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Susceptibility mapping to mass movements in the Jiquiriçá Valley - BA

Mapeamento da susceptibilidade a movimentos de massa no Vale do Jiquiriçá - BA

Ericka Medeiros da Silva¹; Deorgia Tayane Mendes de Souza²; Washington de Jesus Sant'anna da Franca Rocha³; Rodrigo Nogueira de Vasconcelos⁴; Odaimys Socorro Ramos⁵

- ¹ State University of Feira de Santana, Graduate Program in Modeling in Earth and Environmental Sciences, Feira de Santana/BA, Brazil. Email: medeisericka05@gmail.com
ORCID: <https://orcid.org/0000-0002-6924-4252>
- ² State University of Feira de Santana, Graduate Program in Modeling in Earth and Environmental Sciences, Feira de Santana/BA, Brazil. Email: dtmsouza@uefs.br
ORCID: <https://orcid.org/0000-0001-6791-3611>
- ³ State University of Feira de Santana, Graduate Program in Modeling in Earth and Environmental Sciences, Feira de Santana/BA, Brazil. Email: wrocha@uefs.br
ORCID: <https://orcid.org/0000-0002-2175-2792>
- ⁴ State University of Feira de Santana, Graduate Program in Modeling in Earth and Environmental Sciences, Feira de Santana/BA, Brazil. Email: rnvuefsppgm@gmail.com
ORCID: <https://orcid.org/0000-0002-1368-6721>
- ⁵ State University of Feira de Santana, Graduate Program in Modeling in Earth and Environmental Sciences, Feira de Santana/BA, Brazil. Email: ody.socorro@gmail.com
ORCID: <https://orcid.org/0009-0001-9502-8844>

Abstract: This study examines the susceptibility to mass movements in the Jiquiriçá Valley (Bahia, Brazil), an area particularly vulnerable to natural disasters during periods of heavy rainfall. These events, characterized by the gravitational displacement of soil and rock downslope, are influenced by a combination of factors, including climate, topography, and land use, leading to significant environmental and social consequences. The aim is to map mass movement susceptibility in the region under various rainfall and land-use/land-cover (LULC) change scenarios. To achieve this, the Analytic Hierarchy Process (AHP) was utilized in conjunction with Geographic Information Systems (GIS). This methodology involved weighting both conditioning factors (such as slope, soil type, soil texture, relief dissection index, hypsometry, slope aspect, lithology, and geological fault density) and triggering factors (including rainfall data from the historical series of 1970–2000 and December 2021, as well as LULC data from 1985 and 2021). The findings indicate a 15.36% increase in areas classified as having "Very High" susceptibility, particularly in regions characterized by steep slopes and sedimentary lithologies. Conversely, there was a 33.56% decrease in areas classified as having "Low" susceptibility, reflecting an increased risk over time. Thus, this susceptibility mapping is crucial for supporting disaster risk reduction measures and informing land use planning efforts.

Keywords: Geoprocessing; Mass Movement; Analytic Hierarchy Process.

Resumo: Este estudo analisa a susceptibilidade a movimentos de massa no Vale do Jiquiriçá (BA), uma região particularmente exposta a desastres naturais durante períodos de chuvas intensas. Esses fenômenos, que envolvem o deslocamento de solo e rochas em encostas, são influenciados por fatores como clima, relevo e uso do solo, resultando em sérios impactos ambientais e sociais. O objetivo do trabalho consiste em mapear a susceptibilidade a movimentos de massa no referido município quando submetido ao cenário de intensa pluviosidade e mudanças de uso e cobertura da terra. Para isso, foi utilizado o método Analytic Hierarchy Process (AHP) combinado com geoprocessamento, ponderando fatores como declividade, classes de solos, textura dos solos, índice de dissecação do relevo, hipsometria, orientação da vertente, litologia e a densidade de fraturas geológicas, pluviosidade (1970-2000 e 2021) e uso e cobertura da terra (1985 e 2021). Os resultados revelam um aumento de 15,36% das zonas de "Muito Alta" susceptibilidade, especialmente em áreas com relevo acentuado e litologias sedimentares, que favorecem movimentos de massa. Em contraste, houve uma diminuição de 33,56% das áreas classificadas como de "Baixa" susceptibilidade, indicando uma intensificação do risco ao longo do tempo. Portanto, o mapeamento realizado é de suma importância para auxiliar em medidas de prevenção a desastres naturais e subsidiar o planejamento territorial.

Palavras-chave: Geoprocessamento; Movimento de Massa; Processo de Hierarquia Analítica.

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1. Introduction

Mass movements are significant natural events characterized by the downward displacement of soil and rock due to the force of gravity (CEPED, 2013). Their occurrence arises from a combination of conditioning factors, including lithology, slope morphology, geological structures, and hydrogeological conditions, alongside triggering factors such as intense precipitation, human-induced slope modifications, and seismic activity (CAMILO, 2013).

Alongside their environmental consequences, including soil degradation and increased erosion, mass movements often lead to significant loss of life, particularly during periods of heavy rainfall, resulting in recurrent fatalities and burials (SILVEIRA et al., 2014). Between 2004 and 2016, over 4,800 such events were recorded globally, resulting in 55,997 confirmed deaths (FROUDE & PETLEY, 2018).

Between 1991 and 2012, the Brazilian Atlas of Natural Disasters documented 699 mass movement events across Brazil, directly impacting approximately 5.5 million individuals and resulting in 535 fatalities (CEPED, 2013). While the semi-arid northeastern region of Brazil is historically characterized by prolonged droughts, extreme precipitation events have caused significant repercussions in several urban areas (CEPED, 2013).

A notable example is the Jiquiriçá Valley, located in the south-central part of the state of Bahia. The region, officially designated as an "Identity Territory" (a regional planning unit in Brazil), covers an area of 10,736.5 km² and comprises 20 municipalities: Amargosa, Brejões, Cravolândia, Elísio Medrado, Irajuba, Itaquara, Itiruçu, Jaguaquara, Jiquiriçá, Lafaiete Coutinho, Laje, Lajedo do Tabocal, Maracás, Milagres, Mutuípe, Nova Itarana, Planaltino, Santa Inês, São Miguel das Matas, and Ubaíra (BAHIA, 2011).

In December 2021, the Jiquiriçá Valley suffered devastating impacts due to intense rainfall, resulting in a significant number of displaced individuals and considerable property damage (G1 BAHIA, 2021). This month recorded the highest precipitation levels of the year, far surpassing the region's historical monthly averages (<https://portal.inmet.gov.br/>). The extraordinary volumes of rainfall underscore the importance of comprehending the relationship between the rainfall patterns and the dynamics of mass movements, particularly in urban and rural areas facing increasing anthropogenic pressures.

This study aims to assess susceptibility to mass movements in the Jiquiriçá Valley under various rainfall and land-use/land-cover scenarios. The focal point for rainfall analysis is December 2021, as this month not only marked a historical peak in rainfall volume but also concentrated on the extreme events that prompted this investigation. By integrating climatic, geological, geomorphological, and land-use variables within a multi-temporal framework, the study aims to provide technical support for territorial planning and the development of disaster risk reduction strategies. This approach considers the regions increasing vulnerability to climate change and the intensification of human activities.

2. Methodology

2.1 Applied Materials and Methods

This study examined several conditioning factors, including slope, soil types (categorized by development stage and texture), Relief Dissection Index (RDI), hypsometry, slope aspect, lithology, and geological fracture density. The triggering factors analyzed encompassed rainfall from December 1970 to 2000 (historical series) and December 2021, as well as land use and land cover (LULC) data from the years 1985 and 2021.

The selection of these time intervals was informed by the standardized availability of climate data from the WorldClim database for the period 1970–2000, as well as the record-breaking rainfall observed in December 2021. This month was chosen as a specific temporal reference because it recorded the highest rainfall intensity. For land use and land cover data, the years 1985 and 2021 were selected, representing the initial year of the continuous historical series from MapBiomas Brasil and the most recent year available for our analysis.

The research utilized thematic databases from the Superintendence of Economic and Social Studies of Bahia (SEI) at a scale of 1:1,000,000 for geological information and data from the Geological Survey of Brazil at a scale of 1:250,000 for mapping geological fractures and soil characteristics. Additionally, digital elevation models from the Shuttle Radar Topography Mission (SRTM), featuring a spatial resolution of 30 meters, were utilized, enabling the extraction of morphometric variables such as slope, hypsometry, slope aspect, and RDI.

Land Use and Land Cover (LULC) data were sourced from the MapBiomas Brasil platform, featuring a spatial resolution of 30 meters for the years 1985 and 2021. Climate data were retrieved from the WorldClim database, which offers a spatial resolution of approximately 9 kilometers. All data processing and analysis were conducted using ArcGIS Pro software.

2.2 Relief Dissection Index - RDI

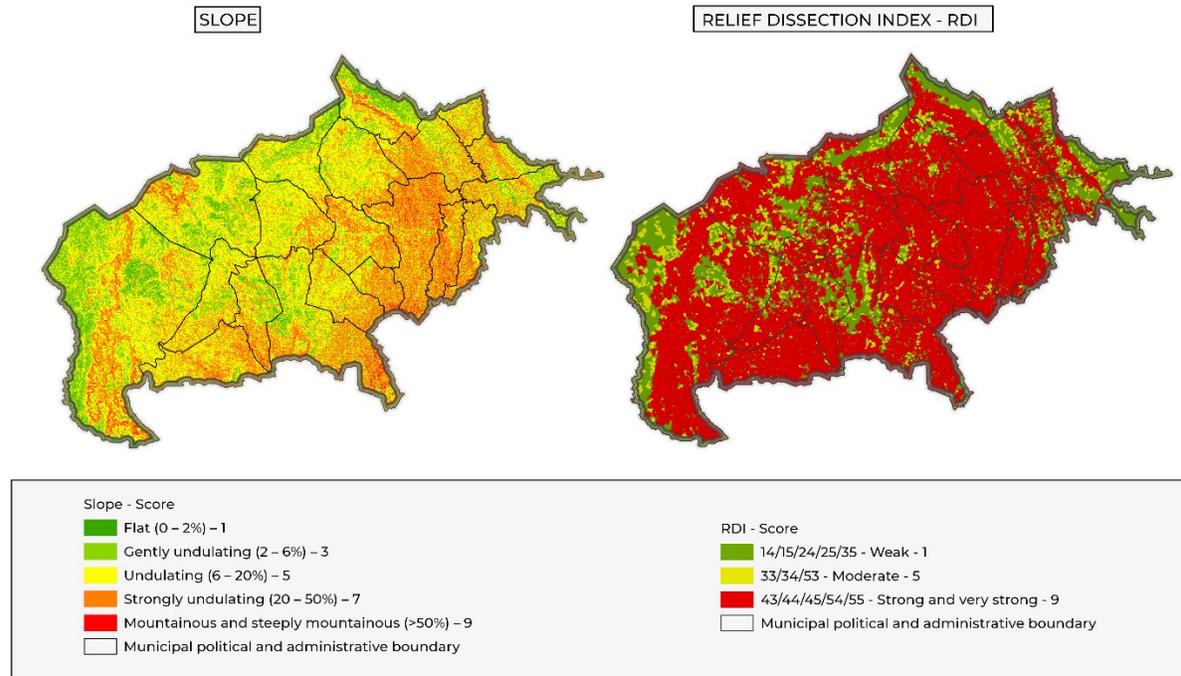
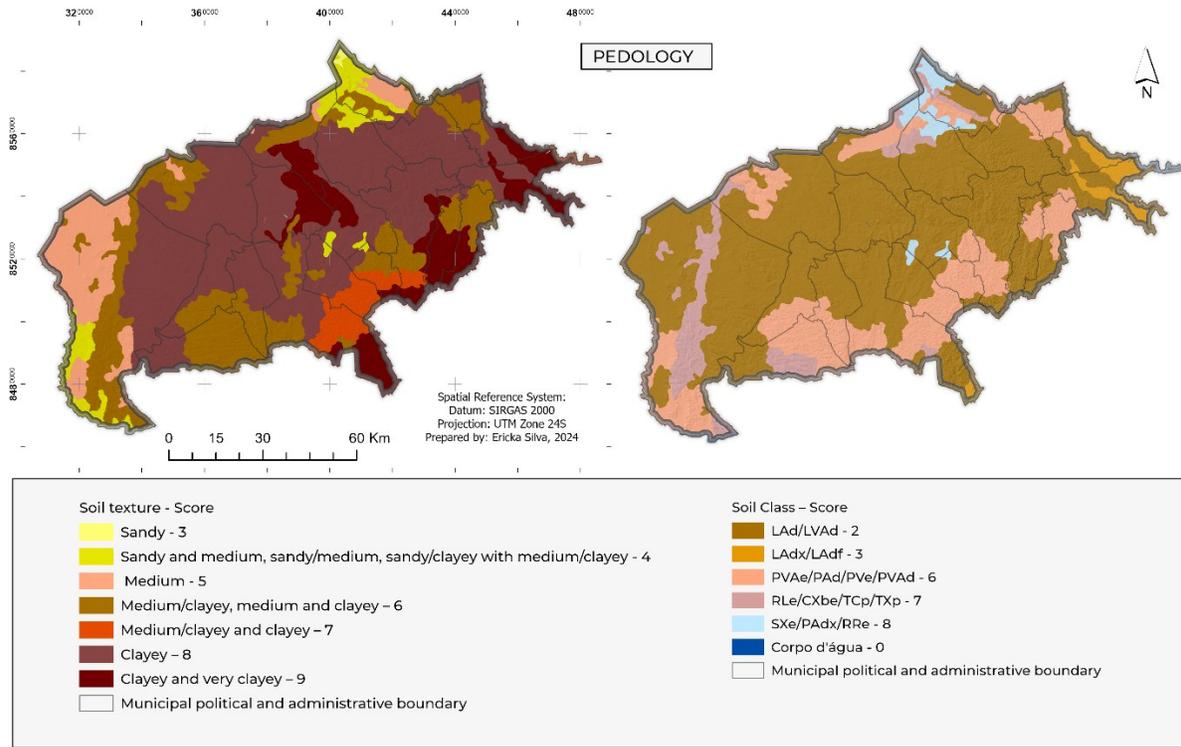
The Relief Dissection Index (RDI) was calculated utilizing the automated methodology established by Lima (2018), which integrates two morphometric variables: Vertical Dissection (VD), representing the relative relief amplitude, and Horizontal Dissection (HD), which pertains to the average dimensions of interfluves. The combination of the VD and HD variables yields the RDI, providing insight into the potential energy or erosive potential available across a specific surface area (LIMA, 2018).

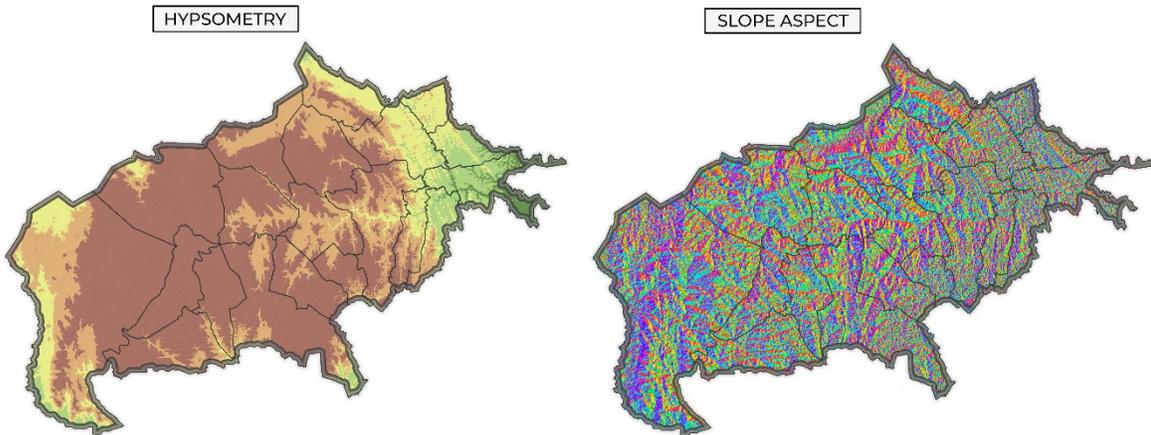
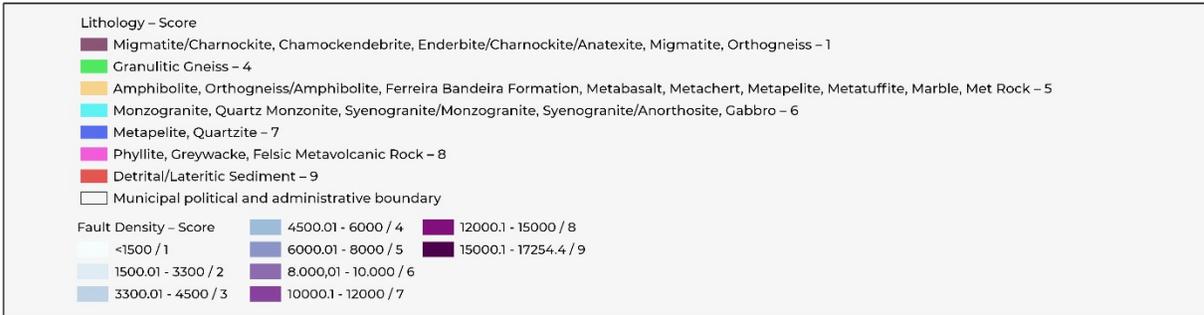
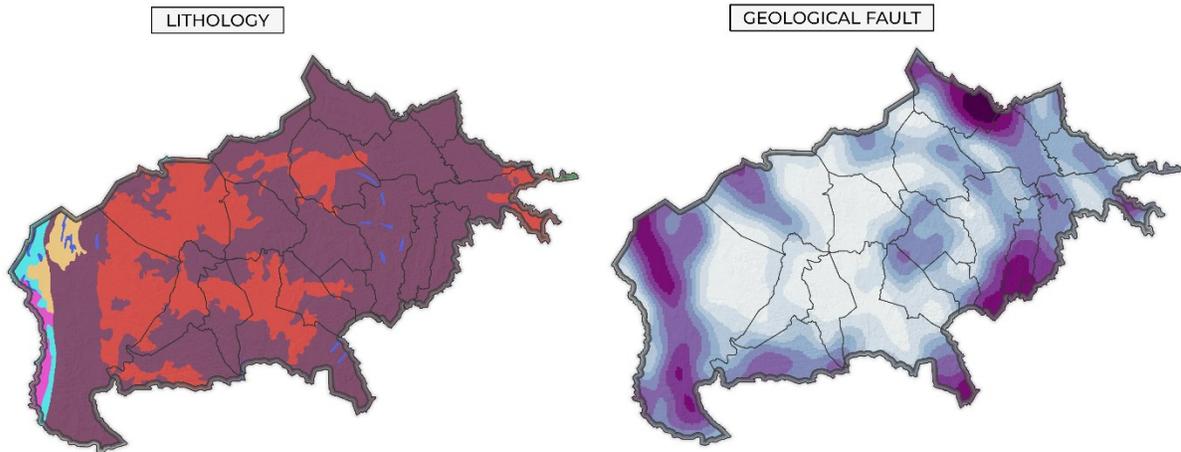
Data extraction was performed using a Digital Elevation Model (DEM) that underwent sink-fill correction and hydrological analyses, including Fill, Flow Direction, and Basin tools, within the ArcGIS Pro environment. The resulting raster was subsequently converted into a vector format, which served as a grid for applying the Zonal Statistics as Table tool to the corrected DEM. This process yielded a table containing various terrain statistics categorized by zone, from which only the "RANGE" field was utilized, as it represents the relief amplitude within each morphological unit (LIMA, 2018).

To represent Horizontal Dissection (HD), we began by calculating the area and perimeter of the interfluve polygons. Following this, we applied the basin length formula proposed by Christofolletti (1970), which divides the perimeter by two to determine the axial length of the interfluves. We then utilized the average basin width formula, also from Christofolletti, where the area is divided by the obtained length, yielding the average dimension of the interfluves. After completing these calculations, we created two additional fields: the first for classifying the interfluve polygons according to established HD criteria, and the second for the combined classification of the VD and HD indices based on the parameters of the Relief Dissection Matrix. This methodology aligns with the third alternative suggested by Guimarães et al. (2017).

2.3 Reclassification and Weighting of Variables for Map Algebra

The variables were reclassified to establish a susceptibility hierarchy for each category, using a scale from 1 to 9, where higher values indicate a greater level of susceptibility. For this study, the scores were assigned by the authors based on specialized literature, including works by Crepani (2001), Bertoni and Lombardi Neto (2008), and Araújo (2021), as well as the researchers' accumulated experience with the other analyzed variables.





1980, was employed to minimize subjectivity in the weight assignment process. The influence of each variable was determined by creating a pairwise comparison matrix, in which the selected attributes were assessed against one another based on their relative significance, as shown in Table 1. These assessments utilized a scale of values ranging from 1 to 9, as proposed by Saaty (1980), and are illustrated in Figure 2. The construction of the matrix and the initial processing were conducted using Microsoft Excel.

Table 1 - AHP Pairwise Comparison Matrix.

	Slope	Land use and cover	Rainfall	Pedology (texture)	Geology	Fracture	Pedology (maturity)	RDI	Hypsometry	Slope aspect
Slope	1	2	2	3	3	4	4	4	5	5
LULC	1/2	1	2	3	3	4	4	4	5	5
Rainfall	1/2	1/2	1	2	2	3	4	4	5	5
Pedology (texture)	1/3	1/3	1/2	1	2	3	4	4	5	5
Geology	1/3	1/3	1/3	1/2	1	3	3	4	5	5
Fracture	1/4	1/4	1/4	1/3	1/3	1	2	3	3	4
Pedology (maturity)	1/4	1/4	1/4	1/4	1/3	1/2	1	2	3	4
RDI	1/4	1/4	1/4	1/4	1/4	1/3	1/2	1	3	4
Hypsometry	1/5	1/5	1/5	1/5	1/5	1/3	1/3	1/3	1	4
Slope aspect	1/5	1/5	1/5	1/5	1/5	1/4	1/4	1/4	1/4	1

Prepared by: author (2024).

1	3	5	7	9
Equally	Moderately	Strongly	Very Strongly	Extremely

Figure 2 - Paired comparison scale.

Source: Adapted from Saaty (1980).

From the comparison matrix, the data were normalized, and relative weights for each variable were calculated. The model demonstrated a Consistency Ratio (CR) of 7.1%, which is deemed acceptable according to Saaty's criteria, as it stipulates that the CR should remain below 10% to ensure logical consistency.

Normalization of the matrix data involved summing the elements in each column of the judgment matrix. Each element was then divided by the total of its respective column, resulting in the normalized matrix. Following this, the average of the values in each row (μ) was calculated for each analyzed criterion. Consequently, the following weights were derived for the variables: 22.7% for Slope, 19.8% for Land Use/Land Cover (LULC), 14.7% for Rainfall, 12.3% for Pedology (Texture), 10.3% for Geology, 6.2% for Geological Fracture, 4.9% for Pedology (Maturity), 4.1% for RDI, 2.9% for Hypsometry, and 2.1% for Slope Aspect.

Following the assignment of scores and relative weights to each variable, a weighted average was calculated to produce the final susceptibility map. The equation used for this calculation is as follows: $Susceptibility = (Slope * 0.227) + (LULC * 0.198) + (Rainfall * 0.147) + (Soil Texture * 0.123) + (Geology * 0.103) + (Fracture * 0.062) + (Soil Maturity * 0.049) + (RDI * 0.041) + (Hypsometry * 0.029) + (Slope Aspect * 0.021)$.

This methodology was employed to create two distinct scenarios for susceptibility to mass movements. The first scenario incorporated eight conditioning variables along with triggering variables associated with land use and cover from 1985, as well as the historical average precipitation for December from 1970 to 2000. In contrast, the second scenario utilized the same conditioning variables but combined them with land use and cover data from 2021 and precipitation records from December of that year.

3. Results and discussion

Mass movements in the study area result from a complex interaction between geological, geomorphological, and climatic factors that directly affect the stability of the soil and slopes. The predominance of plutonic igneous rocks, such as Charnockite and Enderbite, contributes to greater resistance to weathering and erosion in certain areas, promoting slope stability. This resistance is related to their origin and mineral composition, as these rocks are formed from the slow cooling and solidification of magma, resulting in an interconnected crystalline structure, an absence of stratified layers, and a dense

mineral composition. However, the presence of fractures and geological planes of weakness compromises this stability, especially on steeper slopes, significantly increasing the susceptibility to mass movements.

On the other hand, the metamorphic and sedimentary rocks present in the study area tend to exhibit lower resistance to weathering and erosion processes due to their more heterogeneous textures and compositions. Sedimentary rocks, for example, often contain mineral fragments or lithified sediments that can be easily disintegrated when water infiltrates their porous spaces and stratigraphic planes, promoting dissolution and facilitating erosion. Metamorphic rocks, in turn, may be susceptible to disintegration along foliation planes and oriented crystalline structures (CREPANI et al., 2001). Lateritic detrital sediments are also noteworthy, commonly found in the Jiquiriçá Valley, which often develop fragile structures such as crusts and blocks that easily break apart under the action of rain and surface runoff, thereby favoring the triggering of mass movements.

The morphology of the study area also significantly influences susceptibility to mass movements. Altimetric data indicate elevation variations ranging from 100 m to 1,078 m. The distribution of relief in the region shows that 46% of the area is composed of undulating relief, 30% of strongly undulating, 17% of gently undulating, 5% of flat relief, and 2% of mountainous terrain, according to the classification of the Brazilian Agricultural Research Corporation (EMBRAPA, 2006). The central geomorphological units of the area include the Maracás Plateau and the Central Massif (central portion), the Jequié-Mato Rio de Contas Pediplain (western sector), the Paraguaçu Pediplains (north of Maracás and in Milagres), in addition to the Marginal Ranges, Pre-Coastal Massifs, and Interior Plateaus (eastern portion of the Jiquiriçá Valley).

Regarding the Relief Dissection Index (RDI), a predominance of strong and powerful dissection classes is observed, especially on the steepest slopes. The slopes have predominant orientations to the east, northwest, and southwest, which direct surface runoff and accentuate the influence of precipitation, especially in areas with a greater presence of geological fractures. These fractures, in turn, tend to align with the direction of the slopes, contributing to the fragmentation of the rock material and increasing the susceptibility to instability.

The characteristics of the soils also stand out as a relevant conditioning factor. The study area has a significant presence of Latosols and Argisols. Latosols are well-developed and deep soils, marked by more intense pedogenic than morphogenetic processes (CREPANI et al., 2001). They are, in general, well-drained, which reduces the risk of water saturation, and have high density, which can confer greater resistance to erosion (EMBRAPA, 2006). However, Latosols found in the region have a predominantly clayey to very clayey texture, a characteristic that, in events of high rainfall, can increase water retention and, consequently, the risk of instability.

The Argisols, equally significant in the territory, are moderately deep to deep soils with moderate drainage. They have a clayey-textured B horizon underlying A or E horizons with a sandy or medium texture. In the eastern sector of the Jiquiriçá Valley, dystrophic cohesive Argisols are identified, characterized by a dense B horizon (EMBRAPA, 2006). These soils, characterized by medium to clayey textures, can increase susceptibility to mass movements, particularly under saturated conditions.

Vegetation cover, in turn, has undergone significant changes in recent decades, directly impacting soil protection and environmental balance. According to data from MapBiomas (<https://brasil.mapbiomas.org>), in 1985, approximately 40% of the Jiquiriçá Valley's territory was covered by natural vegetation, comprising forest and savanna formations. In 2021, this percentage dropped to 36%, indicating a decline in native vegetation cover. In contrast, there was an increase in the classes of pasture and mosaic of agriculture with pasture, which went from 58% to 62% in the analyzed period. There was also significant growth in non-vegetated areas, with an emphasis on urban expansion, which increased from 9.5 km² in 1985 to 45.4 km² in 2021, and in other non-vegetated anthropogenic areas, which expanded from 25.7 km² to 63.5 km², as presented in Table 2.

Table 2 – Land use and land cover classes in the Jiquiriçá Valley – Ba, in km².

Land Use and Land Cover	1985		2021	
	Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)
Forest Formation	2249.4	21%	1751.6	16%
Savanna Formation	2086.5	19%	2109.9	20%
Forest Plantation	0	0%	39.2	0%
Grassland Formation	61.7	1%	59.9	1%
Pasture	4522.1	42%	4818.6	45%
Mosaic of Agriculture and Pasture	1749.5	16%	1818.6	17%
Urban Area	9.5	0%	45.4	0%
Other Non Vegetated Areas	25.7	0%	63.5	1%
Rivers, Lakes	11.1	0%	21.1	0%
Other Temporary Crops	0.9	0%	1.9	0%
Coffee - Perennial Crop	2.4	0%	3.5	0%

Prepared by: author (2024). Source: MapBiomias (1985, 2021).

In the climatic context, the study area exhibits a significant diversity of rainfall regimes, as classified by the Köppen-Geiger climate classification, with variations ranging from the tropical rainforest climate (Af) to the hot semi-arid climate (BSh) (Alvares et al., 2013). This diversity reflects the geographical heterogeneity of the Jiquiriçá Valley, influenced by factors such as relief, altitude, and proximity to moist air masses from the Atlantic Ocean.

Table 3 presents a comparison between the historical precipitation series (1970–2000) and the data from 2021, revealing significant discrepancies between the two periods. The historical precipitation varied between 4 mm and 200 mm throughout the year, considering different locations within the Jiquiriçá Valley. The months of June (with records ranging from 8 mm to 200 mm, depending on the location) and December (between 85 mm and 144 mm, throughout the study area) stood out as the rainiest in the historical average. In contrast, August had the lowest average precipitation volumes, with variations ranging from 4 mm to 136 mm throughout the region.

Table 3 – Historical series of rainfall distribution (1970 – 2000; 2021) in the Jiquiriçá Valley.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Historical Series of Mean Pluviometric Distribution in the Jiquiriçá Valley 1970 - 2000 (mm)											
71 - 130	63 - 139	58 - 150	35 - 179	12 - 184	8 - 200	6 - 189	4 - 136	10 - 117	32 - 122	66 - 139	85 - 144
Rainfall Distribution in the Jiquiriçá Valley in 2021 (mm)											
45 - 97	56 - 130	14 - 51	45 - 244	3 - 81,2	4 - 110	5 - 236	4 - 129	2,9 - 38	51 - 170	140 - 250	217 - 361

Prepared by: author (2024). Source: WorldClim.

In 2021, the data indicate a significant increase in rainfall volume, particularly in the final months of the year. December recorded a total of 361 mm, a value substantially higher than the historical average for this month. Similarly, November saw precipitation ranging from 217 mm to 361 mm, which is also above the historical records observed in the territory. On the other hand, September was the month with the lowest precipitation in 2021, with only 2.9 mm, a value lower than the regional historical average for the same month, which ranged from 10 mm to 117 mm throughout the Jiquiriçá Valley.

The municipality of Amargosa, one of the most affected by the mass movements that occurred in the region, recorded significant events on December 11, 2021, as reported by G1 Bahia (2021). On that date, the maximum recorded precipitation was 19.8 mm, with an accumulated 94.1 mm in the previous 11 days, 94.16 mm in the following seven days, and 61.26 mm in just four days (Figure 3). According to rainfall thresholds established by Saralori (2003) for Vitória (ES) and Ide (2005) for Campinas (SP), the rainfall behavior observed in Amargosa would classify the city in a state of alert.

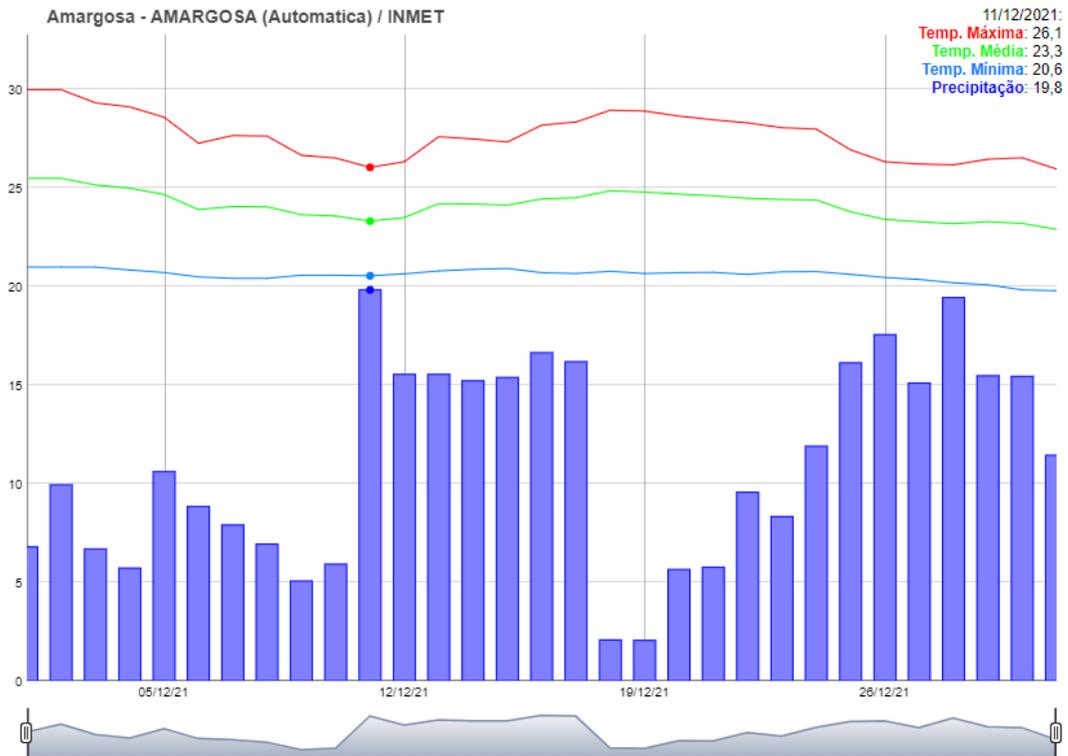


Figure 3 – Precipitation data in Amargosa, December 2021.
 Source: INMET.

In the historical context of average rainfall for December, corresponding to the period from 1970 to 2000, associated with land use and cover data from 1985, Table 4 and Figure 4 present the classes of susceptibility to mass movements in the Jiquiriçá Valley. Approximately 48% of the region's territory was classified as "high" susceptibility, 41% in the "medium" class, 6% in the "very high," and only 5% in the "low." These data reveal a significant predominance of vulnerable areas, with more than 85% of the territory classified as "medium" or "high" in the 20 analyzed municipalities.

Table 4 – Mass movement classes in the Jiquiriçá valley – Ba, with average rainfall corresponding to December 1970 – 2000 and land use and cover of 1985.

Municipality	Mass Movement Susceptibility Classes (December 1970–2000 Historical Average)								
	Area (km²)	Low		Medium		High		Very High	
		Area (km²)	Low (%)	Area (km²)	Medium (%)	Area (km²)	High (%)	Area (km²)	Very High (%)
Maracás	2413	220.6	9%	1361.9	56%	737.9	31%	62	3%
Planaltino	955.2	14.1	1%	269.2	28%	565.1	59%	101.7	11%
Jaguaquara	924.2	30	3%	346.4	37%	463.9	50%	75.2	8%
Ubaira	658.6	10.8	2%	331	50%	294.6	45%	21.2	3%
Brejões	518.3	7.1	1%	158.5	31%	287.7	56%	65	13%
Lafaiete Coutinho	497.9	3.3	1%	129	26%	293.2	59%	65.9	13%
Nova Irarana	475.1	37.5	8%	185.3	39%	221.5	47%	26.2	6%
Irajuba	458.8	17.6	4%	174	38%	248.8	54%	18.5	4%
Laje	449.5	19.6	4%	164.6	37%	233.4	52%	52	5%
Amargosa	431.5	7.1	2%	134.4	31%	281.3	65%	8.5	2%
Milagres	420	54.4	13%	214.5	51%	143.3	34%	2.7	1%
Lajedo do Tabocal	382.8	11.7	3%	140.3	37%	208.9	55%	21.9	6%
Santa Inês	379	6.6	2%	178.3	47%	190.7	50%	3.5	1%
Itaquara	343.9	4	1%	100.8	29%	199.1	58%	39.3	11%
Ibiruçú	322.1	9	3%	118.3	37%	181.3	56%	13.5	4%
Mutuipe	275.7	9.5	3%	90.5	33%	159	58%	12.5	5%
Jiquiriçá	238.5	5	2%	100.9	42%	108.6	46%	23.6	10%
São Miguel das Matas	230.7	9.1	4%	88.4	38%	129.6	56%	0.9	0%
Cravolândia	182.5	2.5	1%	70.9	39%	93.2	51%	15	8%
Elísio Medrado	179.2	5.4	3%	73.6	41%	97.3	54%	0.3	0%
TOTAL	10736.5	484.7	5%	4430.6	41%	5140.1	48%	597.9	6%

Source: author (2024).

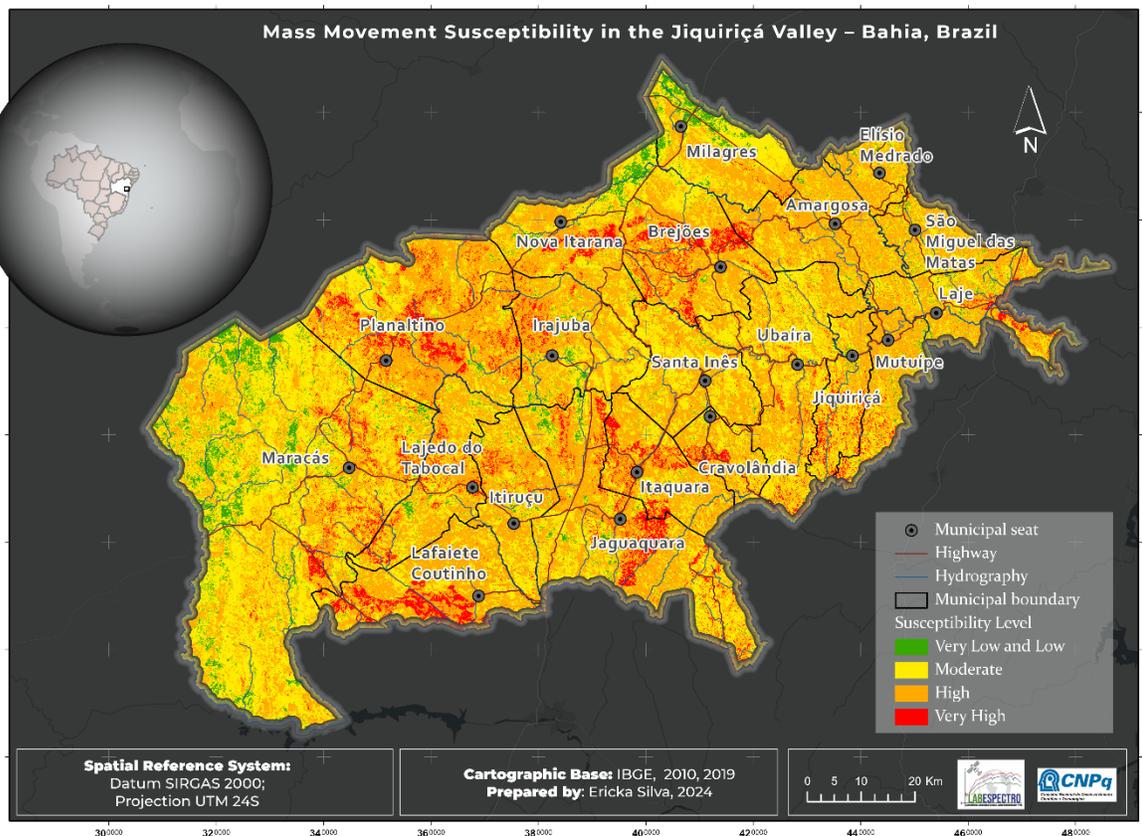


Figure 4 – Map of susceptibility to mass movement in the Jiquiriçá Valley – Ba, with average rainfall corresponding to December 1970–2000 and land use and land cover from 1985.

Source: author (2024).

In the municipalities of Ubaíra, Itaquara, Jiquiriçá, Santa Inês, and Jaguaquara, unregulated urban occupation on unstable slopes and embankments—often conducted without technical supervision—has exacerbated instability processes, particularly leading to planar landslides and accelerated erosion. In Jaguaquara and Jiquiriçá, there have also been reports of rockfalls, especially in regions characterized by rock outcrops and steep inclines (CPRM, 2015; 2018a). Additionally, in Itaquara, Ubaíra, and Santa Inês, the primary risks stem from the occupation of cut areas and unstable slopes, which are further complicated by a lack of drainage and containment infrastructure. In Jaguaquara, this situation is exacerbated by irregular interventions on embankments, which intensify erosive processes and terrain instability (CPRM, 2015, 2017a, 2017b, 2018b). This scenario highlights the urgent need for effective oversight and preventive measures to ensure the safe and sustainable use of these areas.



Figure 5 – Examples of occupations in areas susceptible to mass movements in the Jiquiriçá Valley (BA). Noteworthy are constructions on unstable slopes and embankments in the municipalities of Itaquara and Ubaíra, and the occurrence of rockfalls near residential buildings in Jaguaquara and Jiquiriçá, evidencing the vulnerability of dwellings located in geological risk areas. Source: CPRM (2015; 2017a; 2017b; 2018a).

In examining areas classified as having "very high" susceptibility, it is important to note that this category comprises a smaller percentage of the overall spatial distribution. Nevertheless, municipalities such as Brejões (13%), Lafaiete Coutinho (13%), Itaquara (11%), and Planaltino (11%) have significant portions of their territories within this classification, highlighting sectors at an imminent risk of mass movements.

The "very high" susceptibility class is primarily identified by regions featuring lateritic detrital sediment lithology, situated at elevations above 400 meters (except the municipality of Laje), and characterized by relief that ranges from undulating to significantly mountainous. In these areas, land use is predominantly focused on pasture, and the soils typically possess a clayey to medium-clayey texture, conditions that contribute to instability processes.

This susceptibility is further exacerbated by the high density of geological fractures, particularly in the southern regions of the municipalities of Mutuípe, Jiquiriçá, Ubaíra, Jaguaquara, Lafaiete Coutinho, and the southeastern part of Laje. Similar to the "very high" susceptibility class, the "high" and "medium" susceptibility classes are also prevalent in areas designated for agricultural use, especially in pastures, and in regions characterized by undulating to mountainous terrain. However, they differ from the higher susceptibility class due to the interplay of various environmental and geological factors that influence the level of risk.

In contrast, regions categorized as having "low" susceptibility are predominantly linked to native vegetation cover, such as forests and savanna formations. These areas typically feature flat to gently undulating terrain with a low to moderate degree of relief, which promotes soil stability.

In the most recent analysis, based on the precipitation recorded in December 2021 and the corresponding land use and cover for that period (as shown in Table 5), the findings illustrated in Figure 6 reveal that approximately 52% of the Jiquiriçá Valley exhibits "high" susceptibility. Additionally, 38% falls within the "medium" category, while 6% is classified as "very high," and only 3% is considered "low." These results underscore the prevalence of critical areas, with over 90% of the region falling into the "medium" and "high" susceptibility ranges.

Table 5 – Mass movement classes in the Jiquiriçá Valley – BA, with rainfall and land use and cover from December 2021.

Municipality	Mass Movement Susceptibility Classes (2021)								
	Area (km ²)	Low	Low (%)	Medium	Medium (%)	High	High (%)	Very High	Very High
Maracás	2413	141.9	6%	1269.3	53%	898.7	37%	72.6	3%
Planaltino	955.2	9.8	1%	229.3	24%	594.2	62%	116.8	12%
Jaguaquara	924.2	24.5	3%	302.9	33%	489.7	53%	98.3	11%
Ubaira	658.6	9	1%	307.9	47%	316	48%	24.7	4%
Brejões	518.3	6.6	1%	138.7	27%	304	59%	68.9	13%
Lafaiete Coutinho	497.9	1.9	0%	116.4	23%	307.8	62%	67.3	14%
Nova Itarana	475.1	22	5%	165.4	35%	252.4	53%	30.7	6%
Irajuba	458.8	17.4	4%	162.9	36%	259.4	57%	19.1	4%
Laje	449.5	8.7	2%	123.8	28%	279.4	62%	26.1	6%
Amargosa	431.5	4.7	1%	126.2	29%	289.2	67%	11.2	3%
Milagres	420	30.4	7%	222.2	53%	156	37%	6.2	1%
Lajedo do Tabocal	382.8	6.8	2%	115.4	30%	235	61%	25.5	7%
Santa Inês	379	8.2	2%	189.4	50%	178.1	47%	3.3	1%
Itaquara	343.9	2.3	1%	84.2	24%	212.9	62%	43.8	13%
Itiruçu	322.1	5.8	2%	104	32%	198.3	62%	14	4%
Mutuípe	275.7	5.4	2%	79.9	29%	168	61%	18.1	7%
Jiquiriçá	238.5	3.3	1%	93.7	39%	116.5	49%	24.6	10%
São Miguel das Matas	230.7	5.2	2%	74.1	32%	146.6	64%	2.1	1%
Cravolândia	182.5	1.9	1%	73.2	40%	90.6	50%	15.9	9%
Elisio Medrado	179.2	6	3%	58.7	33%	111.4	62%	0.4	0%
TOTAL	10736.5	322	3%	4037.5	38%	5604.2	52%	689.7	6%

Source: author (2024).

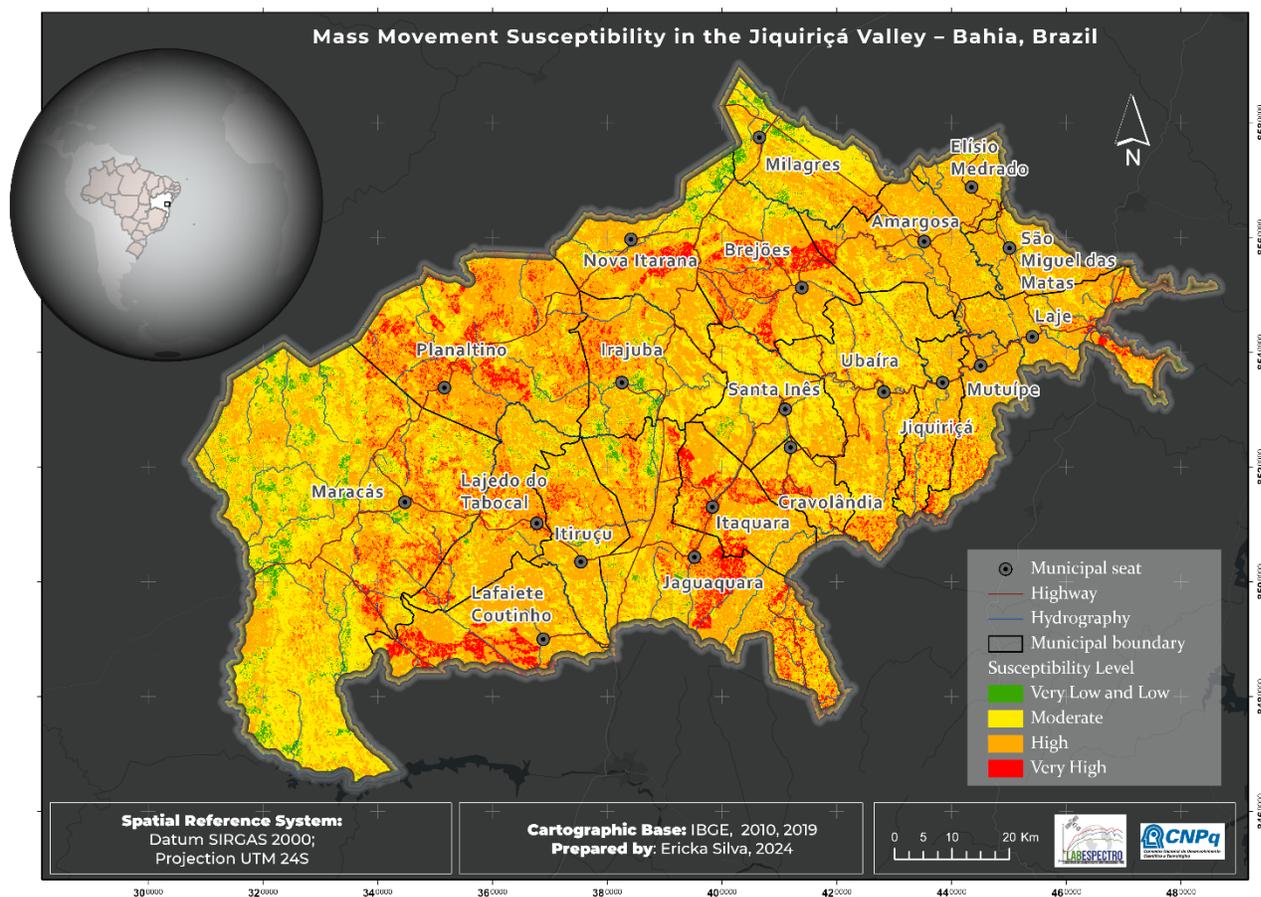


Figure 6 – Mass movement susceptibility map with the variables of rainfall and land use and cover from December 2021. Source: author (2024).

In general, the municipalities within the region have over half of their areas classified as having "high" susceptibility. The exceptions are Maracás (37%), Milagres (37%), Ubaíra (48%), Santa Inês (47%), and Jiquiriçá (49%). While these values are slightly lower, they still represent a significant risk. In contrast, the municipalities of Lafaíete Coutinho, Itaquara, Planaltino, Brejões, and Amargosa have more than 70% of their territories categorized as "high" or "very high" susceptibility, thus highlighting them as priorities for monitoring and mitigation efforts.

In this context, the Geological Survey of Brazil (CPRM), which operates under the Ministry of Mines and Energy, has been engaged in mapping areas classified as having "high" and "very high" geological risk, including mass movements, since 2011. This effort focuses on municipalities identified by the National and State Civil Defenses. The initiative aims to prevent and mitigate social and economic losses associated with natural disasters through a systematic field approach. Notable municipalities assessed in this national effort include Ubaíra, Itaquara, Jaguaquara, and Jiquiriçá, all situated within the Jiquiriçá Valley. Figure 7 illustrates the correlation between the results of the susceptibility model and the areas where mass movements have been documented or anticipated by the CPRM. A strong spatial correlation is evident between the regions classified as "high" and "very high" susceptibility and the CPRM's official records, reinforcing the model's accuracy and validating its effectiveness in identifying critical zones to aid in disaster planning and prevention efforts.

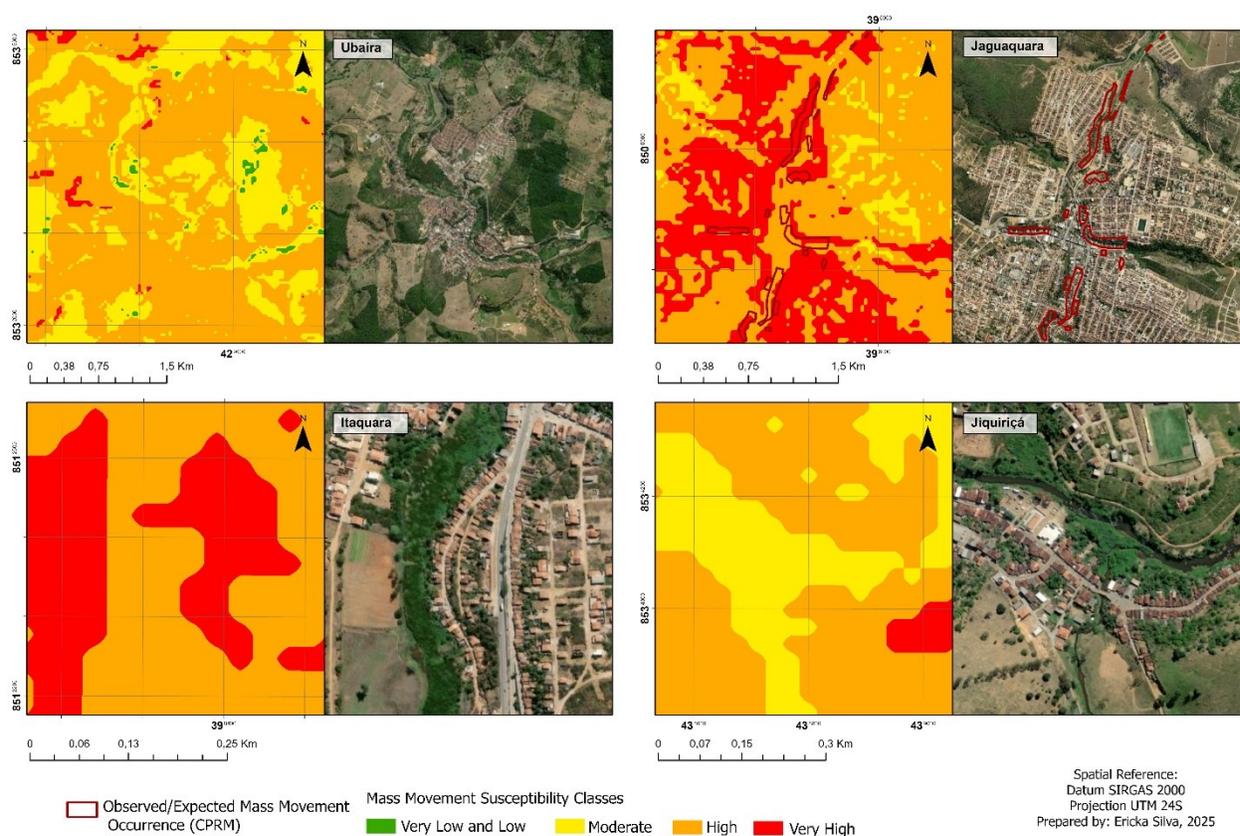


Figure 7 – Comparison between the susceptibility to mass movements (predictive model) and the records mapped by the CPRM in the municipalities of Ubaira, Jaguaquara, Itaquara, and Jiquiriçá (BA). Source: author (2024); CPRM (2015; 2017a; 2017b; 2018a).

A comparison of the scenarios from 1985 and 2021 reveals that twelve municipalities experienced a decrease in areas classified as having "low" susceptibility, while all municipalities reported an increase in areas classified as "high" susceptibility. In eleven municipalities, there was a rise in areas with "very high" susceptibility, whereas in the remaining municipalities, this classification remained stable. Additionally, most municipalities saw a reduction in "medium" susceptibility areas, with the exceptions of Milagres, Santa Inês, and Cravolândia. This indicates a redistribution of risk, characterized by a shift toward higher susceptibility classes. This transformation can be attributed primarily to two factors: (i) a significant increase in precipitation in December 2021 compared to the historical average, and (ii) changes in land use and land cover, particularly the replacement of native vegetation with agricultural and urbanized areas.

3. Final Considerations

The Jiquiriçá Valley features a complex geological and geomorphological configuration, primarily composed of igneous lithologies that exhibit greater resistance to mass movements, alongside lateritic sedimentary formations found in areas marked by "very high" susceptibility. Additionally, the region displays significant hypsometric contrast and a highly dynamic relief.

Latosols, which are widely found throughout the study area, possess a clayey to very clayey texture that promotes water saturation during periods of heavy rainfall. Additionally, numerous municipalities exhibit a high density of geological fractures, many of which are aligned parallel to the slopes, thereby heightening the risk of instability and contributing to the occurrence of gravitational mass movements.

The susceptibility analysis reveals a deterioration of risk conditions over time, as evidenced by a significant increase of 91.8 km² in areas classified with "very high" susceptibility and a corresponding decrease of 165.7 km² in areas classified

as having "low" susceptibility, particularly when comparing the scenarios of 1985 and 2021. These findings demonstrate that the combination of increased rainfall, associated with extreme weather events, along with changes in land use and land cover, plays a significant role in intensifying geotechnical risks.

In light of this scenario, it becomes clear that there is a pressing need for more effective and territorially integrated public policies that focus on the ongoing monitoring of vulnerable areas. Implementing preventive strategies alongside the preservation of native vegetation and the regulation of urban growth is crucial to mitigating the environmental, social, and economic impacts associated with mass movements.

Ultimately, the findings from this study offer valuable technical and scientific support for the development of disaster risk reduction initiatives, thereby contributing to the creation of more resilient communities that adhere to the principles of sustainability and climate change adaptation.

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