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Research article

Landslide susceptibility mapping based on rainfall scenarios: a case study from Sao Paulo in Brazil

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Abstract: Mass movement susceptibility mapping from rainfall data and in situ site characterization constitute an important approach for preventing geological-geotechnical accidents on railroads and highways. A comprehensive site characterization program was conducted to identify slopes with mass movements along the 44 km of SP-171 road in the state of São Paulo, Brazil. Ninety-two slopes with some degree of instability were found along this section of the road, including rupture scars, active erosive processes and the presence of unstable rock blocks. Two scenarios for mass movement susceptibility (100 mm and 500 mm of accumulated rainfall) were defined by overlaying thematic maps of relief, soil type, geology, accumulated rainfall and declivity using geographic information system-based techniques. The results for both scenarios identified the regions with high and medium susceptibility to mass movements; for the scenario of 100 mm of accumulated rainfall; we found that 27% and 73% of the land area of SP-171 is respectively highly and moderately susceptible to landslide events. For the scenario of 500 mm, we found 58% and 40% to be highly and moderately susceptible areas. This study also allowed us to identify the main geotechnical problems along the 44 km of this road, and thus can be used to guide actions and decisions to avoid or minimize such problems.

Keywords: geotechnical cartography; GIS; landslide studies; susceptibility; rainfall

1. Introduction

The identification of landslide areas through the use of a mapping database is an essential tool to the prevention and mitigation of landslide hazards and losses [1,2]. There have been important studies about landslide susceptibility mapping techniques from various countries that have produced a regional landslide susceptibility map, such as fuzzy-based multiple decision techniques, geographic information system (GIS)-based logistic regression techniques, C5.0 decision tree and k-means clustering algorithm-based methods and hybrid ensemble machine learning methods [3–6]. However, many roads in Brazil suffer every year in the rainy season because of damage caused by landslides. Thus, the application of mapping techniques to highways that relate the factors of the physical environment, such as the type of soil, geology, relief, slope and rainfall are essential for the safety of road users.

Roads built in regions naturally susceptible to mass movements are relatively common in Brazil, such as the SP-171 road, which connects two municipalities, Guaratinguetá to Cunha, in the state of São Paulo, Brazil. They are located between two mountain ranges: Serra da Mantiqueira and Serra do Mar. Every year, landslides block this road during the rainy season, making it unsafe; an example is the landslide that mobilized a large volume of geomaterials on November 29, 2017 [7].

There is a lack of landslide records and rainfall data for this region despite the relationship between rainfall events and landslides. Thus, an alternative is to use the satellite rainfall data to overcome the limitations of ground-based techniques [8]. Studies on the physical characteristics of the region have been conducted since 1998 [9–13], and these studies show that mass movements are related to geology, relief, soil type and declivity; however, they have disregarded the rainfall data.

Classes of low and moderate level water infiltration capacity in the soil were obtained in the study region [14]. The use of cartographic techniques integrated with in situ site characterization is important to identify the susceptibility of the physical environment to road slope instability [15]. Geoprocessing techniques allowed the overlaying of thematic maps of the region; thus, it was possible to show the correlation between slope, geology, relief and soil type to study landslide susceptibility [16]. The in situ georeferencing is very important to establish the correlation between biophysical variables in geotechnical road mapping [17].

In the study region, the Instituto de Pesquisas Tecnológicas from the state of São Paulo, Brazil, mapped the susceptibility to mass movements for the municipalities of Guaratinguetá [18] and Cunha [19], where the SP-171 road is located. These maps show that many sections of this road have medium-to-high susceptibility to mass movement. However, they only pointed out the locations with the susceptibility of the natural slopes, disregarding those areas where anthropic interventions occurred, such as the cutting of slopes [20]. In addition, the relationship between rainfall and associated mass movements is still incipient in the region.

This paper describes the relationship between the rainfall data and the events of landslides that occurred in the region of study because many roads in Brazil are susceptible to this hazard in the rainy season. Based on the mapping techniques used, the road SP-171 could be regionally evaluated. In addition, this paper details an application of cumulative rainfall and related thematic maps to determine landslide susceptibility as an approach to highway hazard management; this was achieved by evaluating two scenarios of susceptibility to mass movement on the SP-171 road: one for 100 mm of accumulated rainfall, and another for 500 mm. The study also allowed us to identify the main geotechnical problems along the 44 km of the SP-171 road by in situ site characterization. Five landslide-relevant factors were considered in the input dataset and used to calculate the landslide occurrence: relief, soil type, geology, accumulated rainfall and declivity using GIS techniques.

2. Case study

The SP-171 road, along with its entire extension, spans Vale do Paraíba to Southern Rio de Janeiro, connecting Guaratinguetá, which is the state of São Paulo, to Paraty, which is the state of Rio de Janeiro. The section of the SP-171 road selected for this study is called Rodovia Paulo Virgínio; it runs between Guaratinguetá and Cunha and spans 44 km (Figure 1) under the administration of the São Paulo Highway Department (DER - DR6). There is an area of 44 km^2 along the 500-m route from the axis of the road.

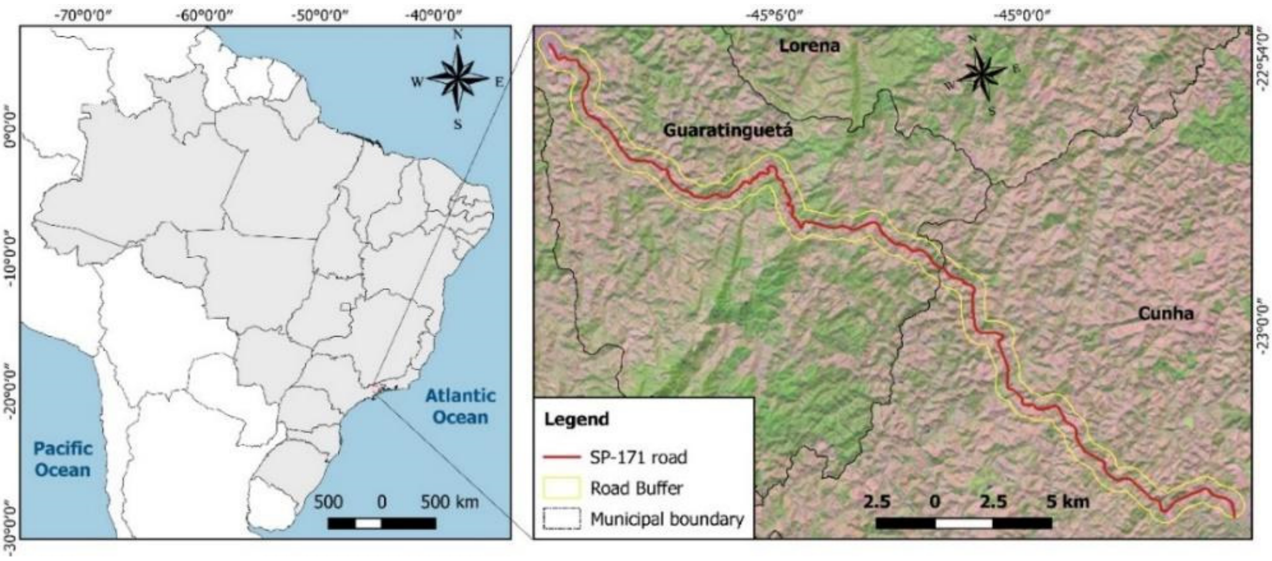

Figure 1. Location of the SP-171 road.

The SP-171 road lies in a mountainous region of the Atlantic Plateau, between the escarpments of Serra do Mar (Coastal Province) and the Middle Vale do Paraíba (depression of the graben of Paraíba), with a crystalline base (migmatitic and granitic rocks) and recent sediments (Quaternary) [21]. Another relief characteristic to be studied at the site is the Serra do Quebra Cangalha. The Serra do Quebra Cangalha acts as a watershed, with Serra do Mar to the east and Serra da Mantiqueira to the west. The vulnerability to natural processes in the Quebra Cangalha Mountains demonstrated a high association between geology, geomorphology and soil type [22]. The region has a humid climate with average monthly rainfall in Guaratinguetá and Cunha of 110 mm and 122 mm, respectively. The greatest rainfall occurs in the summer season (December to February), with monthly rains higher than 200 mm [23].

3. Methods and materials

Both field and office work were conducted. Thematic maps of the region were overlapped and a detailed survey of the landslide data that were related to rainfall events was conducted. The Global Positioning System was used to identify the coordinates of the slopes along the road. The slope stability conditions were evaluated in situ and placed on the map. Data of historical landslide occurrences on the SP-171 road causing the closure were obtained from the DER/SP for the past 10 years, i.e., 2009–2019. A total of 17 locations on the road were closed due to landslide events. Since the DER/SP report does not contain rainfall data, a survey was conducted to gather data on the accumulated rainfall before each closure event in 24, 48 and 72 hours and for 10, 15 and 30 days. The Tropical Rainfall Measuring Mission 3B42RT satellite with a resolution of 0.25° [24] allowed us to produce the rainfall data.

Landslides were analyzed in relation to rainfall occurrences by applying cartography techniques for two scenarios of susceptibility, i.e., up to 100 mm and 500 mm of accumulated rainfall. The average rainfall was obtained based on Embrapa [17] data in the region for the 100 mm scenario. The Preventive Plan of Civil Defense [25] also established this value of accumulated rainfall for the municipalities located in Vale do Paraíba and in Serra da Mantiqueira. The critical rainfall value was set to be 100 mm for the historic valley and 80 mm for the Serra da Mantiqueira in a period of 72 hours. It also established data for the 500 mm scenario based on rainfall values recorded in different locations in Brazil.

The thematic maps used on the QGIS software were as follows:

- Digital elevation model with a resolution of 12.5 m in raster/TIFF format, as provided by the Alaska Satellite Facility [26].
- Geology mapping made available by Companhia de Pesquisa de Recursos Minerais in the vector/shapefile format on a 1:250,000 scale [27].
- Relief patterns on the scale of 1:25,000 in vector/shapefile format [28].
- Maps of soils on a scale of 1:500,000 in the vector/shapefile format [29].

The layers were generated in a raster format, with continuous rainfall values of 100 and 500 mm, to determine the susceptibility at each level of accumulated rainfall. Data from Guaratinguetá and Cunha were used for the susceptibility scenarios for the road axis and 500 m outward (buffer area).

The proposed scenario was established by overlaying the thematic maps (Figure 2). Weights from zero to one were defined for each layer to differentiate the degree of importance and establish correlation with the mass movements that frequently occur on the SP-171 road. Thus, several weight combinations were assumed for each layer of information and the corresponding variables representing the physical environment. The approach that showed the highest correlation with the field observation had the following values: geology = 0.10, relief patterns = 0.10, soils = 0.10, rainfall = 0.20 and slope = 0.50. The variables were valued from one to five within each layer of information. The greater the value, the greater the relevance of each attribute in the susceptibility analysis to mass movement at the studied site.

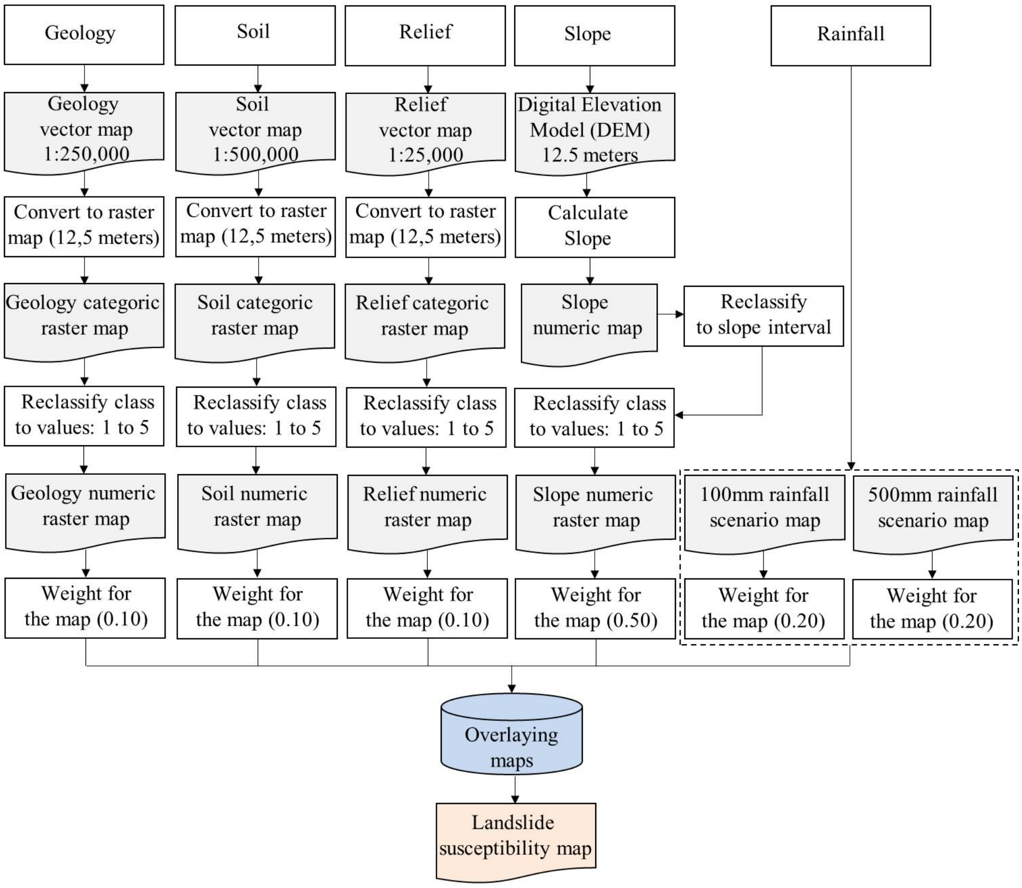

Figure 2. Thematic mapping techniques.

The calculation of susceptibility (S) was performed using the following equation:

$$S = (\text{Geology} \times 0.10) + (\text{Soil} \times 0.10) + (\text{Relief} \times 0.10) + (\text{Slope} \times 0.50) + (\text{Rainfall} \times 0.20)$$

The susceptibility map resulted in values between 2 and 5 that were reclassified in consideration of equal intervals to determine the low, medium and high classes (Table 1).

Table 1. Class and susceptibility values.

Value Susceptibility	Class Susceptibility
2.00 to 2.99	Low
3.00 to 3.99	Medium
4.00 to 5.00	High

4. Results and discussion

4.1. Site assessment and cartographic analysis

Fieldwork showed that the most common geotechnical problems on the SP-171 road are landslides, erosion and rockfalls. We found a total of 51 points with erosive processes, 34 points with landslides scars and 7 points with loose rocks from a landslide inventory containing 92 slopes (Figure 3). Erosion spots tend to occur at several points along the stretch of the SP-171 highway; however, landslides predominate the Guaratinguetá stretch. The points of rockfalls were found to be located along the stretch between the limits of the municipalities corresponding to the Serra do Quebra Cangalha.

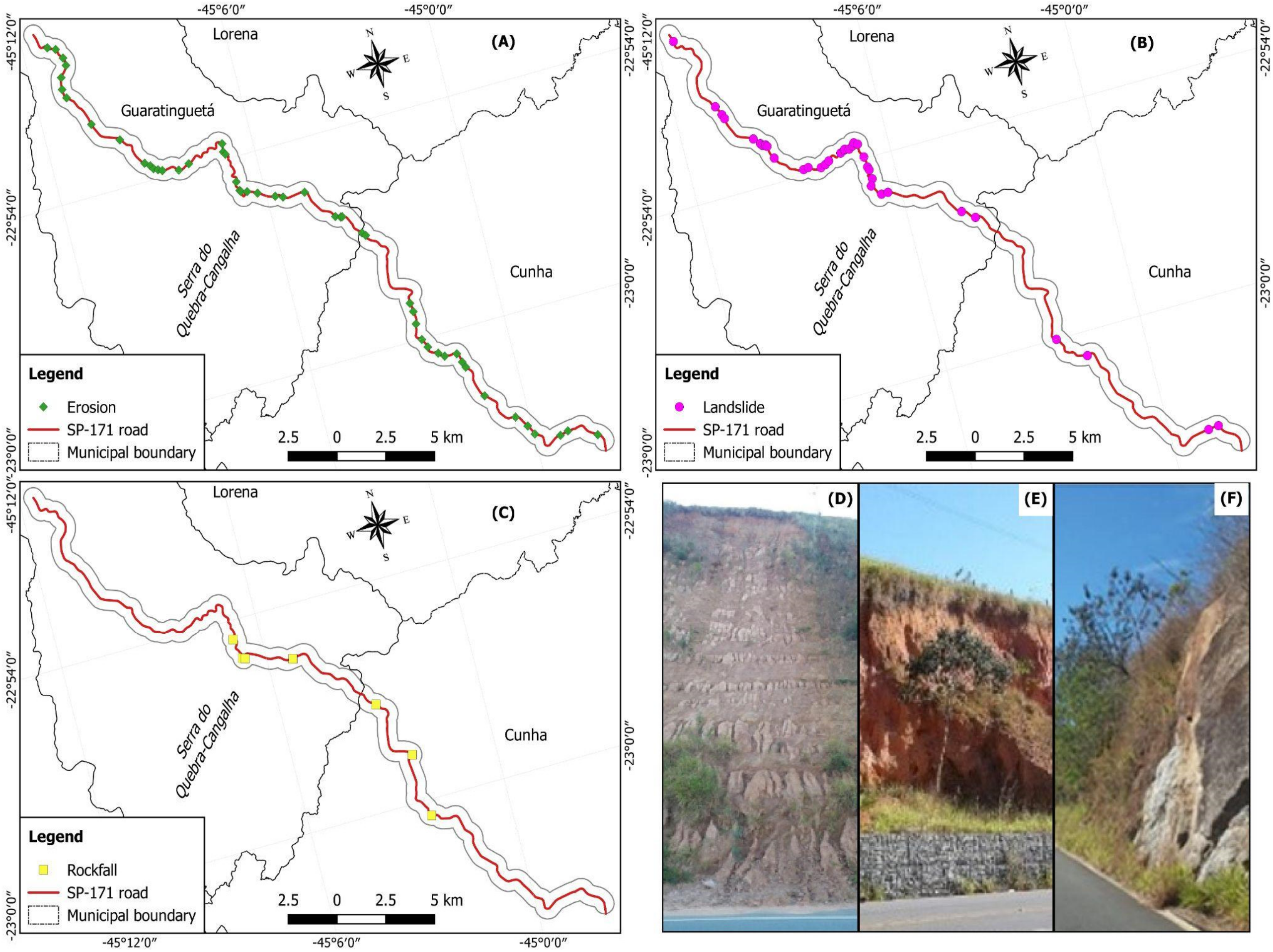

Figure 3. Main geological-geotechnical problems and their typical locations in the area: erosion (A), landslides (B) and rockfalls (C). Examples of erosion (D), sliding (E) and loose rocks and block falling (F).

The potential for soil erosion along the road is high, and it is associated with the intensity of rainfall during the summer, the lack of native vegetation cover, steep slopes and the presence of sandy-to-silty soils [30]. Besides the conditioning factors of the physical environment, anthropic action, such as deforestation, fires and changes in the original geometry of the slopes due to the cuts made to install the road, causes changes in the original physical characteristics of the soil. Unfortunately, cattle grazing eliminated the native vegetation, leaving the soils along the road exposed to weathering, which increases the susceptibility to mass movement [14].

The road crosses five types of reliefs: river plains and terraces, hills, isolated hills, low hills and mountains, with a predominance of low hills. The slopes of Serra do Quebra Cangalha (Guaratinguetá) presented the most geological-geotechnical problems. In this section of the SP-171 road, we observed 30 points to undergo active erosion processes, as well as sliding, which is a long strip of hills that seems to be in a state of instability near Cunha.

The soil map indicated the presence of oxisols, cambisols and argisols. Special attention was paid to the occurrence of oxisols in mountainous reliefs due to the high potential for mass movement [31], 52 slopes were found. The geological map shows the predominance of two lithological units: migmatites (58 slopes) and granitoid suites (36 slopes). The points with erosion, falling blocks and landslides scars are mainly on the slopes higher than 20°, the slopes between 5° and 15° (36 slopes) and the slopes between 15° and 25° (41 slopes), respectively. Figure 4 shows the physical aspects of the road and the points of the slopes.

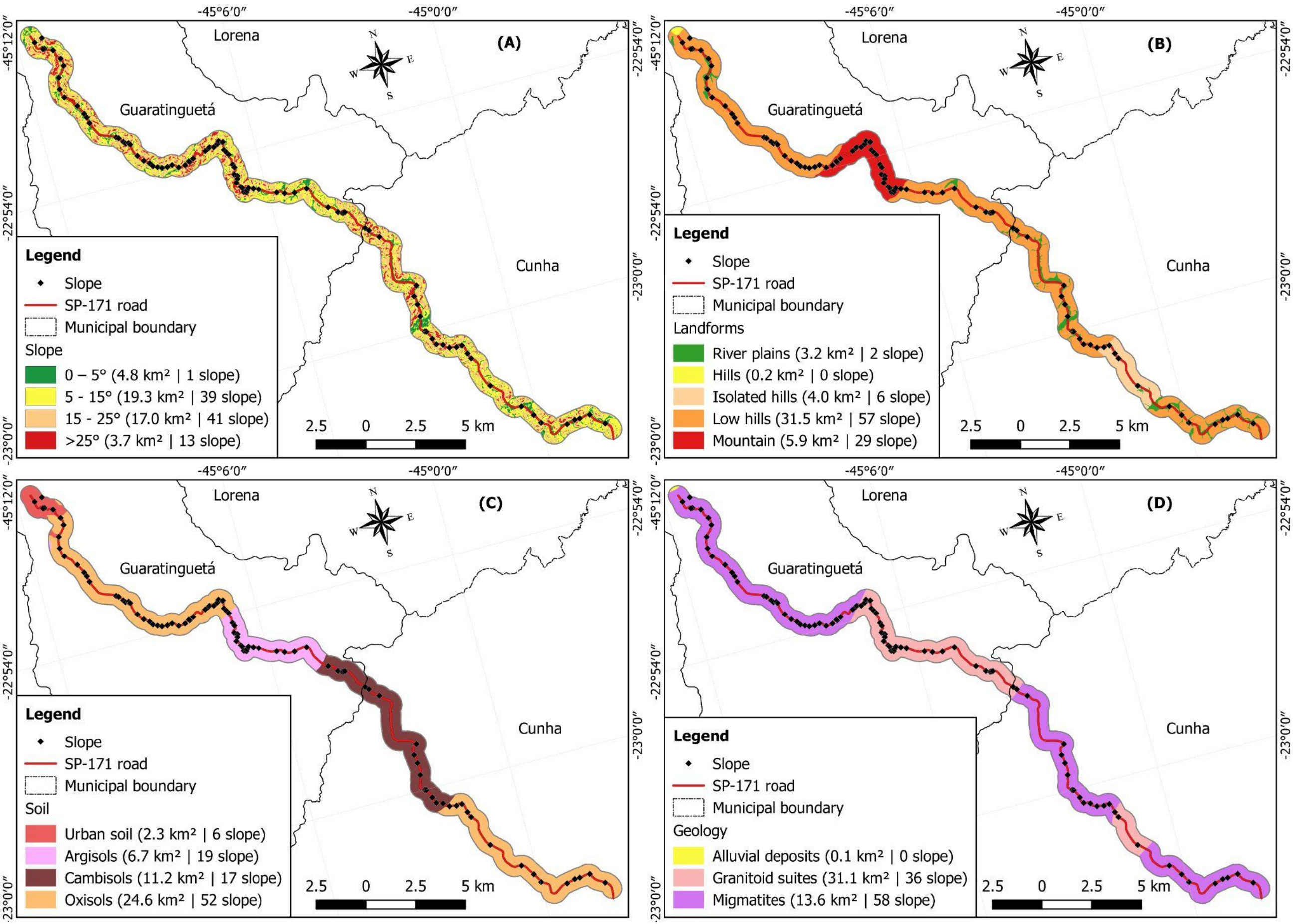

Figure 4. Physical aspects: slope (A), landforms (B), soils (C) and geology (D).

4.2. Scenario of susceptibility to mass movement due to 100 mm of accumulated rainfall

As obtained from DER/SP, the records of road closures due to landslides that were analyzed along with the rainfall data close to the date of the event showed that the value of 100 mm is recurrent for SP-171 road. For example, a landslide occurred on October 1, 2013 due to 73.93 mm of rainfall over a period of 24 hours. The 72-hour accumulated rainfall exceeded 110 mm for this event, which occurred in a place of high susceptibility in the 100 mm accumulated rainfall scenario. Another rupture (identified as Q in Figure 5) occurred as 128.25 mm of rainfall accumulated over 30 days, corresponding to the medium-susceptibility scenario.

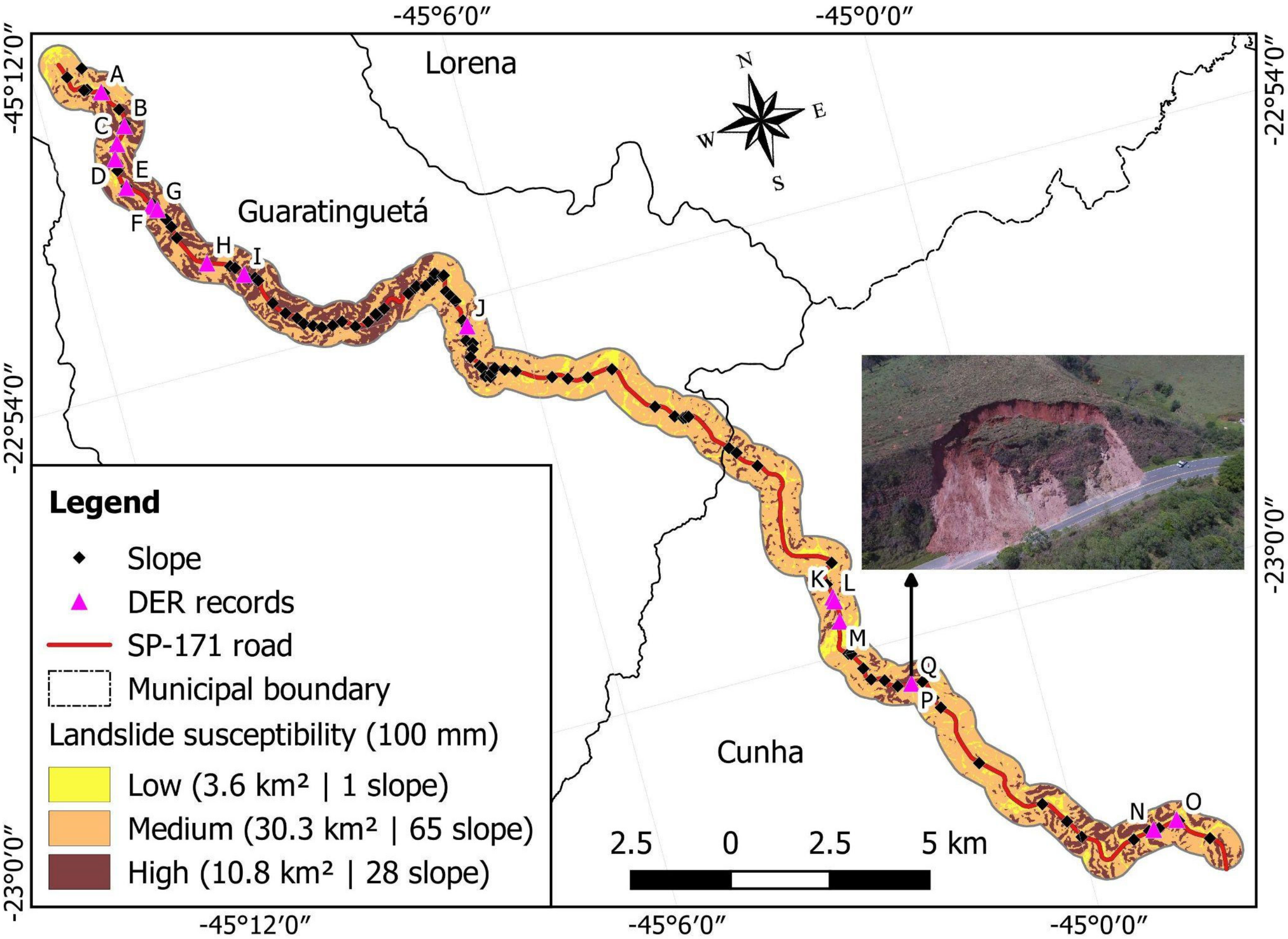

Figure 5. Scenario of mass movement susceptibility for 100 mm accumulated rainfall.

We observed 28 locations with high susceptibility and 65 locations with medium susceptibility for mass movement by considering all of the slopes with geotechnical problems. Six slopes were found to be in the high-susceptibility class, and 11 slopes were found to be in the medium-susceptibility class according to the road closure records from DER-SP. In terms of area, 10.8 km^2 of the road belongs to the high-susceptibility class, 30.3 km^2 belongs to the medium-susceptibility class and only 3.6 km^2 belongs to the low-susceptibility class. Slopes with geotechnical problems or rupture records were found to belong to the low-susceptibility class for mass movement.

Only the slopes less than 5° showed low susceptibility to mass movement for the 100 mm scenario. Slopes up to 8° are sufficient to trigger laminar flow and groove formation. Mass movement (creep and landslides), laminar flow, grooves and ravines can occur for slopes between 8° to 20° (undulating relief) [32].

4.3. Scenario of susceptibility to mass movement due to 500 mm of accumulated rainfall

An increase to the high-susceptibility class was observed along the entire road for the 500-mm scenario, especially for the section near Cunha. The SP-171 road was found to be under medium-to-high-susceptibility conditions over most of its length for this volume of rainfall. Low-susceptibility conditions would occur only for slopes less than 5°, which represents approximately 2% of the road in terms of area. The slopes that showed some type of mass movement at the site were classified as being between medium and high susceptibility (Figure 6). For the susceptibility scenario with 500 mm, the number of high susceptibility slopes increased from 28 to 57 slopes.

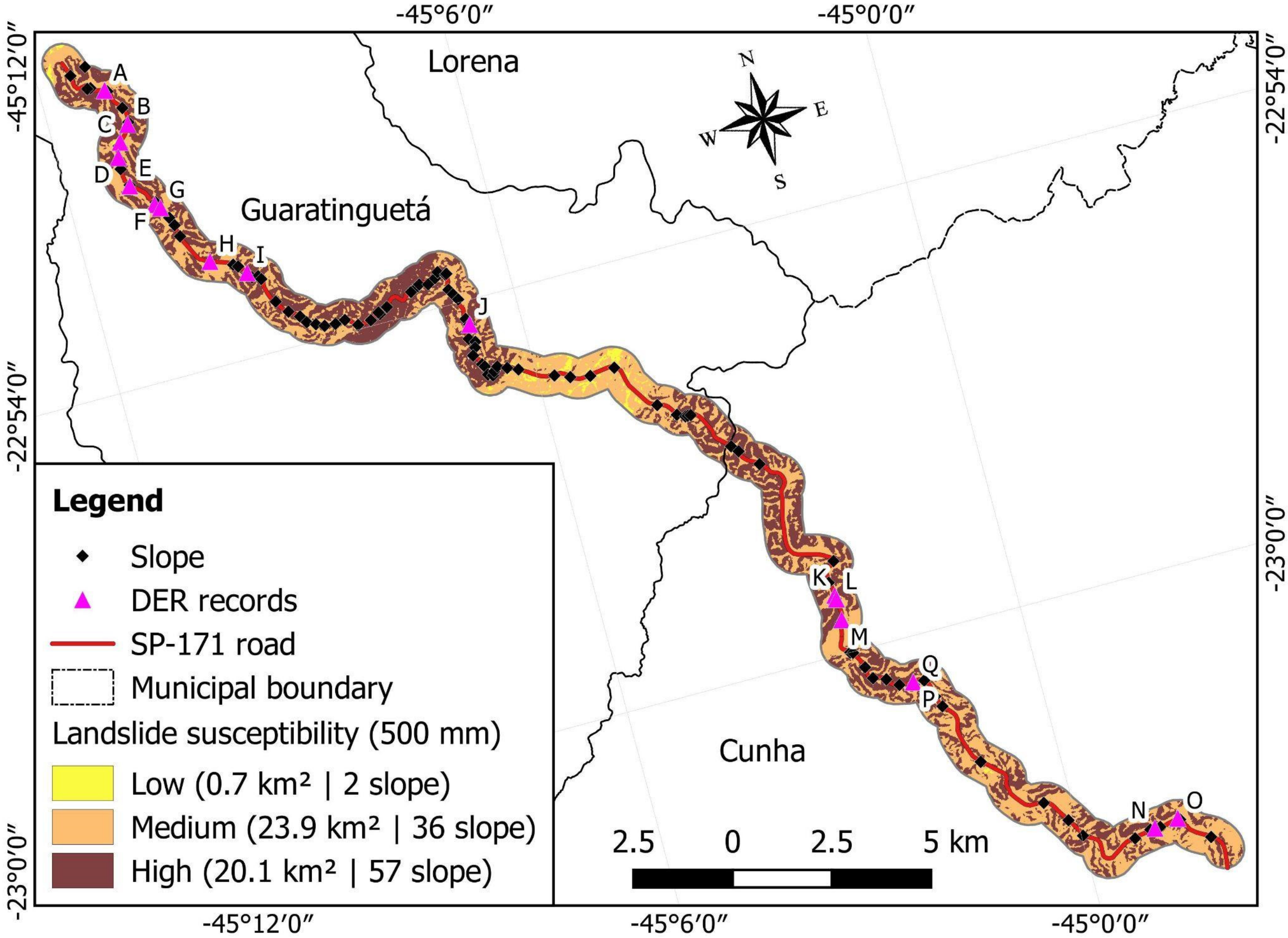

Figure 6. Scenario of susceptibility to mass movement due to 500 mm of accumulated rainfall.

On December 14, 2015, an interruption of the SP-171 road due to a landslide at the 34.50 km point occurred; there was rainfall accumulation of 348.54 mm over 30 days. The 500 mm amount of rain is not often registered in the region; however, catastrophic events have occurred in Brazil due to this amount of rain. For instance, the case of Angra dos Reis, Rio de Janeiro, in January of 2010, which registered 417 mm of accumulated rainfall over a period of less than 48 hours. This disaster caused the death of nine people and 80 missing people [33].

4.4. Rainfall records for landslide events

According to the collected data, it is possible to identify the relationship between landslides along the SP-171 road and the rainy season. Only one landslide (at the 3.4-km point) occurred without rain in the first 24 hours, that is, only one landslide occurred amid the lack of rain; however, 62.91 mm of accumulated rainfall was observed over 10 days. Rainfall accumulation can be sufficient to trigger mass movement, depending on the infiltration capacity, permeability and soil type, even after the rain event [34].

Two other sites, one at the 34.5 km point (on November 29, 2017) and the other at the 16.0 km point, also showed no significant daily rainfall to trigger landslides. It was noted that the 10 days of accumulated rainfall could have been an indicator of these events. Regarding the rain incidence, it was observed that the events occurred after three consecutive days of rain.

Table 2 presents the accumulated rainfall for the day of the road closure record, and for 2, 3, 4, 10, 15 and 30 days before the event; it also presents the number of consecutive days that the rain occurred.

Table 2. Rainfall amount for landslide events recorded by DER/SP.

		Rainfall Records (mm)							
Event	km	24 h	48 h	72 h	96 h	10 days	15 days	30 days	Frequency
Jan 10, 2013	3.0	35.8	38.4	38.5	61.5	94.9	130.6	225.5	4 days
Jan 10, 2013	4.2	35.8	38.4	38.5	61.5	94.9	130.6	225.5	4 days
Jan 10, 2013	1.5	35.8	38.4	38.5	61.5	94.9	130.6	225.5	4 days
Jan 11, 2013	2.5	73.9	109.7	112.3	112.5	161.2	202.7	294.9	5 days
Dec 12, 2015	43.0	0.4	1.3	14.5	14.5	89.3	189.7	301.6	8 days
Dec 12, 2015	34.5	34.5	56.9	57.4	58.3	121.7	239.9	348.5	10 days
Dec 14, 2015	43.5	34.5	56.9	57.4	58.3	121.7	239.9	348.5	8 days
Mar 29, 2016	16.0	5.3	5.3	5.4	12.1	30.5	40.6	133.3	7 days
Jan 08, 2017	5.1	12.6	13.2	16.0	16.0	37.4	61.3	168.6	3 days
Jan 08, 2017	7.0	12.6	13.2	16.0	16.0	37.4	61.3	168.6	3 days
Jan 08, 2017	8.2	12.6	13.2	16.0	16.0	37.4	61.3	168.6	3 days
Nov 29, 2017	34.5	1.0	3.4	7.3	13.9	86.7	108.8	128.9	4 days
Jan 08, 2018	31.1	25.2	53.7	60.4	60.4	104.0	167.2	201.9	19 days
Jan 22, 2018	31.0	19.5	24.7	37.9	38.6	84.0	149.3	296.6	11 days
Jan 22, 2018	31.5	19.5	24.7	37.9	38.6	84.0	149.3	296.6	11 days
Mar 16, 2018	3.4	0.0	20.6	20.8	22.9	62.9	118.7	196.2	3 days

It is worth mentioning that mass movements on the SP-171 road can also occur at low rainfall, e.g., approximately 20 mm in 24 hours or close to 100 mm in 10 days; an example is the event that occurred on November 29, 2017. This failure occurred under the conditions of a cumulative rainfall of approximately 130 mm over 30 days and 0 mm in 24 hours. Low rainfall amounts have a shorter return period and, therefore, occur more frequently. This shows the need for corrective measures to avoid disasters and recurrent traffic disruptions. Furthermore, special attention must be paid to the sediments on the eroded slopes, which can compromise the galleries and drainage systems, reducing their efficiency. Thus, immediate interventions are required for the most critical slopes.

5. Conclusions

Susceptibility mapping was performed to address the fragility of the SP-171 road considering the influence of the region's rainfall on the slope stability. The scenario of mass movement susceptibility for 100 mm of accumulated rain was found to be consistent with the slope instabilities observed in situ, and with those reported by the DER/SP.

The precipitation data indicate that the observed mass movements were associated with values close to 100 mm over 10 days, as well as the occurrence of three consecutive days of rain. For this scenario, 10.8 km^2 of the road was found to be in the high-susceptibility class, with 65 slopes having medium susceptibility. For the 500 mm accumulated rainfall scenario, an area of 20.1 km^2 was found to be in the high-susceptibility class, with the presence of 57 slopes. Special attention should be given to the road section near Cunha due to the high susceptibility to mass movement. It is also important to observe the conditions of the slopes near the Serra do Quebra Cangalha site due to the presence of unstable loose rocks, intense erosion processes and the large number of slopes with landslide scars.

As a first step in regional risk management, this study involved applying rainfall data and the available data on relief, soil, geology and slope characteristics to construct overlaying maps. A weakness of this technique is that the results of this approach are partly subjective, and that the weighting capacity performed varies according to the knowledge of the experts. Also, the scales of the thematic maps used for the overlay of the maps should be in a more approximate scale to better reflect the characteristics of each parameter. However, this technique is consistent with what has been observed on site and suitable for regional studies.

The information contained in the study can be improved in the future and used to establish rainfall thresholds in order to prevent disasters such as those that have been occurring in recent years in the rainy seasons. Rain thresholds can be used for risk prediction, the monitoring of limits and the assurance of forecast alerts from civil defense to the people who use the road every day. The obtained susceptibility map is suitable for application to landslide risk management practices.

Further studies on rainfall thresholds for landslides are required due to the persistent climate changes that cause shifts in the volume, and due to the intensity of rainfall, which causes many landslide disasters on road slopes. This road is also a promising place to conduct studies on the influences of geometry, rock depth [35,36] and vegetation on slope stability. Also, the modeling of landslide susceptibility could be evaluated using machine learning algorithms such as random forests and support vector machines [37,38].

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Conflicts of interest

All authors declare no conflicts of interest regarding this study.

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