better understand the role of heavy rainfall in natural disasters (Alves et al., 2022; Mello et al., 2020).

A rainfall network with a temporal resolution < 15 min for the computation of daily rainfall erosivity (R_{day}) is often lacking in Brazil. Thus, applying a model for R_{day} estimation based on daily rainfall data, which are more accessible and spatially distributed, is critical to linking heavy rainfall events to natural disasters (Chen et al., 2020). In this aspect, Alves et al. (2022) developed a similar index for MRRJ. This index is based on Yu and Rosewell's (1996) study, which proposed a method to estimate the seasonality of R_{day}, and on the index established by Mello et al. (2020).

In this context, climate change and its impacts on the magnitude and frequency of rainfall disasters are uncertain, especially in regions with significant orographic influences (Lyra et al., 2017). Disasters involving landslides have become more frequent and severe during the last decades (CEPED, 2013), especially in mountainous regions of Brazil (Mello et al., 2020). Such facts demonstrate evident changes in the heavy rainfall pattern (IPCC, 2013), and rapid population growth, which result in disorganized urbanization (IPCC, 2022).

It is a fact that climate change has impacted the rainfall pattern in Brazil, with clear changes in rainfall erosivity. However, most studies have focused on annual rainfall erosivity (or RUSLE's R-factor) (Riquetti et al., 2020; Mello et al., 2015), which needs to be further understood as impacts on extreme rainfall events. This study brings as novelty an assessment of climate change impacts on daily rainfall erosivity (R_{day}), being the first investigation in this regard in Brazil. Studies of climate change impacts on daily rainfall remain little studied in tropical and mountainous regions, and their contribution to preventing rainfall hazards is essential. Using a daily rainfall erosivity model, it is possible to assess the frequency of heavy rainfall, respective R_{day}, and impacts of rainfall disasters using daily rainfall projections over the century.

The objectives of this study were to i) apply a seasonal model to calculate R_{day} for the MRRJ throughout the 21st century, using a high-resolution climate model (HadGEM2-ES physically regionalized by the ETA-CPTEC model in the 5 km spatial scale – the 5-km Eta-HadGEM2-ES), and the RCP4.5 and 8.5 IPCC scenarios, ii) map the maximum daily rainfall erosivity (R_{maxday}) to assess the most vulnerable areas of MRRJ throughout the present century, and iii) to project the frequency of $R_{day} > 500$ MJ mm (ha h)$^{-1}$ day^{-1} (a threshold for the harmost events) throughout the 21st century.

Material and Methods

Some aspects of the mountain region of the Rio de Janeiro State (MRRJ)

The MRRJ is located in the Serra do Mar and is characterized by mountainous to steep relief, with altitudes ranging from 400 to 2350 meters (Figure 1). It is located in the unit called "Planalto Reverso" (Garcia and Francisco, 2013), and the soils are predominantly shallow, moderately permeable, and have low natural fertility (Pinto et al., 2018).

The geographic location of the three most populous municipalities, Petrópolis (792 km²), Teresópolis (773 km²), and Nova Friburgo (936 km²), and the digital elevation model for the entire region are shown in Figure 1. The location of the rainfall stations from the National Water and Sanitation Agency (ANA) and the 130 grid points for which the daily rainfall data of the climate projections used in this study are also presented. These three municipalities represent almost 80% of the entire MRRJ population (IBGE, 2010) and have been the most affected by rainfall disasters in Brazil (Alves et al., 2022; Coelho Netto et al., 2013).

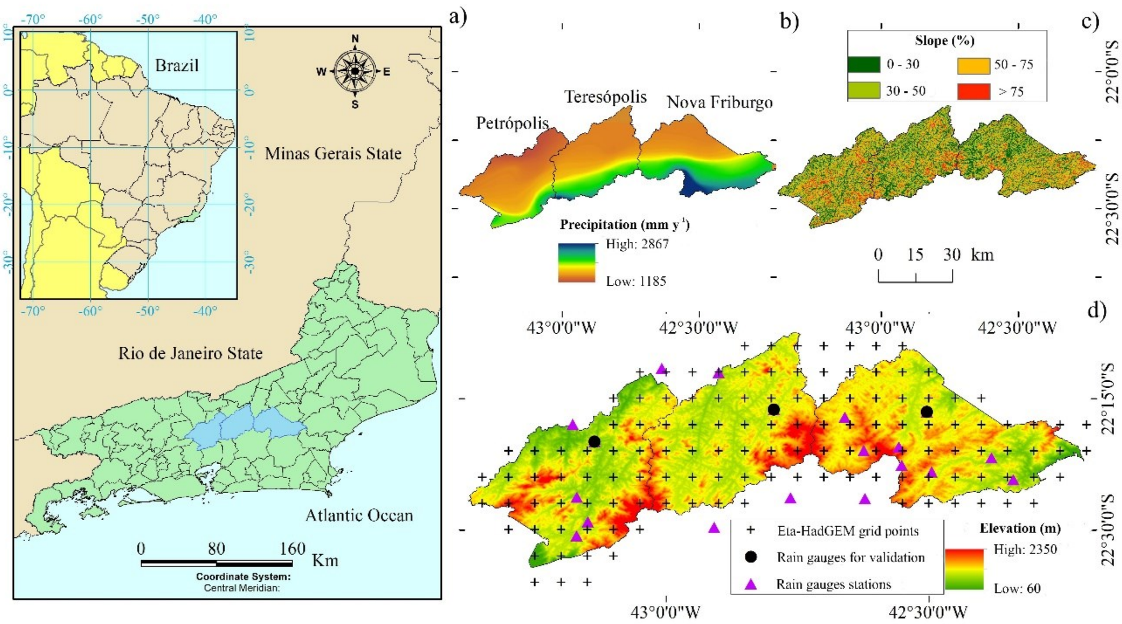

Figure 1. The geographical location of MRRJ (a), with emphasis on Nova Friburgo, Petrópolis, and Teresópolis, annual precipitation map (b), relief (slope) map (c), and the grid points obtained by the 5-km Eta-HadGEM2-ES model and locations of the ANA rain-gauges (d).

The entire MRRJ was originally covered by Atlantic Forest, which was removed to make way for plantations, pastures, and urban centers. Despite currently being fragmented and degraded, especially around urban areas, the Atlantic Forest still represents more than 50% of the region's vegetation cover (Coelho Netto et al., 2013; Garcia and Francisco, 2013; Cardozo and Monteiro, 2019). Garcia and Francisco (2013) found that this biome is present in the steepest and most elevated places. It suffers from fires during the dry period, resulting in the destruction of its vegetation cover, making the surface more susceptible to landslides caused by rain in the summer.

The climate of the MRRJ is Cwb (Köppen climate-type), meaning a mild temperate climate with dry winters and rainy summers. The average annual temperature is approximately 16°C and the average temperature of the hottest month is below 22°C (Coelho Netto et al. 2013). Summers are rainy (more than 70% of rainfall occurs between October and March) (André et al. 2008), and winters are cold and dry (Dourado et al. 2012). The rainfall pattern in the MRRJ is driven by several climatic phenomena, such as i) frontal systems, which act throughout the year and which, combined with the humidity of the Atlantic Ocean, bring significant amounts of rain, ii) convective rains in summer, iii) South Atlantic Convergence Zone (SACZ) during the summer, iv) orographic effects, v) tropical and subtropical cyclones, and vi) maritimity (Reboita et al. 2010).

Daily rainfall erosivity (R_{day}) model to MRRJ

The seasonal model of daily rainfall erosivity fitted by Alves et al. (2022) is based on the studies by Yu and Rosewell (1996) and was used for this study.

$$R_{day} = 3.3888 \cdot \left[1 + 0.4659 \cdot cos(\frac{2 \cdot \pi \cdot j}{24} - \frac{\pi}{6})\right] \cdot Pday^{1.2028} \qquad (1)$$

In which *j* is the fortnight (ranging from 1 to 24) and P is the daily precipitation in a 24-hour interval (mm). It is important to highlight that this model represents the MRRJ since it was determined based on data from 68 stations with precipitation data with a temporal resolution of 10 minutes. The precision statistics presented and discussed by the author showed satisfactory results for estimating the R_{day} (calibration: $C_{NS} = 0.51$; $P_{bias} = -0.56$) and (validation: $C_{NS} = 0.50$; $P_{bias} = -2.22$).

Equation 1 was applied to the daily rainfall data obtained from the ANA rain-gauges to the historical data (baseline) and the climate projections provided by the Global Circulation Climate Model (GCM) (HadGEM2-ES) downscaled by a physical model, the Eta/CPTEC (5-km Eta-HadGEM2-ES).

Maximum daily rainfall erosivity (R_{maxday}) maps were developed considering the highest R_{day} values observed at each grid point provided by the 5-km Eta-HadGEM2-ES model (Figure 1) for the historical period (1961-2005) and three different periods throughout the 21st century (2006-2040, 2041-2070 and 2071-2099). In addition, percentage variation maps of future periods were prepared and referred to the historical data. These maps make it possible to detect areas with greater susceptibility to natural disasters caused by extreme precipitation events throughout the century.

Climate change projections of R_{day} using a high-resolution climate model for the MRRJ

The Eta Regional Climate Model (RCM) was refined by Chou et al. (2012) and Marengo et al. (2012) to provide downscaling of climate change projections in South America at a spatial resolution of 0.20° × 0.20° (20 km horizontally and 38 layers vertically) nested to the HadGEM2-ES, MIROC5, BESM and CANESM2 global climate models (GCMs). Its most recent version was described in detail by Mesinger et al. (2012) and evaluated for long-term simulations by Pesquero et al. (2010), Flato et al. (2013), and Chou et al. (2012, 2014a, b).

The orographic influence on precipitation should be considered to improve the simulation results (Brito et al., 2016; André et al., 2008). Therefore, the spatial resolution of 20 km produces insufficient results for analyzing the frequency of extreme events that cause natural rainfall disasters (Chou et al., 2014a). Thus, a downscaling process was carried out using the Eta-CPTEC model for a 5-km resolution to overcome the coarse resolution (20 km), nesting it to the HadGEM2-ES GCM under the RCP4.5 and RCP8.5 emission scenarios in the period from 1961 to 2100. However, due to the high computational demand, only the Eta-HadGEM2-ES was regionalized for the 5 km scale and is only available for Southeastern Brazil (where MRRJ is located). Lyra et al. (2017) detailed this higher spatial resolution version.

In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013), greenhouse gas concentration scenarios are based on two "Representative Concentration Pathways" (RCP), which are expressed in terms of radiative forcing to the end of the 21st century. The scenarios used in this study were RCP8.5 and RCP4.5 (Van Vuuren et al. 2011), the only ones available for South America. RCP4.5 is considered an intermediate scenario that assumes greenhouse gas emissions stabilization from the middle of the 21st century. This scenario considers a global radiative forcing of approximately 4.5 $W.m^{-2}$. On the other hand, RCP8.5 is a scenario that considers an increase in greenhouse gas emissions by the end of the century, meaning that no implementation of climate policies and continued acceleration of the use of fossil fuels.

Historical (baseline) data (1961-2005) and climate projections (2006-2099) of daily rainfall for calculating R_{day} values considering both scenarios were obtained from the Weather Forecast and Studies Center of the National Institute for Space Research (*CPTEC/INPE*) on the platform called "PROJETA" (Holbig et al. 2018) (https://projeta.cptec.inpe.br/#/about).

The validation of the 5-km Eta-HadGEM2-ES model to estimate R_{day} was conducted with the application of the seasonal model of daily erosivity in the period from 1980 to 2005 (26 years) to calculate the long-term annual average rainfall erosivity (R-factor) considering the data obtained from three ANA rain-gauge stations and the 5-km Eta-HadGEM2-ES for the same period. Daily rainfall < 13 mm was not considered erosive, according to the Alves et al. (2022) study, and thus was not considered in the R-factor calculation.

Critical thresholds of R_{day} MRRJ

R_{day} thresholds are values proposed to identify and alert areas most vulnerable to natural disasters (Mello et al. 2020). These limits have been established through a joint analysis of R_{day} values calculated for rainfall events that caused disasters concomitantly with the consequences observed in recent decades. As a result, the following values were proposed for the MRRJ by Alves et al. (2022):

i) $R_{day} > 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$: "very high" possibility of fatalities; "very high" number of homeless; and "very high" possibility of damage in general

ii) ii) R_{day} between 1,000 and 1,500 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$: presents a "high" possibility of fatalities, a "very high" number of homeless, and a "high" possibility of causing damage to infrastructure and economy

iii) iii) R_{day} between 500 and 1,000 $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$: "medium" possibility of fatalities in urban areas and "low" in rural areas, "medium" impact in terms of homeless, and "medium" possibility of causing damage to infrastructure and economy

iv) iv) $R_{day} < 500$ $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$: "very low" possibility of fatalities, a "low" number of homeless, and a "low" possibility of damage to the economy and infrastructure.

The established R_{day} limits were used to classify the R_{maxday} maps, and the thresholds $1{,}000 < R_{day} < 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ and $R_{day} > 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.day^{-1}$ were also specifically used to analyze the frequency of events causing natural disasters throughout the 21st century as they imply possible fatalities. Therefore, the frequency of these events over the baseline and the three periods (1976-2005, 2011-2040, 2041-2070, 2070-2099) was analyzed. It is possible to observe a slight change in the intervals considered to analyze the frequency of these events used to map the R_{maxday} to consider periods of 30 years of data. Thus, 3900 events were analyzed for each time slice, 30 for each of the 130 grid points generated by the 5-km Eta-HadGEM2-ES model (Figure 1).

Figure 2 presents a flowchart with the steps to calculate the daily rainfall erosivity for the baseline and time slices throughout the century and the conversion of these values to assess the rainfall hazards in MRRJ.

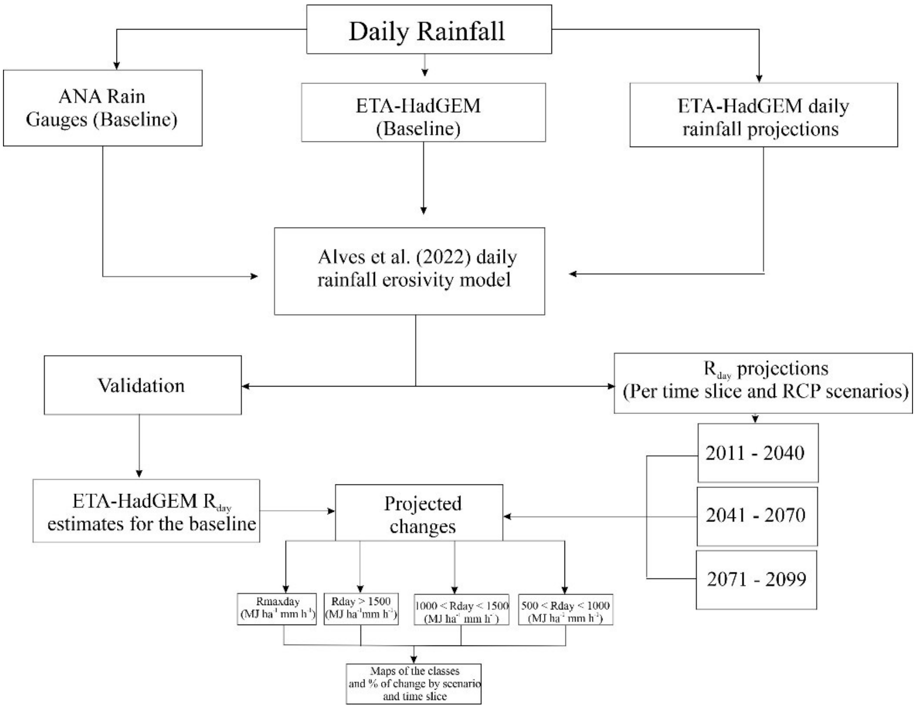

Figure 2. Flowchart with the methodology used to assess the rainfall hazards in MRRJ.

Results and Discussion

Performance of the high-resolution climate model (5-km Eta-HadGEM2-ES model) to calculate rainfall erosivity in the MRRJ

To evaluate the high-resolution climate model in estimating daily rainfall erosivity, we examined its capability to account for RUSLE's R-factor estimation, i.e., the long-term average annual rainfall erosivity, given that R-factor values and patterns are well-known in the study region. Therefore, the R-factor for the ANA rain gauges of Petrópolis, Nova Friburgo, and Teresópolis (Figure 1) was detailed. The R-factor calculated for these three rain gauges using daily rainfall projected by the high-resolution climate model showed a good agreement with the R-factor calculated based on the daily rainfall observed in the ANA rain-gauge stations. The R-factor was 8,537; 10,554 and 7,639 $MJ.ha^{-1}.mm.h^{-1}.year^{-1}$, respectively, to Petrópolis, Nova Friburgo, and Teresópolis, using the observed daily rainfall. Considering the daily rainfall from the 5-km Eta-HadGEM2-ES climate model, R-factor was 9,566 (an overestimate of 10.29%) to Petrópolis, 9,886 (an underestimate of 6.67%) to Nova Friburgo, and 6,057 $MJ.ha^{-1}.mm.h^{-1}.year^{-1}$ (an underestimate of 15.82%) to Teresópolis. These results demonstrate a good correspondence between the R-factor estimated based on the climate model and observations. Furthermore, we can state that this model was able to cope with the strong orographic influence on the rainfall in the region since the ANA rain gauges are located in different locations and altitudes of the MRRJ (see isohyets contour in Figure 1).

Yin et al. (2013) demonstrated through 11 GCM simulations that the HadGEM2-ES model had the best performance under surface conditions and atmospheric circulation (Chou et al., 2019). Furthermore, in analyzing 19 global climate models, Gulizia and Camilloni (2015) concluded that HadGEM2-ES presented the highest spatial correlation between simulated precipitation values and those observed for South America in the baseline. These studies support the 5-km Eta-HadGEM2-ES model to appraise erosivity events throughout the 21st century. It is also needed to highlight the relevance of using a physical model for downscaling the outputs from a GCM in mountainous regions to better capture the orographic effects (Chou et al., 2014a), which is a considerable aspect of the MRRJ climate pattern.

The estimation of R_{day} has been useful in identifying the most vulnerable areas to natural disasters and analyzing the frequency of events associated with these disasters. Although the results of this study were only applied to the MRRJ, the proposed methodological framework can be transferred to other vulnerable areas in the country since there are data with a temporal resolution of 15 minutes for modeling R_{day}.

R_{maxday} mapping in the MRRJ throughout the 21st century

Figure 3 shows the spatial distribution of R_{maxday} and its percentage variation throughout the 21st century regarding the baseline in MRRJ considering the 5-km Eta-HadGEM2-ES model projections. R_{maxday} corresponds to the maximum value calculated by considering a time series with at least 20 years of daily rainfall erosivity (Mello et al., 2020).

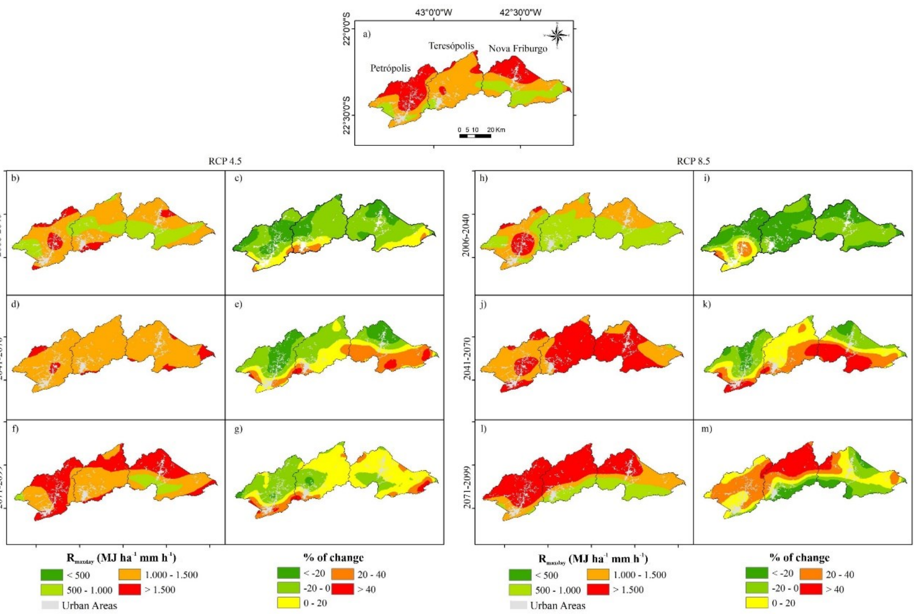

Figure 3. R_{maxday} baseline map (a) and maps of the R_{maxday} and respective relative changes in relation to the baseline throughout the 21st century (RCP4.5: b-g; RCP8.5: h-m).

Considering the baseline map (3a) and maps for the time slices in the RCP4.5 (3b - 3g), almost the entire MRRJ is hit by rainfalls that result in R_{maxday} values that cause disasters with different consequences.

However, regardless of the climatic scenarios, the period with the most extensive spatial coverage of R_{maxday} values > 1,500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ is from 2070 to 2099 (Figures 3f – RCP4.5 and 3l – RCP8.5), especially for the RCP8.5, where the positive relative changes (Figures 3l and 3m) dominate the north region of the largest municipalities. Worthwhile that it is essential to highlight the concentration of these events in the urban areas of Petrópolis and Nova Friburgo, which might result in fatalities.

The 2011-2040 time slice (Figures 3b and 3h, respectively, for RCP4.5 and RCP8.5) presented R_{maxday} values predominantly in the 500 < R_{maxday} < 1,000 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class in Nova Friburgo and Teresópolis, especially for RCP8.5 (Figure 3h). However, for this same time slice, an increase in R_{maxday} in Petrópolis in the ranges that encompass values > 1,000 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ were detected, meaning an increase in the magnitude of the events that can potentially cause significant hazards and fatalities. Thus, in this time slice, which we are crossing now, Petrópolis has been the most vulnerable municipality of the MRRJ to rainfall hazards. This aspect has been observed recently (Alves et al., 2022).

Maps of the relative changes are also presented for both scenarios and were generated to understand the spatial variation of R_{maxday} values regarding the baseline. Positive values mean an increase in R_{maxday}, and negative values represent a decrease in magnitude. Compared to the baseline, there is a decrease in R_{maxday} for the 2011-2041 time slice (Figures 3c and 3i). Except for the southern of the three municipalities and the southwest and central region of Petrópolis, negative values were predominant, meaning a decrease in the R_{maxday} values in MRRJ throughout the century. Although this decrease, R_{maxday} still represents a very harmful situation for MRRJ and needs to be considered carefully in the following decades.

The 2011-2040 time slice projections are less uncertain than the other time slices as we are in the middle of this period, allowing better initial conditions and assumptions for running the model (IPCC, 2022). In this situation, we can expect an increase in the R_{maxday} values for areas of the MMRJ, requiring a careful implementation of actions to minimize rainfall hazards, especially in the Petrópolis region.

These results imply that further attention to the areas that showed positive changes in R_{maxday} must be implemented by the federal and state governments, focusing on the summer and spring periods as such areas are the most vulnerable in the present to landslides and will be throughout the century. Actions like improving the warning systems and meteorological and geological monitoring stations need to be expanded. In contrast, the municipalities need to plan strategies to minimize fatalities, such as ready emergency staff that can respond shortly to the crises and rethink the occupation of these areas in the middle term.

Frequency of the greatest R_{day} events in MRRJ throughout the 21st century

Figure 4 shows the frequency of R_{day} in the 130 grid points (Figure 1d) in MRRJ and another 86 in the neighborhood, resulting in 216 points from the 5-km Eta-HadGEM2-ES outputs for the RCP4.5 and 8.5 scenarios. The range of the baseline and the climate projection data is 30 years for comparative purposes.

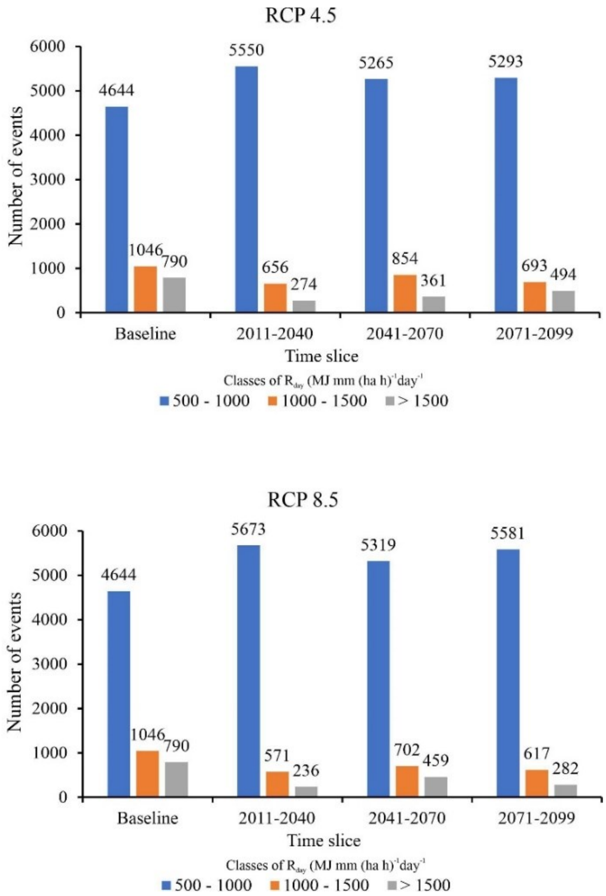

Figure 4. The frequency of the R_{day} projected by the 5-km Eta-HadGEM2-ES model that can result in natural disasters in the MRRJ in the RCP4.5 (a) and 8.5 (b) scenarios for the baseline and the three different periods throughout the 21st century.

The class with the highest frequencies, regardless of the RCP scenario and the period considered, is between 500 and 1000 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ (Figure 4). The events in this class represent 85, 81, and 82% of the occurrences for the 2011-2040, 2041-2070, and 2070-2099 periods, respectively, for RCP4.5. Considering the RCP8.5 scenario, 87, 82, and 86% of the events fall in this range, respectively. In the baseline, 72% of the events were observed in this class. Greater frequencies in the RCP8.5 in relation to the RCP4.5, and for both scenarios, were projected, i.e., significant increases regarding the baseline for this class. Therefore, climate change is expected to increase the number of events in this class, highlighting that they can cause several damages, fatalities included (Alves et al., 2022). Frequencies for this class for RCP8.5 were slightly higher than those for RCP4.5, meaning a reduction of the events that can potentially cause hazards, following the classification proposed by Alves et al. (2022) for MRRJ, i.e., a medium possibility to generate homelessly, damages on the basic infrastructure and fatalities.

Oppositely, for the $1{,}000 < R_{day} < 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class and RCP4.5 scenario, a higher frequency throughout the 21st century than the RCP8.5 was projected. These events are related to the occurrence of disasters with a "high" possibility of fatalities, a "very high" number of homeless people, and a "high" possibility of causing damage to infrastructure and the economy. However, the behavior considering the three analyzed periods was similar for the two scenarios, where the highest frequency of events in this class was verified for the period from 2041 to 2070, being equal to 13% and 11% for the RCP4.5 and 8.5 scenarios, respectively, and 16% for the historical period.

The R_{day} > 1,500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class encompasses the harmost events, which have the lowest frequency. In baseline, it was observed that 12% of these events, and throughout the 21st century, 4, 6, and 8% for the RCP4.5 scenario in the 2011-2040, 2041-2070, and 2070-2099 time slices, respectively. Contrary to the tendency observed for RCP4.5, in which there was a progressive increase throughout the 21st century (Figure 4a), the highest frequency observed for the RCP8.5 was in the 2041-2070 time slice, with 459 R_{day} events > 1,500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$, representing approximately 7% of the total analyzed events.

Concomitantly analyzing the R_{day} classes related to natural disasters with "medium", "high" and "very high" possibilities of fatalities and damage to infrastructure (R_{day} > 500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$), it is observed that the 2041-2070 time slice was the one with the highest frequencies for both RCP scenarios.

Mello et al. (2021) and Alvarenga et al. (2018) used the Eta-HadGEM2-ES in a resolution of 20 km to simulate climate change impacts on streamflow in watersheds of the Southern Minas Gerais and Mantiqueira Range region, which is in neighborhood MRRJ. In both studies, a decrease greater than 40% in the monthly precipitation of the wet period, i.e., from January to April, was projected. In this study, we obtained a reduction in the frequencies of the harmost R_{day} values (> 1,000 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$) of approximately 30% across the time slices and RCP scenarios as a response to the reduction in the amount of monthly rainfall projected. However, we can infer that there will be an increase in the concentration of rainfall in the wet period since a reduction in the total monthly values is more significant than the frequency of extreme events. Thus, summer will continue as the most dangerous rainfall disaster despite the reduced precipitation.

The spatial occurrence of critical R_{day} events throughout the 21^{st} century considering the most severe ones, i.e., 1000 < R_{day} < 1500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ and R_{day} > 1500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ classes are respectively shown in Figure 5.

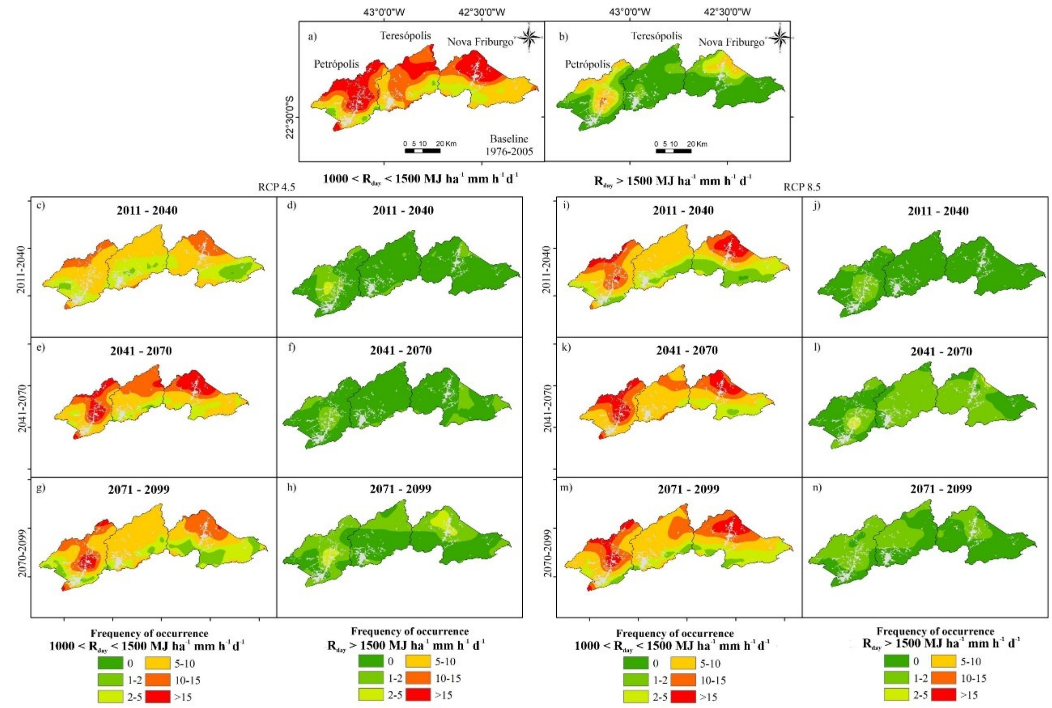

Figure 5. Frequency maps of events in the classes 1,000 < R_{day} < 1,500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ and R_{day} > 1,500 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ projected by the 5-km Eta-HadGEM2-ES model in MRRJ for the baseline and RCP scenarios.

The northern region of Nova Friburgo and the central region of Petrópolis are those with the highest occurrences of R_{day}, for both RCP scenarios, in the $1{,}000 < R_{day} < 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class (Figures 5a – 5g), being greater than 15 occurrences regardless of the time slice. However, between 10 and 15 events were projected for both regions considering RCP4.5 in the 2011-2040 time slice.

Both scenarios have greater spatial coverage of the highest R_{day} values in the 2041-2070 time slice. Compared to the baseline, it is predicted that there will be a decrease in such events in MRRJ in the 21st century. This decrease is more noticeable for Teresópolis, where there was a greater frequency of events in the $1{,}000 < R_{day} < 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class for the baseline, whereas the frequency in this class from projections varies from five to ten events.

The lowest frequencies were observed in the southern Nova Friburgo and Teresópolis and in the southwest Petrópolis, where values were predominant between 1 and 5 events in the $1{,}000 < R_{day} < 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class. This frequency class has a more considerable predominance from 2011 to 2040. The baseline showed higher frequencies and spatial range of values within this R_{day} class. It is important to note that this R_{day} class is related to rainfall with a "high" possibility of fatalities, a "very high" number of homeless, and a "high" possibility of damage to infrastructure and the economy. Thus, in the case of Petrópolis and Nova Friburgo, although a decrease in the frequency of these events throughout the 21st century, it is understood that the highest occurrences will prevail in urban areas for any period or RCP scenario. Therefore, it is necessary to establish alert indexes and efficient public policies to mitigate the impacts caused by such events in the future. Although Teresópolis presented a lower frequency of these events (5 to 10 events) throughout the century, this number of events is high, meaning that this municipality can be hit by a rainfall event in this class once every three years in the 2070-2099 time slice.

The frequency maps of events in the $R_{day} > 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class showed a decrease regarding the baseline. For RCP4.5, it is observed that there would be an increase in the occurrences in the 2070-2099 time slice if compared to the baseline, where the projections for the urban areas of Petrópolis and Nova Friburgo vary from two to five events. Considering the RCP8.5, this frequency of events was observed for the central region of Petrópolis in the 2041-2070 time slice.

Based on the data analyzed and maps, Nova Friburgo and Petrópolis are the most vulnerable to natural disasters with fatalities. However, a significant frequency of events in the $1{,}000 < R_{day} < 1{,}500$ $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ class may occur in Teresópolis, and events in this class can cause disasters with fatalities. Also, there is an increase in the frequency of R_{day} values in the RCP8.5 compared to RCP4.5, except for the 2070-2099 time slice considering the second R_{day} class analyzed (Figure 5m).

The R_{day} values calculated for the "mega-disaster" were equal to 900.1, 1962.8, and 2594.6 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ for Petrópolis, Teresópolis, and Nova Friburgo, respectively, meaning greater impact on the last municipality. Considering the R_{day} value >1962.8 $MJ.ha^{-1}.mm.h^{-1}.d^{-1}$ as the threshold for the "mega-disaster", their frequency throughout the century was 87, 128, and 145 for RCP4.5, 74, 163, and 94 for RCP8.5, for the 2011-2040, 2041-2070 and 2070-2099 time slice, respectively, considering all grid points (Figure 1d). Thus, with these events spatially distributed over MRRJ, the northern region of Nova Friburgo and the central region of Petrópolis (both in their urban areas) will be the ones with the highest frequencies of events like the "mega-disasters". Considering the grid points closest to Nova Friburgo and Petrópolis, five and nine "mega-disasters" throughout the century for RCP4.5, and four and eight for RCP8.5, respectively, were projected. These "mega-disasters" in both municipalities were projected for different years. Thus, a projection of 14 or 12 "mega-disasters" occurring throughout the 21st century for the RCP4.5 and 8.5, respectively, could be projected, which would increase to 17 and 15 when considering Teresópolis.

Our study sheds new insights into the influence of climate change on rainfall disasters. However, we need to point out the limitations of our study that require future studies. For example, only one climate model, downscaled by a physical model (ETA/CPTEC), was adopted here. Because the study region is a mountainous area close to the Atlantic Ocean, i.e., the orographic effect is strong. Although the datasets used in this study are unique for all of South America (5 km), the outputs downscaled in a more satisfactory resolution are indispensable. Nevertheless, the uncertainties associated with the climate model exist, which should be countered using additional models with 5-km resolution and the orographic aspect adequately solved by a physical model.

Conclusions and future studies

The studied region is one of Brazil's most vulnerable to extreme rainfall disasters. To overcome the orographic effect on the rainfall in the region, we used the 5-km ETA/HadGEM2-ES model to analyze the frequency of events that cause disasters, fatalities included. The datasets used in this study are from only one global circulation model (GCM) dynamically downscaled to 5 km resolution. This aspect allowed capturing orographic effects on rainfall spatial and temporal distribution. The Eta-HadGEM2-ES model is the unique model available with such a resolution. Therefore, we can advance in terms of the uncertainty of the GCMs for estimating extreme daily rainfall in an acceptable resolution for this purpose. Other GCMs have been considered in South America but using a resolution of 20 km. Several studies have demonstrated no concordance among them regarding extreme precipitation patterns over the century.

Another relevant study consists in evaluating how large-scale atmosphere drivers like multivariate ENSO index, Southern Oscillation Index (SOI), Tropical Southern Atlantic Index (TSA), Pacific Decanal Oscillation (PDO), Antarctic Oscillation (AAO), Atlantic Multidecadal Oscillation (AMO), and ENSO precipitation index can impact extreme rainfall events that cause hazards in southeastern Brazil. For that, it is imperative to expand a broader study regarding R_{day} modeling to assess statistical analyses, especially multivariate ones (artificial intelligence, principal components analysis, Bayesian regression analyses, among others), and establish possible connections.

In terms of conclusions, we can highlight:

e) The MRRJ presents high R_{maxday} values throughout the 21st century, showing a large coverage of the extreme rainfall in MRRJ, especially from the first time slice.

f) The frequency of events in the moderate impact class (500 - 1,000 MJ mm $(ha\ h)^{-1}$) tends to increase throughout the century, meaning fatalities will continue to occur in MRRJ, although in a lower possibility.

g) The projection along this century is that 17 (RCP4.5) or 15 (RCP8.5) events of the same magnitude, respectively, as the one that caused the "mega-disaster" in 2011 in MRRJ.

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