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Probabilistic Study of Landslide Susceptibility in the Sagrado River Watershed, Brazil

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Abstract: In this paper, we present a probabilistic study of landslide susceptibility at the Sagrado River Watershed in Morretes, Brazil. The area is characterized by slopes higher than 20% in a large part of the relief, variable soil depths, and by strong rainfall intensities due to orographic rains. Taken together, these factors promote the occurrence of translational landslides. Anthropic occupation is distributed along the lowlands and on the less inclined slopes of the Serra do Mar. The infinite slope method was used to determine the distribution of susceptibility to landslides. Input parameters of the model consisted of geotechnical soil parameters, soil layer thickness, slope of the hillside, and matric suction, and the analysis implemented a Monte Carlo probabilistic method. As such, this method allows the quantification of uncertainties due to the variability in geotechnical parameters, which enables the determination of a probability of rupture. The elaboration of susceptibility maps to landslides for unsaturated soil conditions represents a useful tool to support the identification of critical events occurrences in this location.

Key words: Monte Carlo method, landslides, susceptibility assessment, probabilistic analysis.

1. Introduction

Gravitational mass movements are natural processes that are part of the geomorphological evolution of mountain regions. In Brazil, these mass movements are common and recurrent in the south and southeast regions, mainly in the Serra do Mar region. However, the growth of disordered urban occupation in hillside areas has caused a progressive increase in the number of geological accidents associated with these processes. In March 2011, there were more than 2,500 geological accidents on the coast of the State of Paraná [1]. From 1988 to 2022, mass movement resulted in the deaths of 4,146 people, and is the geological process that caused the most fatalities in Brazil [2].

Due to recurring disasters in Brazil, Federal Law No. 12,608 [3] was introduced in 2012 providing guidance for the National System of Civil Defense and Protection and the National Council for Civil Defense and Protection. Additionally, Federal Law No. 12,608 authorized the creation of a disaster information and monitoring system. This law encouraged the Union, states, and cities to adopt necessary actions to reduce the risks caused by natural disasters.

The topography, geology, geomorphology, and processes that lead to instability of an area and the properties and resistance of the soils must be evaluated to carry out adequate analysis of susceptibility to landslides. Due to their high degree of uncertainty, geotechnical problems have been treated through probabilistic analyses. For slope stability studies, probabilistic analyses are conducted using the variability of geotechnical parameters and rainfall events. Furthermore, the use of GIS (Geographic Information Systems) enables the georeferencing of the collected data and assists in the environmental and territorial decision-making processes.

1.1 Definition of the Study Area

The Sagrado River Watershed, with an area of approximately 58.62 km², is located in the city of Morretes, in Serra do Mar (between coordinates UTM-

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E 714.043 and 724.997 and UTM-S 7.173.191 and 7.164.240, time zone 22S).

This watershed is characterized by high slopes, shallow soil depth, frequent vegetation removal by humans and significant orographic rainfall. These conditions promote the occurrence of translational landslides [4]. The anthropic occupation in the Sagrado River Watershed is distributed in the valley bottoms and lower slopes of the hills adjacent to the Serra do Mar.

This area is formed by large deposits of colluvium and talus. The colluvium in this region is highly unstable, prone to planar and rotational landslides, can deliver large volumes of sediment, and form debris flows. Despite being more stable than the colluvium, the talus has a high probability of toppling blocks, providing sufficient material for mass flow. The combination of these unstable materials with high slopes and the vegetation removal results in favorable conditions for gravitational mass movements with high destructive power [1].

2. Material and Methods

The landslide susceptibility distribution is based on infinite slope method, derived from Fiori and Carmignani [5]. Any slope of great extension and with the same soil profile can be considered a slope of unlimited extension. The slope consists of a soil mass subjected to forces due to the weight of material, forces due to water flow, and forces due to shear resistance. These forces act in equilibrium, since the first two add up and tend to move the massif downwards, while the latter resists this movement.

The safety factor of a slope can be calculated using Eq. (1).

$$FS = \frac{C_S + (u_a - u_w) tan\phi^b + \left[\left(\gamma - \frac{h_w}{h}\gamma_w\right) h \cos i\right] tan\phi}{(h\ \ \gamma) \sin i} \tag{1}$$

where C_S represents the cohesion of the soil (kPa); ϕ is the friction angle (degrees); γ is the unit weight of soil (kN/m³); γ_w represents the unit weight of water (kN/m³); h_w is the depth of the saturated soil zone perpendicular to the hillside (m); h is the soil thickness perpendicular to the hillside (m); i is the slope of hillside (degrees); $(u_a - u_w)$ is the matric suction, and ϕ^b represents a parameter that quantifies an increase in resistance due to an increase in suction.

The input parameters of the model consist of the geotechnical parameters of the soil, soil layer thickness, slope of the hillside, and matric suction. To simplify the model, the present analysis omitted the pressure portions of the weight of vegetation on the slopes and the pressure exerted by the wind on the vegetation cover. The saturated soil zone depth was also omitted, as it is generally understood that the water level has no influence on the safety factor in flat areas or in places where the water level is outcropping. In areas with a significant slope, the water level is deep enough so that it does not reach the failure surface adopted in this study [6].

The geotechnical parameters of the soil were determined from laboratory tests of characterization and resistance, and data from previous research. The failure surface depths were estimated from a helicopter flyover of the Sagrado River Watershed. The slope map was prepared from the DEM (Digital Elevation Model) provided by ITCG (Institute of Land, Cartography and Geology of Paraná).

To verify the influence of slope on the susceptibility distribution, Table 1 was used to classify the slope map.

The landslide susceptibility distribution was based on an algorithm developed in Python and inserted into a GIS environment. The algorithm generates the

Table 1 Classification of land relief [7].

Land relief class	Slope (%)
Flat	0-3
Soft wavy	3-8
Wavy	8-20
Strong wavy	20-45
Mountainous	45-75
Steep	>75

necessary files for calculating FS based on the infinite slope method. The generated files are saved in a File Geodatabase (*.gdb) and from this *.gdb the calculation of the probability of occurrence of unstable areas starts from the scenarios generated through Monte Carlo simulations. The variable input parameters used to generate the scenarios are estimated from random numbers within a pre-established range of values. Since the input parameters are independent, that is, the value of one parameter does not influence the value assumed for the other. The developed algorithm is divided into three stages.

2.1 Raster Creation from the Initial Parameters

The average of the unit weight, cohesion, and friction angle parameter values obtained for a given coordinate within the Sagrado River Watershed through laboratory tests were spatialized through a map simplification of rocky substrate and unconsolidated material. The soils were classified according to their origin as sedimentary or residual; however, the group of residual soils was further subdivided based on the original rock due to the significant difference in the properties of the resulting soils. In this way, the following division was obtained: sedimentary soil, residual granite soil, and residual diabase soil.

The value of the suction parameter was determined from the average of data in the literature for a tensiometer installed in Serra do Mar [8-13]. Fixed values of soil depth, unit weight of water, and suction were used for all soils present in the watershed in the form of raster files. These were generated by the algorithm based on the slope raster inserted at the beginning of the model.

2.2 Variation of the Input Parameters and Calculation of the Factor of Safety, FS

The variation ranges of the cohesion and friction angle parameters were given from statistical data analysis obtained in the laboratory and literature. The standard deviations were obtained for each of the soil classes considered, and then the number of pixels present in each of the classes was verified. A weighted standard deviation was carried out to obtain a single range of variation for all soils.

Once the variation range of each of the input parameters has been defined, the safety factor was calculated for each pixel from random variables within the pre-established range of values. When the pixel safety factor was less than 1, the pixel was coded as 1, and when the value of the safety factor was greater than or equal to 1 in a given pixel, it was coded as a 0. Said another way, safety factors considered stable did not make up the sum for determining the probability of rupture. This process was repeated until the established number of iterations was obtained.

2.3 Probability of Rupture

At the end of the iterations, each pixel had a probability of rupture given by Eq. (2).

$$P = \frac{n_i}{n} \tag{2}$$

where P represents the probability of rupture; n_i is the probability of the event occurring or the sum of the number of unstable safety factors; and n is number of elements of the event, namely, number of iterations.

The result of the simulation consisted of a raster of failure probabilities that were classified according to Table 2 to obtain the susceptibility map to landslides of the studied area.

Probability of unsatisfactory performance is the probability that the value of performance function will

Table 2 Adaptation of classification of susceptibility from the reliability indices [14].

Probability of unsatisfactory performance	Degree of susceptibility
0-0.0000003	Null
0.0000003-0.00003	Very low
0.00003-0. 001	Low
0.001-0.006	Below average
0.006-0.023	Average
0.023-0.07	Above average
0.07-0.16	High
0.16-1.0	Very high

approach the limit state or that an unsatisfactory event will occur.

Based on the normal distribution function, the input parameters were classified into fixed parameters and variable parameters. Cohesion, angle of friction, and suction were defined as variable parameters, and fixed parameters were slope inclination, thickness of the soil layer, and unit weight of the soil.

Validation of the susceptibility distribution was obtained from records of landslides in the Sagrado River Watershed from the ITCG database and on-site visits.

3. Results and Discussion

To determine the standard deviation of the input parameters of cohesion and friction angle, data compiled from the literature on soils with the same characteristics as those studied in the Sagrado River Watershed were used [6, 12-13, 15-18].

The values used in the model correspond to the average of the samples for the diabase residual soil due to the absence of laboratory tests. As for sedimentary and residual granite soils, the weighted average of the results of laboratory tests performed with samples obtained in the field was used. The standard deviation corresponded to the weighted average of the standard deviation for each type of soil.

The depth of the soil layer used in the model was 4 m. This value was determined based on the average of estimated depths in the landslide inventory of the Sagrado River Watershed and validated by literature data for translational landslides.

Susceptibility maps were generated after 385 iterations, after which it was considered that there was no significant variation in the susceptibility map based on pixel sensitivity analysis.

The summary of the model's input parameters is presented in Table 3.

Input raster generated determining the probabilistic distribution of susceptibility to gravitational mass movements in the Sagrado River Watershed is shown in Fig. 1.

From the comparison between the results obtained for the susceptibility map and with the slope, it was noted that areas with high and very high susceptibility occurred only in reliefs considered mountainous and steep. It was also observed that below average, average, and above average susceptibility classes occur practically only in mountainous relief. Slopes lower than 45% did not influence the determination of susceptibility, as they presented null susceptibilities.

Subsequently, the "buffer" tool was used in the GIS environment to analyze landslides and residences. When comparing the landslide points with the susceptibility map, it was observed that only 34.5% of the movements occurred in unstable areas, being: 5.6% in below average susceptibility areas, 3.0% in average areas, 4.3% in areas of above average susceptibility, 7.3% in high and 14.3% in areas of very high susceptibility. Therefore, 65.5% of mass movements in the area with susceptibility to gravitational mass movements are considered null.

The results of the quantitative analysis of the occurrence of each susceptibility class in terms of percentage of area is shown in Fig. 2.

For validation consideration, when only the polygons resulting from the mapping of scars from the 2011 event were used, the percentage of null susceptibility area affected by landslides decreases to 55.1%. Thus, the susceptibility distribution in unstable areas becomes: 6.3% in below average susceptibility areas, 3.2% in average areas, 6.3% in above average susceptibility areas, 10.8% in high susceptibility and 18.3% in areas of very high susceptibility.

Table 3 Summary of the model's input parameters.

Type of unconsolidated material	Cohesion (kPa)	Friction angle (degree)	Unit weight (kN/m^3)	Suction (kPa)
Sedimentary soil	15.0 ± 6.0	27.0 ± 6.0	16.3	9.0 ± 7.0
Residual soil—granite	7.0 ± 6.0	38.0 ± 6.0	16.8	9.0 ± 7.0
Residual soil—diabase	11.0 ± 6.0	28.0 ± 6.0	14.1	9.0 ± 7.0

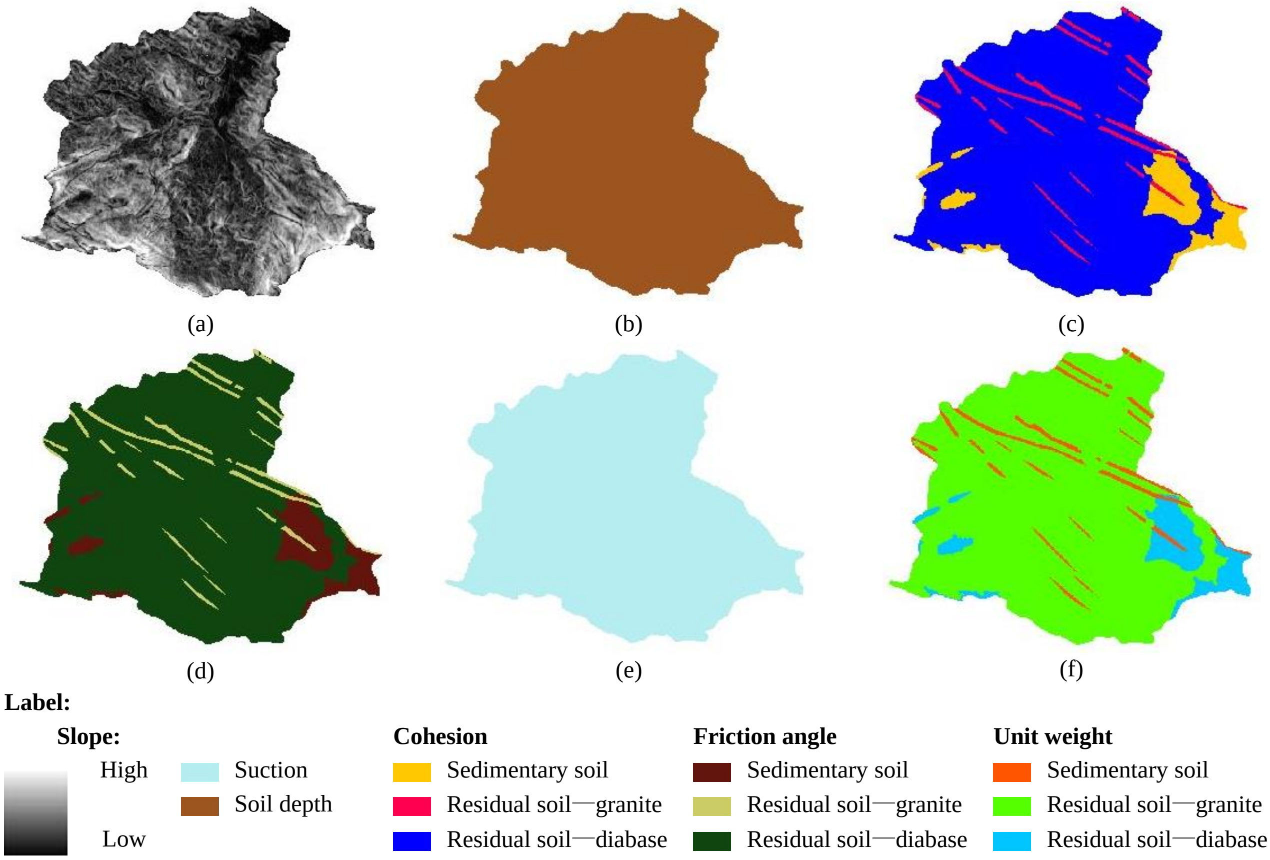

Fig. 1 Input raster. (a) slope; (b) soil depth; (c) cohesion; (d) friction angle; (e) suction; (f) unit weight.

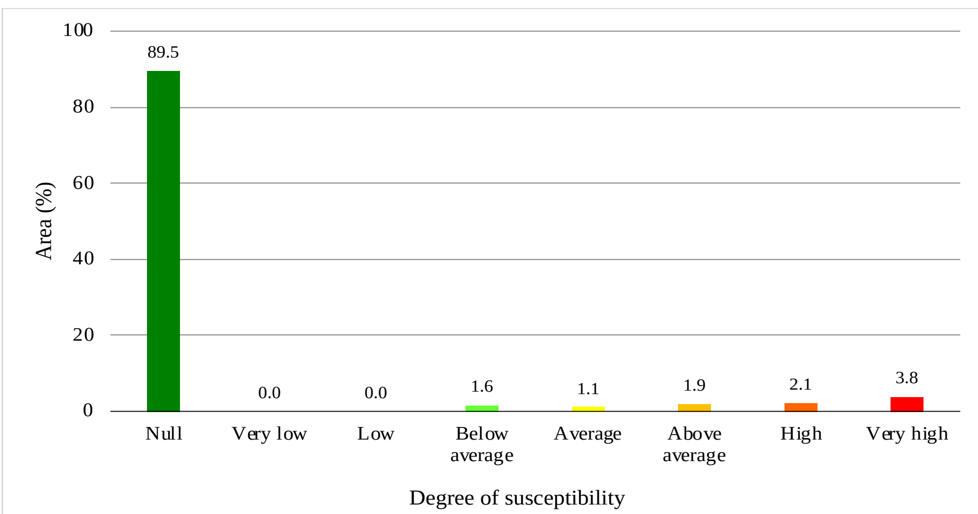

Fig. 2 Distribution of susceptibility classes.

3.1 Back Analysis

Due to the low representativeness of the map generated for the Sagrado River Watershed for the unsaturated soil condition, a back analysis of the resistance parameters for this soil saturation condition was also conducted, considering the same criteria as the original analysis. Table 4 presents the summary of the input parameters used in the back analysis, and Fig. 3 illustrates the susceptibility map obtained as a result of the back analysis with a 30%* reduction in resistance parameters.

Table 4 Summary of the model's input parameters.

Type of unconsolidated material	Cohesion (kPa)	Friction angle (degree)	Unit weight (kN/m^3)	Suction (kPa)
Sedimentary soil	10.5 ± 6.0	18.9 ± 6.0	16.3	9.0 ± 7.0
Residual soil—granite	6.0* ± 6.0	26.6 ± 6.0	16.8	9.0 ± 7.0
Residual soil—diabase	7.7 ± 6.0	19.6 ± 6.0	14.1	9.0 ± 7.0

* The reduction of the cohesion parameter of the granite residual soil was restricted to 25% of the initial value due to the limitation of null cohesion.

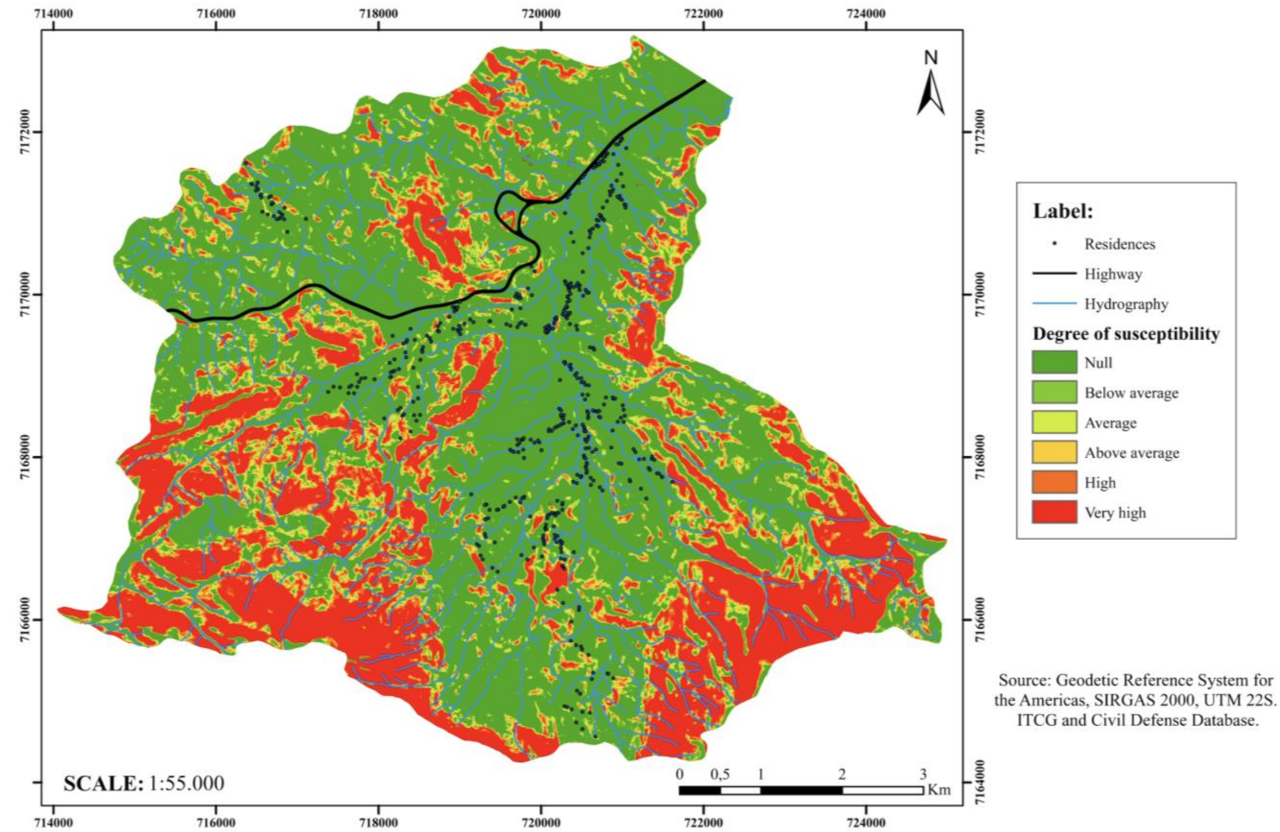

Fig. 3 Landslide susceptibility map obtained from back analysis of resistance parameters.

Fig. 4 summarizes the results of the quantitative analysis of the susceptibility class occurrences in terms of percentage of area from the back analysis. When comparing these values with the percentages obtained with the original parameters, we see a reduction of 32% in the area that was considered null susceptibility. The increase in the area of very high susceptibility was approximately 17%, evidenced by the fact that the parameters obtained in the laboratory do not reflect *in situ* characteristics. Moreover, suction significantly influences the susceptibility of the region since it increases the soil resistance to shear.

Comparing the points of slippage with the susceptibility map generated with a 30% reduction in the resistance parameter values, it is observed that the distribution of susceptibility in the scars of the landslides became: 12.8% in an area of null susceptibility, 2.8% in below average susceptibility, 4.6% in average areas, 4.9% in areas of above average susceptibility, 8.7% in high susceptibility and 66.2% in areas of very high susceptibility. Therefore, 87.2% of gravitational mass movements occurred in unstable areas, a significant increase in adherence when compared to the map generated with parameters obtained in the laboratory test.

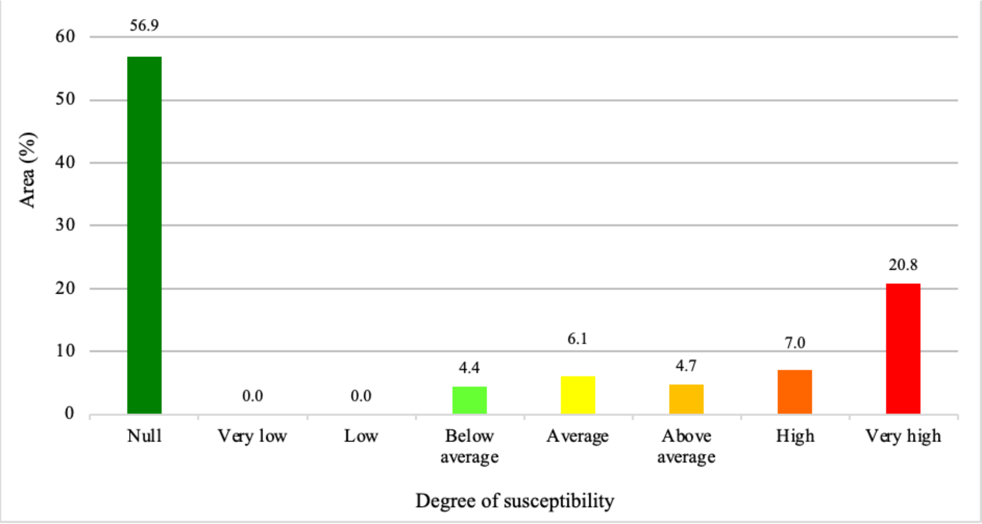

Fig. 4 Distribution of susceptibility classes resulting from the back analysis.

Regarding the areas of registered residences in the Sagrado River Watershed, we found that 95.4% of the area in places of null susceptibility, 1.4% in areas of below average susceptibility, 1.2% in places of average susceptibility, 0.5% in above average susceptibility, 0.6% in high susceptibility and 0.8% in areas of very high susceptibility. In summary, 4.6% of this area is in places with some degree of instability, showing the need to monitor residences in this location.

5. Conclusions

The elaboration of landslide susceptibility scenarios in the Sagrado River Watershed was the main challenge of this work, due to limited computational capacity which constrained cohesion, friction angle, and suction variable parameters, as well as the number of iterations. Despite the difficulties in determining the susceptibility distribution, the results obtained through the back analysis of the soil resistance parameters are considered satisfactory. Approximately 87.5% of the percentage of scar pixels mapped in areas have some degree of instability. Finally, it is concluded that the algorithm used for the elaboration of susceptibility map from the Monte Carlo probabilistic method, inserted directly in the GIS, has a high potential for development and enhancement to increasingly refine subsequent susceptibility analyses.

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