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LANDSLIDE RISK MANAGEMENT USING THE MATHEMATICAL MODEL TRIGRS

GESTÃO DE RISCO A DESLIZAMENTOS DE TERRA UTILIZANDO O MODELO MATEMÁTICO TRIGRS

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RESUMO - Deslizamentos de terra são eventos recorrentes no Brasil, geralmente desencadeados por chuvas intensas. Quando estes eventos ocorrem em áreas urbanas, eles podem acabar se tornando desastres devido aos impactos econômicos, socias e perdas de vidas. A identificação e monitoramento de áreas de risco a deslizamentos de terra é crucial para evitar fatalidades. Diante disso, o objetivo deste trabalho é realizar uma análise temporal da variação do Fator de Segurança em Campos do Jordão, usando o modelo matemático TRIGRS. Durante o período analisado, dois eventos de chuvas intensas foram registrados na área, e desencadearam diversos deslizamentos. Os resultados mostram a eficiência do modelo TRIGRS na identificação das áreas de risco e também sua capacidade de se tornar uma ferramenta para planejamento urbano e previsão de alerta de desastres.
Palavras-chave: Deslizamentos. Análise Temporal. TRIGRS. Suscetibilidade. Gestão de risco.

ABSTRACT - Landslides are recurrent events in Brazil, usually triggered by intense rainfall. When these events occur in urban areas, they end up becoming disasters due to the economic damage, social impact, and loss of human life. The identification and monitoring of landslide-prone areas are crucial to avoid fatalities. Therefore, the aims of this work are a temporal analysis of the Factor of Safety variation in Campos do Jordão, using the mathematical model TRIGRS. During the analyzed period, two heavy rainfall events were recorded in the area, and triggered landslides. The results show TRIGRS efficiency in correctly identify landslide-prone areas and its applicability to become a useful tool for urban planning and early warning systems.
Keywords: Landslides. Temporal analysis. TRIGRS. Susceptibility. Risk management.

INTRODUCTION

The population growth in the world makes that more and more people need to live in areas susceptible to natural hazards. As a consequence, environmental degradation, deforestation, and CO2 emissions have increased in the past decades. Studies also show an increase in the intensity of a natural hazard, which foments the need to monitor and manage risk areas (Houghton, 2003).

Landslides are a natural phenomenon that usually happens in slope areas, triggered by heavy rainfall. Depending on the intensity and the location where a landslide occurs, the displacement of soil, rocks, and mud might affect urban areas becoming a disaster (Wisner et al., 2003). Economic damage, social impact, and deaths are some of the effects of landslides in urban areas (Montgomery & Dietrich, 1994; Larsen & Torres-Sanchez, 1998; Zêzere et al., 2005; Zizioli et al., 2013; Mendes & Valério-Filho, 2015; Mendes et al., 2018a, 2018b; König et al., 2019). In January 2011, after a heavy rainfall event, several landslides happened in Rio de Janeiro state - Brazil, leaving 947 dead, more than 300 people missing, and thousands homeless. It is considered one of the worst disasters in the country (Cemaden, 2016).

In Brazil, it is common to find cities with urban areas going all way up to the slope. The mountainous area of Serra do Mar is the best example. However, the irregular occupation in steep slope areas, associated with environmental degradation, changes the slope stability. The area becomes more susceptible to landslides (Prieto et al., 2017; Mendes et al., 2018a, 2018b). Therefore, the identification and monitoring of landslide-prone areas are essential to disaster risk reduction management.

Different methods have been developed to determine the most susceptible areas, for example Machine learning and statistical methods, such as bivariate-statistical methods, Weight of Evidence, Fuzzy Logic, Logistic Regression, Neural Net-works, and even fractal analysis (Zêrere et al., 2005, Carrara et al., 1991, Bai et al., 2009, Cervi et al., 2010).

Another approach is through physically-based models just like the Shallow Slope Stability Model (SHALSTAB) (Dietrich & Montgomery, 1998), Stability Index Mapping (SINMAP) (Pack et al., 1998), Transient Rainfall Infiltration, and Grid-based Regional Slope-Stability Model (TRIGRS) (Baum et. al, 2008), physically-based Slope Stability Model (dSLAM) (Wu & Sidle, 1995), SLOPE/W and SEEP/W (Geo-Slope, 2016).

To model landslide-prone areas with mathematical models, the characterization of soil physical properties is necessary. The measurement of geo-technical parameters is made directly by collecting disturber and undisturbed soil samples. The samples are analyzed in laboratories to define grain size, specific soil weight, cohesion, liquid, and plastic limits. Additionally, the undisturbed soil samples are necessary to conduct performance tests, such as shear strength and permeability (Jenny, 1945; Guerra & Botelho, 1996).

TRIGRS have been applied in several places, such as Italy (Frattini et al., 2004; Sorbino et al., 2010; Zizioli et al., 2013; Alvioli et al., 2014; Grelle et al., 2014; Bordoni et al., 2015; Ciurleo et al., 2019), United States - USA (Savage et al., 2004; Baum et al., 2008; Godt et al., 2008; Liao et al., 2011; Alvioli & Baum, 2016), Taiwan (Chien-Yuan et al., 2005; Tan et al., 2008; Ku et al., 2017), China (Zhuang et al., 2017), South Korea (Kim et al., 2010; Park et al., 2013; Viet et al., 2017), Colombia (Marín & Salas, 2017; García-Aristizábal et al., 2019), Malaysia (Saadatkhah et al., 2015), Brazil (Listo & Vieira, 2015; Listo, 2016; Simões et al., 2016; Seefelder et al., 2017; Listo et al., 2018; Ávila et al., 2021), and acquired satisfactory results.

Moreover, due to the dynamic approach, TRIGRS provided more precise results than SHALSTAB and SINMAP (Frattini et al., 2004; Sorbino et al., 2010; Zhuang et al., 2017). TRIGRS allows a time-varying analysis of the transient pore-water pressure during rainfall events (Frattini et al., 2004; Chien-Yuan et al., 2005; Baum et al., 2008; Tan et al., 2008; Godt et al., 2008; Kim et al., 2010; Sorbino et al., 2010; Liao et al., 2011; Park et al., 2013; Bordoni et al., 2015; Alvioli & Baum, 2016; Zhuang et al., 2017).

Therefore, this study will apply the mathematical model TRIGRS to identify landslide-prone areas and monitor the Factor of Safety (FS) variation during a rainfall event. This model is an open-source software used worldwide, which provides more precise results than both open-source software SHALSTAB and SINMAP.

STUDY AREA

Campos do Jordão municipality was developed on the crystalline plateau of the Mantiqueira Mountains, located southeast of São Paulo State. With altitudes higher than 2,000 meters and a territorial extension of 290,5 km², the city has 51,157 inhabitants (IBGE, 2016). The climate is characterized by an average temperature of 14,3° C, with annual precipitations varying from 1,205 mm to 2,800 mm (Modenesi-Gauttieri & Hiruma, 2004).

The municipality is delimited by two rifts (Jandiuvira and São Bento do Sapucaí), aging from Pre-Cambrian to Eopaleozoic period. Moreover, high hills and erosive depressions characterize the area. Gneiss, migmatite, granite, quartzite, limestone and amphibolites are found in plateau areas (Hiruma et al. 2001).

Several landslides are registered every year, and they usually happen in the Piracuama stream basin, which corresponds to the neighborhoods Vila Albertina, Santo Antonio, and Britador (Figure 1). This area is characterized by high hills, plateau areas and erosive depressions. The high hills can reach more than 30º of declivity, while in plateau areas it is found gneiss, migmatite, granite, quartzite, limestone, and amphibolites (Hiruma et al., 2001; Modenesi-Gauttieri & Hiruma, 2004; König et al., 2019). A organic clay deposit is found in the erosive depression and, according to (Mendes et al., 2018a, 2018b) this material is very sensitive to human intervention. Therefore, anthropic changes in such areas might affect the original equilibrium conditions of the slope and induce landslides.

One of the worst landslides registered happened

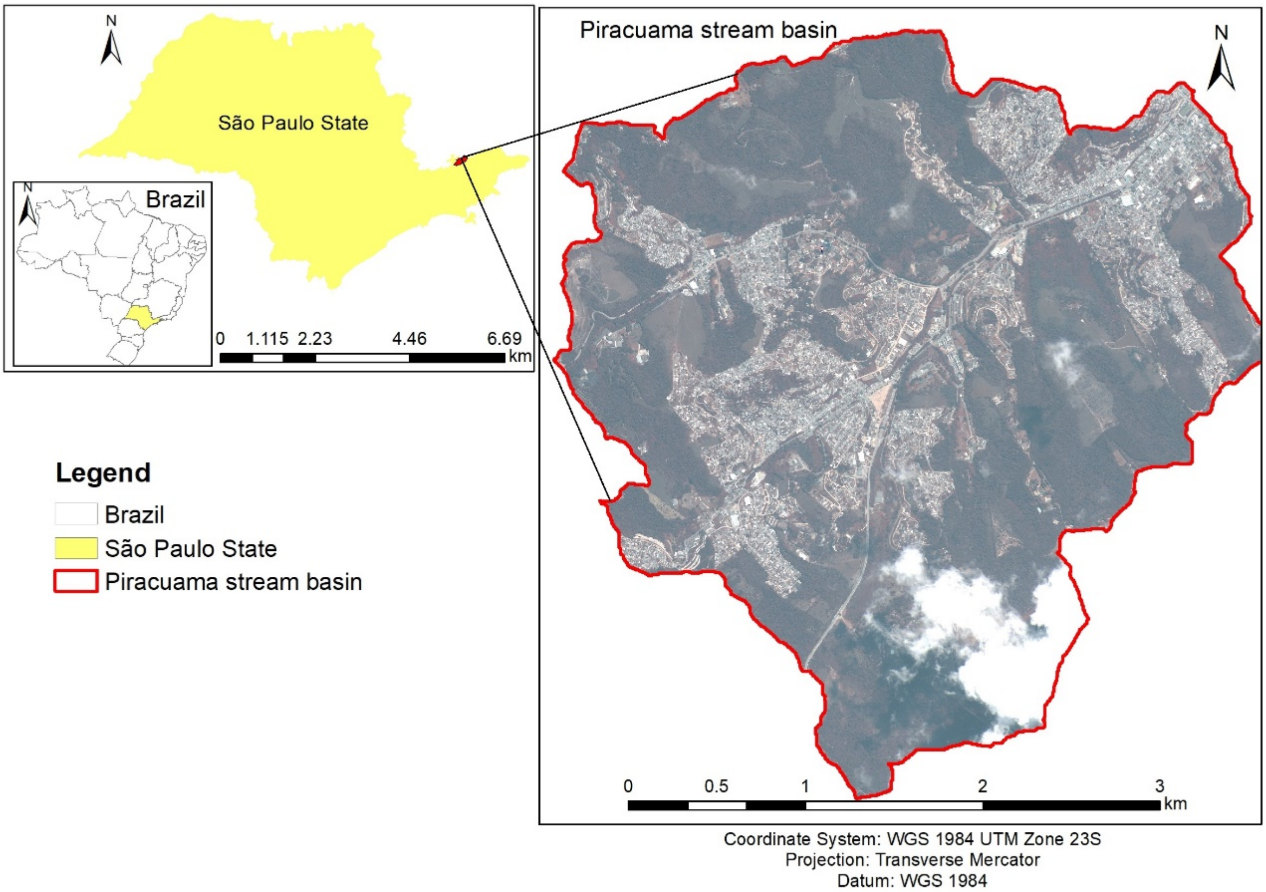

Figure 1 - Study Area - Piracuama stream basin.

in August 1972, which resulted in the death of 17 people and 60 houses buried by the mudflow (Amaral & Fuck, 1973). In 1991, the landslides injured affected 149 people and buried 11 houses (Ahrendt, 2005; Mendes et al., 2018a). Another landslide happened in January 2000 (Figure 2), which resulted in the death of 10 people, more than 100 injured, and 423 houses have several structural damages (Mendes et al., 2018a; Mendes & Valério-Filho, 2015).

Notwithstanding, the recent development of this municipality and large population growth increase the irregular settlements in steep slope areas of the Piracuama stream basin. These people are more vulnerable to the consequences of landslide events, which justifies the importance of monitoring these areas (König et al., 2020, 2019).

When visiting the area, (Mendes et al., 2018a; König et al., 2019) observed that most houses were built in steep slope areas through vertical cuts in slope without retaining wall and are in precarious condition. In addition, pipe leakage was also noticed, which increase the soil moisture, inducing landslides. The anthropic changes are presented in figure 3.

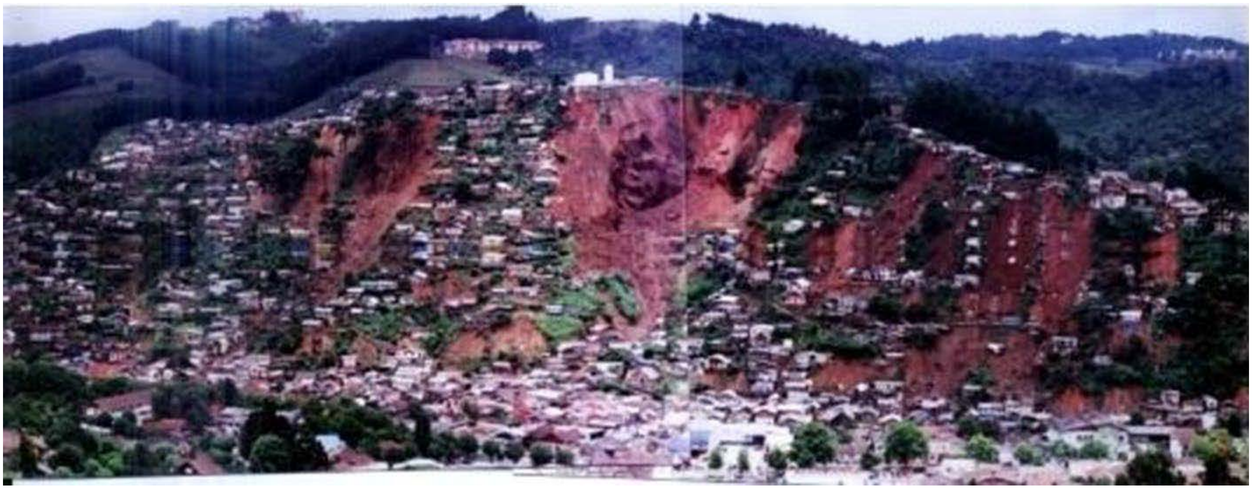

Figure 2 - Landslide in Piracuama stream basin in January 2000 (Source: Neto et al., 2006).

Figure 3 - Pipe leakage (A) and houses build in steep slope areas without retaining walls (B (Source: König et al., 2018).

MATERIALS AND METHODS

Transient Rainfall Infiltration and Grid-based Regional Slope Stability Model – TRIGRS is a mathematical model, developed by Baum et al. (2008), to calculate variations in the Factor of Safety (FS), determining the slope susceptibility to a landslide event. The Factor of Safety is the ratio of the shear strength to the shear stress acting on soil, and it ranges from 1 (stability) to unstable slopes (FS< 1) (Ahrendt, 2005; Baum et al., 2008). During rainfall, the part of the water infiltrates, changing the soil moisture. The water pressure exerted in soil, called transient pore-water pressure, determines the variation in FS, and consequently, in slope stability.

TRIGRS mathematical formulation is based on Iverson's (2000) hydrological model, which is the linearization of the one-dimensional analytical solutions of Richards Equation (Equation 1), associated with a stability model based on the equilibrium limit principle. The model's final formulation is presented in equation 2 (Baum et al., 2008).

$$\left(\frac{\partial \theta}{\partial t}\right) = \left(\frac{\partial}{\partial z}\right)\left[\mathbf{K}(\boldsymbol{\psi})\left(\frac{1}{\cos^2\delta}\frac{\partial \Psi}{\partial z} - \mathbf{1}\right)\right] \quad (1)$$

In equation 1, θ is the soil volumetric moisture content (dimensionless), t is the time (s), z is the soil depth (m), K(Ψ) is the hydraulic conductivity (m/s kPa) in the z-direction, δ is the slope angle, and Ψ is the groundwater pressure head (kPa).

$$FS = \left(\frac{\tan\phi}{\tan\alpha}\right) + \left[\left(\frac{c - \Psi(Z,t)\Upsilon_W \tan\phi}{\Upsilon_S Z \sin\alpha \cos\alpha}\right)\right] \quad (2)$$

In equation 2, c is the cohesion (kPa), ϕ is the internal friction angle (deg.), Ψ(Z,t) is the groundwater pressure head (kPa), γ_w is the unit weight of groundwater (kN/m³), γ_s is the soil specific weight (kN / m³), Z is the layer depth (m), α is the slope angle (0 < α < 90º), and t is the time (s).

Geotechnical and hydrological parameters, such as cohesion, soil specific weight, internal friction angle, and hydraulic conductivity, are used as input data. TRIGRS formulation allows different input values, cell by cell, due to soil´s horizontal heterogeneity. Meaning that the FS is calculate at multiple depths, and each depth has its own soil properties (Savage et al., 2004; Baum et al. 2008).

Mendes et al. (2018a) developed a study at Piracuama stream basin. SPT (standard penetration test) boreholes were drilled over the slopes in different positions, to collect disturbed and undisturbed soil samples.

These samples were analyzed in laboratory to determine the geotechnical parameters, such as cohesion, internal friction angle, hydraulic conductivity, grain size and density.

The results show a significant textural variation, indicating that soil profiles are heterogeneous (Figure 4).

Each layer has specific soil geotechnical and hydraulic properties, meaning high variability on the layer´s behavior with the increase of soil moisture.

To identify the landslide-prone areas and calculate the FS variation in the Piracuama stream basin, this study used the geotechnical parameters provided by Mendes et al. (2018a). The soil heterogeneity was considered, so the authors delimited two depths with the correspondent geotechnical data to be used as input in TRIGRS model. Table 1 present the geotechnical parameters used to calculate the FS variation.

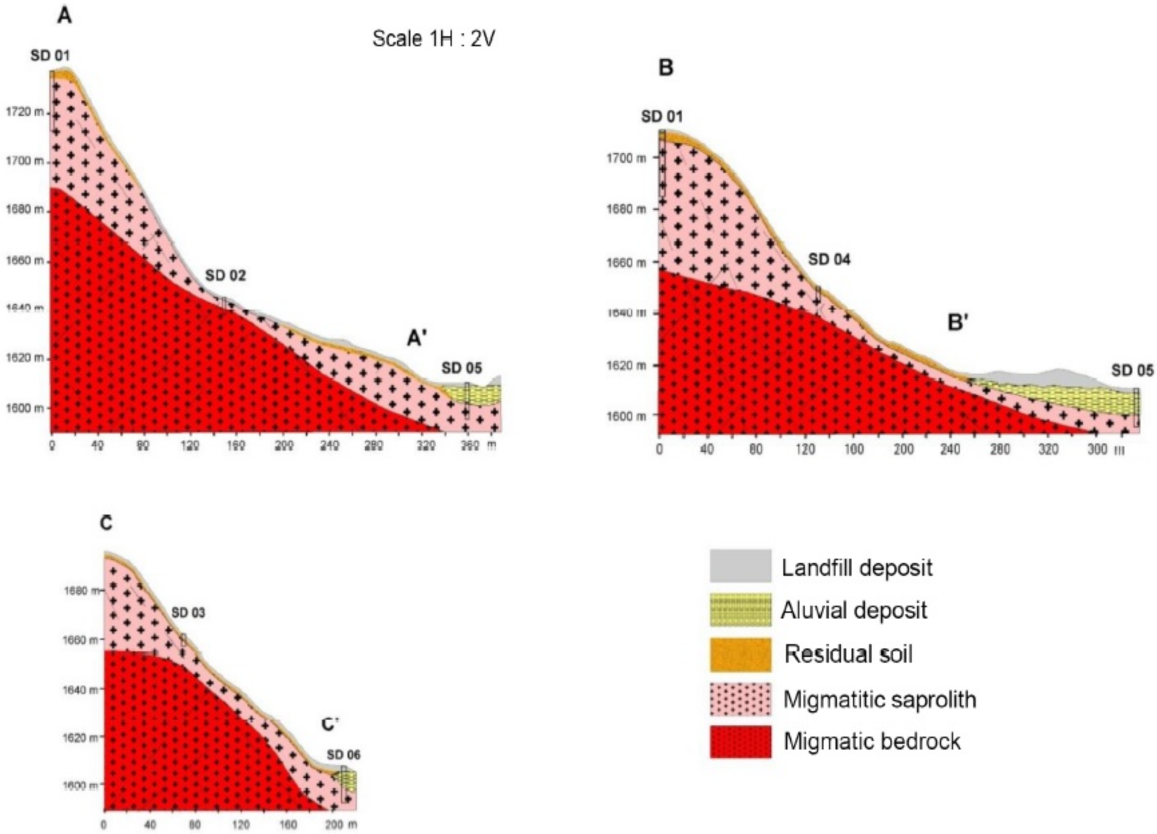

Figure 4 - Soil heterogeneity of Piracuama stream basin (Mendes et al., 2018a).

Table 1 - Geotechnical parameters used as inputs in TRIGRS, acquired from Mendes et al. (2018a).

Input parameters					
Depth (m)	Cohesion (kPa)	Angle of Friction (°)	Hydraulic Conduct. (m s-1)	Hydraulic Diffus. (m s-1)	Specific weight (kNm-3)
1,6	22	43	5,25x10-6	6,45x10-6	18,1
1,6-2,6	19	34	1,18x10-6	6,45x10-6	21,4

TRIGRS uses the declivity map as an input parameter. The declivity map was prepared from DEM (Digital Elevation Model), using the software ArcGIS, and has 5-meters of spatial resolution. The DEM was acquired in the cartographic base of the Municipality of Campos do Jordão, resulting from a data obtained by LiDAR (Light Detection and Ranging).

To analyze the slope stability and FS variation, it was chosen 72 hours, from March 6th to March 8th of 2017. During these periods, two heavy rainfall events occurred in the study area and triggered landslides. There are six rain gauges installed in the Piracuama stream basin, which provide the necessary data to this study. The rainfall values were downloaded from “Mapa Interativo” by Cemaden’s website (http://www2.cemaden.gov.br/mapainterativo/), and organized using Excel software (Figure 5). The daily rainfall data was incorporate in TRIGRS by command line.

TRIGRS is executed by a command-line interface with limited user interactivity (Baum et al., 2008) and generates an ASCII file. The software ArcGIS was used to visualize TRIGRS results and prepare the final maps.

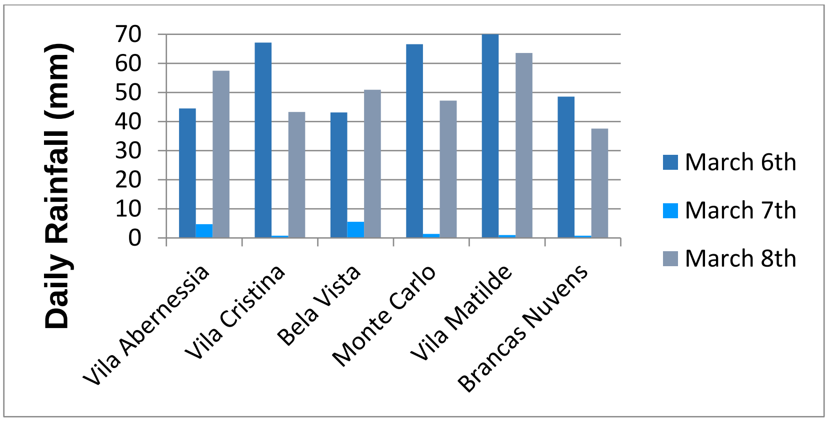

Figure 5 - Daily rainfall registered by six rain gauges.

RESULTS AND DISCUSSIONS

TRIGRS calculates the FS variation during 72 hours, resulting in a susceptible map, as presented in figure 6 to figure 9. The temporal analysis of slope stability shows how the FS decreases during a heavy rainfall event. As time passed, and with the increase in soil moisture, more areas had FS<1 when compared with the initial conditions (represented as 0h). Then, on March 6th, two landslides were registered, and another four on March 8th. According with the authorities, four houses were completed damage due to landslides and, those families were removed from their home.

During the initial period (0h), only a few areas had FS<1, and they correspond to areas with declivities higher than 30º, most of which were located on the top of the hill. The rain gauges registered 70 mm of rainfall on March 6th, and after 24 hours, the slope stability decreased in several areas.

Notice that the areas with 1.1 > FS < 1.5 during the initial period, now have a 0.5 > FS< 1, and two landslides happened. The FS continued decreasing during 48 hours, and another rainfall, with 63 mm registered by rain gauges, happened on March 8th.

After 72 hours of temporal analysis, almost every steep slope area has FS < 1, and the authorities registered four more landslides. TRIGRS shows the most unstable areas according with FS variation.

Almost every steep slope area has an FS<1, but the landslides were registered only in a few areas. This is important to discuss, because the

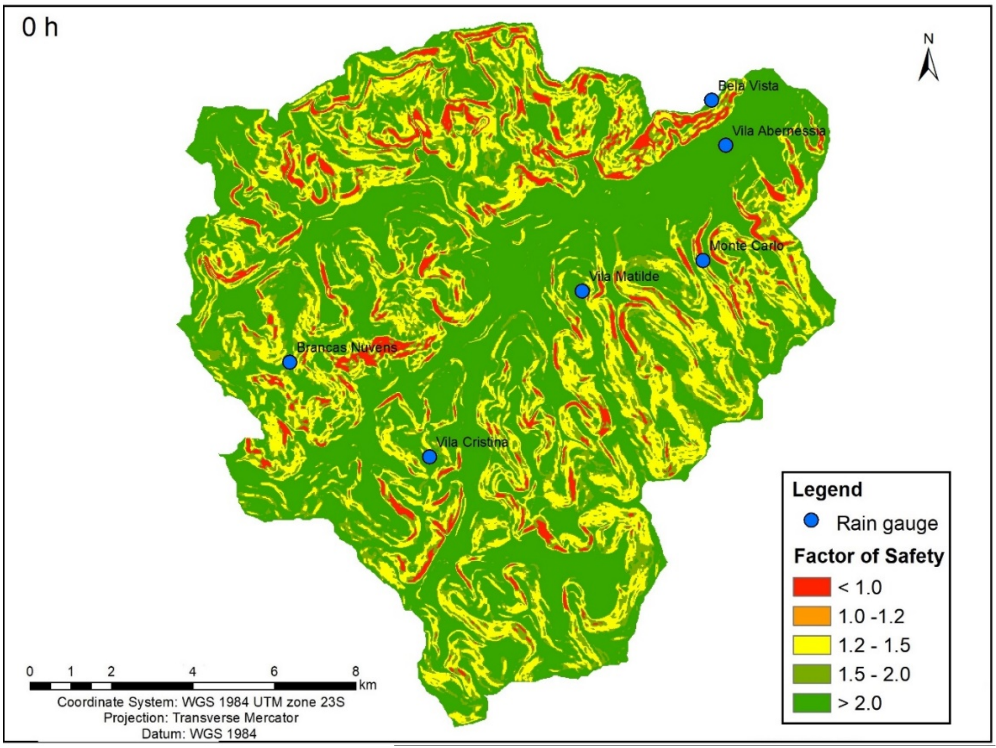

Figure 6 - Temporal analysis of slope susceptibility at 0h.

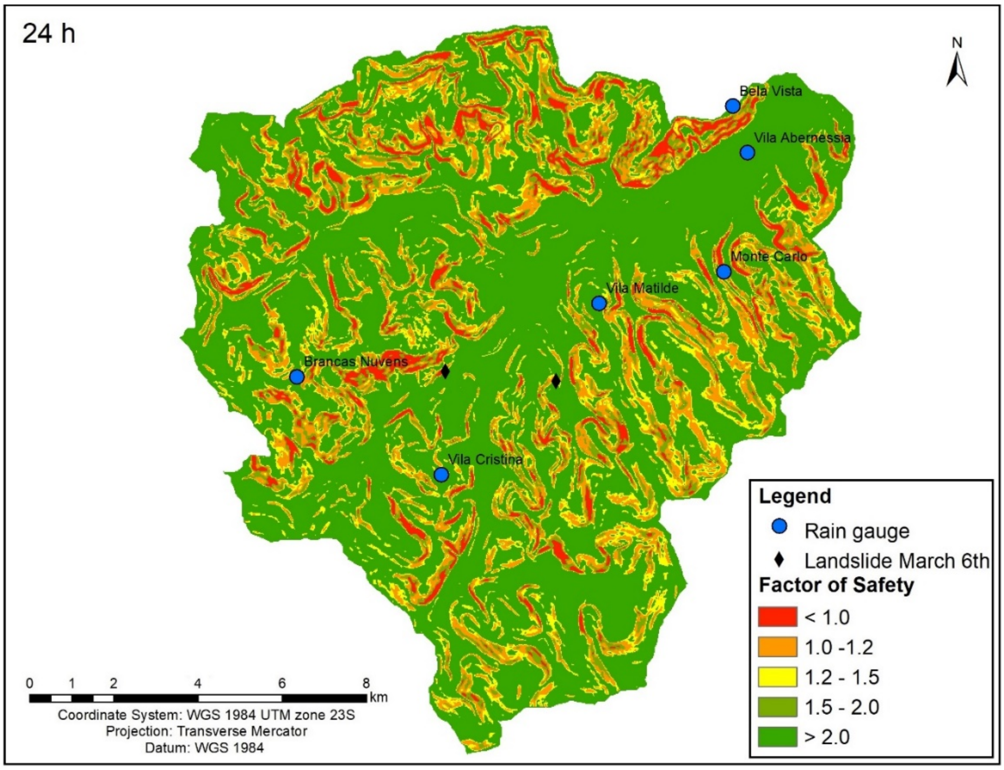

Figure 7 - Temporal analysis of slope susceptibility at 24h.

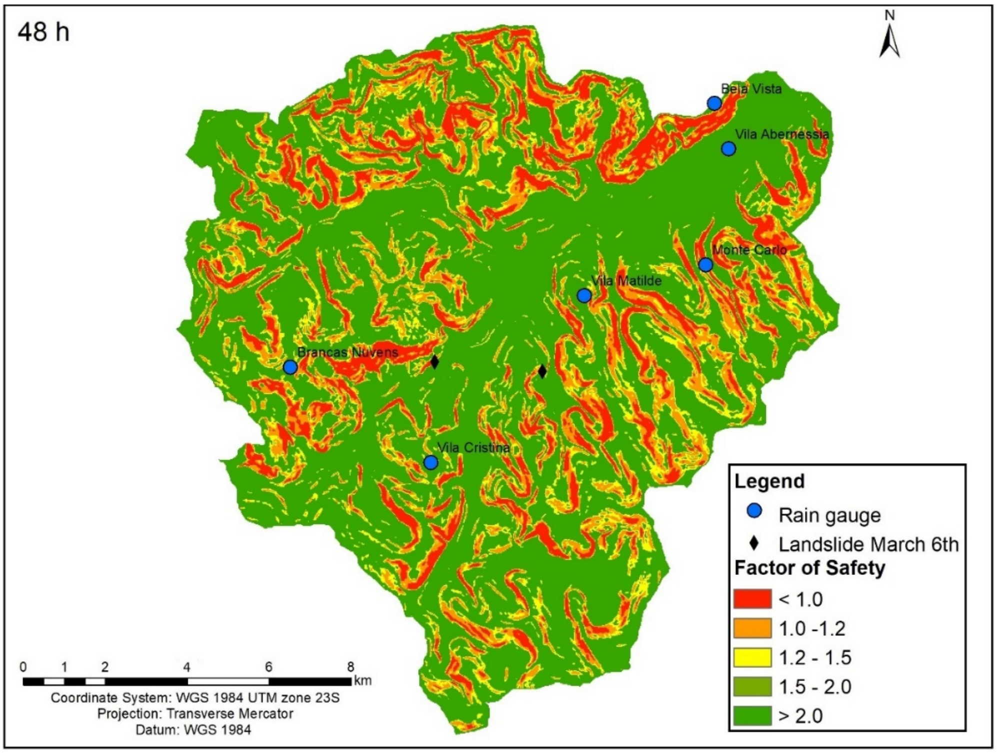

Figure 8 - Temporal analysis of slope susceptibility at 48h.

model indicates the unstable areas, which not necessarily results in a landslide. Some areas, might have slightly differences in the geotechnical parameters, or in the land use and occupation processes. These six landslides registered during the analyzed period, happened in areas with human occupation.

Those people living in steep slope areas made vertical cuts in the slope to build houses, most of which don´t have proper structural foundation, not even retaining walls to prevent from surface ruptures in the slope. Several constructions have pipe leakages, which increase the soil moisture. And these anthropic factors alter the slope original equilibrium conditions, inducing landslides.

Table 2 present the percentage of areas distributed by each FS class. Moreover, we can infer that heavy rainfall triggered these landslides because, during March 7th, any landslides were registered, and the daily rainfall was lower than March 6th and 8th.

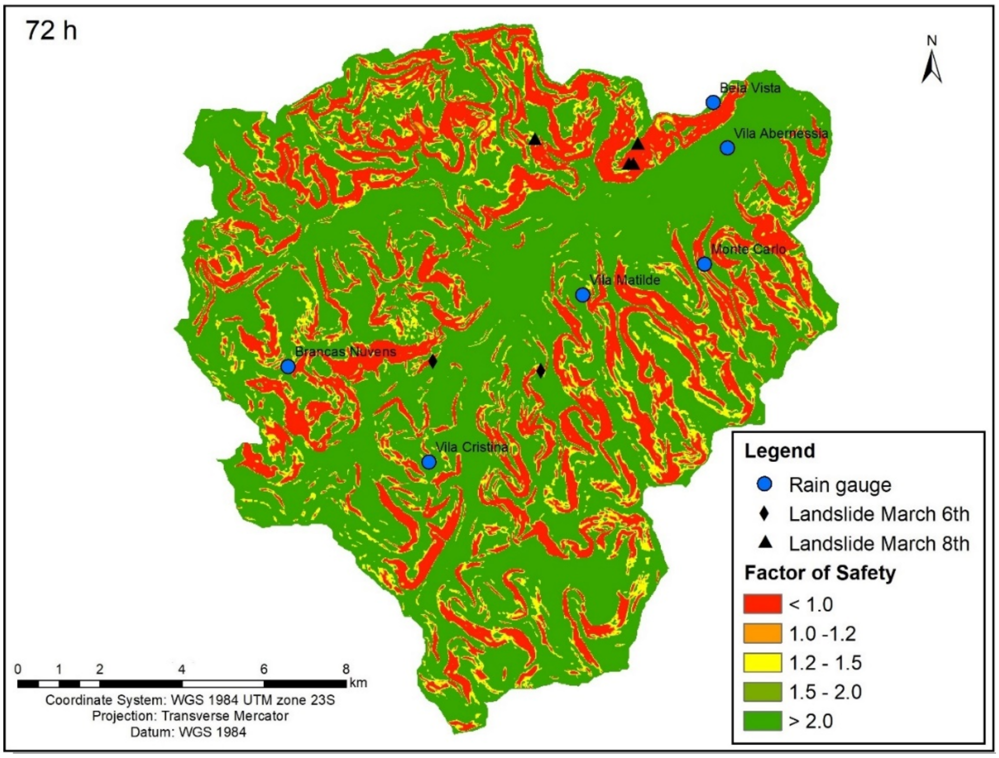

Figure 9 - Temporal analysis of slope susceptibility at 72h.

Table 2 - Variation of unstable classes during 72h.

Factor of Safety	% of areas at 0h	% of areas at 24h	% of areas at 48h	% of areas at 72h
< 1.0	3.83	4.28	12.52	21.38
1.0 -1.2	1.48	13.43	12.47	13.23
1.2 - 1.5	22.19	10.38	11.02	7.97
1.5 - 2.0	18.41	22.43	16.33	14.29
> 2.0	54.09	49.47	47.66	43.12

The analysis of table 2 shows the percentage of areas per FS class during the 72h. The areas classified with FS< 1 increased as time passed, while the stable classes decreased in the study area. In the initial conditions (0h), only 3.83% of the areas were classified as unstable (FS<1.0), but at 72h, 21.38% of the areas had FS lower than 1.

Figure 10 shows the temporal analysis of FS variation on landslides locations. Analyzing the FS of March 6th landslides, an initial FS higher than 1.5 for both locations is noticed, meaning stability in the initial conditions (0h and without rain). Due to rainfall, there is an increase in soil moisture, and consequently, a decrease in FS is noticed.

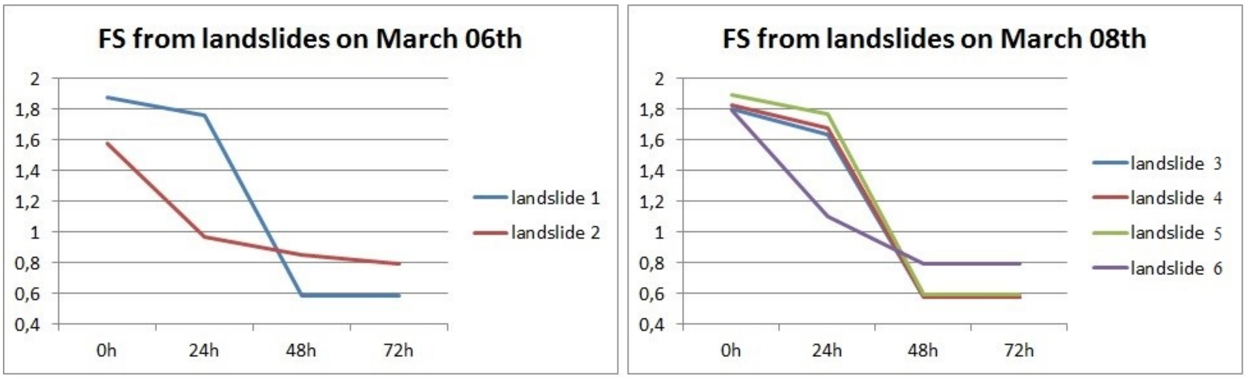

Figure 10 - Variation of FS on the areas where happened landslides.

After 24 hours, the location where the first landslide happened (landslide 1) had an FS slightly lower than 1,8, whereas, on landslide 2 location, the FS is lower than 1. Areas with FS<

1 are considered unstable; thus, the second landslide happened in an unstable area. However, landslide 1 happened with 1 > FS < 1.8, fomenting further discussion about the causes.

Passed 72 hours, landslide 1 location has the lowest FS (FS = 0.6), while landslide 2 location has an FS = 0.8. It is interesting to notice the different behavior between these two areas: the area which corresponds to landslide 1 had a slow decrease of FS during the first 24 hours, but then, the FS rapidly decreased to values lower than 1. Contrarily, the location of the second landslide becomes unstable (FS<1) in 24 hours.

On March 8th, four landslides were registered, three of them with similar curvature patterns and one differing from the others. Landslides 3, 4, and 5 presented an FS > 1.5 during the first 24 hours and a rapid decrease after, with FS = 0.6. Landslide 6 differs from the others because, in 24h, the FS decrease from 1.8 to 1.1, and in 72 hours, FS = 0.8. Furthermore, on March 8th, all four landslides happened when FS was lower than 1.

It is also important to highlight that the landslides happened in steep slope areas, with declivities higher than 25º (Figure 11). According to Prieto et al. (2017), areas with declivity higher than 25° in Campos do Jordão are inappropriate for anthropic changes, either in urban or rural regions. Furthermore, several houses are built in those areas, and this type of environmental modification might induce landslides. The landslide from March 6th that occurred when TRIGRS calculates the FS > 1 probably was provoked by anthropic changes. The soil physical parameters used by TRIGRS to calculate slope stability indicate the area as stable. However, depending on the intensity of human influence in the area, the soil might have different conditions (e. g. lower values of cohesion or higher values of water content) and become unstable easier.

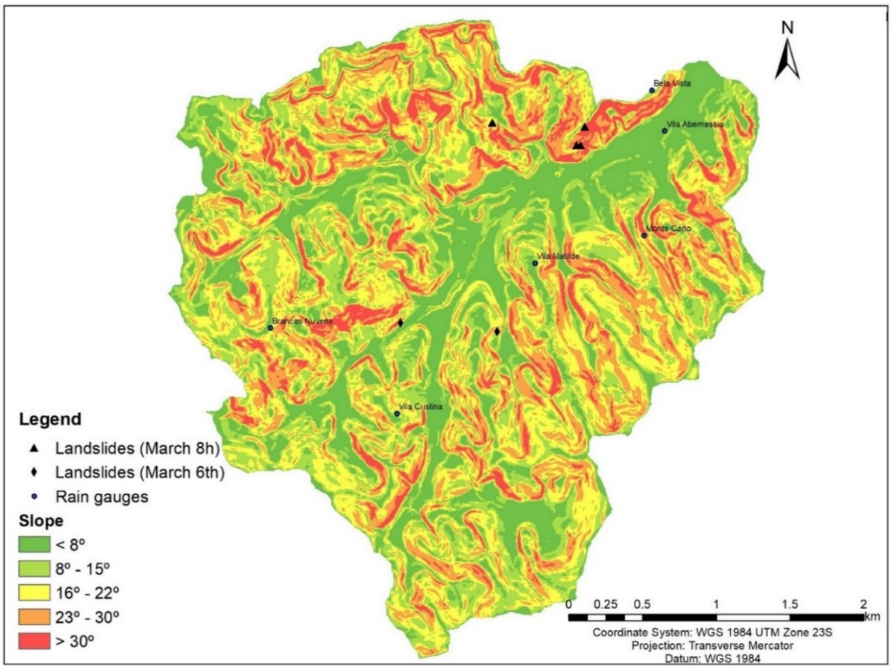

Figure 11 - Declivity map.

The landslide-prone areas identified by Prieto et al. (2017) and Mendes et al. (2018a), and defined by the Geological Institute - IG (2014) in the Piracuama stream basin, is in agreement with unstable areas computed by TRIGRS. The 2017 landslide scars corroborate with the areas computed by TRIGRS as unstable (FS<1), validating the model´s performance. Moreover, the authors defined two statistical indexes to confirm TRIGRS efficiency. The Success Index - SI (Equation 3), which correspond to the percentage of correctly classified unstable classes, and the Error Index – EI (Equation 4), which indicates when the computed unstable class does not correspond with verified landslide scars (Sorbino et al., 2010). The results are presented in table 3.

$$SI = \left(\frac{A_{in}}{A_{uns}}\right) * 100 \quad (3)$$

The variable A_{in} is the computed unstable areas within the triggering areas, and A_{uns} is the triggering areas.

Table 3 - Analysis of TRIGRS success and error index.

Model	Success Index (SI)	Error Index (EI)
TRIGRS	67,3%	11,4%

$$EI = \left(\frac{A_{out}}{A_{stb}}\right) * 100 \quad (4)$$

The variable A_{out} is the computed unstable areas outside the triggering areas, and A_{stb} is the stable areas.

TRIGRS correctly classified the areas with landslide scars as unstable and had a SI of 67.3%. Furthermore, an EI of 11.4% shows the model´s efficiency in identifying landslide-prone areas. High values of SI and low values of EI indicate that TRIGRS classified the slope areas and can be used to monitor the areas and become an early warning tool.

Today, the authorities use a threshold of accumulated rainfall for 72 hours to determine the alert levels for landslides. According to Tatizana et al. (1987) and Santoro et al. (2010), the critical rainfall threshold for Campos do Jordão is 60 mm in 72 hours then, landslides are usually registered. Figure 12 presents the daily rainfall, the 72 hours accumulated rainfall, and the critical threshold.

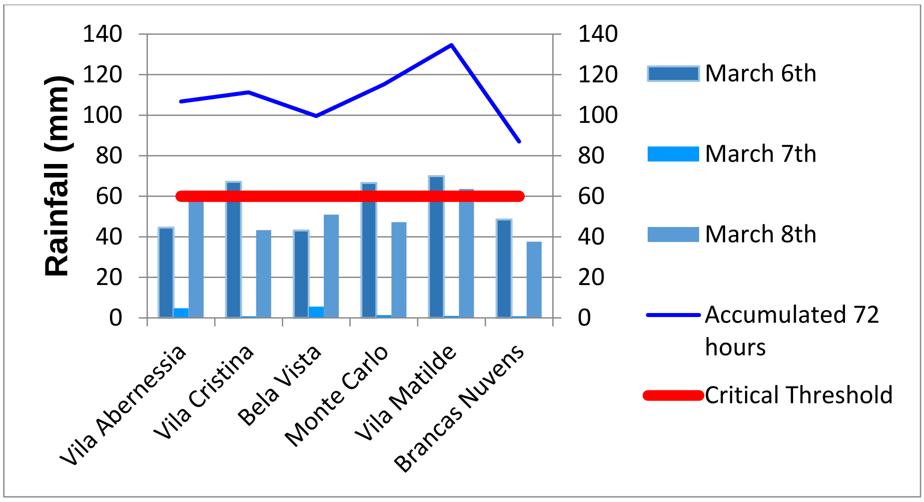

Figure 12 - Daily rainfall registered, the 72 hours accumulated rainfall, and the critical threshold defined.

Analyzing the daily rainfall registered by the rain gauges of the Piracuama stream basin, it is observed, for March 6th, that Vila Matilde rain gauge registered 70 mm, while Vila Cristina and Monte Carlo registered values higher than 60 mm. During this day, two landslides happened. For March 8th, only the Vila Matilde rain gauge registered rain values higher than 60 mm, and four landslides were recorded.

Despite the 60 mm of rain during March 8th, it must be taken into account the total amount of rainfall from days 6th and 7th. It was registered values higher than 120 mm of accumulated rainfall during 72 hours. The accumulated rainfall of one day was higher than what was expected for three days. Consequently, there was an increase in soil moisture, which decreased the slope stability, and several landslides were registered.

It is important to highlight that where the landslides occurred have several irregular settlements with different types of constructions and houses. Mendes et al. (2018a, b) and Mendes & Valério-Filho (2015) suggest that anthropic changes induce landslides due to the vertical cuts in steep slopes, environmental degradation, deforestation, and leakages. And when associated with heavy rainfall in short periods, or higher values of accumulated rainfall over 72 hours, it might trigger landslides, putting those who live in steep slopes areas at risk. The first landslide of March 6th probably was induced by anthropic changes in the slope and triggered by rainfall.

CONCLUSIONS

Landslides are a frequent natural hazard that usually happens in slope areas. To avoid disasters, identifying and monitoring landslide-prone areas are important, especially if there are human occupations.

Different methods are used to identify risk areas, and the mathematical model TRIGRS has been providing excellent results for landslide-prone areas. Therefore, this paper analyzed how the slope stability changes during a rainfall event.

The temporal analysis lasted 72h, which had two heavy rainfall events and six landslides registered.

The geotechnical and hydrological data, such as hydraulic conductivity, cohesion, internal friction angle, resistivity, unit weight, plasticity index, and moisture content, were acquired from the literature and used as TRIGRS input parameters.

As a result, the Factor of Safety changes in agreement with the total amount of rainfall, proving its efficiency for identifying landslide-prone areas. The landslide proves TRIGRS's efficiency in identifying the unstable areas. Moreover, the FS changes in agreement with rainfall intensity, which corroborates the assumption that this model can be used as an early warning to simulate and predict slope instability, avoiding disasters and death.

The authors recommended using weather forecasts to predict the risk areas and improve the preventive removal of those living in risk areas.

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