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Contribution on Debris Flow Forecast

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Abstract: Debris flows are known as one of nature's most catastrophic mass movements, depending on speed, power and high volume. The analysis of the conditioning agents and triggers of this mass movement provides an assessment of each of the factors involved in the slope instability processes, allowing the obtainment of interesting results, regarding its form of action. This work aims to develop a new technique for evaluating and predicting debris flows. Consists of generating maps of slope stability and natural susceptibility to debris flows through geotechnologies, associated with remote sensing data. The chosen case study was the Córrego D'Antas basin located in the mountainous region of Rio de Janeiro and was greatly affected by the debris flows triggered after the extraordinary precipitation event in January 2011. The results obtained were compared with the real characteristics of the event, indicating consistent analyzes that support the use of this methodology for risk analysis and, consequently, assessment of occupancy scenarios and projects of coexistence structures and debris flow mitigation.

Keywords: Debris flow; Geotechnologies; Remote sensing; Risk analysis.

1 General Aspects

Mass movement are natural process or induced, classified according type of granulometry evolved in their matrix, following trajectories that depend on a set of factors that characterize the movement, resulting in risk, losses and enormous consequences socioeconomic. Among the movements, the Debris flow is a very complex movement that occurs suddenly and a sufficient potential to cause catastrophic damage. In general, this movement is triggered by strong precipitations in short periods of time or by light precipitations in long periods of time or even by earthquarks.

In tropical regions, the inappropriate way of reporting Debis flow, the lack of standardization of information and only the registration of big movements are the importance of characterizes the behave of such event. In Brazil the causes of that's movements are associate the big precipitations or persistent precipitations. For a long time, the most relevant cases and taken as a reference in Brazil were those of the mountainous region of Cubatão in São Paulo and Serra das Araras in Rio de Janeiro, in 1967, when atypical rainfall occurred. But in January 2011, a tragedy in the mountainous region of Rio de Janeiro, triggered by an intense rainfall that resulted in storms, surpassed any event that occurred in catastrophic dimensions and data. According to Nunes and Sayão (2014), official fatalities reached 912, but it is estimated that this number is far from representing reality, due to the fact that entire families disappeared.

The slope instability phenomena are conditioned by many factors, such as climate, lithology and rocky backbone structures, morphology, human action and others. The analysis of the geological and geotechnical conditions involved in mass movements provides an appreciation of each of the factors involved in the processes of instability, allowing a better understanding of the way in which these factors work.

The prediction of the occurrence of landslides has assumed increasing importance in the geotechnical literature, with different conceptions of the problem and forms of investigation. Most of the proposed methodologies aim to define areas most susceptible to the occurrence of the process and the characterization of the risk involved, encompassing both the possibility of occurrence of the process and the resulting damages.

The identification and mapping of areas predisposed to the occurrence of catastrophic natural processes, which result in damage and threat to society, is a highly important demand, mainly due to the role it plays in environmental, territorial and risk planning and management situations.

2 Debris Flow

The factors of influence to Debris Flow are numerous and complex but in most of majority include geological structure, topography, characteristic of soil and vegetation, hydrology, intense precipitation and activities human in local. The conditioning geological factors to mass movements consider the type and distribution of materials in the substrate of the slopes that present different behaviors of shear resistance, permeability and other characteristics. The material of substrate can be divided in rock mass and earth massif, including soils, rocks, deposits and geological structures, with specific geotechnical characteristics. According to Motta (2014), there is a critical combination of natural and anthropogenic factors which gives rise to the debris flow process and the relationship between them is responsible for controlling the probability, duration and magnitude of this phenomenon. In this context, movements are caused in particular by two factors: 1. Conditioning factors which are those capable of reducing the resistance of the terrain, making it susceptible to mass movement but not triggering it when analyzed in isolation. The combination of conditions is necessary to start the mass movement, including: -Thin layers of less resistant soil, of colluvial origin or rock weathering; Exposed rocky surfaces, with joints and flaws Vegetation, poor and sparse, exposing slopes to weathering; Rupture of steep slopes, inducing subsequent movements; Extreme weather conditions; Inefficient drainage; Disorderly and illegal occupation of slopes. 2. Triggering factors are those that starting the mass movement: Change in the strength parameters of the materials, such as the decrease in the apparent cohesion effect (suction) due to the increase in humidity, and loss of cementation by dissolution; Increase in the specific weight of slope materials, increasing external demands; Development of positive pore pressures in the soil, subpressures in rocky discontinuities and percolation forces; Alteration of the slope profile by erosion of the most exposed materials.

The methods to analyses of risks of Debris flows changes according the countries and some of them have developed guide on how to qualify and map debris flow risks. According to Jakob (2005) a guide to recognizing and analyzing risks of Debris flow consists of: Risk recognition; Estimation of the probability of occurring; Estimation of magnitude and intensity; Debris flow production and frequency-magnitude relationship; Estimation of the magnitude and intensity of the debris flow; Presentation of risks through maps and description of analyses.

To recognizing the occurrence of Debris flow events is necessary identify: Well-defined channel; Presence of mud tracks with boulders and debris impact scar; Presence of large blocks of rocks and tree trunks that were uprooted and consequently they were getting in the way. Aerial photographs and satellite images are indispensable tools in the recognition and analysis of damage caused by debris flows. Several studies have used the potential of Remote Sensing and Geographic Information System (GIS) tools to identify, model and analyze mass movements through slope instability zoning techniques. In the scope of geotechnologies, remote sensing is inserted, as the nomenclature itself indicates, in the perspective of obtaining data through sensors, without direct physical contact with the object of study.

3 Study Methodology

It consists of generating a natural susceptibility map for Debris flow from an inventory of scars and thematic maps, enabling the correlation of conditioning factors with the events that occurred. It was necessary to gather some information to obtain the map of natural susceptibility to Debris flows: Recognition and mapping of areas where debris flows have already occurred; Information plans for creating thematic maps; Generation of factor maps; Factor weighting using the Analysis Hierarchy Process (AHP).

3.1 Debris flow scar inventory map

The inventory map was created from the recognition and mapping of scars left by debris flow events, obtained through the interpretation of satellite image provided by Google Earth Pro and interpretation of aerial photographs of the place. The creation of an inventory map allows the monitoring of debris flow events in the affected areas and, consequently, the formation of a database for this type of event, in order to record the associated variables, improve knowledge about the movement mechanisms and generate analysis data, aiming at predicting future events.

3.2 Generation of information plans

The information planes simulate reality, providing a conceptual model of the study area. They are generated from data analysis in a GIS environment and are obtained from databases such as the Topodata Project of the National Institute for Space Research (INPE) and the geobank of the Geological Service of Brazil – CPRM. Table 1 shows the information plans used to create thematic maps of the study area, the database from which they were obtained and the respective formats.

Table 1. Characteristics of Information Plans.

Information plan	Font	Format
Altimetry	Folha 22S435_ZN - TOPODATA	*Raster*, 30m resolution
Horizontal Curvature	Folha 22S435_HN - TOPODATA	*Raster*, 30m resolution
Vertical Curvature	Folha 22S435_HN - TOPODATA	*Raster*, 30m resolution
Geological	Folha Nova Friburgo – GEOBANK	Vetorial 1:100.000

From the information plans, the following thematic maps were created in raster format: Altimetry Map; Declivity Map; Horizontal Curvature Map; Vertical curvature map; Geological Map.

3.3 Cross tabulation

The cross-tabulation seeks to correlate the areas where debris flows have already occurred, with the different geological-geomorphological conditions defined for the study area. The method was performed automatically with the ArcGis software, being necessary to standardize all thematic maps in raster format, georeferenced, with the same number of lines and columns, the same spatial resolution and scale. The results obtained with the cross tabulation were later used to standardize the factor maps.

3.4 Standardization of thematic maps

For the generation of factor maps, it was necessary to reduce all thematic maps to a scale of values to enable the comparison between them. The factors were classified using the fuzzy linear function, which replaces the strict definitions of classes “yes” and “no” by a range of values from 0 to 1, in which a certain degree of class pertinence can be reached. Fuzzy logic is a mathematical approach to quantifying uncertain statements. Through membership functions, it is possible to formulate rules, according to which classes can be delimited.

3.5 Definition of weights using the AHP technique

To determine an optimal set of weights for the combination of the different factor maps that condition the debris flows of the study area, the relative contribution of each conditioning factor was evaluated, using the decision support technique called Analysis Hierarchy Process (AHP), developed by Saaty in 1987 and based on the logic of pairwise comparison. The AHP technique has a mathematical basis that allows organizing and evaluating the relative importance between criteria and measuring the consistency of judgments. The different factors are compared two by two and a criterion of relative importance is assigned to the relationship between these factors. in the pairwise comparison, the weights of the criteria are defined according to the decision-maker's judgment and based on the fundamental scale of SAATY. Equation 1 shows how the decision matrix is structured, as proposed by the AHP method:

$$A_{nxn} = \begin{vmatrix} 1 & a_{21} & \cdots & a_{1n} \\ a_{21} = \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & a_{3n} \\ a_{n1} = \frac{1}{a_{1n}} & a_{n2} = \frac{1}{a_{2n}} & \cdots & a_{4n} \end{vmatrix} \tag{1}$$

Then, the eigenvectors of the decision matrix are calculated. The normalized eigenvector, which corresponds to the maximum eigenvalue (λmax), provides the hierarchy or priority order of the criteria being compared.

3.6 Generation of the susceptibility map

For the generation of the natural susceptibility map, an algebra of maps was performed using the weigthed overlay module, of the ArcGIS software, which combines the factor maps with the respective weights weighted by the AHP method.

4 Case Study: Córrego D’antas Basin

The Córrego D’Antas basin is located in the city of Nova Friburgo (Figure 1), in the mountainous region of the state of Rio de Janeiro, Brazil, with an area of 53 km^2.

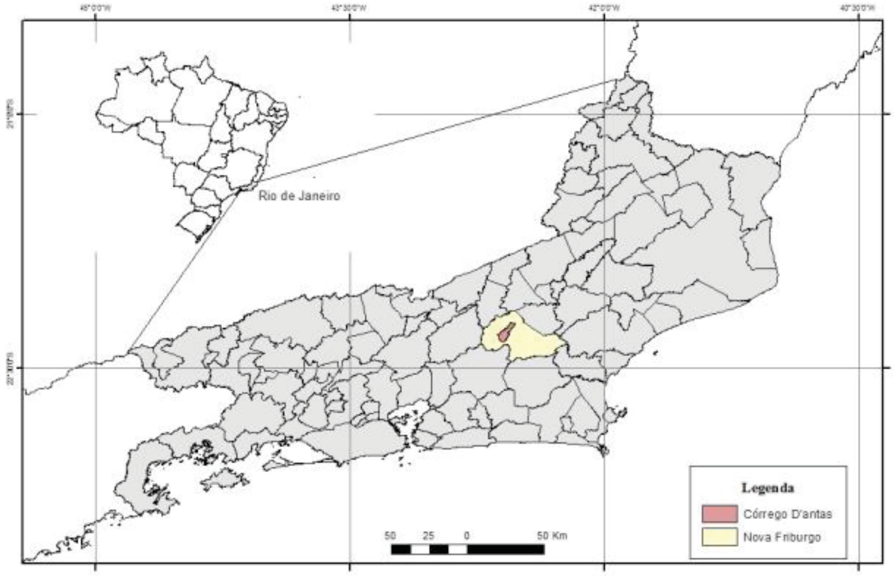

Figure 1. Location of the Córrego D'Antas Basin.

The intense rainfall on the 11th and 12th of January 2011 that hit the mountainous region of Rio de Janeiro gave rise to increases in underpressure resulting from the percolation of water in the fractures and caused the displacement of large volumes of rock, which initiated flows of debris observed in this area.

From the correlation of conditioning factors and the scar inventory regarding the occurrence of debris flows, it was possible to generate a map of natural susceptibility to debris flows in the Córrego D'Antas basin.

The inventory map (Figure 2), containing the cadastral information of 30 debris flows collected from the satellite images of the Google Earth Pro software, dated 01/19/2011 and later imported into the ArcGis software, was used to ponder the classes of each one of the thematic maps, using the cross-tabulation method.

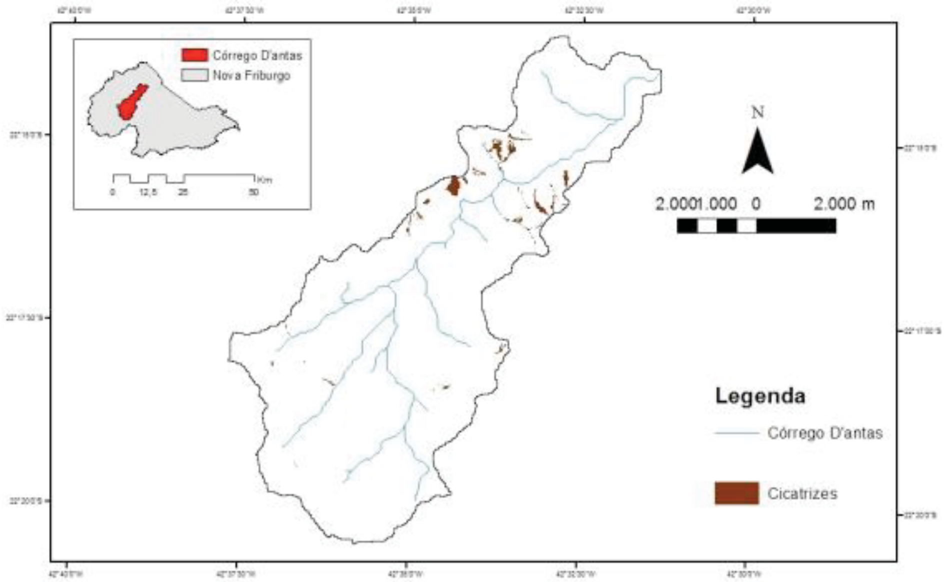

Figure 2. Inventory map of debris flow scars in the Córrego D'Antas Basin.

Figure 3 shows the map of areas naturally susceptible to debris flows to the study area from the proposed methodology, where the areas are scaled from 0 to 1, that is, from least to most susceptible to movement.

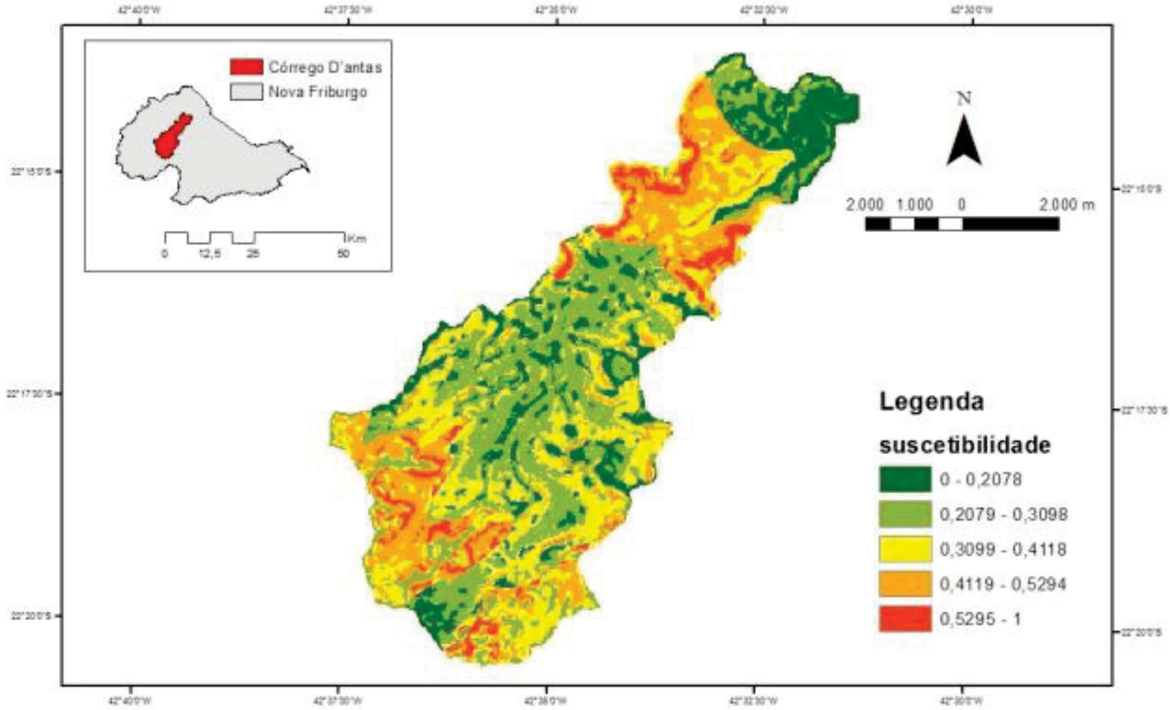

Figure 3. Map of areas susceptible to debris flows.

The map was obtained from thematic maps scaled by the fuzzy linear function, and then each map was weighted by the AHP method, generating factor maps that served as input parameters for the weigthed overlay tool. This tool overlays the layers (factor maps), providing a map of susceptible areas as output data.

The combination of attributes: altitude, slope, vertical curvature, horizontal curvature and geology resulted in the map of natural susceptibility to debris flow that, compared to the inventory of scars mapped on 01/19/2011, showed satisfactory quality. Figures 4 show the area mapped as susceptible to being superimposed on the Google Earth software, corroborating the inventoried scars.

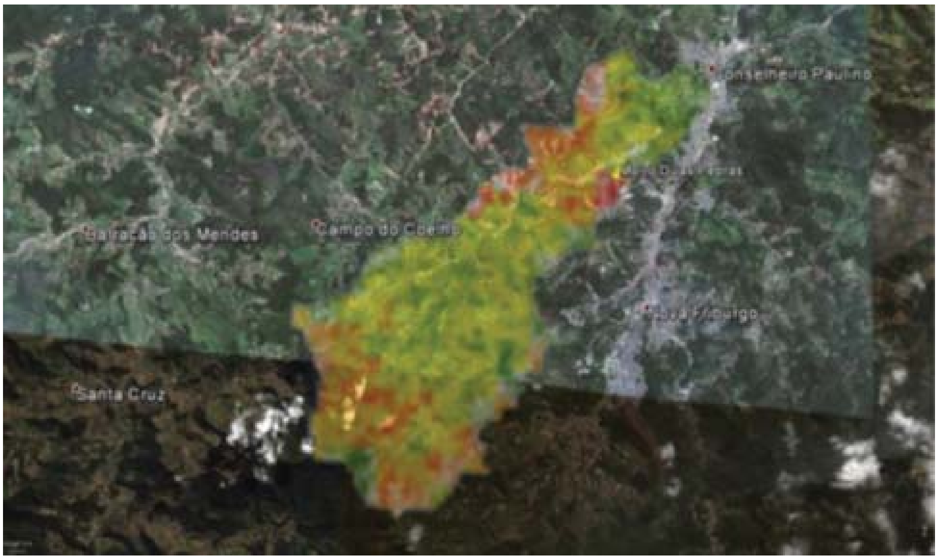

Figure 4. Map overlay of areas susceptible to debris flow in Google Earth.

5 Conclusions

The use of geotechnology to detect areas susceptible to debris flows is an important tool for the application of mitigation and coexistence measures in risk areas. The stages of map generation allow a better understanding of the geological-geotechnical conditions of mass movements.

The new methodology developed is able to represent the events that occurred in the Córrego D'Antas Basin with fidelity and consistency, suggesting its use for detecting areas susceptible to mass movements, mainly debris flows.

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