Sensitivity analysis of conditioning factors to shallow landslides occurrence in tropical environment

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Abstract

Occurrences of shallow landslides are frequent in mountain environments, such as Serra do Mar, located in the southern and southeastern regions of Brazil. These occurrences are conditioned to a set of geomorphological, geological, and climatic conditions. The aim of this paper is to determine which morphological (slope, elevation, aspect, and curvature) and geological (lithology and density of structural lineaments) conditioning factors are more relevant to shallow landslides occurrence in tropical rainforest environment. The procedures adopted were: (I) Morphological and geological maps construction; (II) Bivariate statistical application by the Information Value for each conditioning factor and (III) Sensitivity analysis and determination of the most relevant conditioning factors for shallow landslides occurrence. Results indicate lithology as the most relevant factor, followed by elevation and slope for Serra do Mar. The current study shows importance of lithology to shallow landslides analysis and allows the more effective use of morphological and geological conditions in susceptibility mappings.

1. INTRODUCTION

Shallow landslides are a natural hazard recurrent in Brazil. They are one of the typologies of mass movement which cause the most social and economic losses (IBGE, 2019). Very large landslide events occurred mainly in the southern and southeastern regions of Brazil. One major component is Serra do Mar, a mountainous relief of elevations between 800 and 1800 m and steep slopes (Almeida & Carneiro, 1998), in addition to geomorphological, geological, and climatic conditions.

Serra do Mar was affected by several events causing deaths and infrastructures damages in the region (Vieira & Gramani, 2015) (Figure 1). In 1967, Caraguatatuba city was affected by landslides and debris flows, responsible for human and economic losses (De Ploye & Cruz, 1979; Dias et al., 2016). In 1985, Cubatão city also suffered an event of catastrophic proportions, when 1,742 landslides were triggered causing severe damage to the local industrial park (Nery & Vieira, 2014). One of the most recent events in Brazil occurred in mountain region of Rio de Janeiro in 2011. Landslides culminated in debris flows resulting in 1,000 deaths (Avelar et al., 2011; Dourado et al., 2012).

The high frequency of shallow landslides has been increasing interest and importance of the topic in national scale. Susceptibility assessment can be done by analysis of geomorphological, geological, climatic conditions and, in some cases, anthropic interference.

Morphological factors (e.g. slope, elevation, aspect, curvature) influence the stability of the slopes. Steep areas with availability of materials for movement are examples of sectors with greater susceptibility to movements (Sidle et al., 1985).

Geological factors also influence occurrences of shallow landslides. They define the nature of the rock and its resistance to weathering as well as weathering mantles (Calcaterra & Parise, 2010).

The joint analysis of conditioning factors enables a better approach to the topic, besides identification of patterns of occurrence. The determination of morphological and geological classes more relevant to the process allows the creation of more accurate mappings (Van Westen et al., 2003).

Several studies have performed joint analysis aiming to understand the more important factor to trigger landslides (Sidle et al.,1985; Pachauri & Pant, 1992; Donati & Turrini, 2002; Vieira et al., 2010).

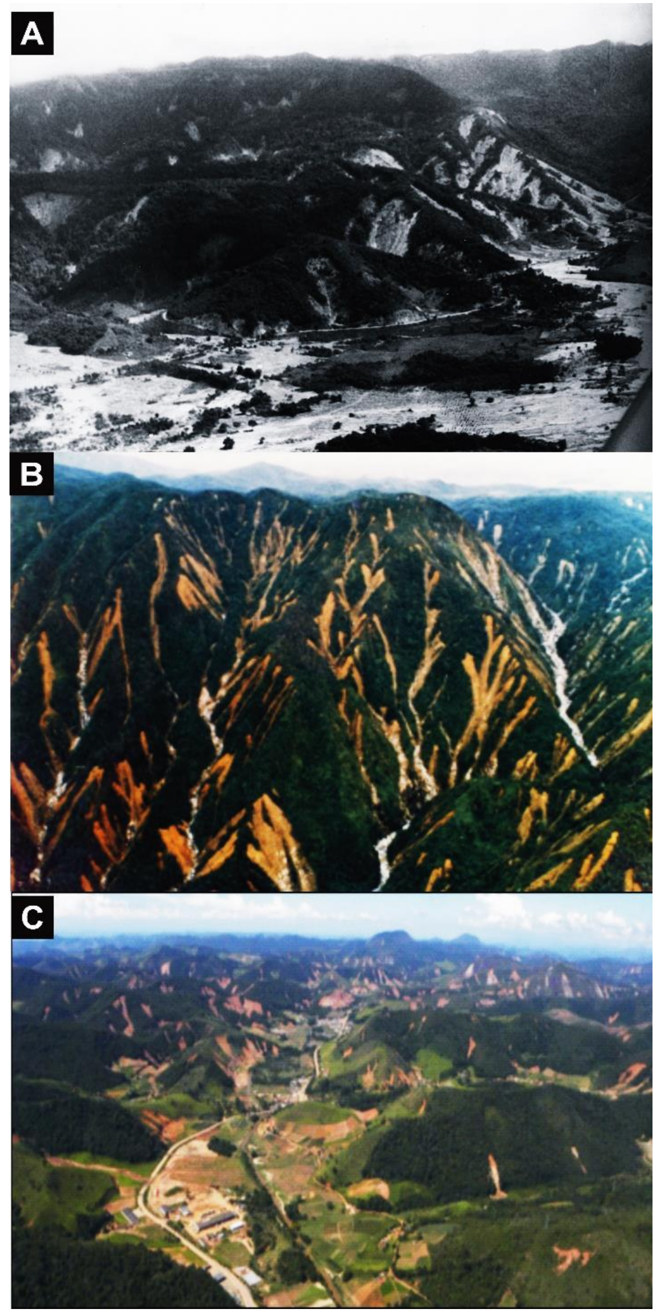

Figure 1. High magnitude events in Brazil. A: Caraguatatuba city in São Paulo state, 1967; B: Cubatão city in São Paulo State, 1988; C: Mountain region of Rio de Janeiro, 2011. Source: GPmorfo; Public archive of Caraguatatuba.

The slope, elevation, curvature, and aspect are the most used morphological factors (Gao, 1993). Geological factors are focused on lithology and structural features.

The aim of this paper is to define the conditioning factor(s) more relevant to shallow landslide occurrences in tropical rainforest environment, based on sensitive analysis. Definition of such conditioning factors can assist in the improvement of products elaborated in the mapping of susceptibility to shallow landslides in mountain environments in Brazil.

2. STUDY AREA

The Serra do Mar is a mountain range located at the southern and southeastern regions of Brazil (Figure 2). It presents elevations up to 1,800 m, approximately 1500 km in length (Vieira & Gramani, 2015), and it is considered the most important relief of the Atlantic edge of the South American continent (Almeida & Carneiro, 1998). Köppen (1936) defines climate of the area as Af (Tropical Wet Climate), no dry season.

Figure 2. Serra do Mar next to Tamoios highway, one of the most important highways connecting plateau to the north coast of São Paulo state, Brazil.

The study area selected to this research was Caraguatatuba city, southeastern coast of Brazil (Figure 3). Caraguatatuba is part of Serra do Mar and it is constantly affected by mass movements, especially shallow landslides. This region is characterized by presence of Atlantic Forest, dense ombrophylous forest, annual average rainfall between 1,600 - 2,000 mm and predominance of igneous and metamorphic rocks (i.e. gneisses, schists, and granites) (Cruz, 1974).

In 1967 a high magnitude event occurred in Caraguatatuba (De Ploye & Cruz, 1979). A high rainfall volume of approximately 600 mm/48 h (IPT, 1988), triggered landslides and debris flows. The event affected urban areas and resulted in 120 deaths, 400 homes destroyed and damage to local infrastructure.

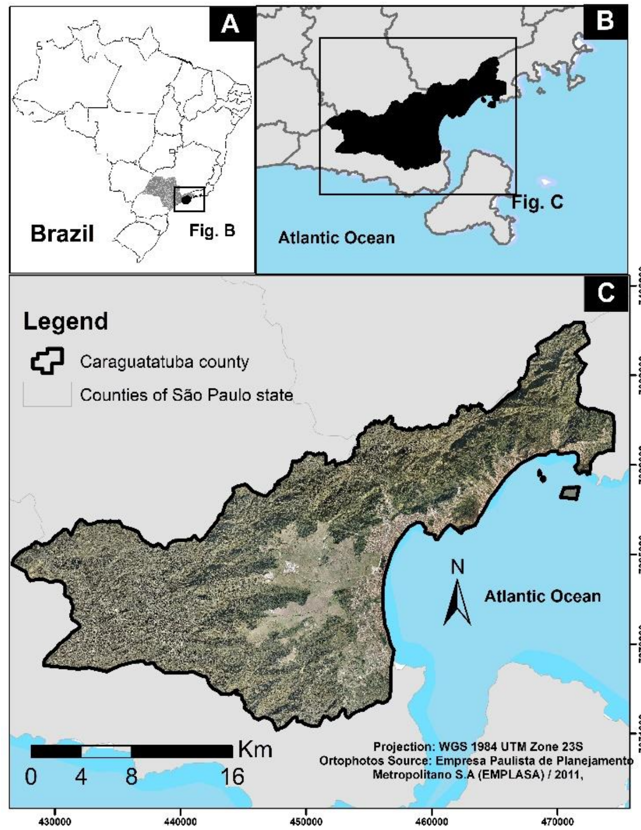

Figure 3. Location of Caraguatatuba (São Paulo state, Brazil).

3. METHODS

3.1. DATA BASE

Four morphological maps were created based on SRTM 30 m (Shuttle Radar Topography Mission): slope, aspect, elevation, and curvature (Figure 4).

Geological maps (lithology and density of structural lineaments) were created from the digitization of the works of Chieregati et al. (1982) and DNPM / CPRM (1991) (National Mining Agency and Mineral Resource Research Company) Scale 1: 50,000 (Figure 4). Both procedures were performed in ArcGIS 10.2 software.

A shallow landslide mapping was used from the 1967 event based on Fúlfaro et al. (1976) (Figure 5). The inventory contains 640 scars and was randomly divided, resulting in two inventories, one for the definition of Information values and one for validation, calculating the Area Under the Success Rate Curve (AUC).

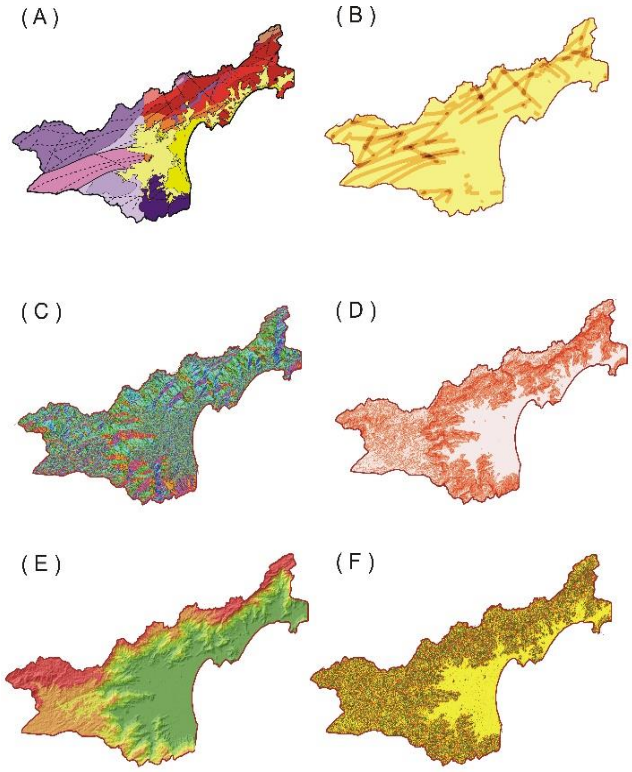

Figure 4. Morphological and geological maps. A: Lithology; B: Density of structural lineaments; C: Aspect; D: Slope; E: Elevation and F: Curvature.

3.2. INFORMATION VALUE

To quantify importance of each conditioning factor (morphological and geological), a bivariate statistical evaluation was performed, with the application of the Information Value (Yan, 1988; Yin & Yan, 1988). For each class of each conditioning factor, the respective Information Value was calculated and represented cartographically. The Information Value is defined by the following equation:

$$\mathbf{Ii} = \mathbf{log}\ \frac{\mathbf{Si/Ni}}{\mathbf{S/N}} \quad (1)$$

Where:

Ii: Information Value
Si: Number of pixels with shallow slides in variable Xi;
Ni: Number of pixels with variable Xi;
S: Total number of pixels with landslides in the total area of study;
N: Total number of pixels in the total area of study.

3.3. AREA UNDER THE CURVE (AUC)

A Sensitive analysis was applied to determine relevance of conditioning factors. The AUC enables comparisons between shallow landslides and morphological / geological factors and was calculated for each one, as performed by Zêzere et al. (2007); Pereira (2009) and Piedade et al. (2011). The curve makes an association between predicted landslides and areas defined as susceptible by information value in the morphological and geological maps. AUC is defined by equation 2:

$$\sum_{i=1}^{n}\left[(\boldsymbol{Ls_i} - \boldsymbol{L_i}) * \frac{\boldsymbol{a_i} + \boldsymbol{b_i}}{\mathbf{2}}\right] \quad (2)$$

Where:

$(Ls_i - L_i)$: Range of the class.
a_i: Corresponding ordinate value L_i.
b_i: Value of the ordinate corresponding to Ls_i.

4. RESULTS AND DISCUSSION

Sensitive analysis identified lithology as the most relevant factor to shallow landslides occurrence; followed by elevation, slope, curvature, aspect, and density of structural lineaments (Table 1).

Table 1. Conditioning factors analysed and success rates.

Conditioning factor	Success Curve (AUC)
Lithology	0,793
Elevation	0,706
Slope degree	0,701
Curvature	0,590
Aspect	0,574
Density of structural lineaments	0,567

There was a significant positive correlation between shallow landslides and all conditioning factors analyzed. Results showed a substantial importance of the nature of rocks and its resistance to weathering. These characteristics act directly on dynamics between slope and drainage system (Sidle et al., 1985), and consequently, generate weathering mantles that are favorable to slope instability (Calcaterra & Parise, 2010). Lithology and weathering mantles can create zones of lithostructural instability and trigger mechanical processes, such as shallow landslides.

Figure 6 shows that only 30% of the lithological map of the study area validates 70% of the shallow landslides. Most of landslides were in two lithotypes, micaceous quartzites and granites (pyroxene-hornblende-granite, hornblende-granite, and biotite granite). In context of Serra do Mar, Dias et al. (2017) studied geological and morphological factors in the Santo Antônio basin in Caraguatatuba and found the micaceous quartzites as more susceptible to the occurrence of shallow landslides. Also, in Caraguatatuba, Cerri et al. (2017) highlighted the importance of altered rocks, mainly gneisses, granite-gneisses and migmatites since these rocks preserve petrographic structures and textures influencing the stability of slopes.

Micaceous quartzites has a wide variation in friction angle according to the level of weathering in Serra do Mar, residual soils from micaceous quartzite have a friction angle similar to a residual sandstone soil and when this lithotype is weathered it loses more than 50% of its resistance to movement (Hoek, 1972; Machado Filho, 2000).

Like quartzite, granite rocks also have different properties depending on weathering in Brazil. Studies on residual soils of biotite granite, were carried out by Heidemann et al. (2018). The analysis identified that the presence of biotite brings a silty and lamellar nature to the material, leading to a low resistance mass movement.

4.1. COMPARISON WITH OTHER STUDIES

Zhang et al. (2016) performed a similar analysis with Information Value method, but for nine conditioning factors (lithology, distance to a fault, elevation, slope, aspect, land cover, distance to a road, distance to a river and precipitation) and found three conditioning factors as the most relevant to shallow landslide occurrence: Land cover, lithology and elevation. Similar order was found in this research.

In the northern region of Portugal, Pereira (2009) performed the same method for eight conditioning factors (management of slope, lithology, land use, cross-sectional profile of slopes, density of faults, aspect, geomorphological units and slope) in two study areas (The Douro Valley and Serra dos Gerês). She found land use and management of slope as the more relevant to shallow landslide occurrence. Lithology was the least relevant factor for the areas, differently from results obtained to Brazil and by Zhang et al. (2016) in China.

These differences can be explained partly by the high level of anthropic activity of landscapes in the north of Portugal. In these locations there is predominance of monoculture of the vineyard with support of mechanization of production in the Douro Valley and traditional polyculture Serra dos Gerês. Human activities may destabilize slopes by creation and/or alteration of land coverage and land use.

By contrast, susceptibility to shallow landslides in the Serra do Mar is directly related to natural factors (i.e. morphology, geology), sectors with anthropic influence are isolated and punctual (Wolle & Carvalho, 1994).

Thus, Caraguatatuba is in a tropical region exposed to abundant rainfall and hot temperatures which makes weather act in quartzites and granites much faster than similar rocks residing in cold or dry regions. The increasing rate of chemical weathering creates susceptible materials with chemical characteristics very different from the original rocks, increasing the possibility of shallow landslide occurrence in the study area.

5. CONCLUSIONS

Application of the sensitivity analysis was efficient and allowed to hierarchize relevance of the conditioning factors in a tropical environment. The use of morphological conditioning factors (slope, aspect, elevation, and curvature) and geological (lithology and density of structural lineaments) made it possible to identify that lithology exerts great influence for the occurrence of shallow landslides in Caraguatatuba. Weather influence (high temperatures and abundant rainfall) act in original rocks through chemical weathering and creates materials with less resistance and susceptible characteristics to shallow landslides. Thus, results reveal material (lithology), in some cases, exerts a greater influence than morphology.

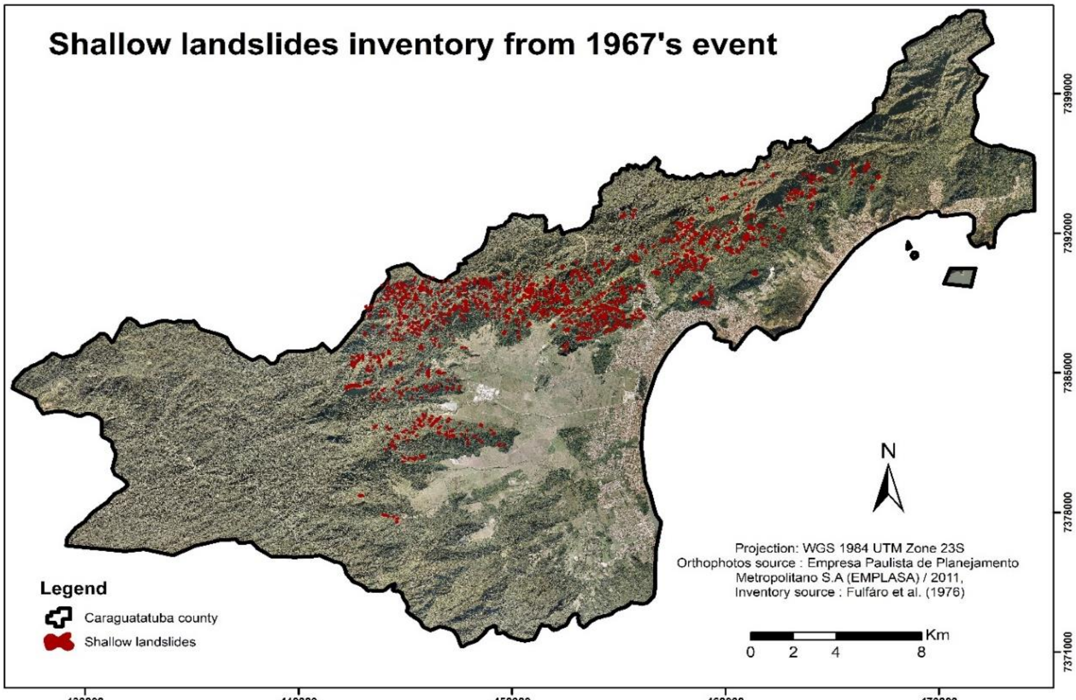

Figure 5. Shallow landslides inventory from 1967 event in Caraguatatuba city.

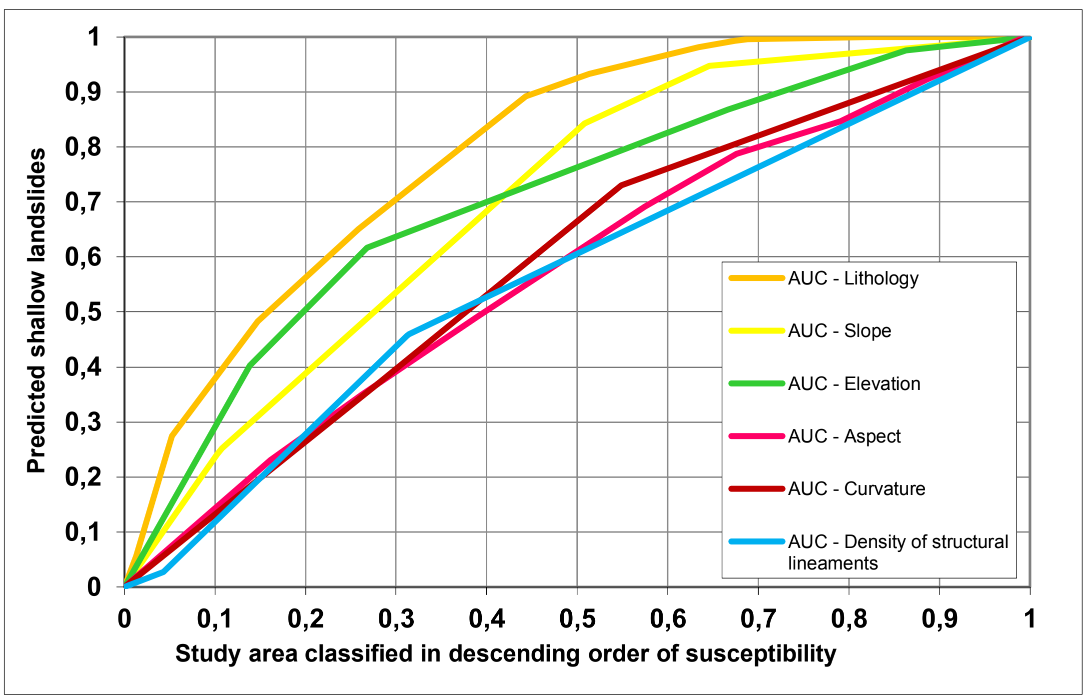

Figure 6. Lithology was the most important parameter on the sensitivity analysis of conditioning factors for the occurrence of shallow landslides.

There is a necessity of geological mapping improvement in Brazil, such as construction of local scale maps to the Serra do Mar (1: 25,000, 1: 10,000 and 1: 5,000). Further research in this field regarding the role of altered rocks in tropical environment would be of great help in understanding shallow landslides, once changing level of weathering in lithologies can provide specific conditions for instability of slopes.

6. ACKNOWLEDGEMENTS

This work was supported primarily by the National Council for Scientific and Technological Development (CNPq) and Postgraduate Program in Physical Geography of University of São Paulo. Acknowledgements for Institute of Technical Research of the State of São Paulo (IPT) for the possibility to participate in the "New Talents" program.

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