

# Different approaches for using Shalstab model to support climatic risk management in power transmission assets: Case study in a transmission line located in Serra do Mar Paranaense, Brazil

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**ABSTRACT:** The goal of this paper is to evaluate the usage of the Shalstab model in the diagnoses of the susceptibility to movements of mass in a Brazilian region through which a transmission line passes. The model is considered using two approaches: i) the classic approach, that is, obtaining a level of the terrain's risk from the  $\log(q/t)$  ratio and, ii) an approach based in relation to the critical daily rainfall values required to determine a rupture. For the parametrization of the geotechnical values required as Shalstab input, a spatialised approach was adopted which considers the lithological variability, since the study area it is located in an ancient fold belt structure. The movement of mass scars used for the validation of results indicate that the model's risk level approach can identify the susceptible areas with a good accuracy. In relation to the critical amount of rainfall to cause ruptures in the study area, precipitations above 100mm/day are dangerous for around 10% of the study area. This precipitation value is very common in the region, which indicates the need for attention, since the transmission line's structures may be hit by ruptures, passage zones and the deposition of movements of mass occurring there.

**Keywords:** Movements of mass, threats to electrical energy transmission lines, Shalstab Model.

## INTRODUCTION

Mass movements are geomorphological processes that may cause incredible landscape transformations in a short time (Young, 1975; Selby, 1993). Due to the typical magnitude involved, these phenomena can put energy transmission and distribution assets at risk. The main consequence is the interruption of the electrical energy transmission due to damage in the network's structure because of it being hit by the rock alteration soil/mantle's rupture or by the passage of these materials or even by their deposition in places of lower altitude. For this reason, mapping the susceptibility to movements of mass of the basins where the electrical energy transmission companies' assets are situated is crucial to reducing the risks.

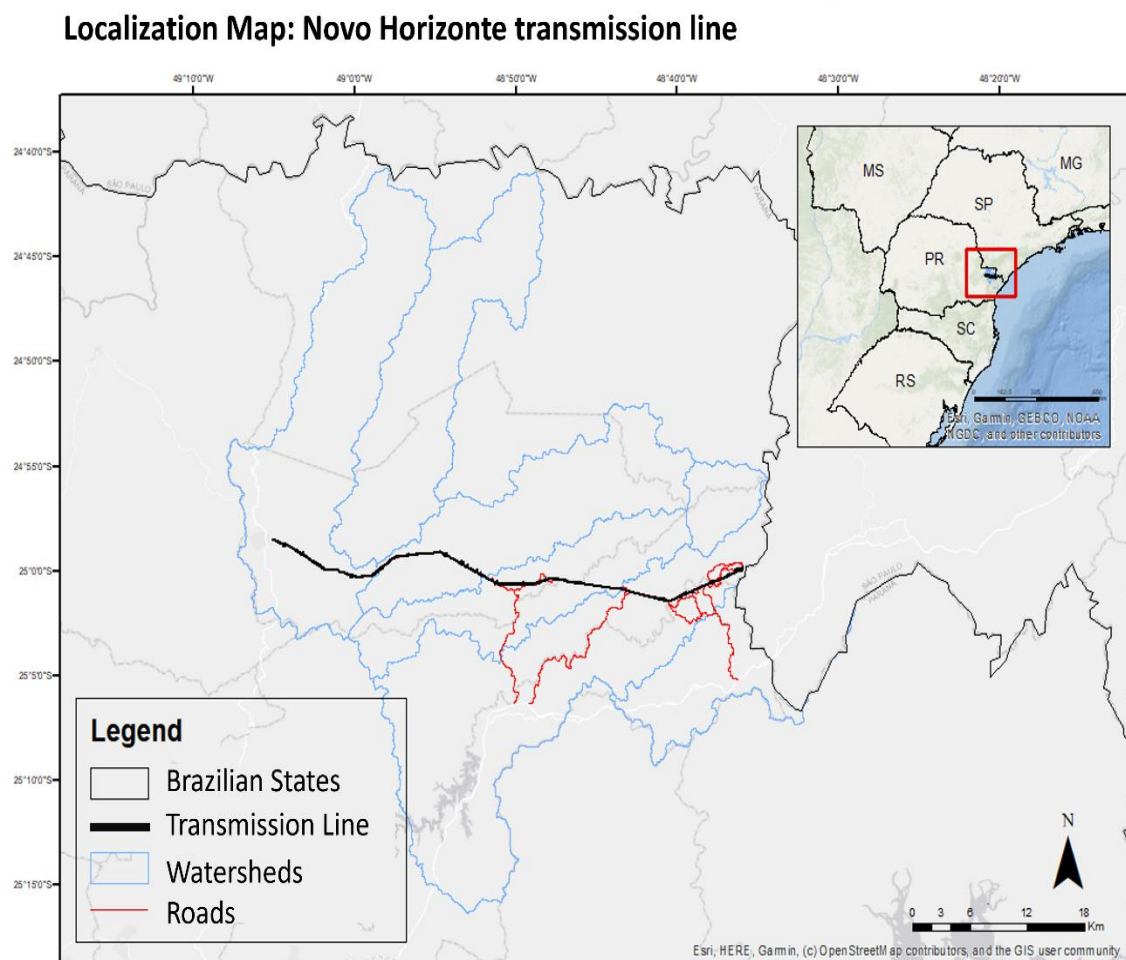
It is possible to note two research fronts in Brazilian literature in terms of modelling the prediction of mass movements. The first involves the use of computer algorithms allied to pluviometric data, geomorphological variables and secondary mappings (soil usage, geology, etc); however, without the direct usage of the soil geotechnical values (Flores, 2018; Sothe et al., 2017; Vanacôr; Rolim, 2012). The second uses prediction models based on geotechnical and hydrological characteristics of the soil combined with variables extracted from digital terrain models (VIEIRA E RAMOS, 2015; VIEIRA, 2007; RIFFEL et al., 2016; MICHEL et al., 2014).

In this second research front, we highlight the works which use the SINMAP (Stability Index Mapping), a stochastic prediction model, and the Shalstab (Shallow Slope Stability Model), which uses a deterministic approach. Regarding landslide prediction, the Shalstab model (MONTGOMERY; DIETRICH, 1994) has been amplyutilized in applications located in Brazil (MELO; KOBIYAMA, 2018). Furthermore, cooperative works between both models show a higher level of assertiveness of the results generated with Shalstab when identifying areas susceptible to landslides (Meisina E Scarabelli, 2007; Michel, 2011; Sisto, 2018; Paul et al., 2019; ZAIDAN et al., 2018). Also, Shalstab presents the possibility of estimating a cliff's susceptibility, from the rainfall values required to provoke a rupture. This capacity is interesting from the point of view of including this model in risk management operational approaches for the occurrence of mass movements.

Due to the good performance of the usage of Shalstab in research done on national soil, this study aimed to assess the usage of this model to realize a diagnosis of the susceptibility to ruptures of soils/regolith in a sector of Serra do Mar Paranaense through which an electrical energy transmission line passes. It presents great lithological variability and compares different scenarios of critical rainfall, starting from a simulated value of hydraulic conductivity.

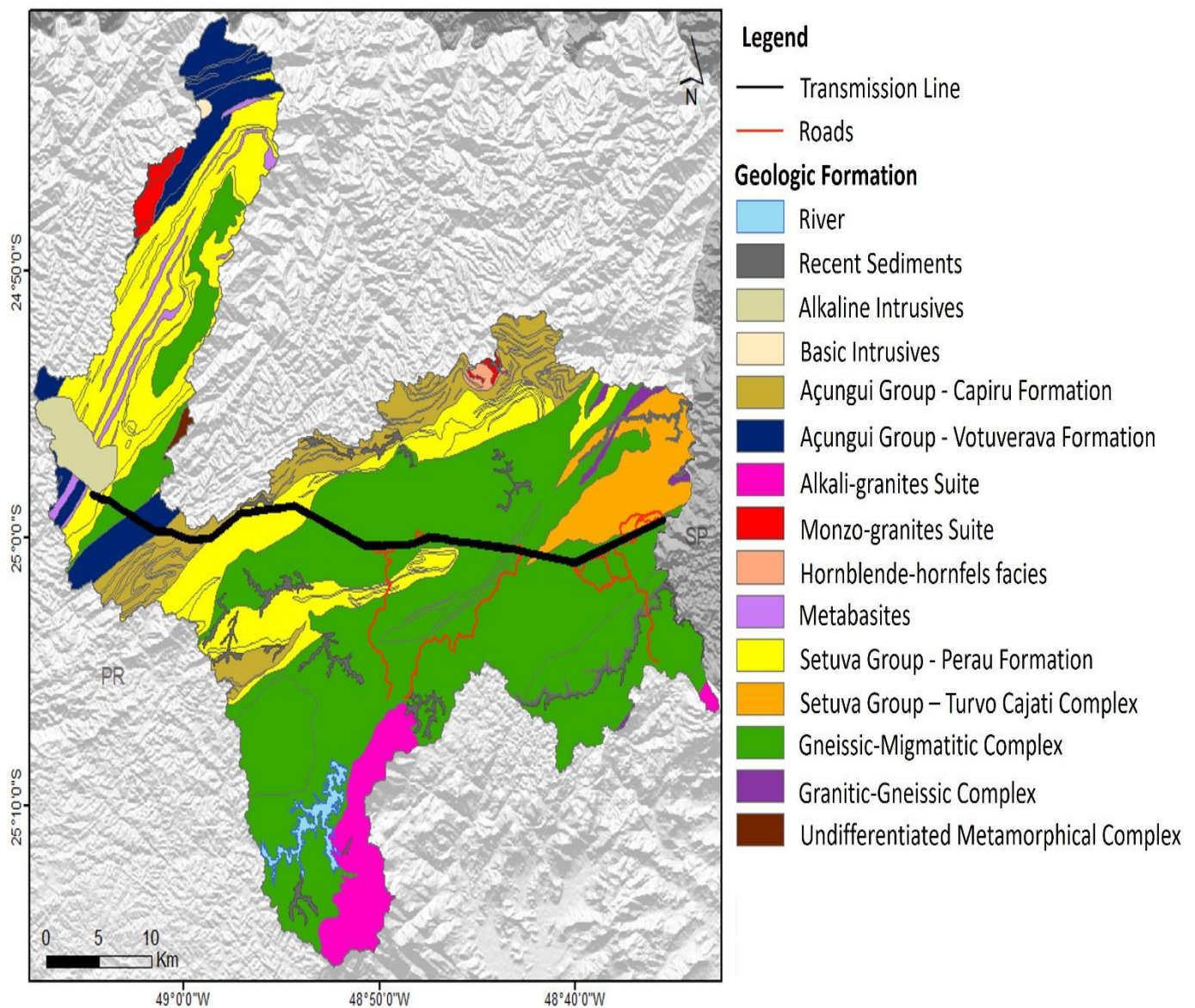
## 1. STUDY AREA

The study area comprehends the set of hydrographical basins which are intersected by a 139kV transmission line (TL) conferred by CPFL Energy, called "TL Novo Horizonte" and its access roads, situated in Serra do Mar Paranaense, in the northeastern region of the state of Paraná (Brazil) (Figure 1).



**Figure 1:** Map of the location of TL Novo Horizonte.

The geology of the study area presents a great lithological diversity (Figure 2) because these terrains compose an ancient fold belt from the Proterozoic age. This diversity gave rise to alteration mantles (regoliths) with many variations in terms of texture, cohesion, hydraulic conductivity and internal attrition angle, not only spatially (X and Y axes) but in depth (Z axis).



**Figure 2:** Map of the geological formations which exist in the basins intersected by the transmission line. Source: Map compiled from the Institute of Soils, Cartography and Geology of Paraná - ITCG's data (ITCG, 2020).

## 2. THEORETICAL BASIS – SHALSTAB MODEL

Shalstab is a deterministic mathematical model for predicting movements of mass caused by ruptures. It was created with the goal of, in a computational and georeferenced environment, estimating the susceptibility of cliffs to ruptures caused translational landslides, since one of its theoretical presuppositions is the infinite slope model (Montgomery; Dietrich, 1994). The following equation expresses the infinite slope model:

$$\tau = c' + (\sigma - \mu).tg\varphi$$

In which:

$\tau$  = shear stress (kPa);

$c'$  = effective soil cohesion (kPa);

$\sigma$  = normal tension to the rupture plane (kPa);

$\mu$  = pore pressure (kPa);

$\varphi$  = internal attrition angle of the soil (degrees).

The model's other presupposition is representing the soil's saturation proportion and, for this, [Montgomery and Dietrich \(1994\)](#) utilized the O'Loughin hydrological humidity model, calculated by  $h/z$  as shown in the following equation:

$$\frac{h}{z} = \frac{Q \cdot a}{T \cdot b \cdot \text{sen } \theta}$$

In which:

$h$  = Height of the water column above the rupture's location (m);

$z$  = Depth of the soil (m);

$Q$  = Groundwater recharge ratio (precipitation) (mm/day);

$T$  = Soil transmissibility (m<sup>2</sup>/day);

$a$  = Drained area (m<sup>2</sup>);

$b$  = Unitary contour length (m);

$\theta$  = Slope inclination (degrees).

By combining and rewriting the equations above, it is possible to arrive at the Shalstab model, which may be implemented in such a way as to obtain an estimate of the critical value of rainfall (mm/day) required to provoke a rupture. In this manner, the Shalstab model may be expressed as:

$$Q = T \cdot \frac{\text{sen } \theta}{(a/b)} \cdot \left( \left( \frac{c'}{\rho_w \cdot g \cdot z \cdot \cos^2 \theta \cdot \tan \varphi} \right) + \left( \frac{\rho_s}{\rho_w} \right) \cdot \left( 1 - \frac{\tan \theta}{\tan \varphi} \right) \right)$$

In which:

$g$  = gravitational acceleration (m/s<sup>2</sup>);

$\rho_w$  = specific density of the water (kg/m<sup>3</sup>);

$\rho_s$  = soil density (kg/m<sup>3</sup>).

It is important to note that to express Shalstab in degrees of susceptibility ( $q/T$  ratio), it is only necessary to consider passing the transmissibility ( $T$ ) to the other side of the equation.

### 3. MATERIALS AND METHODS

The model's entry data were of different natures: geotechnical data (cohesion, internal attrition angle, real density of the soil, likely depth of the ruptured surface), topographical data (steepness, area of contribution) and hydrological data (hydraulic conductivity of the materials, amount of critical rainfall).

#### Geotechnical Parametrization

Given the lithological diversity of the study area, a grouping of lithological types by geological units according to the mineral composition of the most abundant lithologies in each unit of the Geological Map of ITCG (2020). The lithological types represented in each unit estimated characteristics of their alteration mantles (texture, depth, etc.) in a hot and humid environment, such as the study area's. The estimates are based on field knowledge and in technical and scientific works.

What is observed in scientific works using Shalstab is the parametrization based on secondary works that realized geotechnical gauging in alteration soils/mantles with similar chemical and textural characteristics is observed in scientific works. For the initial exploration, we opted to use geotechnical data from [Bini \(2020\)](#), [Bernardes \(2003\)](#), [Silva \(2003\)](#) and [Vallejo et al. \(2002\)](#), whose studied soil characteristics in these works resemble those existing in some portions of the study area. Also gauged was the likely depth of the rupture surface in accordance with what is known of the alteration mantle's thickness of each lithotype.

**Table 1** shows a compilation of the data used in the Shalstab model.

**Table 1:** Spatialization of the geotechnical parameters

Geological Units	Lithotype	Texture	Cohesion	Internal attrition angle	Soil density	Rupture depth
Gneissic-Migmatitic Complex	Quartz-Feldspar unit	sandy-silty to sandy-clay	6.95	31.8	2870	1
Granitic-Gneissic Complex						
Alkali-granites Suite						
Monzo-granite Suite						
Setuva Group - Perau Formation						
Setuva Group - Turvo Cajati Complex						
Alkali-granites Suite	Feldspar-mafic unit	Silico-sandy to sandy-clay	28.7	27	1912	3
Gneissic-Migmatitic Complex						
Açungui Group - Capiuru Formation						
Açungui Group - Votuverava Formation						
Alkaline Intrusives						
Faces Hornblenda hornfels						
Setuva Group - Perau Formation (with presence of biotite)	Mafic unit	silty to silty clay	12.96	15	3020	3
Basic Intrusives						
Metabasites	Limestone Unit	Clay residue from impurities	6.2	24.6	1600	2.5
Açungui Group - Votuverava Formation						
Undifferentiated Metamorphical Complex	Quartzite Unit	Sandy to gravelly	20	37	2600	0.5
Setuva Group - Perau Formation (with the presence of quartzites)						
Açungui Group - Capiuru Formation						
Açungui Group - Votuverava Formation						

As observed on

**Table 1**, different geological units were grouped in five lithotypes. For each lithotype it is estimated that the characteristics of their alteration mantles present similar physical and geomechanical properties or that it possesses a predominant lithology which stands out in relation to the others in its group or geological formation. For the rocks with the presence of minerals which result in weathering mantles with silty to silty-clay textural characteristics, we utilized the parameters presented by [Bini \(2020\)](#) derived from an alteration mantle of the Gneissic-Granulitic Mafic band, whose values are: i) cohesion: 28,7 kPa, ii) internal attrition angle: 27°, iii) soil density: 1.912 kg/m<sup>3</sup>.

For the lithologies which result in sandy or sandy-silty materials, the values cited by [Bini \(2020\)](#) were used, relative to the weathering of the felsic Geissic-Granulitic band, them being: i) cohesion: 6,95 kPa, ii) internal attrition angle: 31,8°, iii) soil density: 2.870 kg/m<sup>3</sup>. For the lithological groups whose rocks originate silty alteration mantles, the same [Bini \(2020\)](#) values were used, derived from the alteration of mafic rocks: i) cohesion: 12,96 kPa, ii) internal attrition angle: 15°, iii) soil density: 3.020 kg/m<sup>3</sup>. Concerning the rock groups with quartzites, the values used were those measured by [Bernardes \(2003\)](#): i) cohesion: 20 kPa, ii) internal attrition angle: 37°. The soil density data was obtained through the work of [Vallejo et al. \(2002\)](#), it being 2.600 kg/m<sup>3</sup>. Finally, considering the rock groups with limestone, the values measured by [Silva \(2003\)](#) were used: i) cohesion: 6,2 kPa, ii) internal attrition angle: 24,6°, iii) soil density: 1600 kg/m<sup>3</sup>.

The depth data of the likely rupture surface were parametrized in accordance with the material present, using the following values: 0,5m, 1m, 2,5m and 3m. These values were estimated in accordance with the larger presence (or absence) of weathering-resistant minerals, such as quartz or alkaline feldspar, which influence the alteration mantle's width. Figure 3 shows the spatialized geotechnical data.

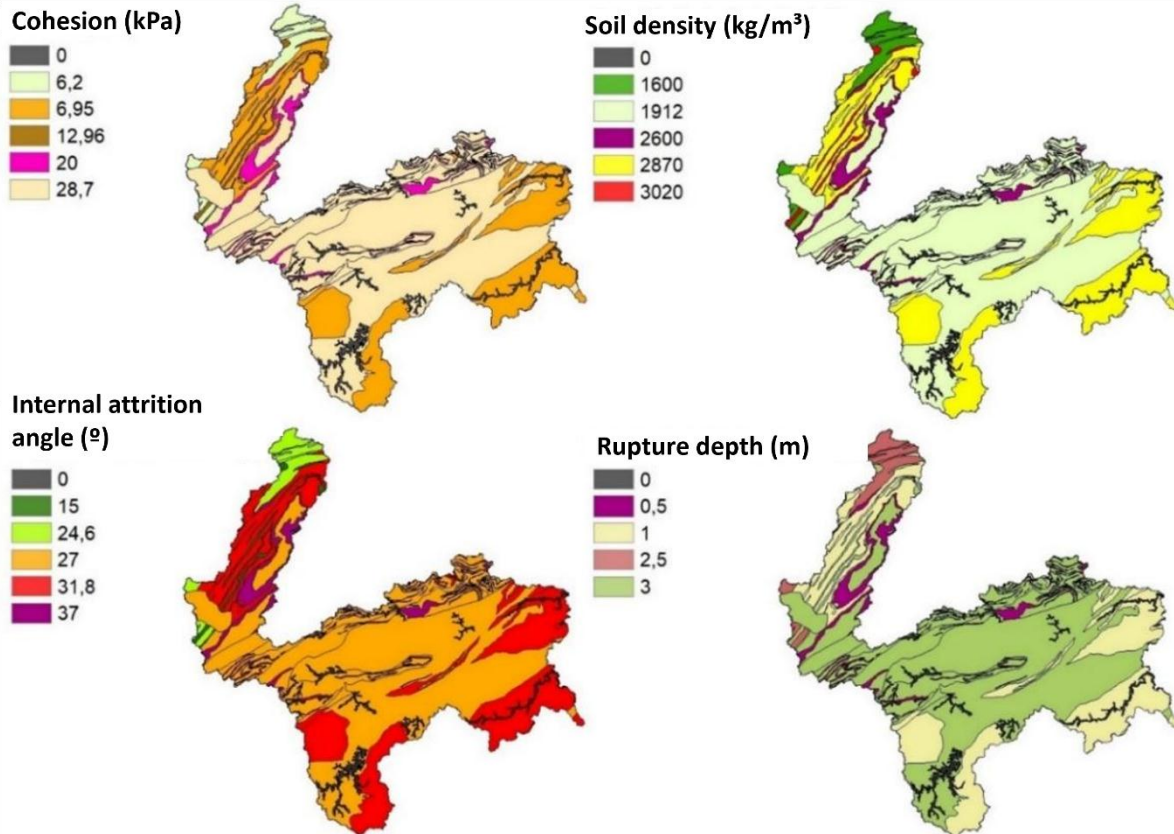


Figure 3: Spatialization of the geotechnical data.

#### Topographical Data

The Digital Elevation Model SRTM 30m was chosen as entry data for the movements of mass prediction model used in this research. For Shalstab's implementation, two geomorphological variables are required: Steepness and Flow Accumulation (also referred to as contribution area). The steepness was generated by means of the Slope tool, present in the ArcGIS platform. The contribution area was generated by means of the TauDEM toolbox (<https://hydrology.usu.edu/taudem/taudem5/downloads.html>).

#### Shalstab's Implementation

This work opted to implement the SHALSTAB equation via the R programming language. The Shalstab model allows for the obtainment of the estimated critical rainfall values required to make a portion of the terrain susceptible to a movement of mass. This option of Shalstab was also assessed in this work in such a way as to aid the creation of subsidies for the analysis of risk scenarios for landslides and debris flows considering different values of rainfall. As was previously shown, for the modelling of critical rainfall, it is necessary to have the transmissibility value ( $\text{m}^2/\text{day}$ ) of the study area's alteration mantle. As there are no values measured in loco, the transmissibility value used was that of Mendonça (2017),  $65 \text{ m}^2/\text{day}$ , for the modelling of the critical rainfall required to provoke movements of mass based on the Shalstab model in a portion of the Serra do Mar situated in the state of Rio de Janeiro.

## 4. RESULTS AND DISCUSSIONS

The susceptibility to ruptures, provoking movements of mass of the landslide and debris flow types, can be analyzed from the results of the Shalstab model for the study area. This susceptibility was generated in terms of two scenarios, considering different possibilities of derivation from the model: i) Shalstab in level of risk [(result of the ratio  $\log(q/t)$ ] pixel by pixel, ii) Critical daily rainfall required to provoke a rupture (Shalstab in terms of "q" - precipitation).

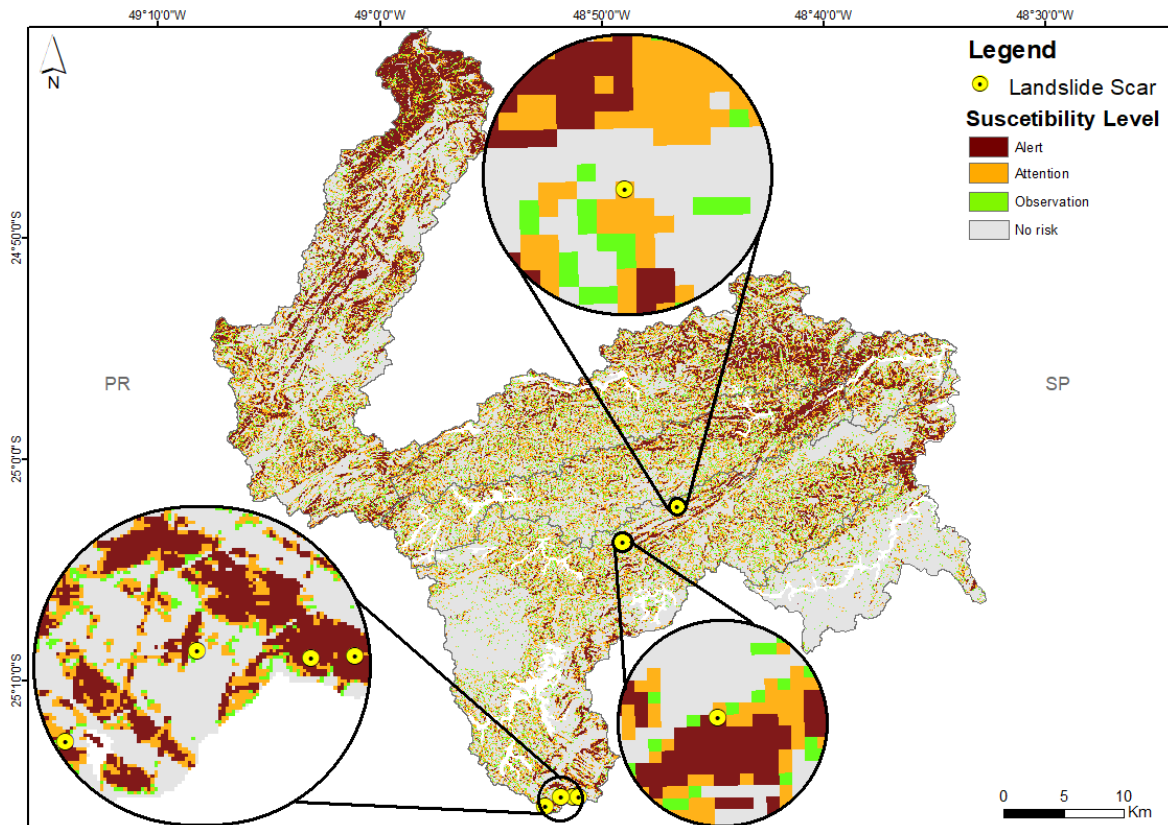
#### Shalstab in level of risk (q/t)

Montgomery and Dietrich (1994) propose a classifying system for the Shalstab results in terms of the  $\log(q/t)$  ratio, which translates into 07 (seven) terrain instability classes. However, for simplification, it was opted to regroup these classes into 3 susceptibility levels: Observation, Attention and Alert, which facilitates the interpretation of results for the lay public who can use this work's results. Table 2 presents the adopted groups of susceptibility levels.

**Table 2:** Classification of Shalstab's values. Source: First two columns: MONTGOMERY; DIETRICH, 1994

SHALSTAB VALUES	CLASSIFICATION	RECLASSIFICATION
Chronic Instability	Unconditionally unstable and saturated	Alert
$\log q/T < -3,1$	Unconditionally unstable and not saturated	
$-3,1 < \log q/T < -2,8$	Unstable and saturated	Attention
$-2,8 < \log q/T < -2,5$	Unstable and not saturated	
$-2,5 < \log q/T < -2,2$	Stable and not saturated	Observation
$\log q/T > -2,2$	Unconditionally stable and not saturated	-
Stable	Unconditionally stable and saturated	

Figure 4 presents the result of the instability model with the reclassified values for the susceptibility levels used in this work.



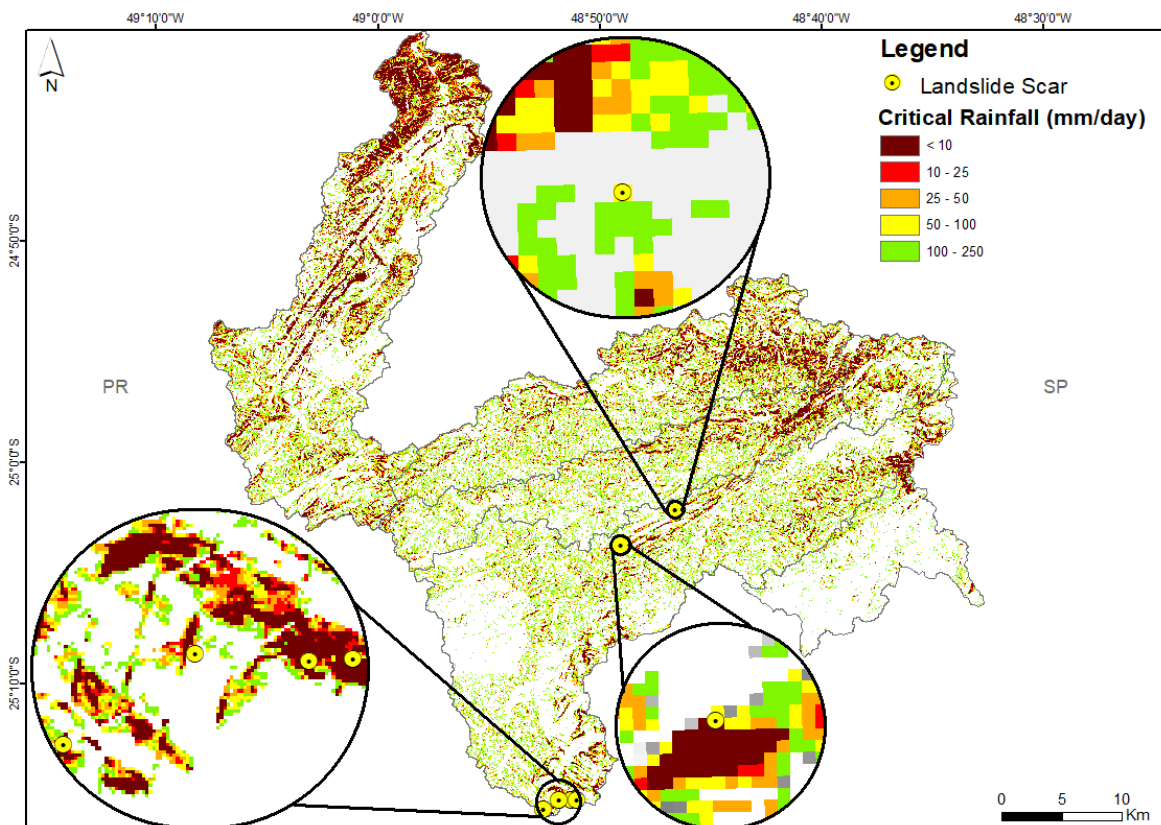
**Figure 4:** Map of pixel by pixel susceptibility to movements of mass map. The pixels in grey inside the study area correspond to those of the classes without attribution in the susceptibility levels.

According to Figure 4, it is noticeable that a significant portion of the study area has the susceptibility levels of “alert” and “attention”. Also noted is that the highest concentration of areas classified as “alert” are situated in higher steepness, which shows how this variable contributes to the configuration of a higher susceptibility. From the geological perspective, these areas are constituted in relief crystals kept by shearing zones and quartzite and shale rocks. It may be added that, even though a higher internal attrition angle, and consequently, resistance is attributed to these rock typologies, they still find themselves in the “alert” and “attention” levels, possibly due to the higher steepness in which they are found. The rocks of the Gneissic-Migmatitic Complex constitute the majority of the terrains of the study area but did not present the same proportion of areas at risk from ruptures, according to the modelling studies.

For the making of validation for the scenario presented by the Shalstab model, research was done in Google Earth's image archive for scars caused by mass movements in the study area. This search sought the identification of movement of mass scars and when a scar was found, an analysis was also done of that portion of the study area, in images before its occurrence. The geographic coordinate of a point in the interior of each scar was collected and spatialized on the result obtained with the Shalstab model. Thus, it was possible to identify 6 movements of mass scars (Figure 5), with two of them being relatively close to roads which give access to TL Novo Horizonte's right of way. The other scars are concentrated in the basin's southernmost portion. Based on that, it was possible to note that only one mapped scar is situated in an area classified as "attention" and all of the remaining scars are in areas classified as "alert". This factor hints us that the modelling is capable of identifying the areas most susceptible to ruptures with a good level of accuracy. It also demonstrates that the generalization done in the diversity of lithologies and its geotechnical and hydrological characteristics was adequate.

### Shalstab in the critical level of rainfall

The movements of the mass prediction model used in this research allow for the obtainment of the estimate of critical rainfall values required to turn a portion of the terrain susceptible to rupturing. This option of Shalstab was also assessed in this work to help create subsidies for the analysis of scenarios of susceptibility to movements of mass considering different values of precipitation. As shown previously, the alteration mantle's transmissibility value ( $m^2/day$ ) is required for the modelling in terms of critical rainfall. As it does not have values measured in loco, the transmissibility value used was the same as adopted by [Mendonça \(2017\)](#),  $65 m^2/day$ . Figure 5 shows the map of critical rainfall obtained using the model.



**Figure 5:** Map of the critical rainfall required to provoke soil ruptures.

In relation to the Shalstab model's logic, the lesser the amount of rain, the more susceptible the area is to the occurrence of ruptures. The locations classified as "attention" and "alert" on Figure 4, were the same that showed smaller volumes of critical rain as the result of the model expressed in terms of critical rainfall (Figure 5). About the 6 landslide scars mapped in the images from the Google Earth platform for the model's validation, 4 of them are in places where the critical rain is of up to 10mm, while the other 2 are in places classified as 10 to 25mm and 25 to 50mm.

Observing Figure 5 it is possible to notice that there are places which, even with less than 10mm of daily rainfall, already have a high degree of susceptibility to terrain ruptures. Furthermore, susceptibility is strongly correlated with the areas with a high steepness, which leaves it in constant danger. It is also noted that a large portion of the study area becomes unstable with the limit of 100mm/day or more.

According to the scenarios described in this research, the study area is likely to suffer alteration soil/mantle ruptures due to the high steepness of the terrains and the different geotechnical parameters in which the soils' alteration mantles present and the high precipitations which occur in the region. The high steepnesses result from the rocks' resistance to weathering and structures inherited from the deformation of the Faixa Ribeira (fold belt). There are also many rocks with different mineralogical natures in a small territory which may cause many discontinuities, which unfortunately are not incorporated in the model. An interesting factor is that the rocks on steeper terrain show thinner alteration mantles/soils, because they derive from more resistant rocks such as quartzites and shales, and thus, would move fewer materials when a movement of mass occurs.

## 5. CONCLUSION

Although there are many articles in Brazilian literature which explore the usage of Shalstab to assess the susceptibility of a region to the occurrence of ruptures, few of those approach the model's usage considering thresholds of critical rainfall. The usage of this model considering the points of critical rainfall is shown to be a fast option for obtaining the spatialization of regions with a higher susceptibility to mass movements, being usable together with the pluviometric monitoring. Differently from Shalstab's result, which is exclusively to map the instability level, this model version allows for the obtainment of dynamic results, meaning that they vary with the rainfall threshold. On the other hand, this model version requires the definition of a value for the soil's transmissibility, which is not easily obtained.

We also highlight that the generalization proposed for obtaining the geotechnical input values seemed adequate for the geological complexity of the study area in this work. Furthermore, the grouping of geological units from what is known in the literature about the characteristics of their alteration mantles in humid climates permitted the inferring of geotechnical parameters of input in the Shalstab prediction model, generating scenarios of susceptibility to ruptures which could be validated with past movements of mass occurrences.

About the critical rainfall thresholds to provoke ruptures in the study area, according to the Shalstab model, rain of 100mm/day is dangerous for many regions, around 10% of the study area. This precipitation value is very common in the region and that is a factor which increases the vulnerability of TL Novo Horizonte's structures to the processes of its settlement site's physical environment. As a suggestion for future works which utilize Shalstab's critical rain scenario, we emphasize the need for field work for in loco measurement and the spatialization of transmissibility for obtaining results with a higher likelihood of obtaining more precise critical rainfall thresholds.

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