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Investigation of landslide hazard areas in the municipality of Cunha (Brazil) and climate projections from 2024 to 2040

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A R T I C L E I N F O

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A B S T R A C T

Climate change can modify the frequency and intensity of extreme rainfall across the globe, leading to changes in hazards posed by rainfall-induced landslides. In Brazil, an example of a location with a high occurrence of landslides and with few studies on the subject is the municipality of Cunha, located in the State of São Paulo. In this way, the main aims of this study are twofold: 1) to identify and analyze areas susceptible to landslides and rainfall-induced landslide hazard in the municipality of Cunha; and 2) by using climate projections from the regional model Eta-HadGEM2-ES under RCP 4.5, to predict new extreme events and possible new landslides in this municipality, from 2024 to 2040. The susceptibility map has been prepared using selected physical-biotic environment elements whereas the hazard map has been produced using precipitation data. Using Eta-HadGEM2-ES climate projections under RCP 4.5, for precipitation events, results project the occurrence of 49 days with landslides for the period between 2024 and 2040. The outcomes of this study are considered of extreme relevance for the local community, public authorities, and decision-makers, to raise awareness regarding future urban planning strategies to prevent and mitigate the effects of catastrophes arising from natural hazard-induced disasters.

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1. Introduction

Natural hazard-induced disasters have presented increasing recurrence and impacts nowadays, being responsible for significant environmental, economic, and social losses (Khan et al., 2020; Panwar and Sen, 2019; Witt et al., 2022). Examples of this were the catastrophic floods and subsequent landslides that occurred in Western Europe in July 2021, which led to at least 184 deaths in Germany and 38 in Belgium and 40 billion dollars in economic costs in Germany alone (Fekete and Sandholz, 2021; Kreienkamp et al., 2021; CRED, 2022) and the heat waves that hit regions of the United States and Canada in June 2021, with temperatures well above 40°C (Philip et al., 2022; Overland, 2021), causing the spread of numerous wildfires and leading to an estimated 815 deaths in Canada and 229 deaths in the US (CRED, 2022).

In Brazil, large areas of the southern and southeastern regions are naturally susceptible to natural hazard-induced disasters, mainly due to intense and frequent rainfall in an environment dominated by plains, narrow valleys, and steep slopes (Tominaga et al., 2009; Mendes et al., 2018; Mendonça and Silva, 2020). The events of floods and landslides caused by heavy rains in 2000 in Campos do Jordão (State of São Paulo) (Mendes et al., 2018); in 2008, 2011, and 2013 in the Itajaí River Basin (State of Santa Catarina) (Gouvea et al., 2017); in 2011 in the mountainous region of Rio de Janeiro (State of Rio de Janeiro) (Dourado et al., 2012), and in 2020 in the Metropolitan Region of Baixada Santista (State of São Paulo), which led to 44 deaths and 17 injuries (Freitas et al., 2022) are some examples of disasters of significant impact in these regions. More recently, an extremely rare precipitation event occurred along the São Paulo coast between February 18th and 19th, 2023, with a precipitation volume reaching 600 mm within 24 h, resulting in 65 deaths and dozens of injuries (residents and tourists) and around two thousand homeless people (Costa, 2023).

This scenario becomes even more worrying when considering climate change and extreme rainfall phenomena, which can intensify the occurrence of precipitation-induced disaster events (Alvioli et al., 2018; Chen et al., 2019; Marengo et al., 2020). The Intergovernmental Panel on Climate Change (IPCC) indicates an increase in global temperatures in the range of 1.2 to 1.7°C and in extreme rainfall by 7% for every 1.0°C, for the period from 2021 to 2040 (IPCC, 2021). Thus, populations residing in risk areas, especially in developing countries such as Brazil, are and will be more exposed and vulnerable to the dangers arising from climatic extremes and their changes, both due to the fragility of their homes and the difficulty of reacting to the environment (Marengo et al., 2020; Silva et al., 2015).

An example of a location with a high occurrence of landslides and with few studies on the subject is the municipality of Cunha, located in the State of São Paulo. According to the publication “Population in risk areas in Brazil”, by the Brazilian Institute of Geography and Statistics - IBGE and the National Center for Monitoring and Alerts for Natural Disasters - CEMADEN, until 2017 there were 853 households in the municipality of Cunha located in risk areas and inhabited by 2680 people, equivalent to 12.3% of the total population (IBGE, 2011; IBGE, 2018a, 2018b).

Thus, there is a growing importance in developing methods that seek to interpret areas with landslide hazard, in the context of climate change, considering the different scales of occurrence of phenomena and aggregating data that interact in multiple ways and in different situations (Silva et al., 2015). Several studies have incorporated data from Global Climate Models (GCM) or Regional Climate Models (RCM) into physically based slope stability models or susceptibility indices and hazard mapping to investigate the effects of climate change on landslides (Silva et al., 2015; Alvioli et al., 2018; Peres and Cancelliere, 2018; Jakob and Owen, 2021; Hürlimann et al., 2022).

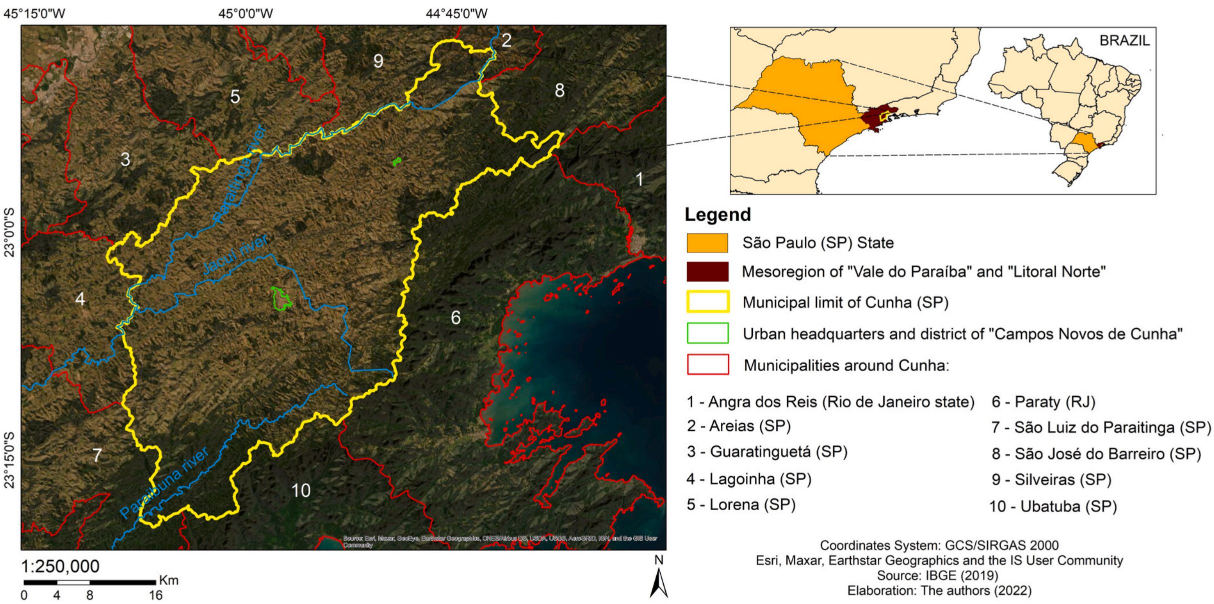

Fig. 1. Characterization of the municipality of Cunha (SP).

RCMs are usually employed for reduced-scale simulations and projections of GCMs, to assess the potential impacts of climate change on regional scales at finer spatial resolution (Maraun et al., 2017; Almagro et al., 2020). The National Institute for Space Research (INPE) developed four sets of downscaled products based on the Eta RCM for Brazil, parts of South America, and adjacent oceans, forced with human forcing scenarios, called Representative Concentration Pathways (RCP), taken from HadGEM2-ES and MIROC5 GCMs simulations and projections (Chou et al., 2014).

In this context, the present study aims to identify the main areas susceptible to landslides and rainfall-induced landslide hazard in the municipality of Cunha, with the help of geoprocessing tools, based on the events that occurred in January 2010 (the most recent major event, with deaths, in the municipality, leading to its choice for this case study). Climate projections were used, through the Eta-HadGEM2-ES model and considering the RCP 4.5 scenario of emissions and climate change, to predict new climate extremes and possible new landslides in the municipality for the period from 2024 to 2040. The results of this study are expected to provide important scientific bases for decision-making in these areas, preventing and/or mitigating future new disasters in the municipality of Cunha.

2. Materials and methods

2.1. Case study context

The municipality of Cunha is a climatic resort, located in the State of São Paulo, between the Serra da Quebra-Cangalha, Serra da Bocaina and Serra do Mar, has a territorial extension of 1407.25 km^2 (SEADE, 2019). It is limited to the municipalities of Ubatuba, São Luiz do Paraitinga, Lagoinha, Guaratinguetá, Lorena, Silveiras, Areias, São José de Barreiro in the State of São Paulo, and Angra dos Reis and Paraty in the State of Rio de Janeiro (Cunha, 2019), as shown in Fig. 1.

The lands of the municipality of Cunha are home to the sources of the Jacuí and Paraibuna rivers, and large areas of the Paraitinga River Basin, forming the Paraíba do Sul River Basin, which covers 3 states and supplies around 14 million people in 184 municipalities (ANA, 2011). The municipality has two fully protected Conservation Units, the Cunha-Indaiá nucleus of the Serra do Mar State Park and part of the Serra da Bocaina National Park, totaling an area of approximately 12,500 ha legally protected within the municipality.

The municipality has small areas of forest remnants, due to the process of replacing the native forest with pastures and annual family subsistence crops. However, currently, these agricultural areas are in a high degree of soil degradation, causing landslides, soil erosion, silting of rivers, destruction of springs, and other types of natural hazard-induced disasters, mainly associated with the lack of public policies and infrastructure investments (Brazil, 2005; Bastos et al., 2018).

According to the IBGE, the population of the municipality of Cunha in the last census carried out in 2010 was about 21,866 people, while in 2018 this number dropped to 21,639 inhabitants (IBGE, 2018a, 2018b). The municipality has 52.4% of households with adequate sanitary sewage; 43.1% of urban households on public roads with trees; and 32.6% of urban households on public roads with adequate urbanization (presence of manholes, sidewalks, paving, and curb) (IBGE, 2018a, 2018b).

The total annual average of rainfall in the municipality of Cunha is approximately 1350.1 mm, taking into account the historical series from 1977 to 2006, according to data from the Regional Superintendence of São Paulo - SUREG, linked to Geological Survey of

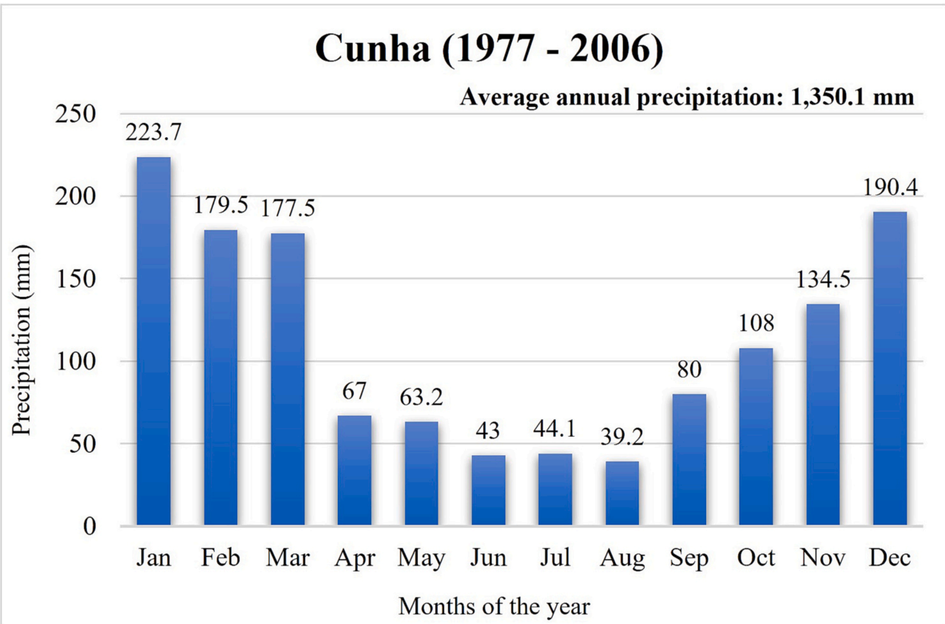

Fig. 2. Average annual precipitation (mm) in the city of Cunha/SP between 1977 and 2006.

Brazil - CPRM, as shown in Fig. 2 (CPRM, 2016). It is worth mentioning that 75% of the precipitation with a volume >100 mm of rain is concentrated between the months of October to March, with January being the month with the highest volume (223.7 mm). The months of April, May, and September also have an important amount of precipitation, while the driest period of the year in the municipality is concentrated between the months of June and August, with rainfall below 50 mm per month. The most recent major landslide event, with deaths, in the municipality was in January 2010, when the volume of rain exceeded the historical average. There were 230 mm of rain in 30 h, against the average of 140 mm for the month of December (Folha de São Paulo, 2010). Six (6) people from the same family died in a landslide on January 1st in the neighborhood of Barra do Bié, 23 km from the center of the municipality, which was isolated due to the collapse of road barriers (O Globo, 2010). In the municipality, around 25 houses were damaged by the collapse of barriers and 12,000 people were directly affected by the disaster event (O Globo, 2010). Fig. 3 shows some environmental and infrastructure damage resulting from the disasters that occurred in Cunha, which made it difficult to provide assistance to the population affected by the rain. It should be noted that the extreme climatological events of January 2010 that culminated in several landslides in Cunha were the same that caused floods in the municipality of São Luiz do Paraitinga (borderline of Cunha). Such occurrences were due to the expressive rainfall that occurred in the Jacuí river and the Paraitinga river, and at their confluence, causing critical water volumes of extravasation.

2.2. Data and methodology

To carry out the present study, several steps had to be completed, which will be described in this section. Just for quick visualization and understanding, Fig. 4 presents a simplified diagram of the methodologies adopted to achieve the proposed objectives.

It is important to clarify the definitions of susceptibility and hazard mapping used in this study. According to studies on disasters, susceptibility is the tendency of a given physical environment to undergo some type of disaster. As proposed by Silva et al. (2015) susceptibility to landslides is understood as the disposition, tendency, or sensitivity that a given geographical area has to suffer this type of disaster. Therefore, for the susceptibility to landslides in any area to be evaluated, a detailed analysis of environmental variables that condition their occurrence is necessary.

Rainfall-induced landslide hazard, in turn, refers to the prediction of the spatial-temporal probability of landslide occurrence in a certain area under the conditions of rainfall processes, based on landslide susceptibility mapping and rainfall data, such as critical rainfall threshold calculations (Lee et al., 2014; Huang et al., 2022).

2.2.1. Database and thematic maps elaboration

The georeferenced database was created using the ArcGIS® 10.8 geoprocessing software. For the municipality of Cunha, the following data were collected, extracted, and processed in the "Shapefile" and/or "Raster" formats, as shown in Table 1.

The datum/projection of origin of each file was redesigned for SIRGAS 2000/UTM 23S, being the most suitable for the study area. It should also be noted that both the LANDSAT-5/TM image and TOPODATA/INPE Digital Elevation Model (DEM) data provide data with a spatial resolution of 30 m. Therefore, the variables of pedology, lithology, and distance from the road network were resampled for this resolution to maintain the regularity of the resolutions of all variables, thus resulting in a map of susceptibility to landslides with the same spatial resolution. All thematic layers were converted to raster format having a 30 m × 30 m cell resolution, and each raster was classified into several classes to calculate the numbers of landslide and non-landslide pixels. Fig. 5 presents the database created for Cunha.

For the susceptibility mapping, seven variables of the physical-biotic environment were selected, including pedology, lithology, land use/cover, slope, profile curvature, plan curvature and distance from roads. *Pedology and Lithology:* For the elaboration of the maps of these variables, the map of pedology and lithology of the State of São Paulo was clipped, using the limits of the study area. *Land use/cover:* A supervised classification was performed with the spectral bands (blue - *B1*, green - *B2*, red - *B3*, near-infrared - *B4,* and mid-infrared - *B5* and *B7*) and the Normalized Difference Vegetation Index - NDVI (the quotient of the difference between the reflectance in the near-infrared and in the red by the sum of the reflectance of these two bands) through the optimization algorithm developed by Cortes and Vapnik (1995), called Support Vector Machine - SVM, in the R software environment (R Core Team, 2021). *Slope:* For the evaluation of this environmental variable, it was necessary to calculate the slope of the terrain as a function of its horizontal distance

Fig. 3. Damage resulting from the disasters that occurred in Cunha in January 2010. a) River flooding in Monjolo, district of Cunha; b) Landslide on Barra do Bié, district of Cunha, as a result of the events and c) Remains of a bridge in the Barra do Bié, district of Cunha. Source: 4x4Brasil (2010).

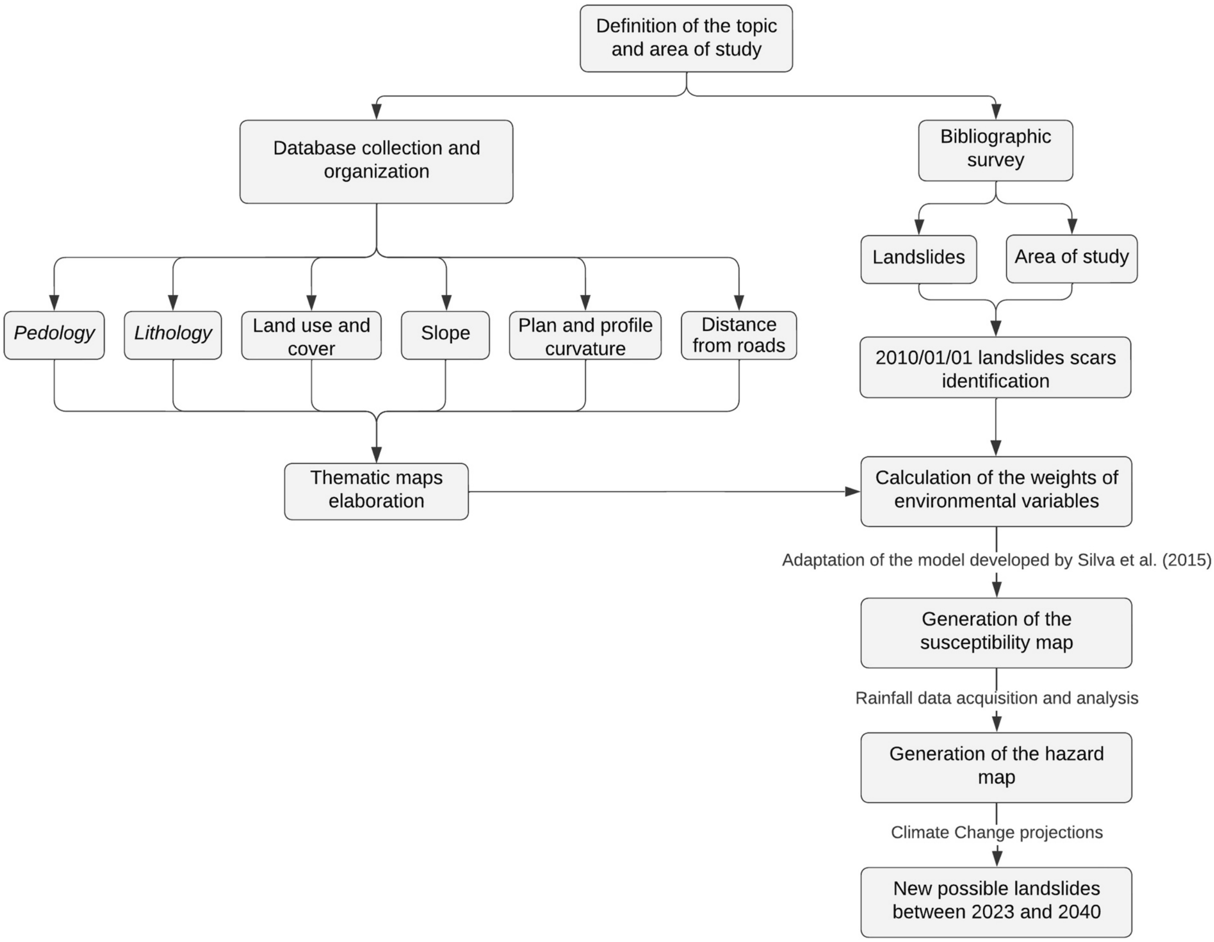

Fig. 4. Methodological flowchart.

Table 1
Data sources used for the present study.

Data	Description	Source
Pedology	Extracted from 1:250,000 São Paulo State pedologic map	(Rossi, 2017)
Lithology	Extracted from 1:750,000 São Paulo State lithologic map	(CPRM, 2006)
Land use/cover	Derived from 30 m Landsat-5/TM image: path/row 218/76, from 2011/09/05	(INPE, 2011)
Slope	Derived from 30 m Digital Elevation Model (DEM)	(INPE, 2008)
Profile Curvature	Derived from 30 m DEM	(INPE, 2008)
Plan Curvature	Derived from 30 m DEM	(INPE, 2008)
Distance from roads	Extracted from 1:250,000 Brazil roads	(CPRM, 2016)
Municipality limits	Extracted from 1:250,000 São Paulo State municipality limits	(IBGE, 2015)
Precipitation	Derived from 0.1° Merge technique	(Rozante et al., 2010)
Landslide location	Evidence of 2010 landslide within the study area	(Google Earth, 2009)

and altitude difference. This was done using the ArcGIS® 10.8 "Slope" tool since the "Raster" collected by the TOPODATA/INPE database provides information regarding altitude information. *Plan and profile curvatures*: Thematic maps were created considering the recommendations of Valeriano (2008), where the scheme of five (5) classes is established with the range of ±0.054°/m for planar terrain (plan curvature) and the range ±0.00125°/m for rectilinear terrain (profile curvature). *Distance from roads:* For the distance variable of the road network, the "Euclidean Distance" tool from ArcGIS® 10.8 was used to create buffers, whose algorithm calculates distances from the center of the cell from the origin to the center of each of the neighboring cells by applying the Pythagorean theorem, where the distance is the hypotenuse (ESRI, 2014).

For hazard mapping, precipitation data were integrated. Based on the day of the climatic extreme that occurred in Cunha (2010/01/01), which is also the reference day for the present study, the following data were collected: daily precipitation (*PD*) - the total

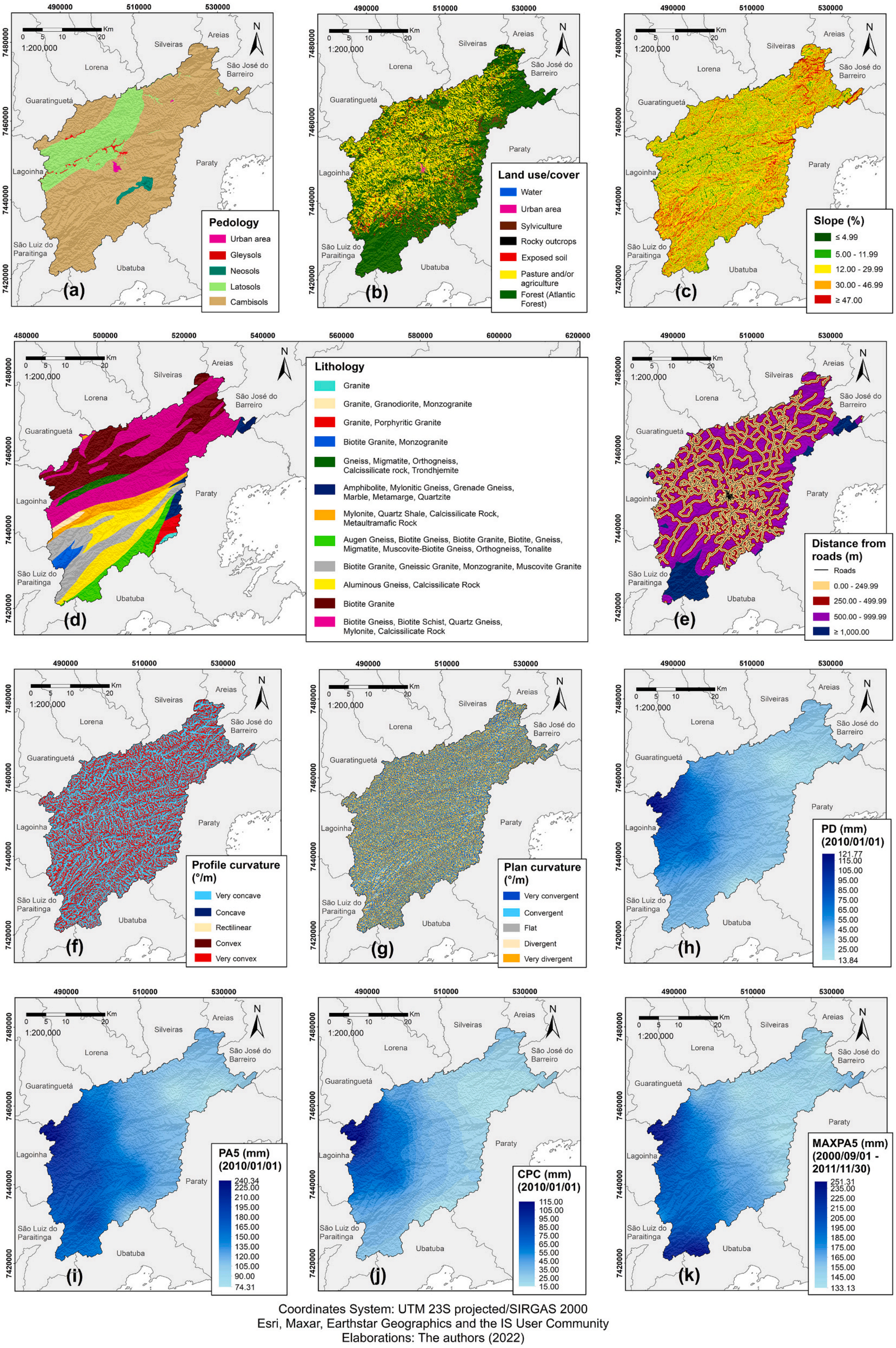

Fig. 5. Thematic maps of the municipality of Cunha. (a) pedology, (b) land use/cover, (c) slope, (d) lithology, (e) distance from roads, (f) profile curvature, (g) plan curvature, (h) *PD*, (i) *PA5*, (j) CPC and (k) *MAXPA5*.

rainfall of the 24 h of the day (2010/01/01); 5-day accumulated precipitation (*PA5*) - the sum of the rain that occurred on 2010/01/01 plus the rain of the 4 days prior to the event; maximum accumulated precipitation of 5 days (*MAXPA5*) - maximum occurrence of rain in 5 days within the historical series from 09/01/2000 to 11/30/2011; and the critical precipitation coefficient (*CPC*) - value that for the municipality of Cunha on 2010/01/01 was enough to trigger landslides.

Regarding the "*PD*", along the municipality of Cunha, it varied from 13.84 mm to 121.77 mm, with a more intense regime in its western portion. The "*PA5*" ranged from 74.31 mm to 240.34 mm, with higher volumes throughout the western and southern portions of Cunha. The "*MAXPA5*" ranged from 133.13 mm to 251.31 mm, with concentrations also in the southern and western portion of the municipality, while the "*CPC*", from 15 to 115 mm, again concentrated in the western limit of the municipality of Cunha.

These data were obtained through the technique called MERGE (Rozante et al., 2010), which consists of combining observed precipitation with satellite precipitation estimates, being generated and operationally made available by the Weather Forecast and Climate Studies Center - CPTEC/INPE. This combination of satellite and rain gauge data for the South American region is based on rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM) satellite and observed data from 1500 stations reported by the Global Telecommunication System (GTS), data collection platforms (PCD's) and regional centers in Brazil, generating precipitation data in a specialized way (Rozante et al., 2010). MERGE data is available with a temporal resolution of 30 min and a horizontal resolution of 0.1 degrees (10 × 10 km).

With the collection of data referring to the days of interest, starting on 01/09/2000, the step taken was to make these data more

Table 2
The number of scars and weights adopted for each class of variable for Cunha municipality.

Pedology			Slope		
Class	Scars	Weight	Class	Scars	Weight
Urban area	5	0.01	<5.00%	5	0.01
Cambisols	685	0.85	5.00–11.99%	46	0.06
Gleysols	0	0.00	12.00–29.99%	309	0.39
Latosols	69	0.09	30.00–47.00%	334	0.42
Neosols	41	0.05	>47.00%	106	0.13

Plan curvature			Profile curvature		
Class	Scars	Weight	Class	Scars	Weight
Very convergent	255	0.32	Very concave	478	0.60
Convergent	108	0.14	Concave	27	0.03
Flat	90	0.11	Rectilinear	8	0.01
Divergent	102	0.13	Convex	24	0.03
Very divergent	245	0.31	Very convex	263	0.33

Land use/cover			Distance to roads		
Class	Scars	Weight	Class	Scars	Weight
Rocky outcrops	29	0.04	0.00–249.99 m	314	0.39
Water	0	0.00			
Sylviculture	1	0.00	250.00–499.99 m	203	0.25
Forest (Atlantic Forest)	323	0.40			
Pasture and/or Agriculture	384	0.48	500.00–999.99 m	160	0.20
Exposed soil	62	0.08			
Urban area	1	0.00	≥1000.00 m	123	0.15

Lithology		
Class	Scars	Weight
Biotite Granite	140	0.18
Granite, Porphyritic Granite	0	0.00
Gneiss, Migmatite, Orthogneiss, Calcissilicate rock, Trondhjemite	6	0.01
Aluminous Gneiss, Calcissilicate Rock	104	0.13
Mylonite, Quartz Shale, Calcissilicate Rock, Metaultramafic Rock	111	0.14
Biotite Gneiss, Biotite Schist, Quartz Gneiss, Mylonite, Calcissilicate Rock	209	0.26
Granite	2	0.00
Amphibolite, Mylonitic Gneiss, Grenade Gneiss, Marble, Metamarge, Quartzite	0	0.00
Augen Gneiss, Biotite Gneiss, Biotite Granite, Biotite, Gneiss, Migmatite, Muscovite-Biotite Gneiss, Orthogneiss, Tonalite	18	0.02
Biotite Granite, Monzogranite	19	0.02
Biotite Granite, Gneissic Granite, Monzogranite, Muscovite Granite	185	0.23
Granite, Granodiorite, Monzogranite	6	0.01

representative in terms of spatial resolution, estimating the probable precipitation data through spatial interpolation technique. For that, the Inverse Distance Weighted (IDW), an objective analysis method that does not consider the topographical effect, was used, with the help of the tool available in ArcGIS® 10.8. IDW determines precipitation at the interpolating point by assigning larger weights to observation stations closer to the target grid (Lu and Wong, 2008; Jeong et al., 2019). The weight is a function of inverse distance, and the method assumes that the variable being mapped decreases in influence with distance from its sampled location (ArcGIS, 2021).

2.3. Survey of landslide scars and adopted weights

To establish weights for the classes of variables, it was adopted the methodology by Silva et al. (2015), in which the weight for a type of class from each variable is proportional to the number of landslides that occurred in its corresponding area. So, after investigating events that happened in the municipality of Cunha, it was observed that there was a record of successive natural hazard-induced disasters in the period of January 2010, especially on 2010/01/01, with fatal victims. So, scar points from landslides that occurred in the municipality during this period were obtained.

Based on georeferenced data of point features, provided by CPRM, 343 points of ravines and landslide scars were recorded. As these points did not have the exact date of occurrence, they were verified using Google Earth images closer to the date of the event, collecting only the scars that occurred in the period of analysis and other points that were not identified by the CPRM mapping. This verification was also carried out through the satellite image repository made available by Google Earth, with all points within the date of occurrence. Overall, 800 landslide scars were sampled, and the weights of the variables, with values ranging between “0.00” and “1.00” were calculated, according to Table 2.

2.4. Equation of susceptibility to landslides

To map the susceptibility to landslides, the variables adopted were compared in a pairwise matrix, according to the AHP methodology, generating a weight of 0.00 to 1.00 for each one, considering the influence of these conditions on the occurrence of these events. The foundation of the AHP consists of the decomposition and synthesis of the relationships between the criteria until a prioritization of its indicators is reached, approaching a better response of a single performance measurement (Saaty, 1990).

Decision-making starts from the point where the decision-maker must the intensity of the relevance of each criterion in comparison with another, and the elements are organized into decision matrices (Saaty, 1990).

The necessary and sufficient condition for consistency is that the “principal eigenvalue” - λ_{max} is equal to the number of rows or columns of the pairwise comparison matrix. The eigenvalue is calculated by using Eq. 1.

$$\lambda_{max} = \sum_{j=1}^{n} T_j \ x \ W_j \tag{1}$$

where T is the normalized eigenvector; and W is the sum of comparison matrix columns.

The Consistency Index (CI) of a pairwise comparison matrix indicates how far the eigenvalue is from the theoretically expected value n. This deviation is given by the expression ($\lambda_{max} - n$). This difference is measured in relation to the number of degrees of freedom of the matrix ($n - 1$), as shown in Eq. 2.

$$CI = (\lambda_{max} - n)/(n - 1) \tag{2}$$

The Consistency Ratio (CR) calculated by Eq. 3, is the comparison between the consistency index (CI) with the “Random Consistency Index” (RI).

$$CR = CI/RI \tag{3}$$

According to Saaty (1980), CR values <0.10 indicate that there was no inconsistency in the values assigned to the judgments, and higher values indicate that the judgments performed need to be reviewed.

To define the hierarchy of variables, the scar with victims was adopted as a reference point. So, the model developed was calibrated through this point, relating it to the scar with the highest susceptibility value obtained for the municipality. In other words, the closer to zero the difference between the maximum susceptibility and the susceptibility where there were deaths, the fewer errors would be

Table 3
Comparison matrix of susceptibility variables to landslides in the municipality of Cunha.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	w (weights)
(1) Distance from roads - DMV	**1.00**	3.00	5.00	7.00	8.00	9.00	9.00	**0.34**
(2) Slope - DEC	0.33	**1.00**	3.00	5.00	7.00	8.00	9.00	**0.27**
(3) Pedology - PED	0.20	0.33	**1.00**	3.00	5.00	7.00	7.00	**0.19**
(4) Plan curvature - CH	0.14	0.20	0.33	**1.00**	3.00	4.00	5.00	**0.11**
(5) Land use/cover - UCS	0.13	0.14	0.20	0.33	**1.00**	2.00	3.00	**0.05**
(6) Profile curvature - CV	0.11	0.13	0.14	0.25	0.50	**1.00**	1.00	**0.02**
(7) Lithology - LIT	0.11	0.11	0.14	0.20	0.33	1.00	**1.00**	**0.02**
Consistency Rate (RC)	**0.09**							

expected in the model.

To achieve the smallest difference between the highest susceptibility value and the scar value with fatal victims, the best result obtained from this analysis is presented in Table 3.

Thus, after calculating the susceptibility by Eq. 4, it was obtained that 0.69 was the maximum value obtained, while for "Scar with victims", it was the value of 0.68, representing, therefore, a difference of 0.01. In this way, the final equation for the susceptibility to landslides for the municipality of Cunha was as presented in Eq. 4:

$$S = \sqrt{(0.34\ DMV + 0.27\ DEC + 0.19\ PED + 0.11\ CH + 0.05\ UCS + 0.02\ CV + 0.02\ LIT)} \quad (4)$$

where *S* is the Susceptibility to landslides; *DMV* is the Distance from roads; *DEC* corresponds to the variable slope; *PED* is related to pedology; *CH* is the plan curvature; *UCS* is the land use/cover; *CV* is the profile curvature and *LIT* corresponds to the lithology.

After assigning the respective weights for each class of variable, Eq. 4 was introduced in the input of the "Raster Calculator" tool, responsible for executing the map algebra function, in ArcGIS® 10.8. Lastly, the final indices were generated and then reclassified by using the "Reclassify" tool according to the classes presented in Table 4 and thus the final thematic map was obtained. Finally, the 800 identified landslide scars were plotted, and the susceptibility values were raised for each scar point, also calculating the simple arithmetic mean of susceptibility, an index called the Average General Susceptibility Index (IMGS).

2.5. *Equation of landslide hazard*

Variables related to precipitation were added to the susceptibility mapping to map the landslide hazard, originating the Eq. 5.

$$\mathrm{LH} = \frac{\mathrm{S} + \sqrt{\left[\left(\frac{\mathrm{PD}}{\mathrm{CPC}}\right) + \left(\frac{\mathrm{PA5}}{\mathrm{MAXPA5}}\right)\right]}}{2} \quad (5)$$

where *S* is the Susceptibility to landslides; LH corresponds to the landslide hazard; *PD* is Daily Precipitation; *CPC* is the Critical Precipitation Coefficient; *PA5* is 5-day accumulated precipitation and *MAXPA5* is Maximum accumulated precipitation of 5 days (01/09/2000–30/11/2011).

2.6. *Eta-HadGEM2-ES RCP 4.5 climate projections and new events between 2024 and 2040*

Precipitation values were projected for the period from 2024/01/01 to 2040/12/30 through the RCM Eta HadGEM2-ES under RCP 4.5 (Chou et al., 2014). The RCP 4.5 projection considers the stabilization of methane emissions and a slight increase in carbon dioxide emissions. Linked to this, with the stabilization of world energy demand, this projection is congruent and optimistic with precise climate public policies using various technologies and strategies to reduce greenhouse gas emissions and reforestation programs (San José et al., 2016; Silveira et al., 2016).

The values from this simulation represented the new precipitation values that were again used in the 2nd mathematical term of Eq. 5. The Eta HadGEM2-ES climate model has a spatial resolution of 20 km horizontally, covering 38 layers vertically. In order to uphold data consistency, daily precipitation data from Eta HadGEM2-ES model which cover the municipality of Cunha from 2024/01/01 to 2040/12/30 were collected, and the same IDW methodology implemented for other variables was applied, interpolating the data to the same grid points with 30 m × 30 m of cell resolution. In addition, the *CPC* value adopted was the minimum within the established range (with a variation of 10.00 mm), since the minimum value of 15.00 mm was identified as being enough to trigger landslides within some areas of Cunha municipality. The *PA5* was also calculated within the range of years of interest, verifying the minimum value for landslides to occur, therefore, this value was fixed. Finally, the value of *MAXPA5* was also extracted.

Using the methodology described above, information was collected for the period between 2024 and 2040 under RCP 4.5. The PA5 exceeded the landslide threshold, with the highest susceptibility value, therefore the landslide hazard was calculated again, from Eq. 5. The calculation was performed using a spreadsheet in Microsoft Excel® (Microsoft Excel, 2019), with the data obtained from the projections and those extracted from ArcGIS® 10.8. According to Silva et al. (2015), for a landslide to occur, the landslide hazard result must be ≥0.70. Thus, the dates that resulted in these values were counted as days subject to new extreme events and landslides.

3. Results and discussion

In this section, the results obtained from the study will be presented and discussed. This section will be divided into three topics,

Table 4
Classification of landslide susceptibility index.

Values	Class
0.00–0.19	Very Low
0.20–0.39	Low
0.40–0.59	Moderate
0.60–0.69	High
≥0.70	Very High

where the first one will present the final landslide susceptibility map; followed by the final landslide hazard map; and finally, the possible number of new extreme events and landslides for the period from 2024 to 2040 under RCP 4.5.

3.1. Susceptibility to landslides in the municipality of Cunha

The susceptibility map for the municipality of Cunha was generated through map algebra in ArcGIS® 10.8 software, using the respective variables from the Eq. 4, resulting in the map shown in Fig. 6.

The outcomes shown in Fig. 6, that on the day of the event (2010/01/01), most of the municipality was in a situation of high susceptibility. In other words, within the range established in Table 4, a total of 592 scars had susceptibility points between 0.60 and 0.69. Moreover, the high susceptibility class represented 61.43% of the municipality, within 858.91 km^2. This indicator reveals that, for the municipality of Cunha, only a minimum amount of precipitation would be necessary to trigger landslides, since the threshold for this occurrence is 0.70. Therefore, the "Scar with victims", which obtained a value of 0.68 for susceptibility, also already showed a high tendency toward the occurrence of these types of disasters.

In Fig. 6, it also can be noted that the average susceptibility class to landslides, with values ranging from 0.40 to 0.59 (37.23% of the areas in the municipality of Cunha), was the one that presented 206 scars. Overall, the very low, low and very high classes represented very little influence for the municipality of Cunha, and only the low susceptibility class counted scars (2) and with a territorial extension of 18.75 km^2, which represents 1.34% of Cunha. The very low class had no contribution to the municipality, as did the very high class. This last class is expected, since for landslides, according to the present study, the trigger (rain) is necessary for its occurrence, reaching values ≥0.70.

These results allow us to compute, through the susceptibility values of each of the 800 scars, the General Average Susceptibility Index (IMGS), which is shown in Fig. 7. This index gives a better understanding of the weight of each variable regarding susceptibility. It, therefore, represents the average weight of each variable, such as susceptibility.

In this way, it can be seen that the IMGS was 0.62, that is, most of the municipality was classified as being highly susceptible to landslides. The decreasing order of the preponderance of the variables was: pedology (0.73); profile curvature (0.47); land use and cover (0.40); slope (0.35); distance from the road network (0.29); plan curvature (0.24); and lithology (0.19). The predominant soil type in Cunha municipality is Cambisols, covering 78.45% of the municipal area. They are shallow and highly erodible, normally not

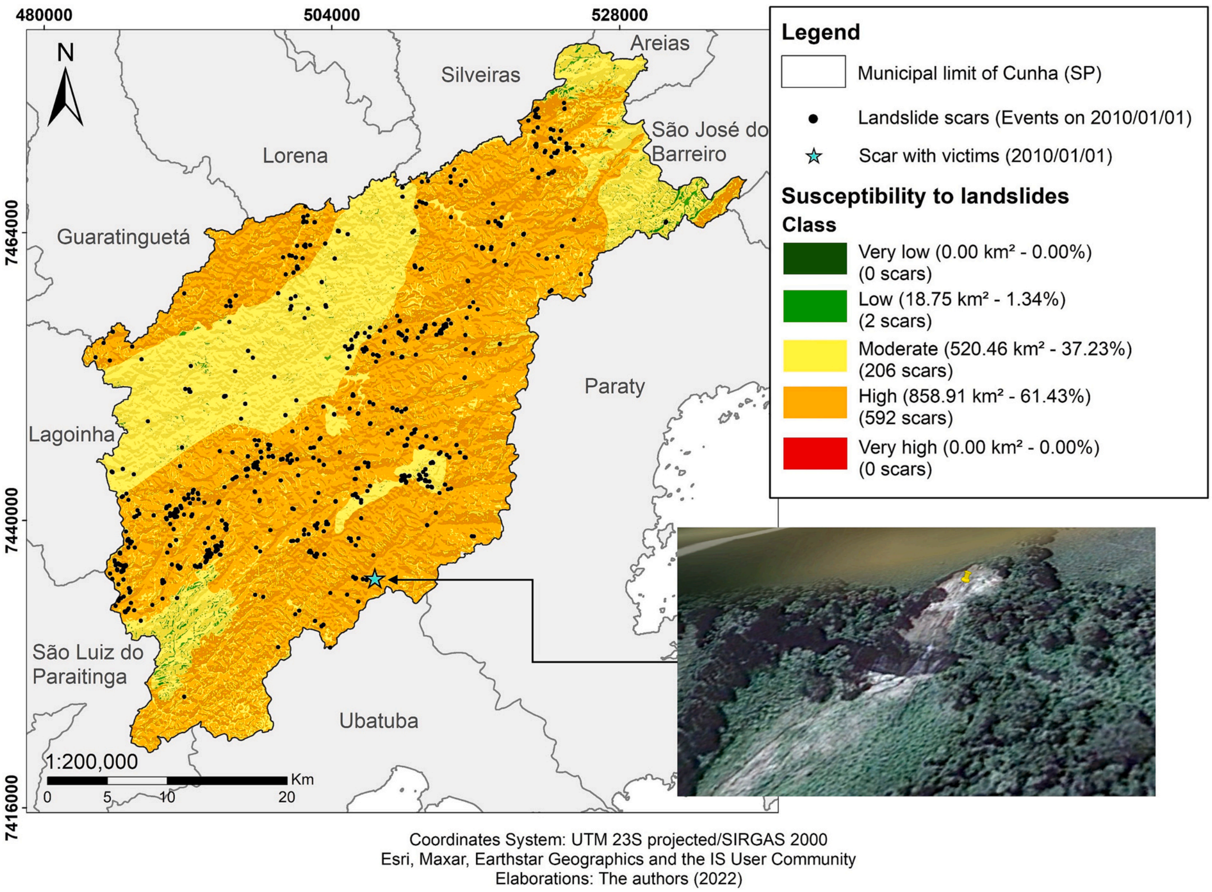

Fig. 6. Map of susceptibility to landslides in the municipality of Cunha.

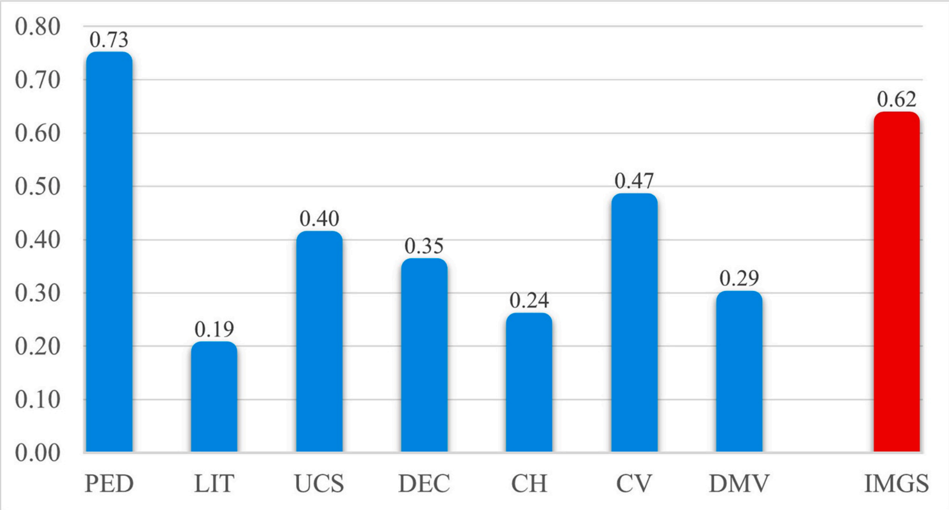

Fig. 7. Overall average index of each variable and IMGS.

allowing intensive use, and laminar erosion can occur up to furrows and gullies, exposing their subsoil in a short period (Antunes et al., 2013; EMBRAPA, 2003). Due to their fragility, these types of soil are important in the investigation of possible new natural disasters in the municipality.

However, despite the fact that for landslides to occur, the modeling result must present a value ≥0.70, a variable alone, even with values above 0.70, is not capable of triggering these events. The example of the municipality of Cunha shows that the combination of other factors is also relevant. In the extreme climatological event that took place in Cunha on 2010/01/01, which culminated in the death of six people from the same family, the buried residence was located in the Barra do Bié district, approximately at a distance of 150.00 m from the road network. According to Brenning (2015), it was identified that landslides have a higher incidence of occurrence at distances of up to 150.00 m from the roads in mountainous regions of developing countries, due to often inadequate drainage systems and mechanical destabilization of slopes by undercutting and overloading.

The slope is also another important factor linked to the instability of the slopes since it has an influence on the speed of displacement of the material (Rodrigues, 2013). Federal Law No. 6766/1979 prohibits the urbanization and occupation of areas with a slope >30% (approximately 17°) unless specific requirements of the competent authorities are met (Brazil, 1979). These areas represent 33.91% (474.30 km^2) of the municipality and it is noted that there are houses in Cunha that do not obey these laws, being framed in risk sectors and more prone to landslides. Angle values in the range of 15° to 35° affect slope susceptibility due to the increase in soil shear stress, which is corroborated by researchers who found that most landslides in their research area formed on slopes in these ranges (Lee and Min, 2001; Ercanoğlu et al., 2004; Hong et al., 2017; Pham et al., 2017).

In addition to all these factors, according to Bastos et al. (2018), the agricultural activities developed in the municipality of Cunha are causing the degradation of natural resources such as soil, water resources, forest, and biodiversity. Due to failures in herd management, pasture degradation has occurred and consequent low productivity, leading small rural landowners to give up activity in the municipality. Persichillo et al. (2017), in their study on the northern end of the Italian Apennines, found that abandoned cultivated lands are highly prone to shallow landslides, given that the lack of agricultural maintenance increased surface runoff and consequently intensified erosion processes and instability phenomena.

After this explanation, Table 5 presents the classes from each variable on the point with fatalities. It is possible to observe that for the location where there were deaths, in relation to the slope, it was located on a slope between 30.00 and 47.00%, being unfit for occupation. In addition, regarding the distance from the roads, it is located very close to the road, with values between 00.00 and 249.99 m, being more prone to landslides.

Table 5
Weights classes for each variable on the scar with fatal victims.

Variables	Weights	Classes
Pedology	0.85	Cambysols
Lithology	0.02	Augen Gneiss (…)
Land use/cover	0.40	Forest
Slope	0.42	30.00–47.00%
Plan curvature	0.32	Very convergent
Profile curvature	0.33	Very convex
Distance from roads	0.39	0.00–249.99 m

3.2. Landslide hazard in the municipality of Cunha - 2010/01/01

The landslide hazard map for the municipality of Cunha, shown in Fig. 8, was generated through map algebra in ArcGIS® 10.8 software, combining the susceptibility data with the rainfall indexes obtained for 2010/01/01. There are many classification methods available, such as quantiles, natural breaks, equal intervals, and standard deviations (Ayalew and Yamagishi, 2004). The categorization adopted as a form of representation, considering the data distribution histogram, was the quantile, which divides the classes into the equal coverage area, assigning the same number of cells in each class. Several studies in the context of disasters used quantile classifiers and produced excellent results, such as Jaafari et al. (2014), Abdulwahid and Pradhan (2016), Baeza et al. (2016) and Raduszynski and Numada (2023).

In the case of landslide hazard for Cunha, several quantile configurations were tested to define the areas that represented the most critical situations with landslides, that is, of very high landslide hazard to these types of disasters. To help categorize these classes, some works were taken as a reference for a better definition. Comparing the studies found, based on the variables and methodology used, the one that most resembles the present study was that of Jaafari et al. (2014), which combined the use of data from lithology, slope, profile curvature, precipitation, and the survey of 103 landslides. For the authors, the high and very high classes involved approximately 50% of the study area, almost equally divided, i.e., 24.93% for the high and 24.52% for the very high class. Thus, according to the tests performed for Cunha municipality, it was found that respectively 30% and 20% for the high and very high classes presented the most satisfactory results. Overall, the very high landslide hazard class is above 80% of the values found for Cunha, while 20% corresponds to the most critical. In addition, very low and low were limited by the 10% quantile; while the medium and high, by 30% quantiles of 30%, as can be seen in Fig. 8.

Regarding Fig. 8, >25% of the scars were identified in the very high class (213 scars). Outcomes show that the medium to very high classes are considered the most important, for which 731 scars were counted. This corresponds to 91.38% of the total amount collected from the 800 scars. In assertiveness levels, the greater the number of scars inserted in these more critical classes, the better the result. Thus, in the low and very low classes, only 33 and 36 scars were registered, adding up to 8.62% of the registered amount. Overall, the results allow us to conclude that the technique adopted to obtain the landslide hazard map presented more satisfactory results in the most critical areas of the municipality of Cunha.

In terms of precipitation, it was found that the lowest values for the occurrence of landslides were:

- Daily precipitation (*PD*): 15.70 mm;

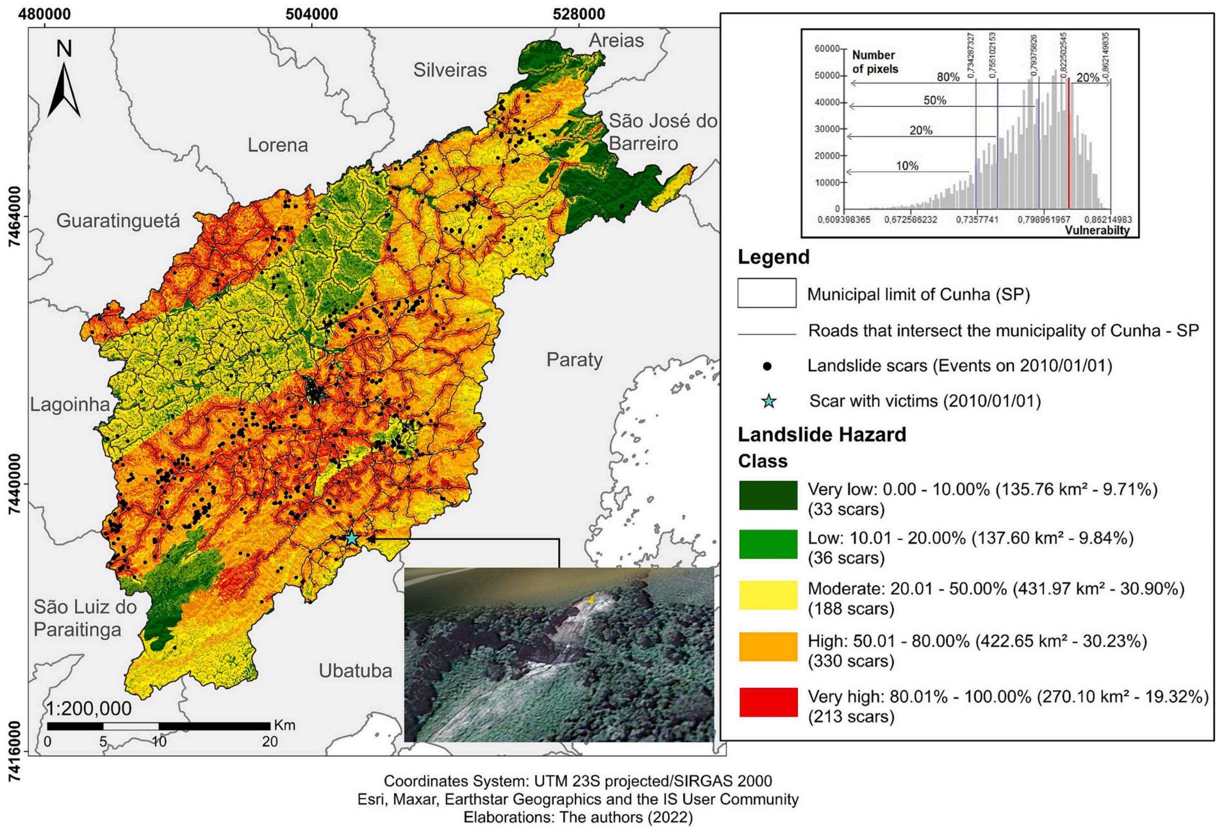

Fig. 8. Map of landslide hazard in the municipality of Cunha - 20.00% most critical.

- 5-day accumulated precipitation (*PA5*): 79.30 mm;
- Critical precipitation coefficient (*CPC*): 15.00 mm; and
- Maximum 5-day accumulated precipitation (*MAXPA5*): 135.82 mm.

Therefore, given the characteristics of the municipality of Cunha and exposure to meteorological conditions, daily precipitation events of a magnitude of 15.70 mm associated with 5-day accumulated precipitation of 79.30 mm would be enough to trigger new landslide events. Analyzing soil saturation is important since infiltration is one of the main factors for the rupture of slopes and mass movements (Campos, 2017).

Regarding the quantiles, Table 6 presents the various intervals of each landslide hazard class, depending on the distribution of pixels in the histogram of the map in Fig. 8. With this new classification and analysis of the histogram, better correlations are allowed for the distribution of landslides throughout the municipality. The density of landslides (DL), e.g., the ratio that establishes the scars per km^2 obtained in the landslide hazard map survey, reveals the occurrence within each class, as can be observed in Table 7.

The observation of Table 7 shows that the maximum DL obtained was 0.79 scars/km^2, for the very high class. Some authors report that very high frequencies of landslides are around 1.79 (Sarkar and Kanungo, 2004). However, for Cunha municipality, it is necessary to verify that the areas are very large, even with a high number of scars. It is possible to notice that in some areas there was a greater concentration of landslides, while in others, less. As a justification for such behavior, Rickli and Graf (2009) mention that the use and coverage of the area of interest, including forests and open areas, are essential for the variation of this behavior of landslide density. Finally, the comparison between the present model and the survey of images and results previously presented, is noteworthy that the most affected areas by the events of January 2010 were rural areas. The damages included collapsed bridges, and barriers, in addition to the destruction and road interdiction. This fact has completely isolated districts and prevented emergency actions by the public authorities to help the local population. Overall, this model and methodology were able to identify several of these critical areas and bring central points to the search for effective solutions to combat these recurring problems in this municipality.

3.3. Climate projections Eta-HadGEM2-ES RCP 4.5 - Occurrence of new events between 2024 and 2040

Finally, projections for precipitation values for the period from 2024 to 2040 under RCP4.5 were used for Cunha municipality. Thus, for this present study, the values of 15.00 mm of daily precipitation and 79.30 mm of accumulated precipitation over 5 days were identified as meteorological thresholds for landslides. From them, the days and values in which such conditions were reached were collected, as well as the value of the maximum accumulated precipitation of 5 days, within the new period of interest. From this, landslide hazard indices were again calculated for the 800 scars.

Thus, by the calculations performed and according to the precipitation data of future rains generated by the Eta HadGEM2-ES RCM under RCP 4.5 climate change scenario, for the period 2024/01/01 to 2040/12/30, there may be 49 dates of the mentioned period with situations of landslides in the areas of the municipality of Cunha, whose landslide hazard indices surveyed presented values $\geq$0.70.

Therefore, Table 8 presents the monthly and annual distribution with possible future dates of landslide occurrences within the analyzed period. It can be observed that the days are concentrated precisely during the rainy season in the municipality of Cunha, which spans from November to March. The year identified with the highest propensity for landslide cases is 2038, while the expected month with the highest incidence corresponds to November.

According to the study by Almagro et al. (2020), where the performances of global and regional models over Brazil were investigated, the Eta HadGEM2-ES was recommended for use in the Brazilian Atlantic Forest biome, since positive low-variation biases were identified, in the order of 2.00%, related to lateral conditions of boundaries carried out from GCM to RCM. The model proved to be efficient in the simulations of the rainy and dry seasons, given its adequate use for regions with steep topography, due to its vertical coordinate Eta (Chou et al., 2014).

The effects of these new rainfall events in Cunha may have repercussions in adjacent municipalities, such as Lagoinha and São Luiz do Paraitinga, especially regarding floods, citing those that occurred in these municipalities in January 2010. The Jacuí river has its source in Cunha, and the Paraitinga river has its source in Areias (SP) and has an important portion that crosses the municipality of Cunha, the expressive volume of rainfall directly impacts neighboring municipalities, being able to overflow and trigger other types of natural disasters, especially hydrological in nature.

In this way, given the possibility of a high number of new extreme events, it is observed and understood that with these results it is extremely important and necessary that validation of the data for the correct understanding of the geological processes that may occur in the municipality of Cunha. However, the difficult and precarious risk management in Brazil makes it difficult to obtain conclusive data for validation.

To exemplify these cases, in Brazil, some authorities lamented yet another tragedy involving heavy rains on the coast of São Paulo - Brazil in February 2023, which resulted in the death of >50 people. Recalling that the storms killed >200 people in Petrópolis - Rio de

Table 6
Criticality thresholds for landslide hazard classes.

Most critical class (%)	Very low (10%)	Low (10%)	Moderate (30%)	High (30%)	Very high (20%)
Landslide hazard	0.61–0.72	0.73–0.75	0.76–0.78	0.79–0.81	0.82–0.86

Table 7
Density of landslides (DL) per km^2.

Landslide hazard	Scars	Area (km^2)	DL
Very Low	33	135.76	0.24
Low	36	137.60	0.26
Moderate	188	431.97	0.44
High	330	422.65	0.78
Very high	213	270.10	0.79
Total	**800**	**1398.08**	–

Table 8
Monthly and year distribution of dates with the projected landslides between 2024 and 2040 in Cunha municipality.

Month / Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
2024	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2025	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2026	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2027	2	0	0	0	0	0	0	0	0	0	0	0	**2**
2028	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2029	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2030	0	0	0	0	0	0	0	0	0	0	1	0	**1**
2031	0	0	0	0	0	0	0	0	0	0	5	0	**5**
2032	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2033	0	0	1	0	0	0	0	0	0	0	6	0	**7**
2034	3	2	0	0	0	0	0	0	0	0	1	0	**6**
2035	0	1	0	0	0	0	0	0	0	0	1	1	**3**
2036	2	0	1	0	0	0	0	0	0	0	0	2	**5**
2037	0	0	1	0	0	0	0	0	0	0	1	0	**2**
2038	4	2	0	0	0	0	0	0	0	0	4	4	**14**
2039	1	1	0	0	0	0	0	0	0	0	0	1	**3**
2040	0	1	0	0	0	0	0	0	0	0	0	0	**1**
Sum	**12**	**7**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**19**	**8**	**49**

Janeiro - Brazil in 2022, he emphasized the lack of prevention measures, such as the absence of monitoring centers, and the leniency of municipal governments in Brazil regarding construction in high-risk areas (Brazil, 2023). Torrential rains recorded in the Serrana Region of Rio de Janeiro in 2011 caused landslides and floods, leaving a trail of over a thousand casualties. These events highlighted to the government the need to prioritize the disaster risk agenda, which had long been neglected, perhaps due to a lack of understanding of the true impacts of natural events on Brazilian society (Folha de São Paulo, 2020).

In this context, given that the Civil Defense of the Municipality of Cunha lacks adequate infrastructure for disaster risk management, it does not have a historical record that confirms the exact locations of landslides. When landslides occur in easily accessible areas of the municipality, print, television, and internet media publish information about these events. As an example, we highlight the landslide that occurred in the municipality of Cunha on January 8, 2022, duly reported by the internet media outlet CBN Vale do Paraíba (2022). The rain was so intense that several bridges leading to rural neighborhoods in Cunha were washed away, leaving residents stranded in their neighborhoods. There were also reports of other landslides that occurred between March 31 and April 3, 2022, at Pedra da Macela (a tourist attraction in the municipality of Cunha), as reported by Band Vale (2022), which stated that at least 5 landslides occurred at this location, although without precise records of the exact locations of the occurrences. Finally, on February 12, 2022, as reported by Jornal Atos (2022), at least five neighborhoods in Cunha lost bridges due to heavy rains on that date. There were reports of complete slope failures, among other infrastructure damage. Due to the vast territorial extent of the municipality and the loss of communication and access to various neighborhoods, it is difficult to ascertain the exact dates of these events, as well as their correct locations, hindering proper monitoring. The municipality also has 400 to 500 bridges connecting rural neighborhoods to the urban center, which also complicates transportation and the proper support to communities.

Thus, knowledge of these events is quite deficient, relying solely on media outlets and news reports, due to the limited disaster control and prevention infrastructure in Brazil, especially in more rural municipalities like Cunha.

Therefore, it is important to produce works on these areas and that the public power has access to these data and thus develops and implements new public policies related to land use and occupation, as well as alerting and monitoring precipitation events, to make the community more resilient in the face of these types of disasters, mitigating new social (human), environmental and economic losses, not only in the municipality of study but also in its surroundings. Integrated management between these municipal governments would strengthen the fight against environmental disasters.

4. Conclusions

The development of this study allowed the assessment of areas in the municipality of Cunha that are most susceptible to landslides and have high levels of landslide hazard. To calculate the susceptibility to landslides in the municipality of Cunha, were included the environmental variables pedology, lithology, land use and cover, slope, plan curvature, profile curvature, and distance from roads. For the study of landslide hazard, the date of 2010/01/01 was chosen for analysis, when with the occurrence of high rainfall in the municipality of Cunha, several landslide events were triggered in its territorial extension, culminating in six human losses. For this date, among the large number of mass movements that occurred, 800 scars were then identified.

From the outcomes obtained for the susceptibility to landslides, it was found that the preponderant variable for the model was pedology, with an average index of 0.73, while the General Average Susceptibility Index (IMGS), of all the variables of the model, was 0.62.

In terms of the meteorological variables for the landslide hazard map of the municipality of Cunha, daily precipitation values above 15.00 mm and accumulated precipitation of 79.30 mm in 5 days, might trigger landslide events. Using a percentile of 20.00% for the very high landslide hazard class, the landslide density (DL) for Cunha was 0.79 landslides/km^2.

Lastly, the data retrieved from Eta HadGEM2-ES under RCP 4.5 climate projections, allowed us to evaluate the period from 2024 to 2040 and predict that 49 different extreme precipitation events may occur, thus pointing out the possibility of the occurrence of new landslides. It is, therefore, necessary to invest in public policies to prevent these types of disasters in the municipality of Cunha. The implementation of mitigation measures could avoid the damages of the past, such as the fall of barriers and bridges that highly impacted the rural region of Cunha, isolating several communities, and preventing the action of the Civil Defense, among other bodies. Authorities should also be aware of the relevance of urban planning adaptation strategies mainly on the expansion of occupations and on the roads that interconnect the entire municipality shortly.

The outcomes of this research reinforce a greater commitment to the UN 2030 Agenda through the Sustainable Development Goals (SDGs), mechanisms that can help reduce landslide events and their impacts on populations. Among these SDGs, the following are relevant to this study: Goal 10 "Reduced Inequalities" which involves, for example, the adoption and implementation of integrated policies and plans for inclusion, climate change mitigation and adaptation, resource efficiency, and disaster resilience; and Goal 13 "Climate action", which has as one of its premises to promote mechanisms for capacity building for climate change-related planning and effective management in the least developed countries, including with a focus on women, youth, and local and marginalized communities.

Overall, it would be of enormous value to educational and research institutions, as well as to the municipality of Cunha, to create a free-access database. This should gather information and georeferenced data on the various themes of the municipality, and the engagement of the City Hall, Civil Defense, the population, and other organizations. Once more data exists, it is possible to advance in the research and update it, representing more clearly and truthfully the reality of the municipality of Cunha, allowing new research and integrated management within the community.

CRediT authorship contribution statement

Irving Rodrigues de Souza: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft. **Débora Luisa Silva Teixeira:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Marcelo Barbio Rosa:** Data curation, Formal analysis, Methodology, Software, Writing – review & editing. **Luiz Tadeu da Silva:** Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Jean Pierre Henry Balbaud Ometto:** Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Danúbia Caporusso Bargos:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Cristina Andrade:** Resources, Writing – review & editing. **Elsa Paula Figueira Ferreira Morgado de Sampaio:** Writing – review & editing. **Paulo Valladares Soares:** Writing – review & editing. **Thiago Bazzan:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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References

4x4Brasil, 2010 4x4Brasil, 2010. Cunha: Estrada Cunha - Paraty. https://www.4x4brasil.com.br/forum/trilhas/65580-estrada-cunha-paraty-2.html (accessed 24 April 2022).

Abdulwahid, W.M., Pradhan, B., 2016. Landslide vulnerability and risk assessment for multi-hazard scenarios using airborne laser scanning data (LiDAR). Landslides 14 (3), 1057–1076. https://doi.org/10.1007/s10346-016-0744-0.

Almagro, A., Oliveira, P.T.S., Rosolem, R., Hagemann, S., Nobre, C.A., 2020. Performance evaluation of Eta/HadGEM2-ES and Eta/MIROC5 precipitation simulations over Brazil. Atmos. Res. 244, 105053. https://doi.org/10.1016/j.atmosres.2020.105053.

Alvioli, M., Melillo, M., Guzzetti, F., Rossi, M., Palazzi, E., von Hardenberg, J., Brunetti, M.T., Peruccacci, S., 2018. Implications of climate change on landslide hazard in Central Italy. Sci. Total Environ. 630, 1528–1543. https://doi.org/10.1016/j.scitotenv.2018.02.315.

ANA, 2011. Sistema Interligado Nacional: Bacia do Rio Paraíba do Sul. https://www.ana.gov.br/sar/sin/b_paraiba-do-sul (acessed 02 December 2022).

Antunes, F.S., Campos, T.M.P., Polivanov, H., Calderano, S.B., Andrade, A.G., 2013. Desenvolvimento de classes e unidades geo-pedológicas a partir da interação entre a pedologia e a geotecnia. Rev. Luso-Bras. Geotec. 127, 61–79. https://doi.org/10.14195/2184-8394_127_3.

ArcGIS, 2021. How IDW Works, p. 2021. https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/how-idw-works.htm (accessed 02 May 2022).

Ayalew, L., Yamagishi, H., 2004. Slope movements in the Blue Nile basin, as seen from landscape evolution perspective. Geomorphol. 57, 95–116. https://doi.org/10.1016/S0169-555X(03)00085-0.

Baeza, C., Lantada, N., Amorim, S., 2016. Statistical and spatial analysis of landslide susceptibility maps with different classification systems. Environ. Earth Sci. 75 https://doi.org/10.1007/s12665-016-6124-1.

Bastos, S.B., Bestaku, A., Soares Filho, I., Motta, I.C.N., Rabelo, T.C., 2018. Transição agroecológica da pecuária em Cunha-SP e região. Cad. Agroecol. 13. https://cadernos.aba-agroecologia.org.br/cadernos/article/view/1658 (accessed 10 December 2022).

Brazil, 1979. Lei N. 6.766 de 19 de Dezembro de 1979: Dispõe sobre o Parcelamento do Solo Urbano e dá outras Providências. Casa Civil, Braesília, DF. http://www.planalto.gov.br/ccivil_03/LEIS/L6766.htm (accessed 07 December 2022).

Brazil, 2005. Viver na Mata Atlântica: Recuperação de Matas Ciliares junto a Agricultores Familiares da Estância Climática de Cunha - SP. Ministério do Meio Ambiente, Brasília, DF. https://antigo.mma.gov.br/component/k2/item/8140-sp-cunha.html (accessed 07 December 2022).

Brazil, 2023. Senado Federal. Rádio Senado. Desastres Naturais. Senador alerta para a falta de prevenção e ação em desastres. Senado Federal, Brasília, DF. https://www12.senado.leg.br/radio/1/noticia/2023/02/23/senador-alerta-para-a-falta-de-prevencao-e-acao-em-desastres (accessed 15 August 2023).

Brenning, A., 2015. Landslide susceptibility near highways is increased by 1 order of magnitude in the Andes of southern Ecuador, Loja province. Nat. Hazards Earth Syst. Sci. 15, 45–57. https://doi.org/10.5194/nhess-15-45-2015.

Campos, L.E.P., 2017. Use of Unsaturated Soil Parameters on Slopes. http://www.geotecnia.ufba.br/arquivos/ST5-Tp03.pdf (accessed 07 December 2022).

CBN Vale do Paraíba, 2022. Rodovia que liga Cunha a Paraty é bloqueada após deslizamento de barreira. https://www.cbnvale.com.br/rodovia-que-liga-cunha-a-paraty-e-bloqueada-apos-deslizamento-de-barreira/ (accessed 15 August 2023).

Chen, C.-W., Tung, Y.-S., Liou, J.-J., Li, H.-C., Cheng, C.-T., Chen, Y.-M., Oguchi, T., 2019. Assessing landslide characteristics in a changing climate in northern Taiwan. Catena 175, 263–277. https://doi.org/10.1016/j.catena.2018.12.023.

Chou, S.C., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G., Nobre, P., Marengo, J., 2014. Evaluation of the eta nested in three global climate models. Am. J. Clim. Chang. 3, 438–454. https://doi.org/10.4236/ajcc.2014.35039.

Cortes, C., Vapnik, V., 1995. Support-vector networks. Mach. Learn. 20, 273–297. https://doi.org/10.1007/BF00994018 (accessed 18 December 2022).

Costa, W.M., 2023. Storms and catastrophe in São Sebastião - SP at carnival 2023. Confins 58. https://doi.org/10.4000/confins.50176.

CPRM, 2006. Mapa geológico do Estado de São Paulo. https://geosgb.cprm.gov.br/ (accessed 25 November 2022).

CPRM, 2016. Cartas de Suscetibilidade a Movimentos Gravitacionais de Massa e Inundações - São Paulo. https://www.cprm.gov.br/publique/Gestao-Territorial/Prevencao-de-Desastres/Cartas-de-Suscetibilidade-a-Movimentos-Gravitacionais-de-Massa-e-Inundacoes—Sao-Paulo-5088.html (accessed 05 November 2022).

CRED, 2022. Disasters Year in Review 2021. n. 66. UCLouvain, Brussels. 2022.. https://cred.be/sites/default/files/CredCrunch66.pdf (accessed 15 December 2022).

Cunha, 2019. Prefeitura Municipal de Cunha: A cidade. https://www.cunha.sp.gov.br/a-cidade/ (accessed 29 November 2022).

Dourado, F., Arraes, T.C., Silva, M.F., 2012. The mega-disaster in the Serrana region of Rio de Janeiro: the causes of the event, the mechanisms of mass movements and the spatial distribution of post-disaster reconstruction investments. Anu. Inst. Geoscienc. 35, 43–54. https://doi.org/10.11137/2012_2_43_54.

EMBRAPA, 2003. Levantamento de reconhecimento de baixa intensidade dos solos do Estado do Rio de Janeiro. EMBRAPA, Rio de Janeiro. https://www.embrapa.br/solos/busca-de-publicacoes/-/publicacao/1037806/levantamento-de-reconhecimento-de-baixa-intensidade-dos-solos-do-estado-do-rio-de-janeiro (accessed 25 November 2022).

Ercanoğlu, M., Gökceoğlu, C., Van Asch, T.W.J., 2004. Landslide susceptibility zoning north of Yenice (NW Turkey) by multivariate statistical techniques. Nat. Hazards 32, 1–23. https://doi.org/10.1023/B:NHAZ.0000026786.85589.4a.

ESRI, 2014. Understanding Euclidean Distance. https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analysttoolbox/understanding-euclidean-distance-analysis.htm (accessed 25 November 2022).

Fekete, A., Sandholz, S., 2021. Here comes the flood, but not failure? Lessons to learn after the heavy rain and pluvial floods in Germany. Water 13, 3016. https://doi.org/10.3390/w13213016.

Folha de São Paulo, 2010. Deslizamento mata 6 da mesma família no Vale do Paraíba. https://www1.folha.uol.com.br/fsp/cotidian/ff0201201010.htm (accessed 28 April 2022).

Folha de São Paulo, 2020. Brasil paga alto preço pela falta de política integrada de gestão de risco de desastres. https://www1.folha.uol.com.br/colunas/rafael-munoz/2020/10/brasil-paga-alto-preco-pela-falta-de-politica-integrada-de-gestao-de-risco-de-desastres.shtml (accessed 15 Aug 2023).

Freitas, A.A., Oda, P.S.S., Teixeira, D.L.S., Silva, P.N., Mattos, E.V., Bastos, I.R.P., Nery, T.D., Metodiev, D., Santos, A.P.P., 2022. Meteorological conditions and social impacts associated with natural disaster landslides in the Baixada Santista region from March 2nd–3rd, 2020. Urban Clim. 42. https://doi.org/10.1016/j.uclim.2022.101110.

Globo, O., 2010. Turistas morrem soterrados em deslizamento de terra em Cunha, SP. https://oglobo.globo.com/politica/turistas-morrem-soterrados-em-deslizamento-de-terra-em-cunha-sp-3075311.

Google Earth, 2009. Explore Google Earth. http://earth.google.com/ (accessed 14 November 2022).

Gouvea, R.L., Menezes, J.T., Campos, C.C.G., Moreira, G.F., 2017. Extremos de precipitação e ocorrência de deslizamentos de terra na bacia do rio Itajaí. Rev. Gestão Sustentabilidade Ambient 6, 276–295. https://doi.org/10.19177/rgsa.v6e32017276-295.

Hong, H., Ilia, I., Tsangaratos, P., Chen, W., Xu, C., 2017. A hybrid fuzzy weight of evidence method in landslide susceptibility analysis on the Wuyuan area, China. Geomorphol. 290, 1–16. https://doi.org/10.1016/j.geomorph.2017.04.002.

Huang, F., Chen, J., Liu, W., Huang, J., Hong, H., Chen, W., 2022. Regional rainfall-induced landslide hazard warning based on landslide susceptibility mapping and a critical rainfall threshold. Geomorphol. 408, 108236. https://doi.org/10.1016/j.geomorph.2022.108236.

Hürlimann, M., Guo, Z., Puig-Polo, C., Medina, V., 2022. Impacts of future climate and land cover changes on landslide susceptibility: regional scale modelling in the Val d'Aran region (Pyrenees, Spain). Landslides 19, 99–118. https://doi.org/10.1007/s10346-021-01775-6.

IBGE, 2011. Censo Demográfico 2010. IBGE, Rio de Janeiro. https://www.ibge.gov.br/estatisticas/downloads-estatisticas.html (accessed 20 November 2022).

IBGE, 2015. Portal de mapas. https://portaldemapas.ibge.gov.br/portal.php#mapa206426 (accessed 09 November 2022).

IBGE, 2018a. IBGE Cidades. https://cidades.ibge.gov.br/brasil/sp/cunha/panorama (accessed 20 November 2022).

IBGE, 2018b. População em áreas de risco no Brasil | 2010. IBGE, Rio de Janeiro. https://www.ibge.gov.br/geociencias/informacoes-ambientais/estudos-ambientais/21538-populacao-em-areas-de-risco-no-brasil.html?=&t=acesso-ao-produto (accessed 21 November 2022).

INPE, 2008. Topodata: Banco de dados geomorfométricos do Brasil. http://www.dsr.inpe.br/topodata/ (accessed 08 November 2022).

INPE, 2011. Cátalogo de imagens. http://www.dgi.inpe.br/CDSR (accessed 08 December 2022).

IPCC, 2021. IPCC Sixth Assessment Report - Working Group 1: The Physical Science Basis. https://www.ipcc.ch/report/ar6/wg1/ (accessed 20 November 2022).
Jaafari, A., Najafi, H.R., Pourghasemi, H.R., Rezaeian, J., Sattarian, A., 2014. GIS-based frequency ratio and index of entropy models for landslide susceptibility assessment in the Caspian forest, northern Iran. Int. J. Environ. Sci. Technol. 11, 909–926. https://doi.org/10.1007/s13762-013-0464-0.
Jakob, M., Owen, T., 2021. Projected effects of climate change on shallow landslides, north Shore Mountains, Vancouver, Canada. Geomorphol. 393, 107921. https://doi.org/10.1016/j.geomorph.2021.107921.
Jeong, H., Ahn, J., Lee, J., Shim, K., Jung, M., 2019. Improvement of daily precipitation estimations using PRISM with inverse-distance weighting. Theory. Appl. Climatol. 139, 923–934. https://doi.org/10.1007/s00704-019-03012-6.
Jornal Atos, 2022. Prefeitura de Cunha executa obras após pontes serem arrastadas em temporais. https://jornalatos.net/regiao/cidades/cunha/cunha-executa-obras-apos-pontes-serem-arrastadas-em-temporais/ (accessed 22 Aug 2023).
Khan, A., Gupta, S., Gupta, S.K., 2020. Multi-hazard disaster studies: monitoring, detection, recovery, and management, based on emerging technologies and optimal techniques. Int. J. Disaster Risk Reduct. 47, 101642. https://doi.org/10.1016/j.ijdrr.2020.101642.
Kreienkamp, F., Philip, S.Y., Tradowsky, J.S., Sarah, F.K., Lorenz, P., Arrighi, J., Belleflamme, A., Bettmann, T., 2021. Rapid Attribution of Heavy Rainfall Events Leading to the Severe Flooding in Western Europe during July 2021. https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf (accessed 02 December 2022).
Lee, S., Min, K., 2001. Statistical analyses of landslide susceptibility at Yongin, Korea. Environ. Geol. 40, 1095–1113. https://doi.org/10.1007/s002540100310.
Lee, S., Won, J., Jeon, S.W., Park, I., Lee, M.J., 2014. Spatial landslide hazard prediction using rainfall probability and a logistic regression model. Math. Geosci. 47, 565–589. https://doi.org/10.1007/s11004-014-9560-z.
Lu, G.Y., Wong, D.W., 2008. An adaptive inverse-distance weighting spatial interpolation technique. Comput. Geosci. 34, 1044–1055. https://doi.org/10.1016/j.cageo.2007.07.010.
Maraun, D., Shepherd, T.G., Widmann, M., Zappa, G., Walton, D., Gutiérrez, J.M., Hagemann, S., Richter, I., Soares, P.M.M., Hall, A., Mearns, L.O., 2017. Towards process-informed bias correction of climate change simulations. Nat. Clim. Chang. 7, 764–773. https://doi.org/10.1038/nclimate3418.
Marengo, J.A., Alaves, L.M., Ambrizzi, T., Young, A., Barreto, N.J.C., Ramos, A.M., 2020. Trends in extreme rainfall and hydrogeometeorological disasters in the metropolitan area of São Paulo: a review. Ann. N. Y. Acad. Sci. 1472, 5–20. https://doi.org/10.1111/nyas.14307.
Mendes, R.M., Andrade, M.R.M., Tomasella, J., Moraes, M.A.E., Scofield, G.B., 2018. Understanding shallow landslides in Campos do Jordão municipality – Brazil: disentangling the anthropic effects from natural causes in the disaster of 2000. Nat. Hazards Earth Syst. Sci. 18, 15–30. https://doi.org/10.5194/nhess-18-15-2018.
Mendonça, M.B., Silva, D.R., 2020. Integration of census data based vulnerability in landslide risk mapping - the case of Angra dos Reis, Rio de Janeiro, Brazil. Int. J. Dis. Risk Reduct. 50, 101884. https://doi.org/10.1016/j.ijdrr.2020.101884.
Microsoft Excel, 2019. Version. United States of America: Microsoft 365®, 2019. https://www.microsoft.com/ (accessed 19 November 2022).
Overland, J.E., 2021. Causes of the record-breaking Pacific northwest heatwave, late June 2021. Atmos. 12, 1434. https://doi.org/10.3390/atmos12111434.
Panwar, V., Sen, S., 2019. Economic impact of natural disasters: an empirical re-examination. Margin: J. Of Appl. Econ. Res. 13, 109–139. https://doi.org/10.1177/0973801018800087.
Peres, D.J., Cancelliere, A., 2018. Modeling impacts of climate change on return period of landslide triggering. J. Hydrol. 567, 420–434. https://doi.org/10.1016/j.jhydrol.2018.10.036.
Persichillo, M.G., Bordoni, M., Meisina, C., 2017. The role of land use changes in the distribution of shallow landslides. Sci. Tot. Environ. 574, 924–937. https://doi.org/10.1016/j.scitotenv.2016.09.125.
Pham, B.T., Bui, D.T., Prakash, I., Dholakia, M.B., 2017. Hybrid integration of multilayer perceptron neural networks and machine learning ensembles for landslide susceptibility assessment at Himalayan area (India) using GIS. Catena 149, 52–63. https://doi.org/10.1016/j.catena.2016.09.007.
Philip, S.Y., Kew, S.F., Van Oldenborgh, G.J., Anslow, F.S., Seneviratne, S.I., Vautard, R., Coumou, D., Ebi, K.L., Arrighi, J., Singh, R., Van Aalst, M., Pereira Marghidan, C., 2022. Rapid attribution analysis of the extraordinary heatwave on the Pacific coast of the US and Canada June 2021. Earth Syst. Dynam. 13, 1689–1713. https://doi.org/10.5194/esd-2021-90.
R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/ (accessed 02 December 202).
Raduszynski, T., Numada, M., 2023. Measure and spatial identification of social vulnerability, exposure and risk to natural hazards in Japan using open data. Sci. Rep. 13, 664. https://doi.org/10.1038/s41598-023-27831-w.
Rickli, C., Graf, F., 2009. Effects of forests on shallow landslides: case studies in Switzerland. For. Snow Landsc. Res. 82, 33–44, 2009. https://www.dora.lib4ri.ch/wsl/islandora/object/wsl%3A15351 (accessed 13 December 2022).
Rodrigues, C.S., 2013. Mapeamento de suscetibilidade a escorregamentos de Nova Friburgo-RJ por meio de inferência fuzzy e elaboração de cenários de alerta com uso do TERRAMA2. 2013. Thesis (Master Degree in Remote Sensing). National Institute for Space Research, São José dos Campos. http://urlib.net/sid.inpe.br/mtc-m19/2013/08.03.20.54 (accessed 11 December 2022).
Rossi, M., 2017. Mapa pedológico do Estado de São Paulo: revisado e ampliado, 1. Instituto Florestal, São Paulo, p. 2017, 118p.
Rozante, J.R., Moreira, D.S., Gonçalves, L.G.G., Vila, D., 2010. Combining TRMM and surface observations of precipitation: technique and validation over South America. Weather Forecast. 25, 885–894. https://doi.org/10.1175/2010WAF2222325.1.
Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, Nova Iorque, 287 p.
Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
San José, R., Pérez, J.L., González, R.M., Pecci, J., Garzón, A., Palacios, M., 2016. Impacts of the 4.5 and 8.5 RCP global climate scenarios on urban meteorology and air quality: application to Madrid, Antwerp, Milan, Helsinki and London. J. Comput. Appl. Math. 293, 192–207. https://doi.org/10.1016/j.cam.2015.04.024.
Sarkar, S., Kanungo, D.P., 2004. An integrated approach for landslide susceptibility mapping using remote sensing and GIS. Photogramm. Eng. Remote Sens. 70, 617–625. https://doi.org/10.14358/PERS.70.5.617.
SEADE, 2019. Perfil dos Municípios de São Paulo. Fundação Seade, Brasília. https://www.seade.gov.br/ (accessed 12 December 2022).
Silva, L.T., Sampaio, E.P.F.F.M., Corte-Real, J.A.M., Rodriguez, D.A., Carnauba Medeiros, F., Moraes, B.E., França, D.G.M., 2015. Susceptibility and vulnerability to landslides—Case study: Basin of river Bengalas-City of Nova Friburgo-Brazil. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and Territory. Springer, Switzerland. https://doi.org/10.1007/978-3-319-09300-0_101.
Silveira, C.S., Filho, F.A.S., Martins, E.S.P.R., Oliveira, J.L., Costa, A.C., Nobrega, M.T., Souza, S.A., Silva, R.F.V., 2016. Climate change in the São Francisco river basin: an analysis for precipitation and temperatMudanças climáticas na bacia do rio São Francisco: Uma análise para precipitação e temperatura. Rev. Bras. Recur. Hidr. 21, 416–428. https://doi.org/10.21168/rbrh.v21n2.p416-428.
Tominaga, L.K., Santoro, J., Amaral, R., 2009. Desastres Naturais: Conhecer para Prevenir. Instituto Geológico, São Paulo, p. 2009, 196 p.
Vale, Band, 2022. Visitação à Pedra da Macela é suspensa após queda de barreiras em Cunha. https://www.band.uol.com.br/band-vale/noticias/visitacao-a-pedra-da-macela-e-suspensa-apos-queda-de-barreiras-em-cunha-16503834 (accessed 15 August 2023).
Valeriano, M.M., 2008. Topodata: guia para a utilização de dados geomorfológicos locais. INPE, São José dos Campos, 72 p. http://mtc-m16c.sid.inpe.br/col/sid.inpe.br/mtc-m18@80/2008/07.11.19.24/doc/publicacao.pdf (accessed 19 November 2022).
Witt, A., Sachser, C., Fegert, J.M., 2022. Scoping review on trauma and recovery in youth after natural disasters: what Europe can learn from natural disasters around the world. Eur. Child Adolesc. Psychiatry. https://doi.org/10.1007/s00787-022-01983-y.