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MAPPING OF SUSCEPTIBILITY TO NATURAL DISASTERS THROUGH THE USE OF FUZZY LOGIC IN THE MUNICIPALITY OF ALEGRE-ES

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ABSTRACT

Among the various problems that Brazil currently faces, few have a social and human impact as significant as those related to natural phenomena and their negative consequences for society, especially geotechnical events and floods. In a country like Brazil, which suffers from a lack of urban planning and adequate investments in infrastructure to prevent this type of occurrence in various spheres, recurring tragedies accumulate year after year, always accompanied by the perception that they could have been avoided. On the other hand, the geosciences have been increasingly open to new geotechnologies. In this context, the present work presented new paths that offer useful resources to seek short to medium-term solutions, helping to overcome the various challenges related to this theme, both at the national, regional and municipal levels. Thus, the methodology related to geotechnologies and its various techniques was used, with emphasis on Fuzzy Logic, which was the main pillar of this study. In the end, the methodology adopted proved to be effective in pointing out the areas of greatest susceptibility to geotechnical problems and flooding, revealing great potential for future applications of greater complexity and scope.

Keywords: Geotechnology. Geotechnics. Flooding. Fuzzy Logic.

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INTRODUCTION

The municipality of Alegre faces recurrent natural disasters of various forms and magnitudes, including earth movements and floods, which are treated as a priority in this work. In February 2022, for example, local and regional newspapers reported that the region was impacted by unexpected high volumes of precipitation in a short period. This phenomenon has resulted in multiple cases of flooding and landslides throughout the municipality, causing significant material and human damage. Among the consequences, there were two deaths, dozens of homeless families, destruction of public property, in addition to the partial closure of stretches of highways and local streets (DIÁRIO DO NORDESTE, 2022). The following year, in January 2023, the event was repeated with less intensity, but even so, heavy rains caused landslides and the fall of a power pole on BR-482, generating inconvenience and considerable material costs for the population and local authorities (CALIMAN, 2023).

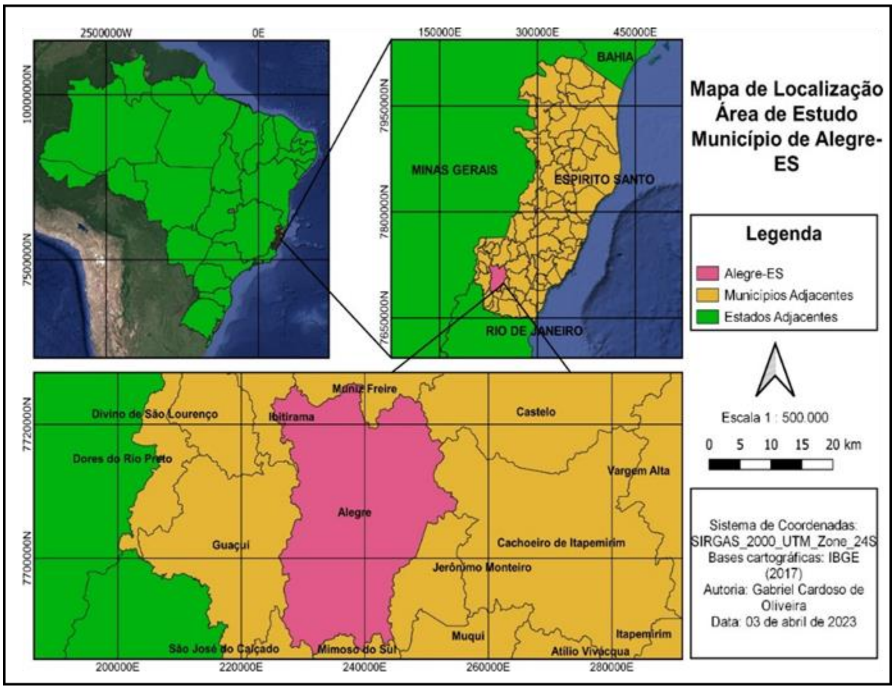
Although there is knowledge about the most affected neighborhoods, which have symptoms such as poles, fences and displaced trees, scars on the ground and gullies (geotechnical processes), in addition to the proximity to drainage areas (floods), there is still a need for a more detailed and practical mapping. Previous studies, such as that of Augusto Filho (1998), highlight that the geographical delimitation of the areas most vulnerable to these phenomena, together with the identification of the main causative factors – whether anthropic, such as disorderly occupation, or natural, such as physiographic aspects – are essential for a more effective prevention.

Landslides and large-scale flooding are frequent in Alegre, especially during periods of higher rainfall. Thus, the present work aims to carry out more in-depth studies on the dynamics of these processes in the municipality, aiming to prevent and mitigate future occurrences through the use of geotechnologies and their various tools, with emphasis on Fuzzy Logic, also known as Fuzzy Logic (MACHADO, 2018).

LOCATION OF THE STUDY AREA

The study area is located in the municipality of Alegre, Espírito Santo, located in the southern region of Espírito Santo and with bordering relations with the neighboring cities of Cachoeiro de Itapemirim, Jerônimo Monteiro, Muniz Freire, Mimoso do Sul, Guaçuí, Ibitirama, São José do Calçado and Castelo. The city, with a population of just over 30 thousand inhabitants according to the Brazilian Institute of Geography and Statistics (IBGE, 2023) is located about 200 kilometers from the state capital, Vitória, and its main access roads are through the federal highway BR-101, and the state highways ES-482 and ES-483 (Figure 1).

Figure 1 - Location Map referring to the study area, centered in the municipality of Alegre, Espírito Santo.



Source: Prepared by the author.

OBJECTIVES

The general objective of the research was to use the Geographic Information System (GIS) to map the critical points in relation to the occurrence of natural disasters, focusing on events of a geotechnical nature and floods in the municipality of Alegre. The main purpose is to assist municipal public management, the academic community and civil society in the processes of identification, prevention and mitigation of these vulnerabilities, presenting in a didactic way the geoprocessing techniques that can be applied to support these initiatives.

The specific objectives of the research were:

Acquire and analyze geographic data freely available on the internet, such as municipal boundaries, urbanized areas, digital elevation models, among others;

Produce cartographic products, represented by maps that contain morphometric, geological, geomorphological and hydrological data, useful for geotechnical and flood interpretation in the region, facilitating the processes of prevention and anticipation of these phenomena in the study area;

Use Fuzzy Logic as the main methodology, organizing the data and criteria mentioned in two final maps that illustrate in a precise and verifiable way in the field the distribution of geotechnical and flood risks in the study area.

PHYSIOGRAPHIC ASPECTS

The physiographic aspects related to geomorphology, pedology, vegetation, hydrography and climate will be addressed below, for a better analysis of the region and direct relationship with the attributes of regional geology.

REGIONAL GEOLOGY

The municipality of Alegre is regionally associated with important geotectonic structures, such as the Mantiqueira Province, the São Francisco Craton and the Araçuaí-Western Congo Orogen.

According to Bizzi et al. (2003), the Mantiqueira Province is composed of Paleoproterozoic remnants (2.5 to 1.6 Ga) and a succession of collisional belts, controlled by transpressive riding systems towards the cratonic margins. Regarding the compartmentalization of these belts, Heilbron et al. (2004) describe the Mantiqueira Structural Province as an extensive orogenic complex, resulting from the interaction of the Araçuaí, Ribeira, Apiaí and Dom Feliciano Orogens. This province is controlled by the interference zone between the Brasília and Ribeira Orogens, formed during the Brasiliano-Pan African Neoproterozoic Orogeny, which culminated in the amalgamation of the Western Gondwana Paleocontinent.

The Araçuaí-Western Congo Orogen corresponds to the northern segment of the Mantiqueira Province and is made up of passive margin deposits, suture zones, magmatic arcs and sin to post-collisional plutons (PEDROSA-SOARES et al., 2007). Its basement is formed by high-grade metamorphic rocks, dating from the Archean to the Paleoproterozoic, included in the Caparaó Suite and in the Guanhães, Gouveia, Porteirinha, Mantiqueira, Juiz de Fora and Pocrane Complexes (PEDROSA-SOARES et al., 2007).

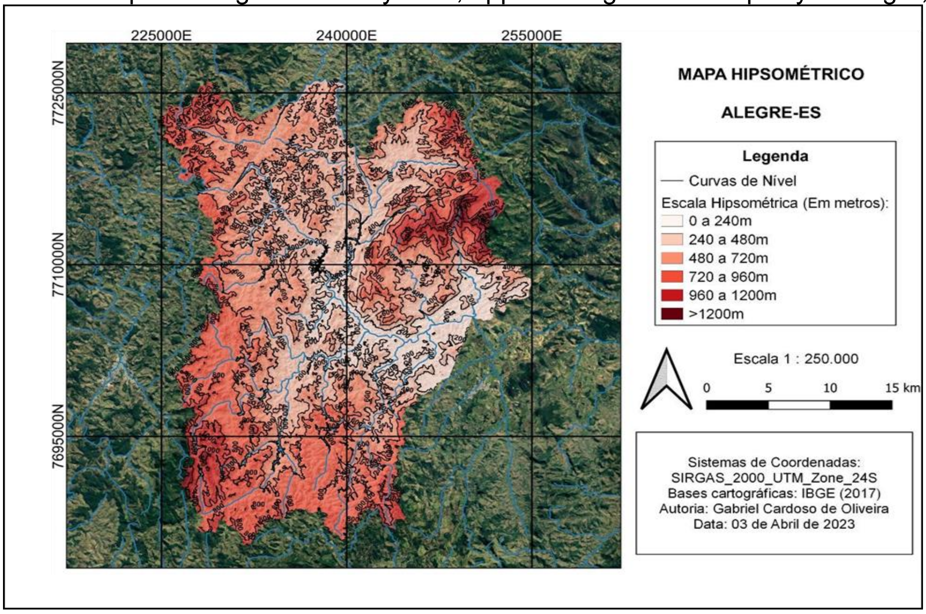
GEOMORPHOLOGY

According to information from the Municipality of Alegre (2023), the altitude in the municipality varies from 120 meters at the lowest points to more than 1,300 meters at the highest, characterizing a very rugged relief, modeled by predominantly metamorphic crystalline rocks and inserted in the geomorphological unit of the Mar de Morros (AB'SÁBER, 2003). This unit is marked by the presence of numerous dissected hills, forming a typical relief.

Regarding the subdivisions of the geomorphological regions of Espírito Santo, the study area is inserted in the Northern Mantiqueira Plateaus, characterized by strongly dissected mountains, with dissection processes influenced by rivers that adapt to lithological and structural weaknesses (CUNHA, 2016). In addition, Pacheco (2011) describes the geomorphological attributes of Alegre as the result of significant tectonic activity, followed by modification by consecutive cycles of dissection. These processes contributed to the formation of large faults, which directly influence the local hydrology, in addition to very closed and steep "V" valleys.

Another relevant aspect in relation to the geomorphological attributes of the study area is the hypsometric features observed, with minimum altitudes around 100 meters and maximums above 1,200 meters, distributed throughout the territory of Alegre (Figure 2).

Figure 2 - Hypsometric map referring to the study area, approaching the municipality of Alegre, Espírito Santo.



Source: Prepared by the author.

SOILS AND VEGETATION

The Municipality of Alegre (2023) describes that the predominant soils in the municipality are "shallow, well-drained, with low susceptibility to erosion, acidic, very porous and of low natural fertility," mainly associated with red-yellow oxisols and cambisols. Pacheco (2011) reinforces this characterization, highlighting the dominance of the red-yellow latosol in the region, describing it as a typical, clayey, mesoferric, deep, acidic dystrophic soil, and generally present in undulating relief.

Regarding vegetation and land use, the predominant biome in the area is the Atlantic Forest (IBGE, 2023), characterized by dense or mixed forest formations, with tall trees with robust trunks, as well as shrubby vegetation in shaded areas. The main economic activities and land uses in Alegre are centered on coffee growing and agriculture, which justifies the presence of extensive areas around the city dedicated to the cultivation of coffee and other crops, as well as large regions of pastures for cattle and horses.

HYDROGRAPHY

The municipality of Alegre is located in the Itapemirim River Basin, formed by the confluence of the Braço Direito Norte and Braço Esquerda Norte rivers. The basin covers an area of 6,014 km² and has springs located in the region of the Caparaó National Park and in the Serra de São Domingos (AGERH, 2020).

Locally, the hydrography of Alegre is characterized by several bodies of water, including streams, waterfalls and numerous intermittent drainages that flow into the Itapemirim River. These drainages are distributed throughout the municipal territory (DE LIMA, 2021).

WEATHER

According to data provided by the Municipality of Alegre (2023), the municipality has a predominantly humid to subhumid tropical climate, with an average annual rainfall of 1,200 mm. The average annual temperature is 23°C, and can reach up to 36°C during the summer.

As for the distribution of precipitation, the highest concentration of rainfall occurs between the months of November and March, representing 60% to 70% of the annual total. In contrast, the driest period runs from April to September, characterized by a long winter interval with milder temperatures and extremely scarce precipitation (PACHECO, 2011).

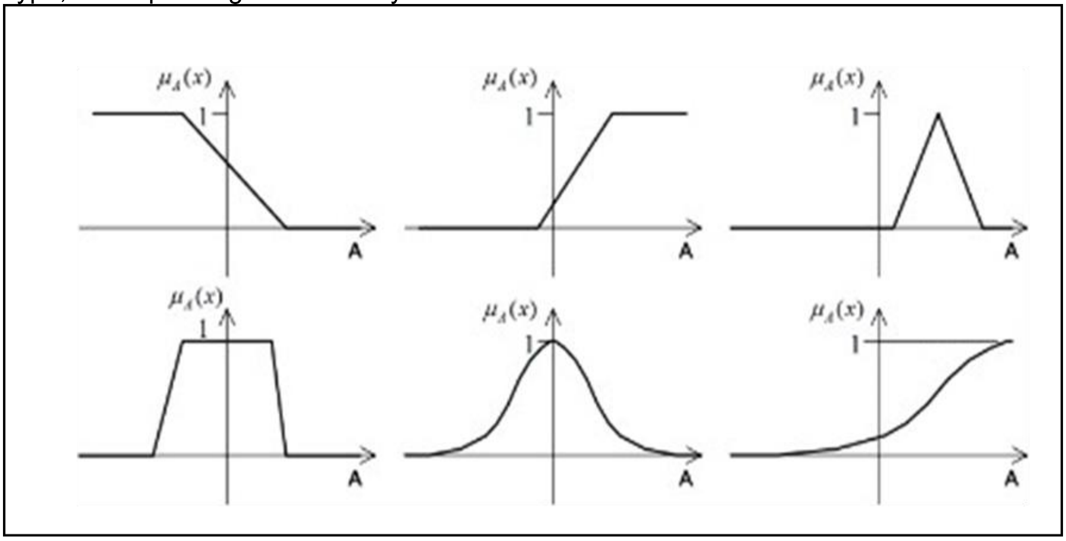
METHODOLOGY

To meet the objectives outlined, the scientific methodology adopted was divided into the three traditional stages of geosciences: pre-field, field and post-field, described below.

In the pre-field phase, a theoretical study of the theme was carried out through the collection of bibliographic, cartographic and geographic data from the portals of competent agencies, such as IBGE and Embrapa, as well as historical reports and journalistic records, which served as case studies to contextualize the subject. Then, this information was interpreted and organized. For this, a database of the study area was built for later geoprocessing, including the acquisition of a Digital Elevation Model (MDE – SRTM image – 1 arcsecond) with all the necessary hypsometric information.

After the treatment and processing of the MDE, the maps of Slope, Concavity, Roughness and LS Factor (Topographic Factor) were prepared to evaluate the geotechnical risks, and the maps of Slope, Slope Height, Proximity to Drainages, Convexity and Topographic Moisture Index (TWI) for the flood risks. As illustrated in Figure 3, Fuzzy Logic was applied to these maps, using linear pertinence functions (positive for geotechnical criteria and negative for flood criteria, on a scale of 0 to 1). Then, the maps were reclassified, with the values closest to 1 to 0 being classified from 4 to 1, where 4 corresponds to very high risk, 3 to high risk, 2 to medium risk and 1 to low risk for the occurrence of floods and landslides. The data were processed using the free software QUANTUM GIS (QGIS, 2023).

Figure 3 - Common forms used for the function of relevance of Fuzzy Logic, with emphasis on the variation of the Linear type, corresponding to the variety chosen for the realization of the work.



Source: FUNDAMENTALS of Fuzzy Logic. Intelligent Computing, 2015. Available at: <http://computacaointeligente.com.br/conceitos/fundamentos-da-logica-fuzzy/>. Accessed on: March 20, 2023.

Subsequently, with the individual maps of each of the mentioned parameters duly prepared (four for geotechnics and five for flooding), the final maps were generated, which compiled these data into two cartographic products. One of the maps covers the four criteria selected for geotechnical risks, while the other is directed to the five criteria chosen for flood risks. Both were built with the aim of flagging and quantifying these risks as broadly, accurately, and effectively as possible.

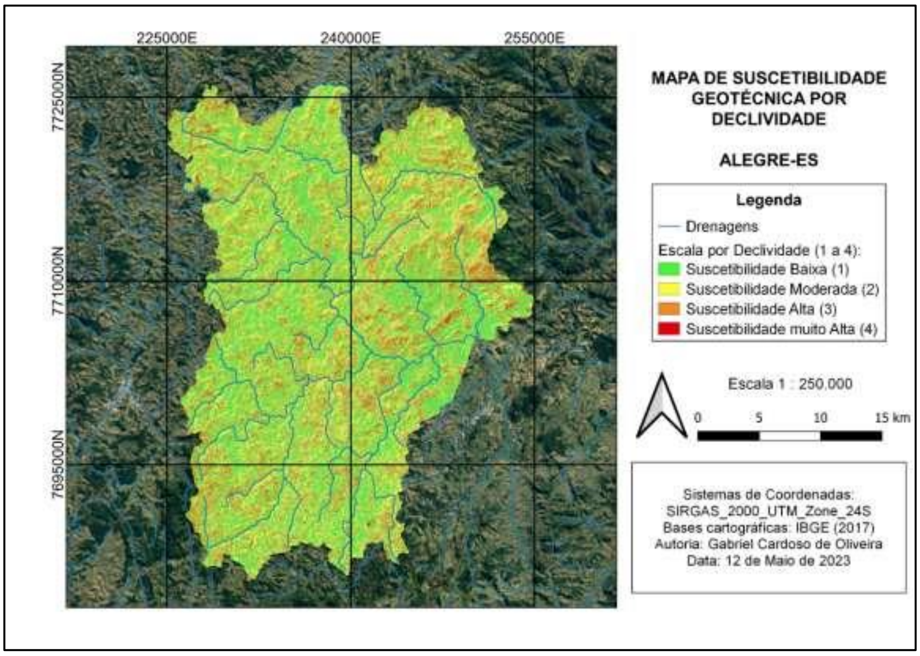
Then, a field visit was carried out to the locations identified as the most critical in both final maps. The purpose of this visit was to observe in practice the usefulness and precision of the risks indicated by the maps prepared.

Finally, in the post-field stage, it was possible to evaluate the compatibility between the indications of the maps and the reality observed during the field visit. This analysis led to a final evaluation of the performance of the method used for the proposed purposes, as will be detailed below.

GEOTECHNICAL SUSCEPTIBILITY MAPPING

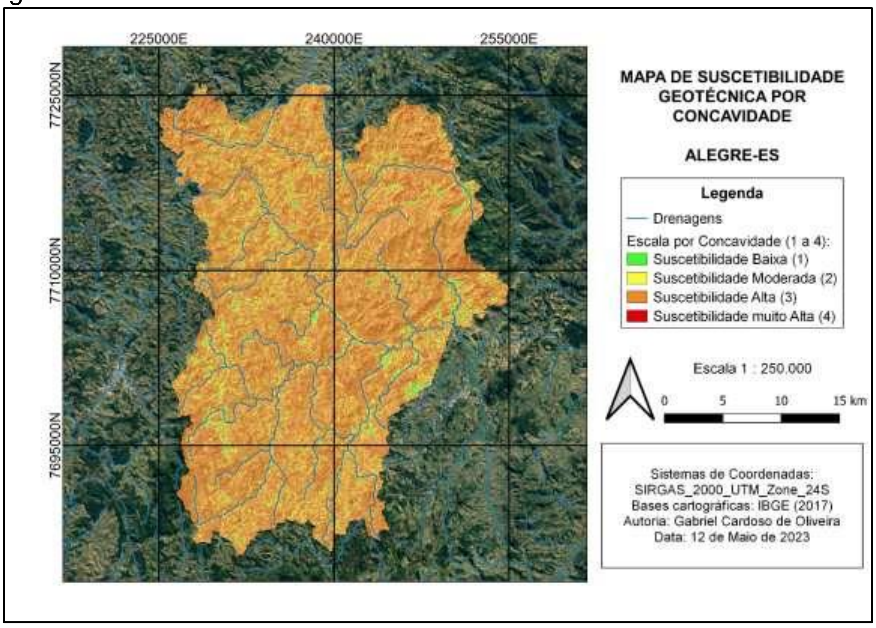
Initially, it is essential to start this analysis from the data acquired, since they were used to prepare the thematic maps referring to the relevant attributes for the quantification of geotechnical risk (Slope, Concavity, Roughness and LS Factor), applied to the entire territory of Alegre. These maps were treated with corresponding pertinence functions, using positive linear Nebula Logic techniques, taking into account the localities theoretically identified as higher risk (reddish zones). The results are presented in Figures 4 to 7.

Figure 4 - Geotechnical Susceptibility Map by Slope Scale of the municipality of Alegre - ES, applied to the vulnerability of geotechnical occurrences.



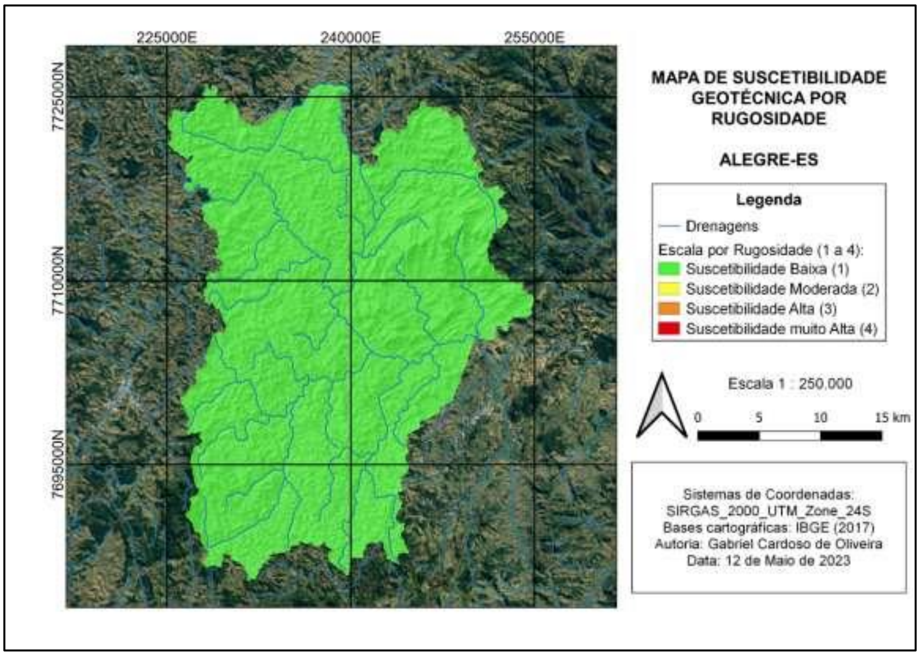
Source: Prepared by the author.

Figure 5 - Geotechnical Susceptibility Map by Concavity Scale of the municipality of Alegre – ES, applied to the vulnerability of geotechnical occurrences.



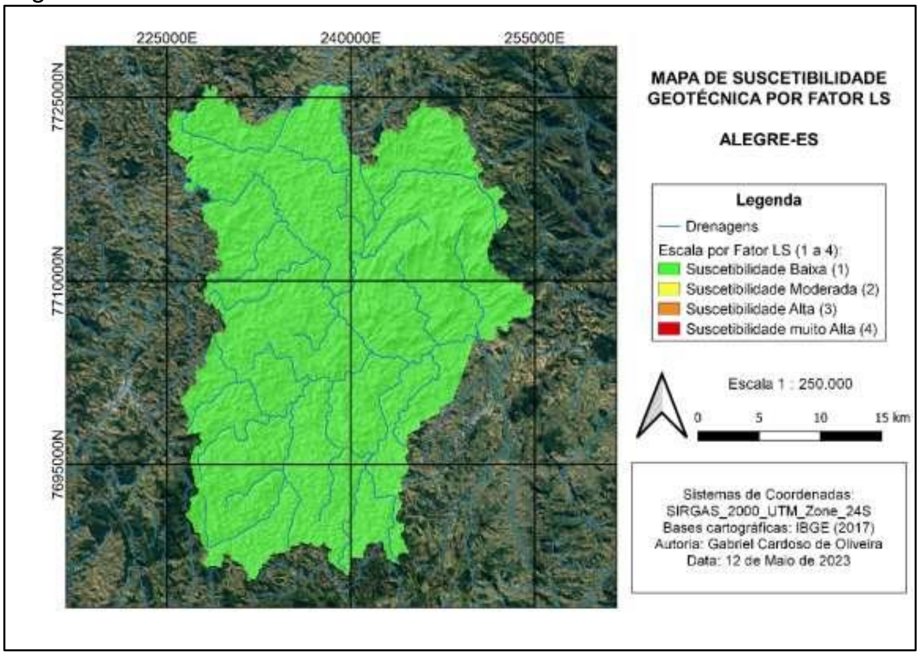
Source: Prepared by the author.

Figure 6 - Geotechnical Susceptibility Map by Roughness Scale of the municipality of Alegre – ES, applied to vulnerability



Source: Prepared by the author.

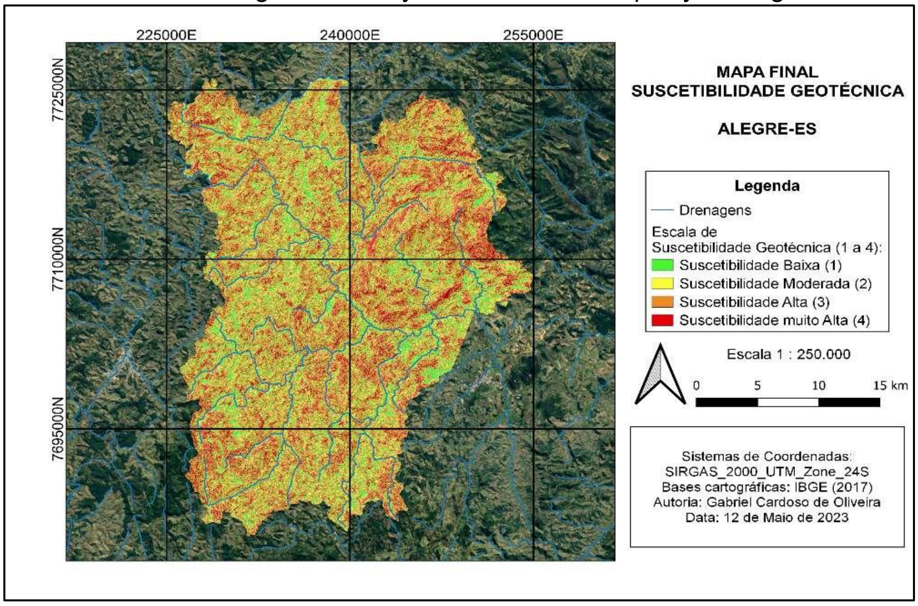
Figure 7 - Geotechnical Susceptibility Map by LS Factor Scale of the municipality of Alegre – ES, applied to the vulnerability of geotechnical occurrences.



Source: Prepared by the author.

Then, all the maps mentioned were incorporated into the fuzzy gamma equation (QGIS, 2023), making it possible to agglutinate the data into a single final product that represents a geotechnical risk scale, categorized from 0 (very low risk) to 1 (very high risk), as shown in the map in Figure 8.

Figure 8 - Final Map of Geotechnical Susceptibility applied, containing the compilation of the four geotechnical attributes recorded above and referring to the study area of the municipality of Alegre – ES.



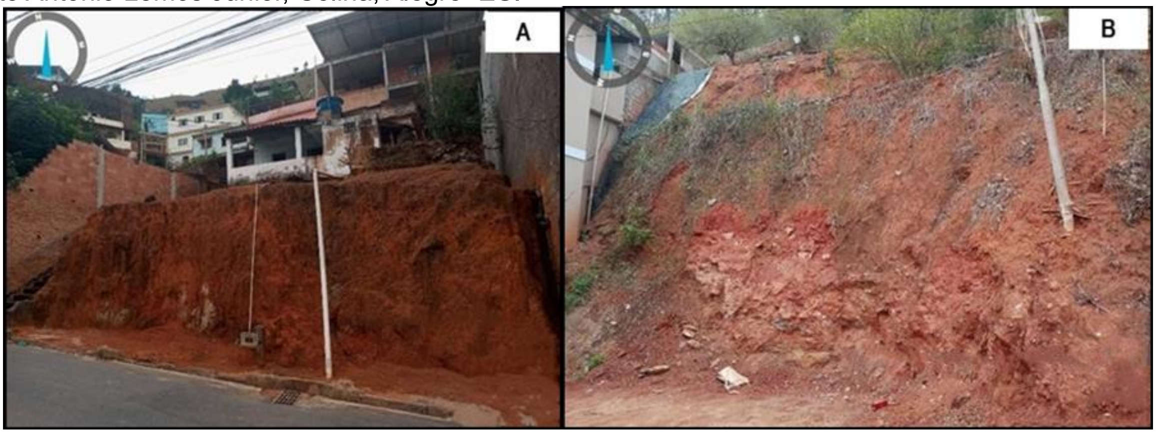
Source: Prepared by the author.

In addition, the next stage focused efforts on the practical confirmation of the effectiveness of the risk scale proposed in the generated map. To this end, field activities were carried out between June 8 and 9, 2023, visiting in person the places theoretically identified with risk closer to 4 in the cartographic products previously generated, always prioritizing places with high (3) or very high (4) risk levels.

It is important to mention that these validation visits were concentrated in the central region of the municipality, due to its higher population density in relation to the rest of Alegre, in addition to being an area already visited in a scientific initiation work with a similar theme. This choice is also due to logistical issues and easy access.

With this, the images presented in Figure 9 were obtained, allowing the confirmation of the high degree of risk indicated on the map, through visits and practical field observations, thus validating the methodology used for the preparation of the Final Geotechnical Risk Map presented previously.

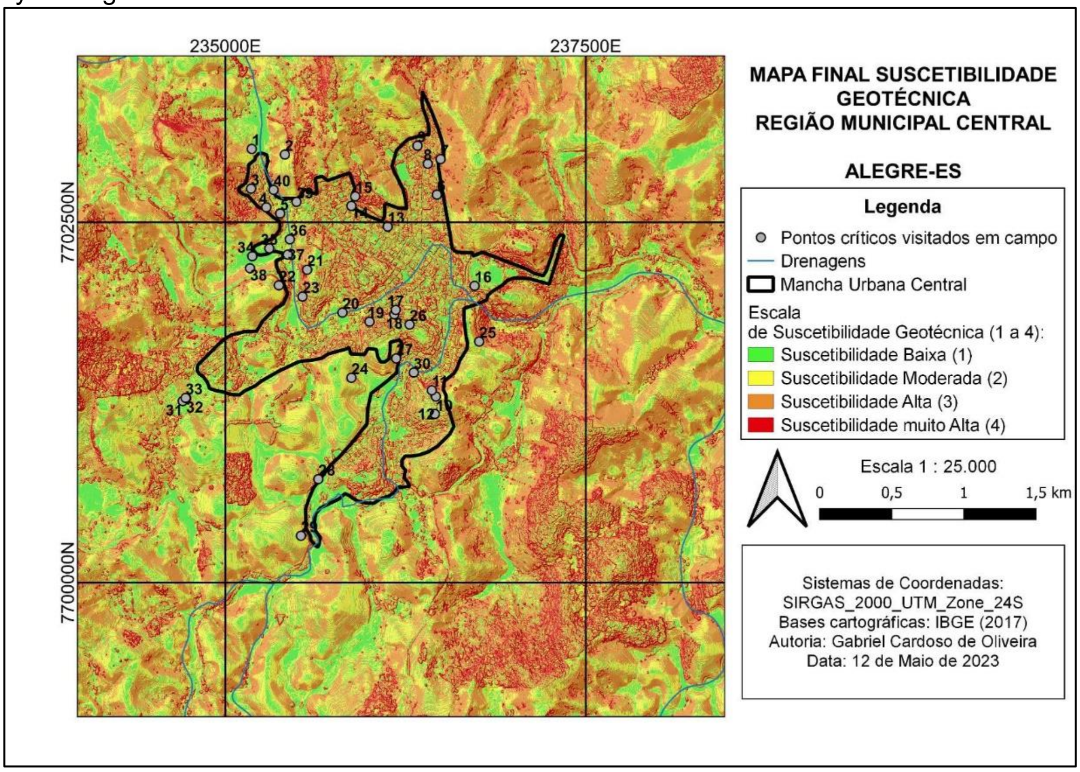
Figure 9 - A) Point 8: Slope under house with hanging pipes, located on Rua João Bravo, in the Nova Alegre neighborhood in Alegre-ES; B) Point 15: Location with evidence of earth movements in a lot located at Rua Prefeito Antônio Lemos Júnior, Colina, Alegre–ES.



Source: Prepared by the author.

Then, it was followed by the comparison between the susceptibility observed in the field with that indicated by the final map previously prepared, plotting the points visited on the central region of the municipality (Figure 10). The comparisons were made using the confusion matrix and are quantified in Tables 1 below.

Figure 10 - Final Geotechnical Susceptibility Map, with points of greatest interest visited in the center of the municipality of Alegre - ES.



Source: Prepared by the author.

Table 1 - Total geotechnical points carried out and their compatibility with the risk scale.

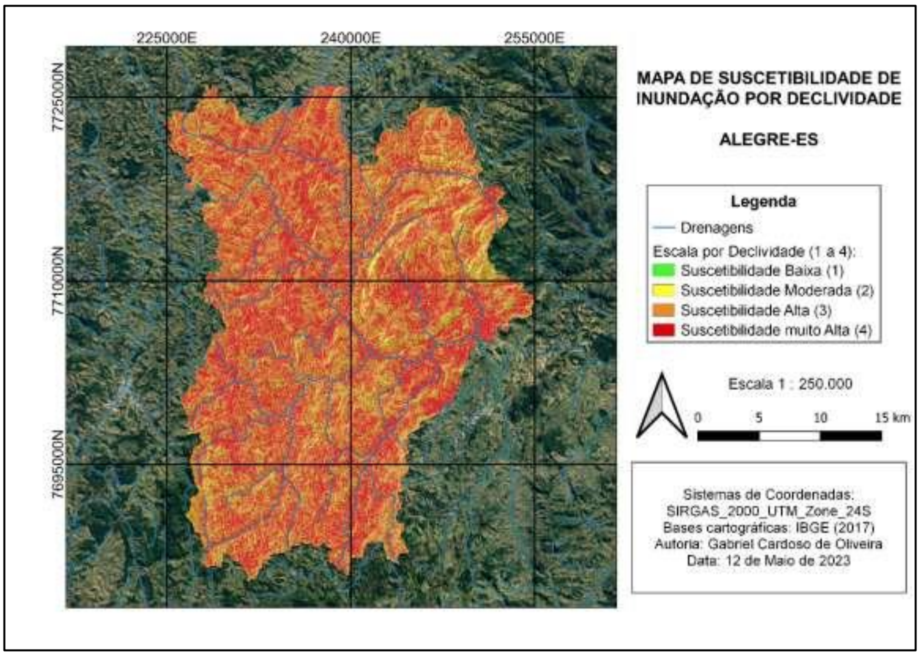
Geotechnical Susceptibility Class	1	2	3	4	Wi
1	0,1559	0	0	0	0,1905
2	0	0,1683	0,1122	0,0561	0,261
3	0,0263	0,0443	0,2657	0,1329	0,4213
4	0	0	0	0,16	0,1272
Total	0,1822	0,3738	0,3592	0,0848	
HERSELF PA [%] UA [%] General Accuracy	0,0351 85,5469 81,8182 73,9101	0,0744 55,845 80	0,0637 80,647 68,75	0,0424 100 66,6667	

Legend: IF = standard error; PA = producer's accuracy; UA = user accuracy. Source: Prepared by the author.

FLOOD SUSCEPTIBILITY MAPPING

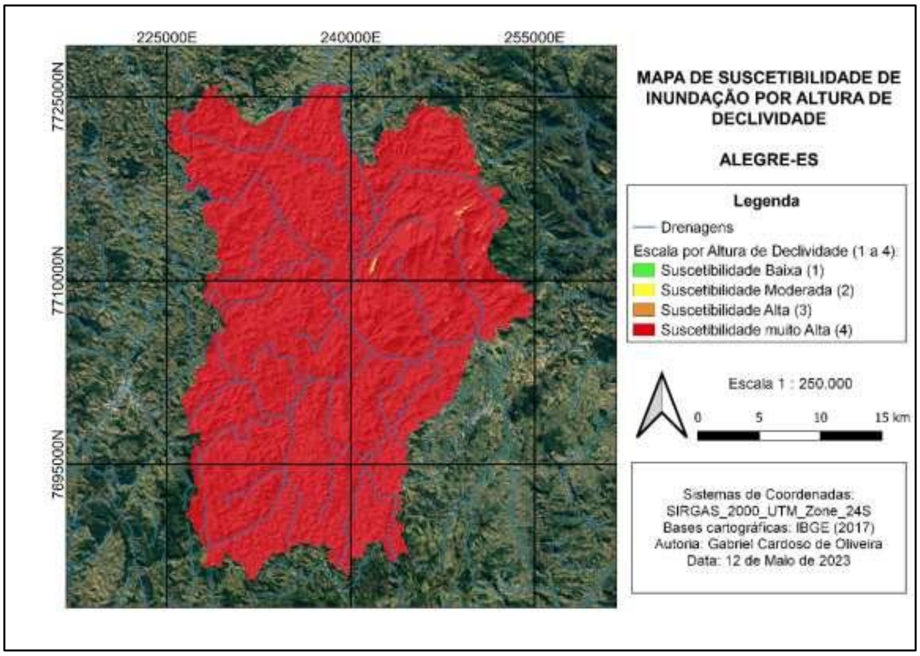
Subsequently, following the same process for the theme of floods, thematic maps pertinent to the risks of flooding phenomena were prepared. These maps include Slope, Slope Height, Drainage Proximity, Convexity and Topographic Wetness Index (TWI), applied to the entire territory of Alegre. The new maps were also treated with specific pertinence functions, correlated again with linear Fuzzy Logic techniques, this time in a negative character, as represented in Figures 11 to 15.

Figure 11 - Map of Flood Susceptibility by Slope Scale of the municipality of Alegre – ES, applied to the vulnerability of flood occurrences.



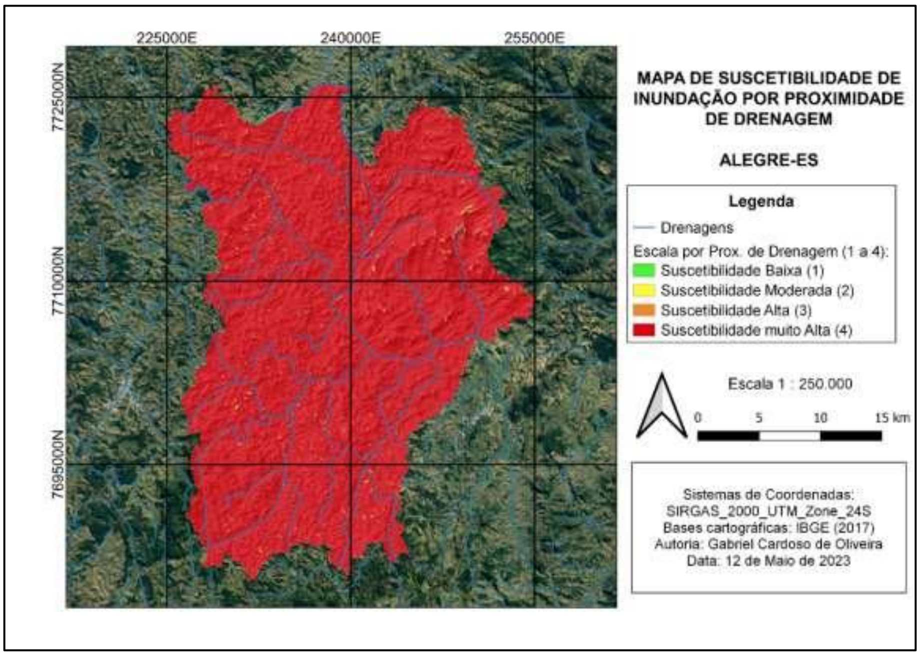
Source: Prepared by the author.

Figure 12 - Flood Susceptibility Map by Slope Height Scale of the municipality of Alegre – ES, applied to flood risk.



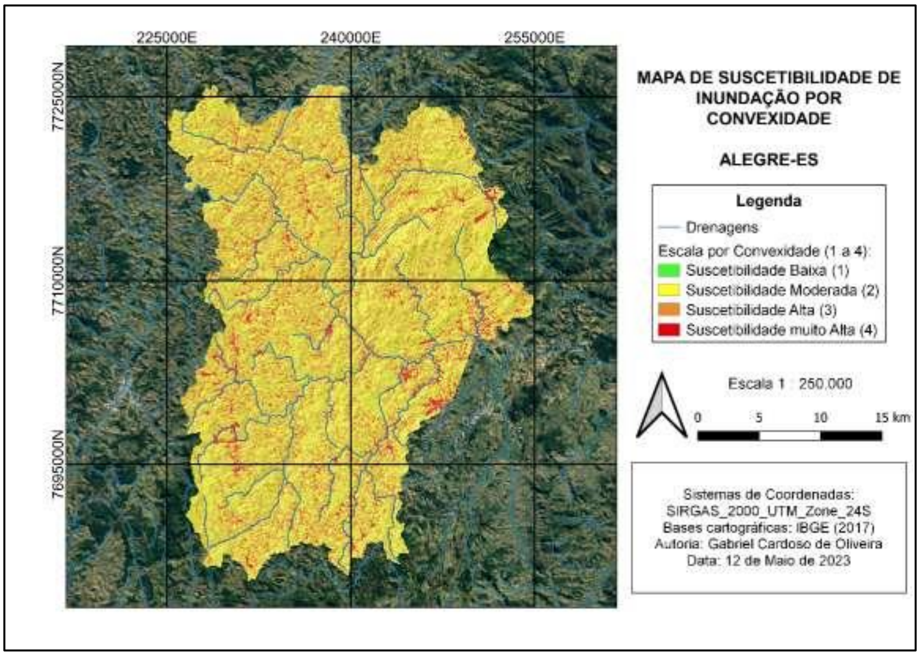
Source: Prepared by the author.

Figure 13 - Flood Susceptibility Map by Drainage Proximity Scale of the municipality of Alegre – ES, applied to the vulnerability of flood occurrences.



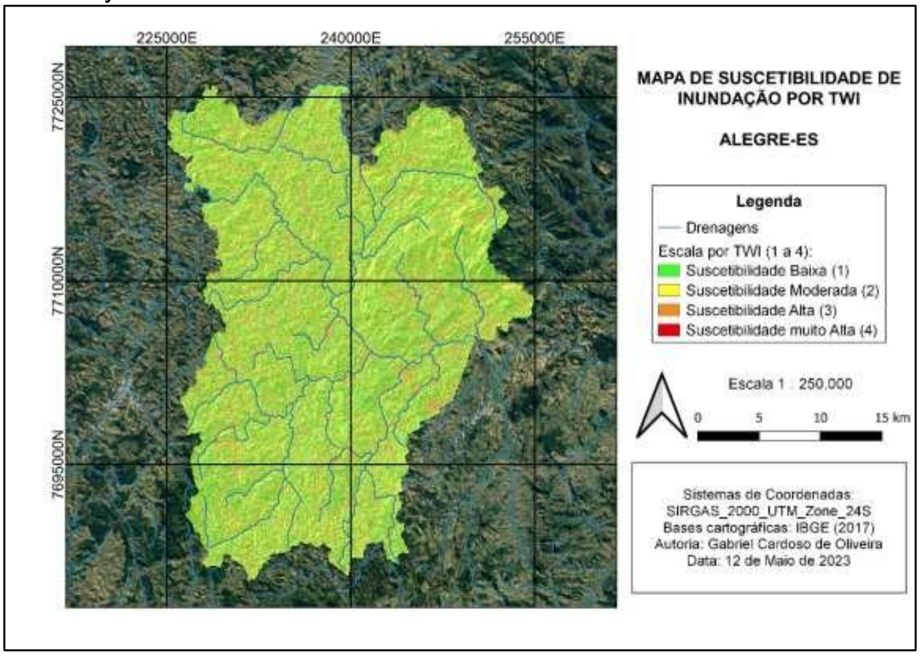
Source: Prepared by the author.

Figure 14 - Flood Susceptibility Map by Convexity Scale of the municipality of Alegre – ES, applied to the vulnerability of flood occurrences.



Source: Prepared by the author.

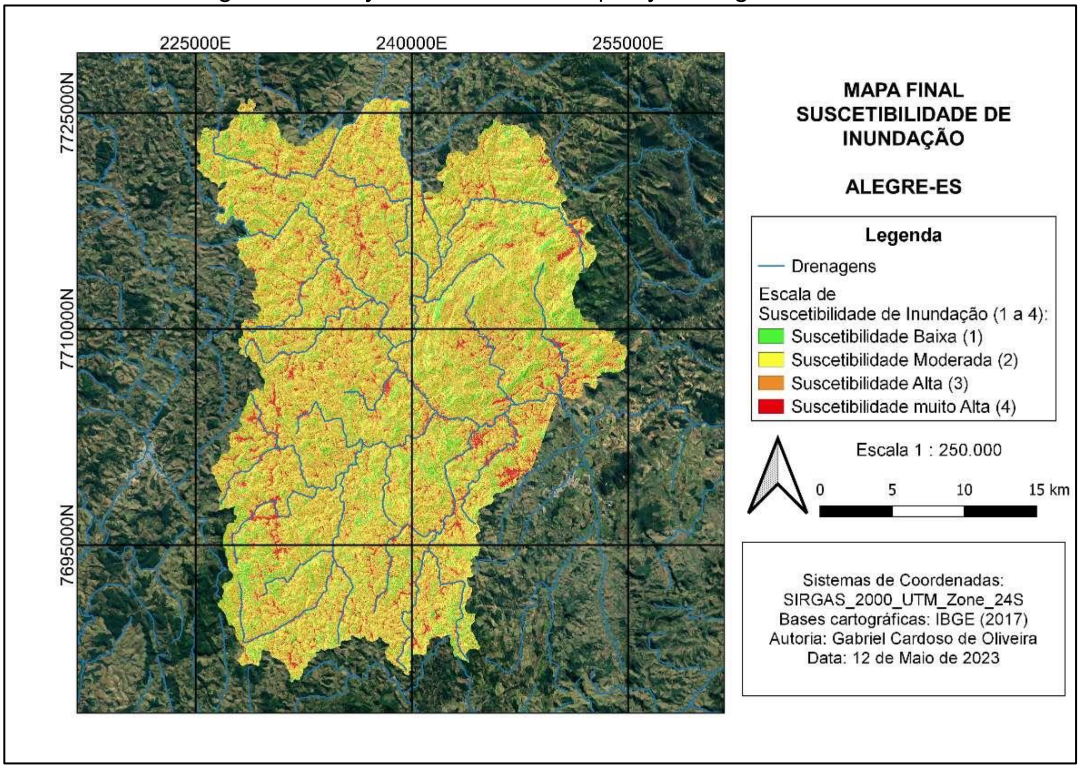
Figure 15 - Flood Susceptibility Map by Topographic Wetness Index (TWI) of the municipality of Alegre – ES, applied to the vulnerability of flood occurrences.



Source: Prepared by the author.

Then, using Fuzzy Logic again in its Gamma variety (QGIS, 2023), it was possible to agglutinate the data contained in the aforementioned maps into a single and new final product, presenting a flood risk scale, categorized from 0 (low risk) to 4 (very high risk), as shown in the following final map (Figure 16).

Figure 16 - Final Map of Applied Flood Susceptibility, containing the compilation of the five flood attributes recorded above and referring to the study area of the municipality of Alegre – ES.



Source: Prepared by the author.

Then, the field stage was carried out, also held between June 8 and 9, 2023, with the objective of validating the cartographic data built during the pre-field, this time applied to the theme of flooding. Again, for reasons already mentioned, the visits were directed to the center of the municipality of Alegre, prioritizing the places identified on the map as having high (0.75) or very high (1) risk levels.

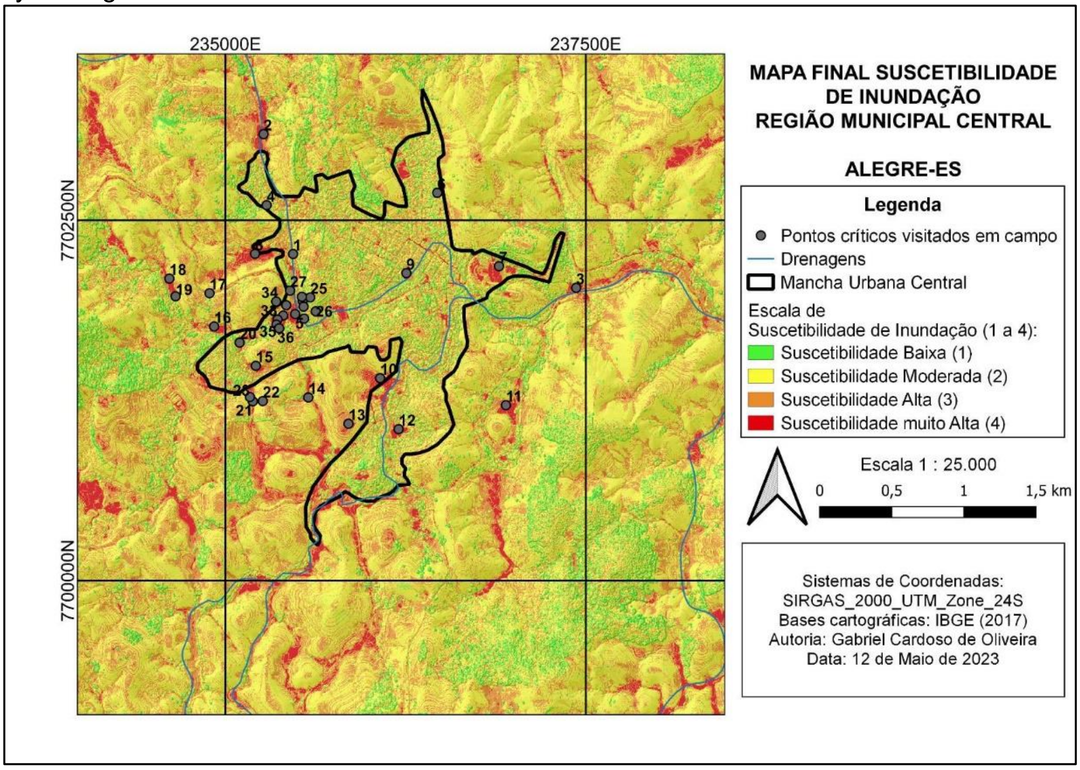
Thus, the images below (Figure 17) were captured, making it possible to verify the usefulness of the map for the identification and prevention of natural disaster risks, in this case, related to flooding processes.

Figure 17 - A) Point 4: Downhill dirt road near the drainage at Rua dos Espanhols, Colina, Alegre–ES; B) Point 6: Slope on unoccupied land on Rua Tristão Soares Campos in Alegre-ES.

Source: Prepared by the author.

Finally, the final comparisons between the content of the map and the observations made in the field were made, positioning the points visited and verifying the compatibility between the theoretical susceptibility proposed by the map and that observed in practice (Figure 18). These comparisons were prepared using a confusion matrix and are quantified in Tables 2 below.

Figure 18 - Final Map of Flood Susceptibility, with points of greatest interest visited in the center of the municipality of Alegre – ES.



Source: Prepared by the author.

Table 2 - Final overall accuracy of the Final Flood Risk Map generated, with the comparison between the data of the original product and the data verified in the field, within the delimited flood risk scale from 1 to 4.

Flood Susceptibility Class	1	2	3	4	W i
1	0,097	0	0	0	0,097
2	0	0,5546	0	0	0,5546
3	0	0	0,2969	0	0,2969
4	0	0	0	0,0514	0,0514
Total	0,097	0,5546	0,2969	0,0514	
HERSELF	0	0	0	0	
PA [%] UA [%] Overall accuracy [%]	100,00 100,00 100,00	100,00 100,00	100,00 100,00	100,00 100,00	

Legend: IF = standard error; PA = producer's accuracy; UA = user accuracy. Source: Prepared by the author.

DISCUSSION

It is important to highlight that, for the success of the general objective of the research, the data collected in the field needed to coincide, even partially, with the susceptibility scale contained in the two final thematic maps prepared during the pre-field. This alignment was achieved, since an expressive accuracy rate of more than 70% was obtained in both cases, both in the Final Geotechnical Susceptibility Map and in the Final Flood Susceptibility Map. The first presented a performance of 73.9%, while the second achieved a remarkable 100% accuracy.

Thus, the effectiveness of GIS and, especially, of Nebulous Logic as effective tools for monitoring natural disasters of this nature was proven, in addition to being viable and promising in solving problems related to these themes.

In this way, it can be certified that the results obtained and recorded in the final maps are aligned with the ideas already mentioned by Zuquette (2004), reiterating the hypothesis that maps intended for the prevention of natural events of this type should present an acceptable compatibility between what is addressed in theory and what is found in practice.

In addition, it is relevant to highlight the presence of previous studies in the literature with a similar approach, which applied Fuzzy Logic in the geotechnical (MACHADO, 2018) and flood (CARVALHO, 2022) contexts. In both works, the prioritized technique was similar to the one chosen for the project described here and was applied with similar objectives, resulting in conclusions considered satisfactory and above the expectations initially outlined.

The work of Machado (2018), for example, applies the technique in locations in the state of Santa Catarina (SC) and concludes that the results obtained provided greater precision in the delimitation of areas of geotechnical vulnerability in the region. In turn, Carvalho (2022) directs his methodology to studies in the state of Espírito Santo (ES) and, based on the statistical results found, confirms a greater vulnerability to flooding in the metropolitan and coastal regions of Espírito Santo.

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