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Mapping susceptibility to mass movements in the urban area of Areia-PB.

Mapeamento de suscetibilidade a movimentos de massas na área urbana de Areia-PB

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Abstract: Disasters on Brazilian urban slopes are consequences of a set of geomorphometric weaknesses, intensified by human action. The identification of areas whose natural dynamics favor the instability of the massif is a subsidy for the planning and occupation of urban space. Therefore, the management units need reliable and optimized data for decision making. Faced with the conditions of the municipality of Areia/PB, a municipality located in a mountainous region of the state, this study aimed to map the areas most susceptible to the occurrence of mass movements on slopes through a model based on GIS and AHP (Analytic Hierarchy Process). Eight mappable criteria were considered for the study. After applying the GIS-AHP method, it was observed that the results were compatible with the data collection and previous studies prepared for the city. The criteria of Roads, Geology, Land Use and Coverage and Slope were the most critical in this analysis. In total, 51.9% of the studied area is in the highest susceptibility classes. It was also observed that 91.7% of the mass movement points mapped during the field work were found in the areas of greatest susceptibility.

Keywords: Environmental Disasters; Multicriteria; Geoprocessing.

Resumo: Desastres em encostas urbanas brasileiras são consequências de um conjunto de fragilidades geomorfométricas, potencializados pela ação humana. A identificação de áreas cuja dinâmica natural favorece a instabilização do maciço é um subsídio para o planejamento e ocupação do espaço urbano. Para tanto, as unidades gestoras precisam de dados confiáveis e otimizados para a tomada de decisão. Diante das condições do município de Areia/PB, município situado em uma região serrana do estado, esse estudo objetivou mapear as áreas mais susceptíveis a ocorrência de movimentos de massas em encostas através de um modelo baseado em SIG e AHP (Analytic Hierarchy Process). Foram considerados 8 critérios mapeáveis para o estudo. Após aplicação do método SIG-AHP, observou-se que os resultados foram compatíveis com o levantamento de dados e estudos prévios elaborados para cidade. Os critérios de Estradas, Geologia, Uso e Cobertura do Solo e Declividade foram os mais críticos nesta análise. No total, 51,9 % da área estudada está nas classes mais altas de suscetibilidade. Observou-se ainda que 91,7 % pontos de movimentos de massa mapeados durante os trabalhos de campo encontram-se nas áreas de maior suscetibilidade.

Palavras-chave: Desastres ambientais; Multicritério; Geoprocessamento.

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1. Introduction

Disasters on urban slopes are the result of a set of geomorphometric weaknesses, enhanced by human actions. The increase in the urbanization of cities makes it necessary to identify regions, whose natural dynamics favor the instability of soil masses on the slopes. The identification of potentially unstable areas represents an alternative to the planning and management of urban space, as well as its occupation. According to Kamp *et al*., (2008) the first step in any assessment and management of damage due to mass movements is an inventory map. Next, it is necessary to produce a susceptibility map, with the spatial distribution of the event control parameters, a hazard map, which includes a temporal framework, with the probability of mass movements occurring within a period of time. specified and, finally, the creation of a risk map, which describes the expected cost of damage caused throughout the affected area. For Achour and Purghasemi (2020), preparing a susceptibility map is vital for preventing slope instability processes.

Mass movements are geodynamic processes caused by variables from different categories such as geological, geomorphological, geotechnical factors, climate change and human activities. From a geological point of view, the soil profile and the geotechnical properties of the materials that make up the mass are crucial in influencing slope instability (LIRA *et. al*, 2020). Gerscovich (2016) states that natural slopes are always subject to instability problems, due to the actions of gravitational forces that induce movement, which, in turn, receives contributions from both natural and anthropogenic parameters. It is worth mentioning that each factor can influence more directly than others.

Much of the mapping of slopes in Brazil is carried out using qualitative methodologies, whose analyzes are based on the opinion of experts, through observations obtained in the field and information from residents of the region. Although it can support environmental risk mitigation actions, many researchers on the subject believe that the method approach generates a certain subjectivity regarding the final result obtained. Therefore, it is necessary to improve traditional techniques in order to mitigate this deficiency (BEZERRA *et al*., 2020).

Currently, Geographic Information Systems (GIS) play a fundamental role in mapping susceptibility to mass movements on slopes. Through GIS, multiple geoscientific data, whether spatial or spatial, can be processed and analyzed. In this sense, the use of the GIS environment incorporating decision support routines are mechanisms that can simplify data valuation, reduce inconsistencies and provide elements that allow a more objective indication of the mapped areas (NASCIMENTO, MARQUES E SIMÕES, 2022; BAHRAMI, HASSANI AND MAGHSOUDI; 2021).

Although there are more modern mapping methodologies, the Analytic Hierarchy Process (AHP) has proven to be suitable in susceptibility assessments for areas with a lack of detailed inventory (CHANU, BAKIMCHANDRA; 2022). This method has been successfully used in the literature as a way of explaining and quantifying subjective aspects involved in evaluating slope movements, reducing the subjectivity of the analysis and making studies more systematic (FARIA, 2011; BEZERRA *et al*, 2020).

Given the current situation in the municipality of Areia (PB), with a disorderly occupation history and frequent reports of mass movements, the objective of this study was to map the urban area of the municipality, distinguishing susceptibility classes, based on spatial multi-criteria analyzes in software SIG. The results achieved with this research can support decision-making by the municipal management responsible for urban administration, as they allow for broader action and a more integrated view of aspects of land use and occupation.

2. Methodology

2.1 Characterization of the study área

The study was developed in the urban portion of the municipality of Areia, state of Paraiba, located 122.5 km from the capital João Pessoa. The municipality has 269.13 km² of territorial area and approximately 2.5 km² of urban area. The population of the last census is 22,633 inhabitants and the demographic density is 84.1 inhabitants/km² (IBGE, 2022). The municipality of Areia (PB) is located in Brejo Paraibano, which consists of a region with high topography, strongly undulating relief, under conditions of humid climate and high rainfall, whose urban occupation has extended along slopes and valley bottoms. Figure 1 shows the location of the municipality in the state of Paraiba, as well as the outline of the urban area, where this research was carried out.

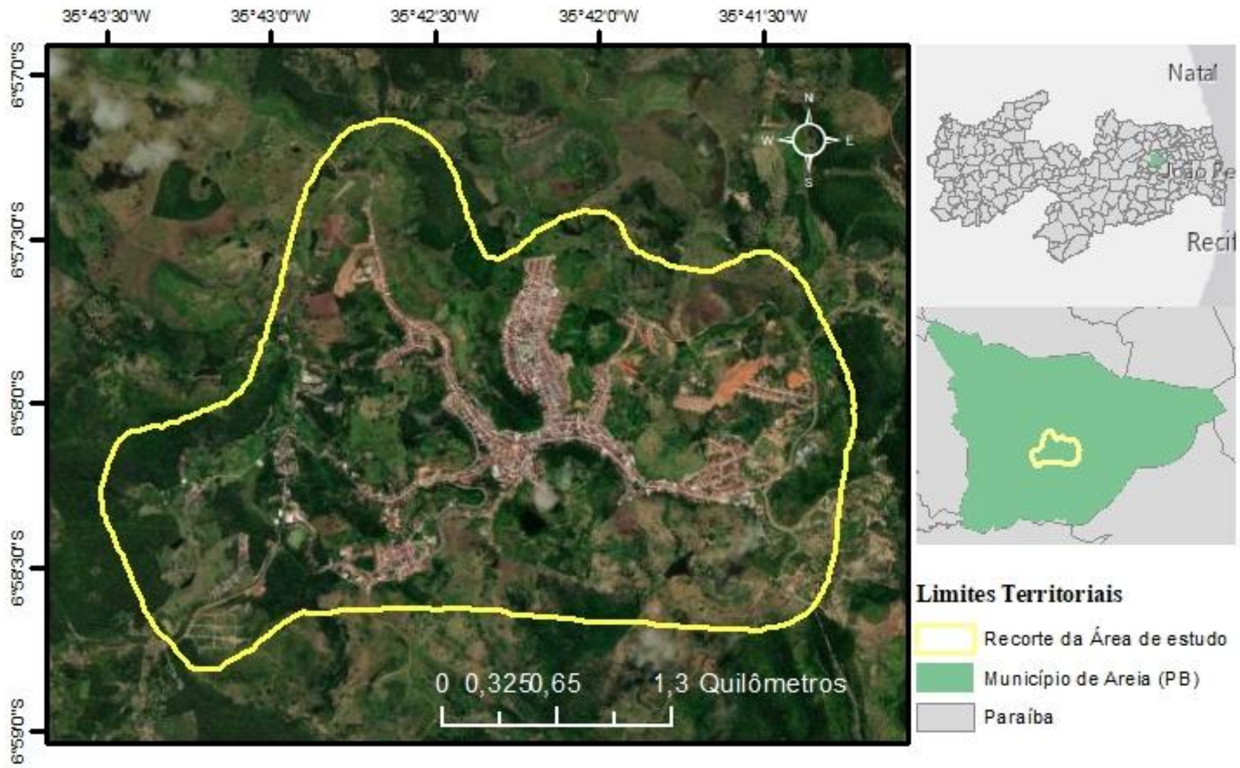

Figure 1 – Location of the study area.
Source: Authors (2023).

Areia (PB) has a history of mass movements, especially in the rainy season, although there is no documentation of these events. Furthermore, the municipality lacks a master plan that maps and delimits areas unsuitable for occupation. In 2015, the Mineral Resources Research Company (CPRM) identified four sectors at high risk of landslides in the urban area of the municipality, through observations of construction conditions, topography and slope of the land, water flow conditions and evidence of geological processes (CPRM, 2015).

Implanted on the steep terrain of the Borborema mountain range, the urbanization model of Areia (PB) does not deviate from the national trend, where most of the time cities grow without planning and managing the use of urban space, contributing considerably to the occupation of geologically fragile areas (COSTA, 2012). Therefore, the most vulnerable areas are those of the demographic explosion (1901-2005), where safe buildings and structurally fragile buildings coexist. Even with the vulnerability triggered by environmental characteristics and land use and occupation, the municipality's Master Plan does not provide short and long-term solutions and mediations for the geomorphological-urban landscape at risk (MARQUES *et al*, 2017).

Sousa (2020) and Lira (2022) collected and studied deformed and undeformed samples from these areas, by carrying out laboratory tests and simple recognition surveys. The materials studied were classified as residual soils, highly weathered, potentially collapsible and highly compressible. When in the presence of water, they showed a reduction in shear resistance mainly due to the total loss of the cohesion portion, when compared to the soils tested in the non-flooded condition, which is indicative of unstable soils.

The municipality under study has a predominance of strongly undulating relief, with the presence of hills, low mountains and mountain escarpments. The existence of flat surfaces generates discontinuities in the municipality's relief, favoring the percolation of fluids, detachment of blocks and plates from cut slopes, weathering and erosion. It has a predominance of clay-siltic-sandy soils, with erosivity varying from moderate to high (CPRM, 2016). Inserted in the geoenvironmental unit of Planalto da Borborema, the municipality has a Tropical Rainy climate, with dry summers. The rainy season begins between the months of January and February and ends in September, and can last until October (CPRM, 2015). In the last year (2022), the rainy period occurred between March and August, with a maximum rainfall of 107.80 mm in March (AESA, 2023).

Pastures predominate, covering more than half of the studied area. Next, the forest-sized vegetation, which represents the presence of dense and humid vegetation, surrounded by the Caatinga vegetation. Construction areas correspond to 15.4% of soil coverage, and represent areas structured by buildings and the road system. Agricultural crops, exposed soil and shrub vegetation are not very representative in the studied area, totaling 5.4% of coverage (ANDRADE, MACHADO, 2018).

The geology of the municipality's urban area is made up of the Serra dos Martins Formation, the Itaporanga Intrusive Suite and the São Caetano Complex, with the latter predominating. The São Caetano Complex has a metasedimentary and metavolcaniclastic sequence. According to Santos (1995), metasedimentary rocks are metamorphic rocks that originate from a sedimentary rock, while metavolconoclastic rocks are metamorphic rocks that originate from volcanic rock composed of fragments or clasts of pre-existing minerals and rocks. The Serra dos Martins Formation is interpreted as being deposited in a fluvial environment, where at the top of the formation there is a red to purple lateritic crust, with angular, poorly sorted quartz pebbles. The Itaporanga Intrusive Suite comprises monzogranites to coarse porphyritic syenogranites, containing Mg-hornblende and micas with Mg-biotite composition (GALINDO *et al*., 2006).

Regarding the municipality's pedology, there is a predominance of the class of Eutrophic Red Argisols, soils with a high content of iron oxides and high fertility (CPRM, 2015; EMBRAPA, 2021).

2.2 Application of the AHP methodology – Structuring

The application of GIS-based AHP has been successfully used in the literature as a way of explaining and quantifying subjective aspects involved in slope assessments, reducing subjectivity and making studies more systematic. The flexibility of the qualitative approach and the consistency of the quantitative approach have emerged as an effective alternative for determining areas prone to extreme events (FARIA, 2011).

In general, three steps guide problem solving using AHP: problem decomposition, comparative judgments and synthesis of priorities. The decomposition stage consists of structuring the problem into hierarchical levels, “from the most general to the most particular and concrete” (SAATY, 1987). In this way, 8 possible conditioning factors were selected for analysis, as well as their respective classes were determined. Figure 2 illustrates the structuring of the problem.

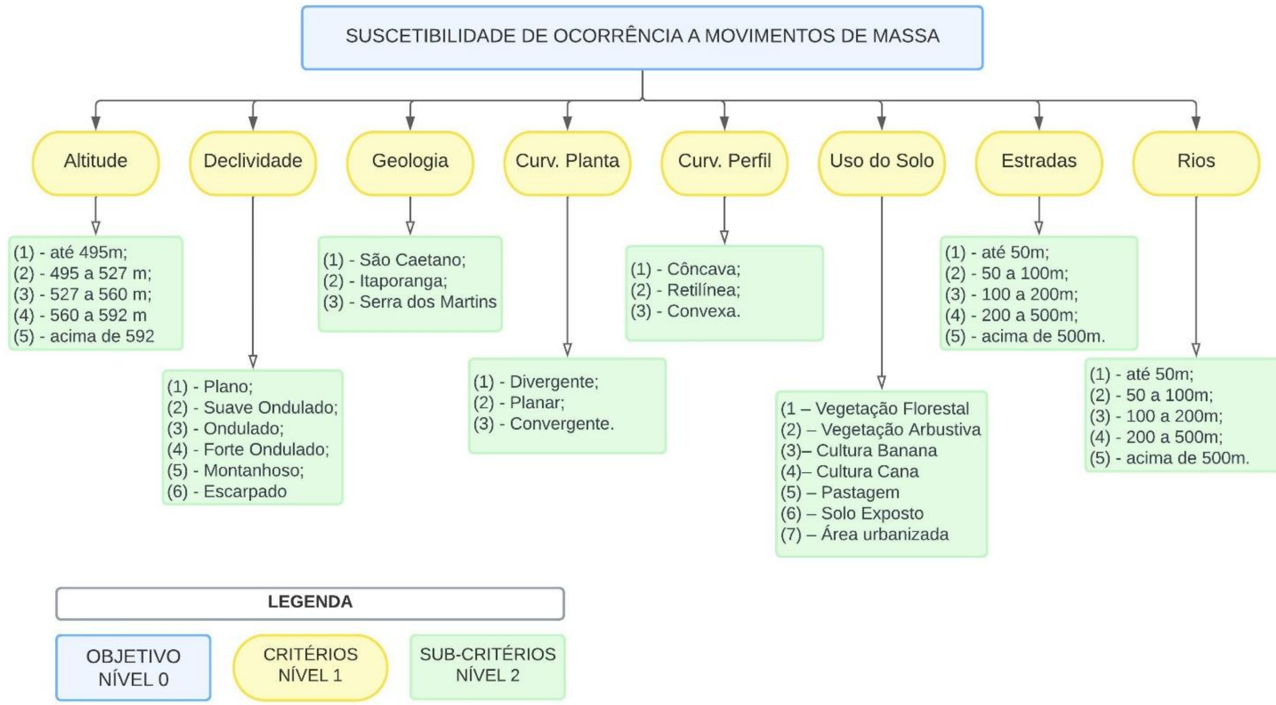

Figure 2 – Hierarchical structure for applying the AHP method in the municipality of Areia (PB).
Source: Authors (2023).

Altitude: Influences several biophysical parameters and anthropogenic activities which, in turn, can generate slope failures and affect their stability (PRADHAN, KIM, 2016). The altitude map was prepared using the Copernicus DEM (Digital Elevation Model), Digital Elevation Model (DEM) of the European Copernicus Program. The criterion was grouped into 5 classes of equal intervals.

Slope: Mass movement is more common when slopes are steeper than the natural angle of repose of the substrate and when there is not enough cohesion to inhibit slope failure (KAMP *et al*., 2008). The slope map was derived from the Copernicus DEM (ESA, 2022). The criterion was reclassified into 6 classes, according to the Embrapa classification (1979).

Morphology: The shape of the terrain characterizes the surface in concave-convex-flat shapes and their variations. It acts as a parameter of surface flow concentration or dispersion and has a strong influence on slope stability in steep terrain (PRADHAN; KIM, 2016). The terrain curvature variables were divided into plan morphology (horizontal curvature) and profile (vertical curvature), the elaboration of which was derived from the Copernicus DEM. The horizontal curvature was reclassified into convergent, planar and divergent, while the vertical curvature was classified as concave, straight and convex.

Geology: Variations in lithological units condition the occurrences of mass movement, as they have different degrees of susceptibilities. Many researchers in the area used lithology as an input parameter to evaluate the susceptibility of movements (MEZUGHI *et al*., 2012). The geological map was prepared based on the interpretation of the lithostratigraphy map, made available by CPRM (2015), containing 3 lithological units: São Caetano Complex (NP1sca), Serra dos Martins Formation (Ensm) and Itaporanga intrusive suite (NP3□2it25).

Soil use and cover: The effect of soil cover on the potential for mass movement involves aspects of mechanical stabilization due to the presence of roots, depletion of soil moisture through transpiration, overload of the weight of trees and windbreaks (ZHANG *et al*., 2016). Product III of the Integrated Geoenvironmental Diagnosis Project of the Municipality of Areia, Paraiba, was used, whose objective is Characterization of Land Use and Coverage in the municipality.

Distance to road: Human activities such as building construction, excavations, tunneling and road construction have negative impacts on slope stability due to the slope shear effect, resulting in increased shear stress level in the embankment

(FAN *et al*, 2017). Considering the regions close to roads as more critical, the distance map for roads was prepared using the Street Face Base, from the IBGE database as a reference (IBGE, 2021). Some manual adjustments were necessary, using "Google Earth pro" for modeling.

Distance to drainage: The existence of bodies of water close to slopes can negatively affect stability, due to the erosion process and the presence of moisture in the materials that make it up (ABAY; BARBIERI; WOLDEAREGAY, 2019). The distance map for drainage was based on the Brazilian Main Drainage product, from the AESA database (2020).

All maps were grouped into a database in raster format, converted to the same scale and spatial resolution and served as the basis for the multi-criteria spatial analysis of this research. Figure 3 shows the generated maps.

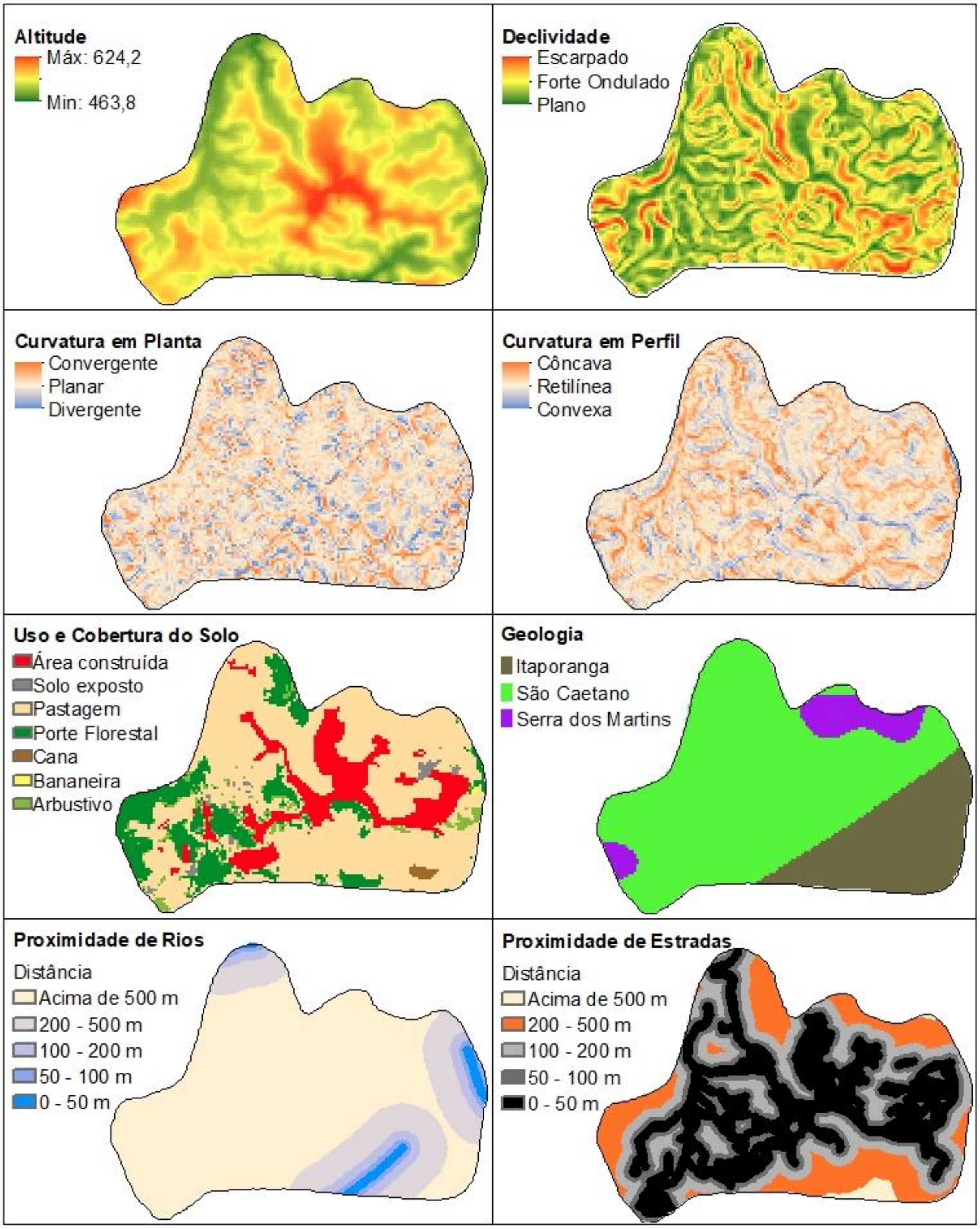

Figure 3 – Thematic maps.
Source: Authors (2023).

2.3 Field research

As there is no official data regarding the occurrences of mass movements, this information was collected through field research, with the support of the Environment Secretariat of the Municipality of Areia (PB), which provided resources for visits to the sites critical, based on complaints and denunciations from the population itself. The main objectives of this research were to map these points of instability and understand whether the selected factors were representative for that region.

The longitudinal and latitudinal coordinates of the event locations were obtained using a GPS and subsequently taken to “Google Earth Pro”, through the “Add marker” function, to facilitate the identification of points. The areas that were inaccessible for obtaining coordinates were acquired through observation and manual work using the aforementioned software.

The field research also provided support for the preparation of the AHP matrix, regarding the valuation of the previously mentioned instability criteria. In this way, the points of occurrence of mass movements were analyzed, relating them to the topographic, geological and anthropogenic conditions in the respective areas, with the aim of identifying the factors that most influence disasters.

2.4 Application of the AHP methodology - Judgments

Once the structure of the problem has been defined, comparative judgments are made, which were carried out by the author of the work in consensus with 3 other experts in the area, based on the experience of other studies of mass movements and knowledge of the municipality under study. The comparisons used the Saaty scale (1990), where values from 1 to 9 are used in paired comparisons of the indicators, with 1 meaning the same degree of importance of one criterion in relation to the other, and 9 meaning the extreme importance of a criterion. about another. It is called the Saaty Fundamental Scale, and is shown in Table 1.

Table 1 – Importance judgment scale in the AHP Method.

Valores numéricos	Termos verbais	Explicação
1	Igual importância	Duas alternativas contribuem igualmente para o objetivo
3	Moderadamente mais importante	Experiência e julgamento favorecem levemente uma alternativa em relação a outra
5	Fortemente mais importante	Experiência e julgamento favorecem fortemente uma alternativa em relação a outra
7	Muito fortemente mais importante	Alternativa fortemente favorecida em relação a outra e sua dominância é demonstrada na prática
9	Extremamente mais importante	A evidência favorece uma alternativa em relação a outra, com grau de certeza mais elevado
2,4,6,8	Valores importantes intermediários	Quando se procura uma condição intermediária entre duas definições

Fonte: Adapted from Saaty (1990).

In this way, a paired comparison matrix was created, answering the question: “when we consider two elements, i on the left side of the matrix and j at the top, which among them satisfies the criterion more, that is, which is considered more important under this criterion, and, with what intensity?”. Table 2 presents the results of the parity judgments.

Table 2 – Paired Comparison Matrix.

	USO SOLO	DECLIVIDADE	ESTRADAS	GEOLOGIA	CURV PERFIL	CURV PLANTA	DRENAGEM	ALTITUDE
USO SOLO	1,00	2,00	2,00	3,00	3,00	4,00	5,00	7,00
DECLIVIDADE	0,50	1,00	2,00	3,00	3,00	3,00	4,00	7,00
ESTRADAS	0,50	0,50	1,00	3,00	4,00	4,00	4,00	5,00
GEOLOGIA	0,33	0,33	0,33	1,00	3,00	3,00	3,00	5,00
CURV PERFIL	0,33	0,33	0,25	0,33	1,00	3,00	3,00	5,00
CURV PLANTA	0,25	0,33	0,25	0,33	0,33	1,00	3,00	3,00
DRENAGEM	0,20	0,25	0,25	0,33	0,33	0,33	1,00	3,00
ALTITUDE	0,14	0,20	0,20	0,20	0,20	0,33	0,33	1,00

Source: Authors (2023).

The weights for the indicator classes were determined using the methodology used by Meirelles *et al* (2017), where the matrix data were reclassified on a scale that varies from 1 to 5 (1: very low, 2: low, 3: medium, 4: high and 5: very high), in ascending order of importance and influence. These notes represent the values in each class of information plans and were defined based on analyzes of mass movement locations.

After the pairwise comparison, the priority synthesis step is performed, the objective of which is to determine a set of relative weights, which is the normalized eigenvector of the matrix elements. Although different methods have been used to derive priorities, the eigenvalue technique is used to calculate weights, which is one of the most common:

- Add the values in each column of the reciprocal matrix;
- Divide each element in the matrix by its column total (the resulting matrix is called the normalized pair comparison matrix and the sum of each column is 1);
- Calculate the average of the elements in each row of the normalized matrix, that is, divide the sum of the normalized scores for each row by the number of criteria. These averages provide an estimate of the relative weights of the criteria being compared.

In this way, after the judgments made, the normalization matrix is obtained and, subsequently, the eigenvector, which represents the importance of the criteria. The result is presented in Table 3.

Table 3 – Normalized Matrix and corresponding eigenvector.

	USO SOLO	DECLIVIDADE	ESTRADAS	GEOLOGIA	CURV PERFIL	CURV PLANTA	DRENAGEM	ALTITUDE	AUTOVETOR
USO SOLO	0,307	0,404	0,318	0,268	0,202	0,214	0,214	0,194	**0,265**
DECLIVIDADE	0,153	0,202	0,318	0,268	0,202	0,161	0,171	0,194	**0,209**
ESTRADAS	0,153	0,101	0,159	0,268	0,269	0,214	0,171	0,139	**0,184**
GEOLOGIA	0,102	0,067	0,053	0,089	0,202	0,161	0,129	0,139	**0,118**
CURV PERFIL	0,102	0,067	0,040	0,030	0,067	0,161	0,129	0,139	**0,092**
CURV PLANTA	0,077	0,067	0,040	0,030	0,022	0,054	0,129	0,083	**0,063**
DRENAGEM	0,061	0,051	0,040	0,030	0,022	0,018	0,043	0,083	**0,043**
ALTITUDE	0,044	0,040	0,032	0,018	0,013	0,018	0,014	0,028	**0,026**

Source: Authors (2023).

Finally, to analyze the integrity, quality and coherence of the judgments, sensitivity analysis is performed. Saaty proposed the following procedure:

a) Calculation of the maximum eigenvalue (λ max), whose result must be equal to or very close to the number of rows (or columns) of the pairwise comparison matrix n for the comparison matrix to be considered consistent.

$$\lambda\, máx = \sum t \times w$$

where T is the normalized eigenvector and w corresponds to the sum of the columns of the comparison matrix for each criterion.

b) Calculation of the Consistency Index (CI), which indicates how much the calculated eigenvalue differs from the expected theoretical value

c)

$$IC = \frac{\lambda\ máx - n}{n - 1}$$

d) Calculation of the Consistency Ratio (RC), whose result must not exceed the range of 0.1, for matrices larger than 5x5.

$$RC = \frac{IC}{CA}$$

where, the CA value (Random Consistency Index) is taken from Table 4:

Table 4 – Random Consistency Index.

N	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (CA)	00	00	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49

Fonte: Saaty (1980).

2.5 Map algebra

This step consists of overlaying the criteria maps, considering their respective importance, given by the AHP method. The spatial value of each cell in the mapped area was calculated by multiplying the weights of the criteria by the weights of the respective sub-criteria. In this way, the Susceptibility Index was obtained, as shown in the equation:

$$IS = \sum p_n \times x_n$$

Where, IS = Susceptibility Index; pn = weight of criterion n; xn = sub-criterion score, corresponding to criterion n.

Finally, the map was reclassified into five susceptibility classes, from very low to very high susceptibility.

3. Results and Discussions

3.1 Geoenvironmental analysis of the municipality

The municipality of Areia (PB) is located at the beginning of the Borborema Plateau, a region typically with high altitudes. The buildings in the urban center are located in the highest regions, around 568 m, extending into the surrounding abyss, where natural shrub formations predominate. The city had strongly undulating terrain across approximately 42% of its entire length, with some areas showing mountainous relief. Close to the urban center, there are the slopes of the resort "O Quebra" with slopes reaching around 70% incline.

In the higher altitude areas of the municipality, the rectilinear-convex profile predominates, where surface runoff diverges. The lowest areas have a concave curvature, increasing the accumulation of moisture down the slope. Just as the divergent areas were observed, for the most part, on the slopes of the plateaus, the convergent areas are seen in the depressed areas.

Even with the urban area in evidence, pasture areas predominate, composed of low and medium-sized shrubs. Forest vegetation, consisting of a portion of humid and dense vegetation, is also representative. It is worth mentioning that the removal of plant protection can favor mass movement, initiating erosion processes. The same happens with the construction of roads, where the removal of base material from slopes is harmful, both in upstream and downstream areas. On the other hand, little influence of hydrological factors, such as rivers and streams, was found.

The lithological unit NP1sca (São Caetano Complex) is predominant in the area, comprising a metasedimentary and metavolconoclastic sequence. Lithological variations are a fundamental condition for susceptibility studies, as they cause a difference in the resistance and permeability of rocks and soil. However, if used as isolated geological data, it is insufficient for an assessment with this bias.

3.2 Fieldwork – Inventory

From the field research, it was verified the great geomorphological fragility of the municipality's landscape, consisting of very steep terrain, high altitudes and a large portion of exposed soil. It was observed the existence of very precarious buildings, without sanitation, located along the slopes, improvised retaining walls, with signs of deterioration, containment solutions that do not meet technical specifications, in addition to the lack of awareness among the population itself, which, certainly, because they are not aware of the conditions of mass movements, they promote inadequate measures, acting and intensifying, above all, the processes of soil erosion. Part of these problems are the result of the lack of a master plan, which provides guidelines to the population, delimiting areas unsuitable for occupation.

Through field research, 24 points of instability were identified within the urban area, as well as the presence of instability features. Figure 4 shows the location of these points.

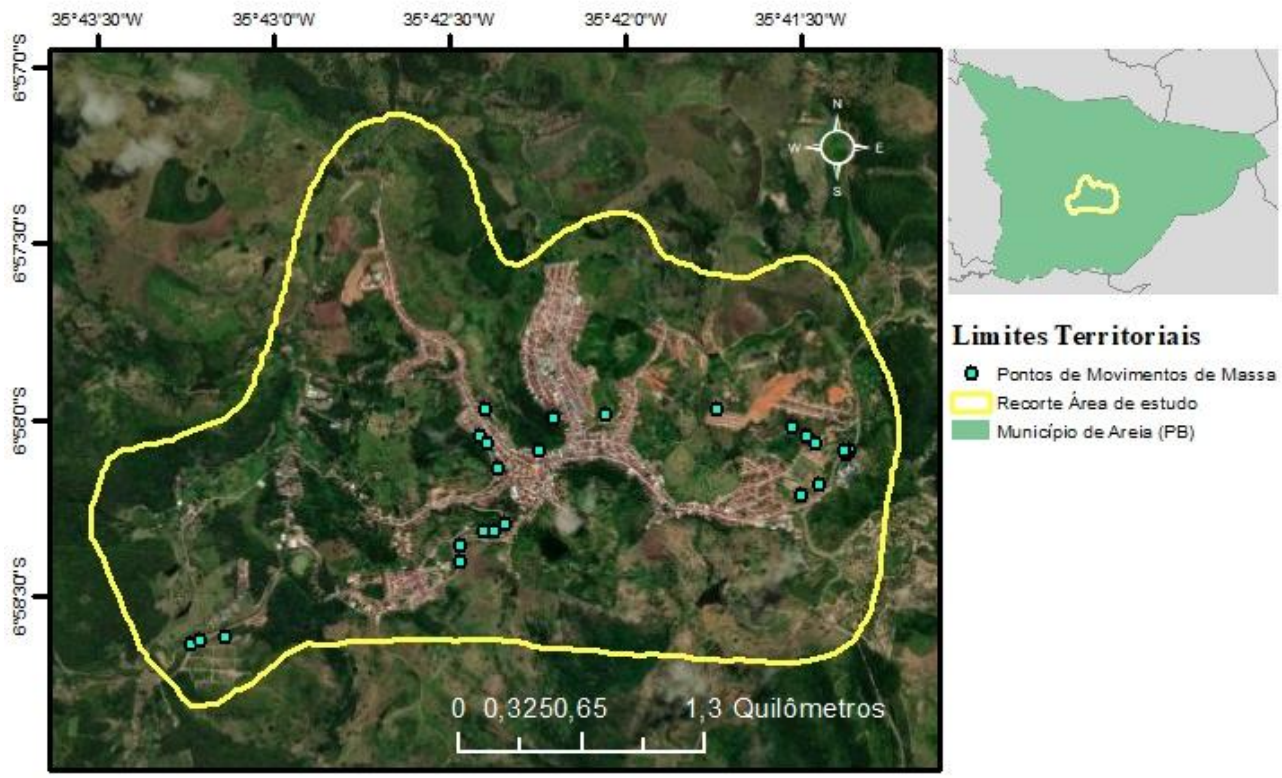

Figure 4 – Mapped mass movement points.
Source: Authors (2023).

Making a correlation between the control parameters and the distribution of events, it was noted that the greatest influence was the criteria of Roads, Geology, Coverage and Slope.

3.3 AHP Decision Matrix

After comparative judgments, followed by matrix normalization operations, the relative weights for each criterion were obtained. As well as for the sub-criteria, where scores were assigned, based on the assessment of the conditions of the instability sites, surveyed in the field research. The result is presented in Table 3.

Table 4 – Results of criteria and sub-criteria judgments.

INDICATORS	WEIGHTS (%)	CLASSES	GRADES
Land use and cover	26,5	1 – Forest Vegetation	1
		2 – Shrub Vegetation	2
		3 – Banana Culture	1
		4 – Cane Culture	1
		5 – Pasture	5
		6 – Exposed Soil	1
		7 – Urbanized area	4
Slope	20,9	1 – Plan (0 - 3%)	1
		2 – Smooth Wavy (3 - 8%)	2
		3 – Wavy (8 - 20%)	3
		4 – Strongly wavy (20 - 45%)	5
		5 – Mountainous (45 - 75%)	3
		6 – Scarp (> 75%)	1
Distance to road	18,4	1 – 0 - 30m	5
		2 – 30 - 60m	4
		3 – 60 - 120m	1
		4 – 120 - 240m	1
		5 – > 240m	1
Geology	11,8	1 – São Caetano	5
		2 – Itaporanga	3
		3 – Serra dos Martins	1
Profile Curvature	9,2	1 – Convex	3
		2 – Flat	2
		3 – Concave	5
Plan Curvature	6,3	1 – Divergent	5
		2 – Plan	2
		3 – Convergent	3
Distance to stream	4,3	1 – 0 - 30m	1
		2 – 30 - 60m	1
		3 – 60 - 120m	1
		4 – 120 - 240m	4
		5 – > 240m	5
Elevation	2,6	1 – 463 – 495 m	1
		2 – 495 – 527 m	2
		3 – 527 – 560 m	5
		4 – 560 – 592 m	4
		5 – > 592m	3

Source: Authors (2023).

The result corroborates the analysis by Zang *et al*. (2016), whose “Land use” criterion was the most representative, in a comparative analysis with 7 other criteria. His research highlighted the importance of soil cover in slope failures, given that the occurrence of landslides was greater in settlement zones than in dense forest areas. It is worth highlighting the similarity of land occupation in the author's study area with Areia (PB), where population growth resulted in the construction of settlements and public services in hillside areas.

Performing the same analysis for the "Slope" criterion, Kristanto *et al*. (2020) also identified that areas with a high potential for mass movements are mostly controlled by this criterion, admitting that slopes with a considerably steep angle of inclination are at greater risk of movement occurring.

Mezughi *et al*. (2012) states that "Roads" are considered one of the most important factors in controlling slope stability. The author observed that many areas of movement occurred close to highway construction works, due to the extraction of material in the lower portion of the slopes, removing the support of the soil mass.

The geological factor generally appears as an important factor in influencing movements (SAADATKHAH, KASSIM and LEE, 2014; PARK *et al*., 2012), especially geological units composed of weathered soil layers. Although most landslides occur in just one geological unit, Complexo São Caetano, it is observed that this is a unit that covers almost the entire area, with no comparison parameter.

As in the analysis by Bezerra (2019), it is possible to see that the results of the weights of the slope morphology indicators, in plan and in profile, presented very similar performance in favoring the occurrence of mass movements, in addition to representing little influence on the mass movements. In general, the curvature of the relief is best interpreted when associated with hydrological conditions, since surface runoff follows the geometry of the slope.

Fan *et al*. (2017) showed that most of the instability points in their study area occurred close to streams, as they caused saturation of the material at the base of the slope. On the other hand, the hydrological parameter in Areia (PB) was not very representative, as few points were observed close to the rivers.

The "Amplitude" criterion, analogous to the analysis by Abay *et al*. (2019), was shown to be less prevalent in slope failures, compared to 6 other criteria. This result occurred especially because the variation in altitude may be related to the occurrence of different environmental dynamics, such as types of vegetation and precipitation.

The sensitivity analysis shows the coherence regarding the judgments made by the experts. Table 5 presents the result of this analysis for the reciprocal matrix.

Table 5 – Sensitivity analysis.

Matrix Order	8
Maximum eigenvalue (λ máx)	8,858
Random Consistency Index (CA)	1,4
Consistency Index (IC)	0,123
Consistency Ratio (RC)	8,8 %

Source: Authors (2023).

The Consistency Ratio (CR) result was less than 10% (8.8%) as recommended by the AHP methodology proposed by Saaty, representing an acceptable level of consistency in the comparisons made. Another indication of coherence in the judgments made by experts is the approximation of the value of the maximum eigenvalue (λ max) to the order of the comparison matrix.

3.4 Susceptibility map to mass movements in the urban area of Areia-PB

After assigning the scores and weights for each information plane, map algebra was performed, where the thematic maps were superimposed, multiplying the respective weights of each criterion. With the generation of the final susceptibility map, a reclassification was carried out, where the resulting matrix data was divided into five intervals, varying the degree of susceptibility from low to very high. Figure 5 presents the result of the superimposition.

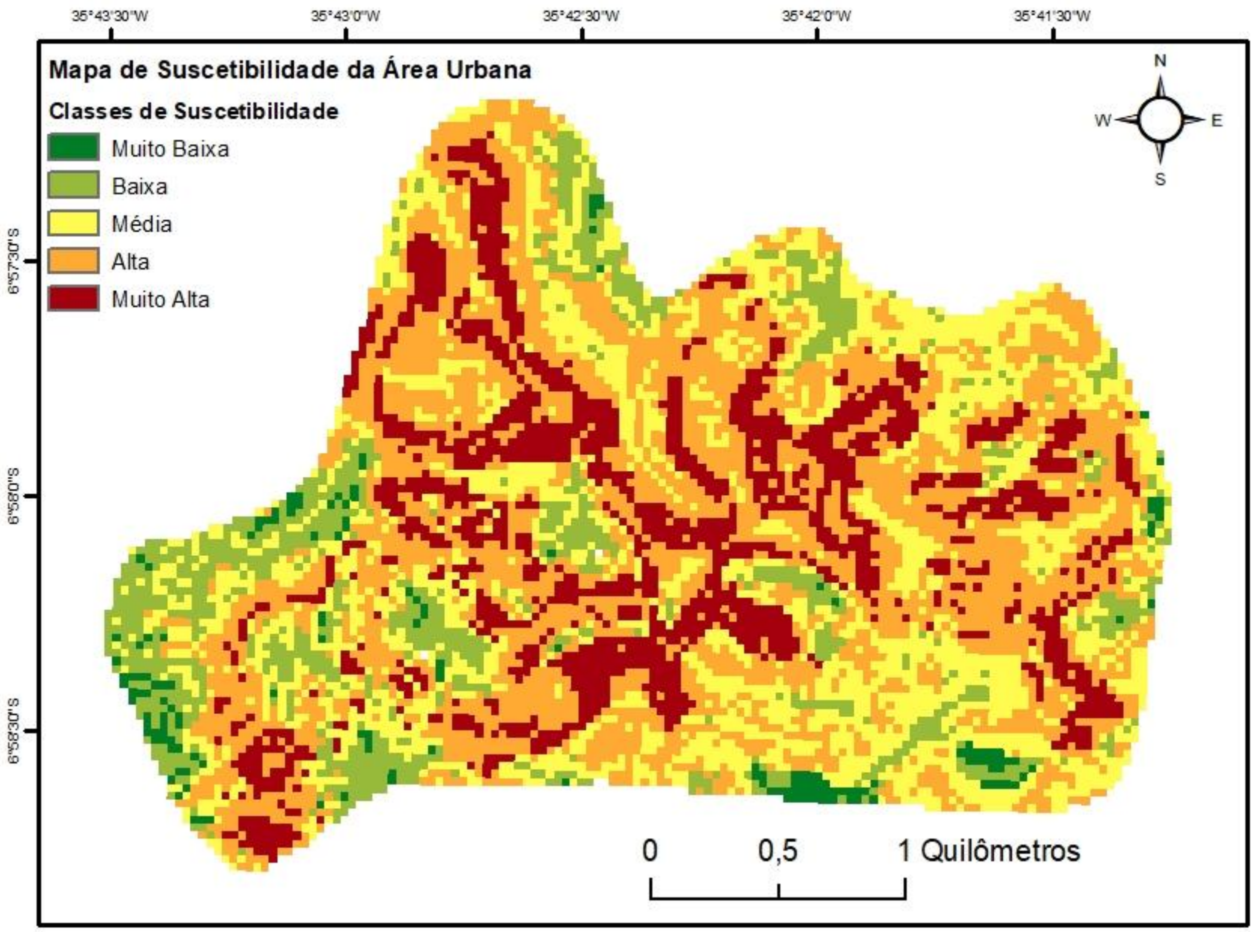

Figure 5 – Mass movement susceptibility map.
Source: Authors (2023).

3.5 Validation of results

Relating the degrees of susceptibility with the location of the points of occurrence of mass movements in the final susceptibility map, it is noted that the majority of these events are located in the "Very high" class (58.3%), where, together with the "High" class, they reach approximately 91% of the total. These results are presented in Table 6.

Table 6 – Occurrences of mass movements by susceptibility classes.

Degrees of Susceptibility	Area (%)	Mapped occurrences	%
Very low	2,1	0	-
Low	12,8	0	-
Moderate	27,6	2	8,3 %
High	38,3	8	33,4%
Very High	19,2	14	58,3%
TOTAL	**100 %**	**24**	**100 %**

Source: Authors (2023).

Carrying out a comparative analysis of the susceptibility map of the urban area of the municipality of Areia (PB) with the risk areas identified by CPRM (2015), it can be seen that the four areas described by the company are included in the

"High" and "High" and "High" areas. Very High" susceptibility, presenting potential for instabilities, which adds reliability to the map presented.

4. Final considerations

This research mapped the susceptibility to mass movements in the municipality of Areia (PB), through a multi-criteria analysis carried out in GIS software. The susceptibility map prepared shows the critical points of the municipality according to the control parameters chosen and verified on site. This type of integrated approach plays a crucial role in the urban management of municipalities and can act as a subsidy for planning the prevention and recovery of the area affected by mass movements.

The application of multi-criteria analysis through AHP in the study of susceptibility to mass movements enabled satisfactory results, generating a map consistent with what was observed in field research, as well as in work carried out in the municipality and in the various bibliographies used. Despite the low availability of accurate information and official databases, this study can support the necessary decisions to direct correct urban management, prioritizing interventions in order to reduce the risk and avoid disruptions caused by episodes of mass movements.

It is worth highlighting the careful and personalized analysis for each area of study in conjunction with the study of the inventory. Mass movements are influenced by several, often conflicting, factors, which vary significantly from place to place. Thus, the appropriate selection and evaluation of conditioning factors for use in AHP is essential for this topic, since each study area has particularities, given the variation in the locations of occurrences. It is important to understand, in addition to the factors that are part of the instability process, the degree of influence of each one.

Even if the effectiveness of the results achieved is confirmed, it is important to highlight the need for new studies, as well as the use of more modern methodologies that can quantify with greater accuracy the potential of soil instability processes. With this, the importance of public authorities in improving the inventory database stands out, encouraging the participation of the population, to assist in a better understanding of the control parameters of occurrences, generating more reliable results and capable of providing better predictions about the spatial distributions of mass movement occurrences in the study area.

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