Shalstab and TRIGRS: Comparison of Two Models for the Identification of Landslide Susceptible Areas

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ABSTRACT: Landslides are natural phenomena occurring worldwide. In Brazil, such events are recurrent and usually preceded and triggered by heavy rainfall. When occurring in urban areas, these catastrophic events cause disasters, such as economic damage, social impacts, and fatalities. So the identification and monitoring of the landslide-susceptible areas is extremely important and has been made with mathematical models. The objective of this study is to compare and analyze the performance of two different physically-based models: Shalstab and TRIGRS for the identification of landslide-susceptible areas.

KEYWORDS: Shalstab, TRIGRS, Susceptibility, Landslides.

1. Introduction

Gravitational mass movements, such as landslides, are surface transformations with the displacement of soils, debris, and rocky blocks (König et al., 2019). According to Cruden and Varnes, (1996), landslides occur when there is a surface rupture with soil and rock sliding through the slope. When it occurs in urbanized areas, they cause significant damage to structures and infrastructures, social impact and, sometimes human losses (Montgomery 1994; Larsen and Torres-Sanches 1998; Mendes et al. 2018a, b; Mendes and Valerio-Filho 2015; Zererê et al. 2005, Zizioli, et al. 2013). During the last decade, there was an increase of extreme weather conditions, such as heavy rainfall for hours and or days, floods and drought (Houghton, 2003). In Brazil, the landslides are usually triggered by heavy rainfall and occur during the rainy season (December to March). From 1991 to 2012, 699 landslides were registered in Brazil, and 79,8% of them happened at the southeast region of the country (Brasil, 2013).

The identification of landslide-susceptible areas can be performed using statistical methods (Carrara et al., 1991; Bai et al., 2009; Cervi et al., 2010; Li et al., 2012) and physically based models such as the Shallow Slope Stability Model (SHALSTAB) (Montgomery and Dietrich 1994; Dietrich and 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), TRGIRS-unsaturated (Savage et al. 2004), physically-based Slope Stability Model (dSLAM) (Wu and Sidle 1995), SLOPE/W and SEEP/W (Geostudio, 2005).

Different analysis methods and the comparison of results improves the quality and reliability of each method, highlighting and identifying the most important factors which caused the landslides in the area under study (Zizioli et al. 2013). In this frame, the objective of this paper is to compare two physically based models Shalstab and TRIGRS, in the identification of the landslide-susceptible areas in Vila Albertina (Campos do Jordão municipality, Brazil).

2. Materials and Methods

2.1. Study Area

The study area is Vila Albertina neighborhood, SE São Paulo State (Brazil) (

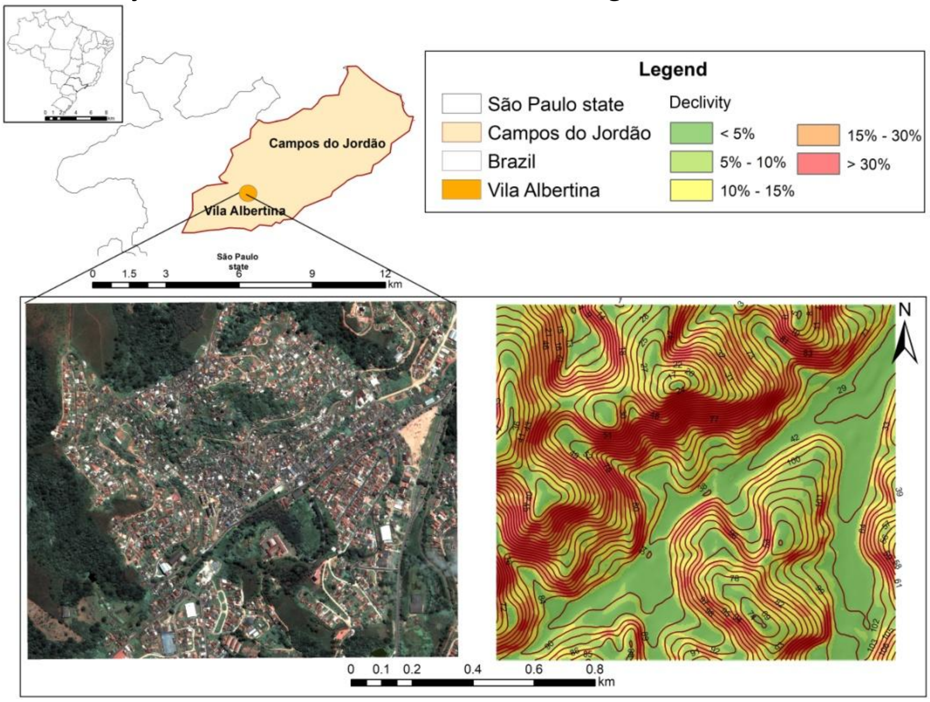

Figure 1). Located on a crystalline plateau, with altitudes above 2000 m and annual precipitations varying from 1205 to 2800 mm (Modenesi-Gauttieri and Hiruma, 2004), this area has recorded recurrent landslide events. One of the most catastrophic landslides recorded, occurred in August 1972, resulting in 17 fatalities and 60 houses buried by the mudflow (Amaral and Fuck, 1973). In January 2000, another landslide event caused 10 fatalities, over 100 injured and 423 strongly damaged houses (Mendes and Valerio-Filho, 2015; Mendes et. al 2018a,b). Geologically this area is delimited by two rifts namely: Jandiuvira and São Bento do Sapucaí, from Pre-Cambrian to Paleozoic age, presenting high mountains and erosive depressions (Hiruma et al. 2001, König et al. 2019). Thus, in the steep slope areas are irregular occupation, vertical cuts in the slope and the vegetation was removed. These anthropic changes decrease the slope stability, inducing landslides events.

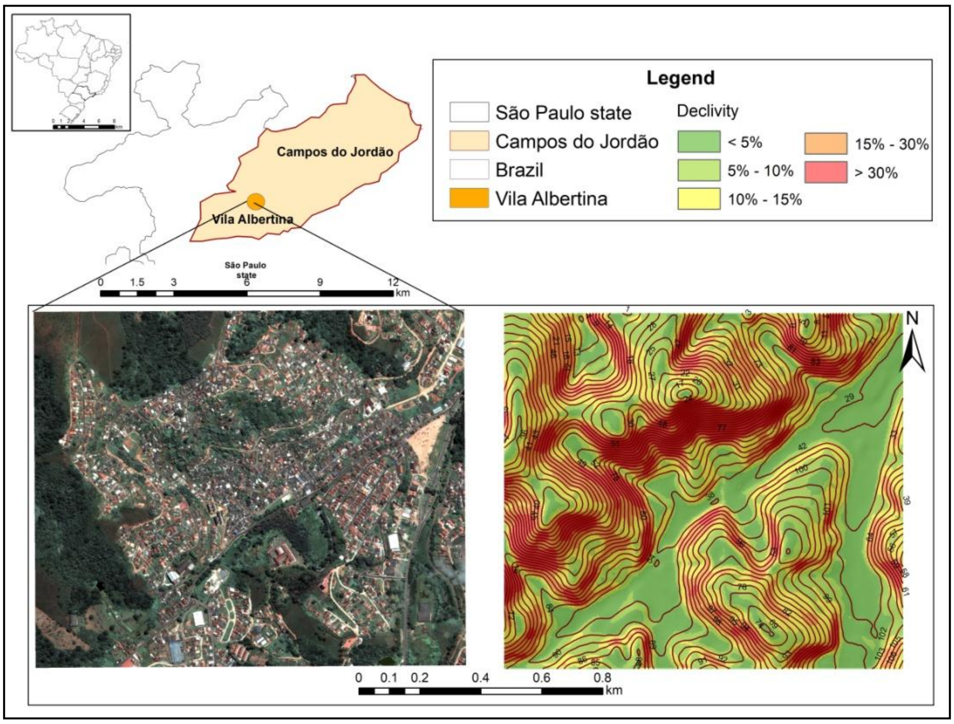

Figure 1. Study Area.

2.2. Shalstab model

The Shalstab - *Shallow Landsliding Stability Model*, develop by Dietrich and Montgomery (1998), is a mathematical model to identify landslides-susceptible areas. Its formula is based on the infinity slope stability model, defined by the Mohr-Coulomb law, and the steady-state hydrological model, developed by O´Loughlin (1986) as presented in Equation 1.

$$\log\left(\frac{q}{t}\right) = \frac{\sin\theta}{\frac{a}{b}} * [\left(\frac{c'}{\rho w * g * z * \cos^2\theta * \tan(\varphi^1)}\right) + \frac{\rho s}{\rho w} * (1 - \left(\frac{\tan\theta}{\tan\varphi^1}\right)] \qquad (1)$$

Where q is the rain recharge, t is the soil transmissivity, θ is the inclination (degrees), a is the contribution area (m²), b is the contour size (m), c' is the soil cohesion (kPa), φ is the soil internal angle (degrees), ρs is the soil density ($kg*m^{-3}$), g is the gravitational acceleration, z is the soil thickness (m) and ρw is the water density ($kg*m^{-3}$).
Shalstab calculates the critical threshold of rainfall for the occurrence of a surface rupture and, consequently, a landslide (Montgomery and Dietrich, 1994; Dietrich and Montgomery, 1998; Vieira and Ramos, 2015; König, et al. 2019).
The input data are topological and hydrological parameters, physical and mechanical properties of the soil, such as density, cohesion, the internal friction angle and a digital terrain model (Reginatto et al., 2012; Michel et al., 2012, 2014; König, et al. 2019).

2.3. TRIGRS model

The mathematical model TRIGRS (Transient Rainfall Infiltration and Grid-based Regional Slope- Stability Model) was developed by Baum et al. (2002) to calculate the variation of the Factor of Safety (FS), due to the change in transient pore-pressure and soil moisture during a rainfall infiltration.
This model, written in the Fortran language, associates the hydrological model based on Iverson's (2000) which linearized one-dimensional analytical solutions of Richards Equation (eq.2) and a stability model based on the equilibrium limit principle, giving rise to its final formulation (eq. 3). It represents the vertical rainfall infiltration in homogeneous isotropic materials (Baum et al. 2002).

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

Where θ is the soil volumetric moisture content (dimensionless), t is the time (s), z is the soil depth (m), Kz is the hydraulic conductivity (m/sKPa) in the z-direction, and Ψ is the groundwater pressure head (kPa).

$$FS = \left(\frac{\tan\phi}{\tan\alpha}\right) + \left[\left(\frac{c - \Psi(Z,t)Y_w \tan\emptyset}{Y_s Z \sin\alpha \cos\alpha}\right)\right] \qquad (3)$$

Where c is the cohesion (kPa), ϕ is the internal friction angle (deg.), γw is the unit weight of groundwater (kN/m³), γs is the soil specific weight (kN / m³), Z is the layer depth (m), α is the slope angle ($0 < \alpha < 90°$), and t is the time (s).

The TRIGRS input data are the geotechnical parameters (cohesion, soil specific weight, hydraulic conductivity, and angle of friction), as well as hydrological data (initial infiltration rate and initial water table height) and rainfall duration and intensity. The model allows the variation of input values such as soil properties cell by cell because it takes account of the horizontal heterogeneity. According to Baum et al. (2002), "the model results are very sensitive to the initial conditions, particularly the steady component of the flow field and initial depth of the water table".
Figure 2 represents the components of TRIGRS model in which during a rainfall event, infiltration and surface run-off happen at the same time. There is an increase in the groundwater table and consequently the increase in water pore-pressure.

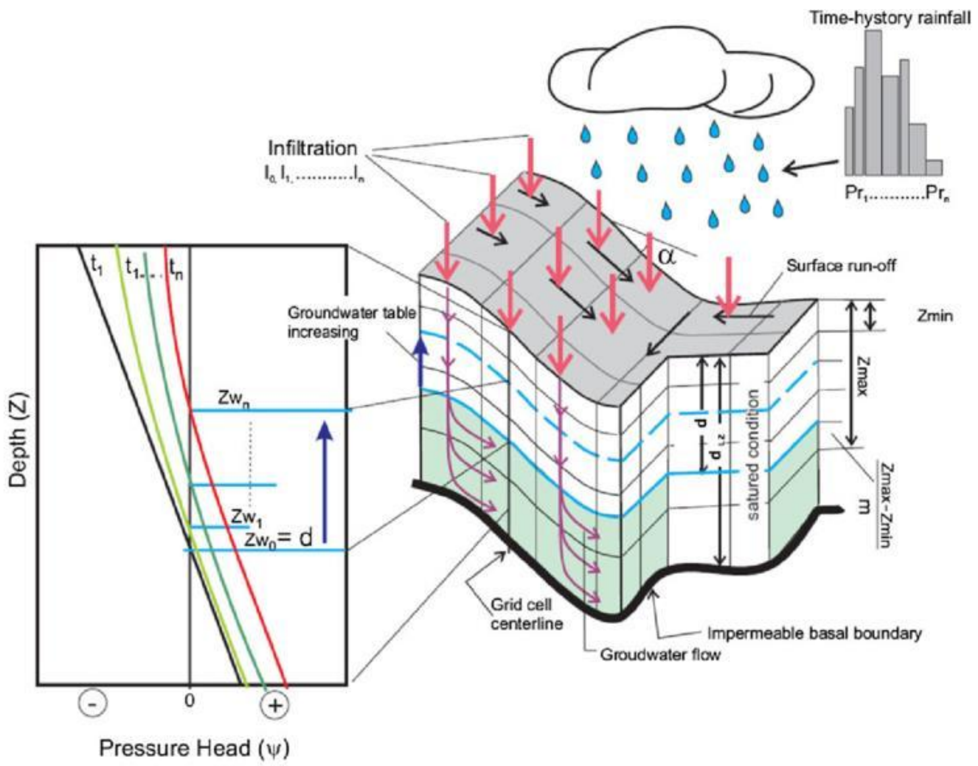

Figure 2. TRIGRS components. Source: Grelle, et al. 2014.

2.4. Input data

The modeling of landslides-susceptible areas using Shalstab and TRIGRS requires geotechnical parameters such as cohesion, soil specific weight, hydraulic conductivity, internal friction angle, and the rainfall duration and intensity. The input parameters presented in Table 1 and the rainfall values presented in Source: Mendes et al. (2018a)

Table 2 were acquired from the literature of previous studies at Campos do Jordão (Mendes et al. 2018a). The landslides scars were acquired from König et al., 2019.
The analyzed period is January of 2000, whereas a heavy rainfall that lasted from January 1th to 4th, resulted in the death of 10 people, more than 100 injured and 423 structurally damaged houses (Mendes et. al 2018a,b; Mendes and Valerio-Filho, 2015).

Table 1. TRIGRS and Shalstab input parameters.

Input parameters					
Depth (m)	Cohesion (kPa)	Angle of Friction (°)	Hydraulic Conduct.(m s-1)	Hydraulic Diffus. (m s-1)	Specific weight (kNm-3)
1,0	19	34	1,18x10^{-6}	6,45x10-6	21,4
1,0-2,5	14	42	3,76x10-6	6,45x10^{-6}	17,5
2,5-5,0	42	28	3,09x10-6	6,45x10^{-6}	17,8

Source: Mendes et al. (2018a)

Table 2. Daily accumulated rainfall.

Date	01/01/00	02/01/00	03/01/00	04/01/00	Total
Daily rainfall	101,0 mm	120,0 mm	60,0 mm	144,5 mm	425,5 mm

Source: Mendes et al. (2018a)

3. Results and Discussion

3.1. Analyzing the results of TRIGRS and Shalstab

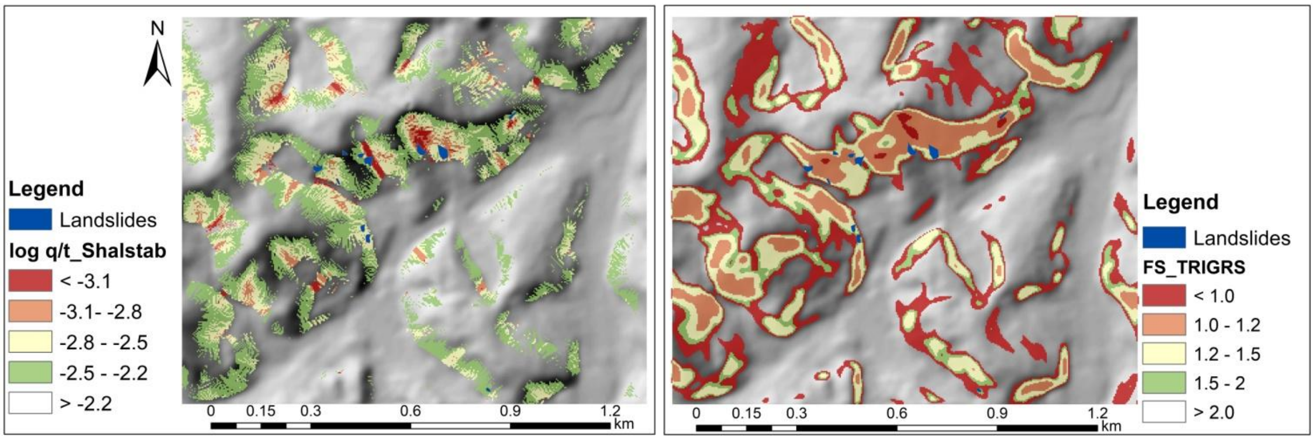

Figure **3** presents the landslide susceptibility maps created using the two mathematical models Shalstab and TRIGRS.

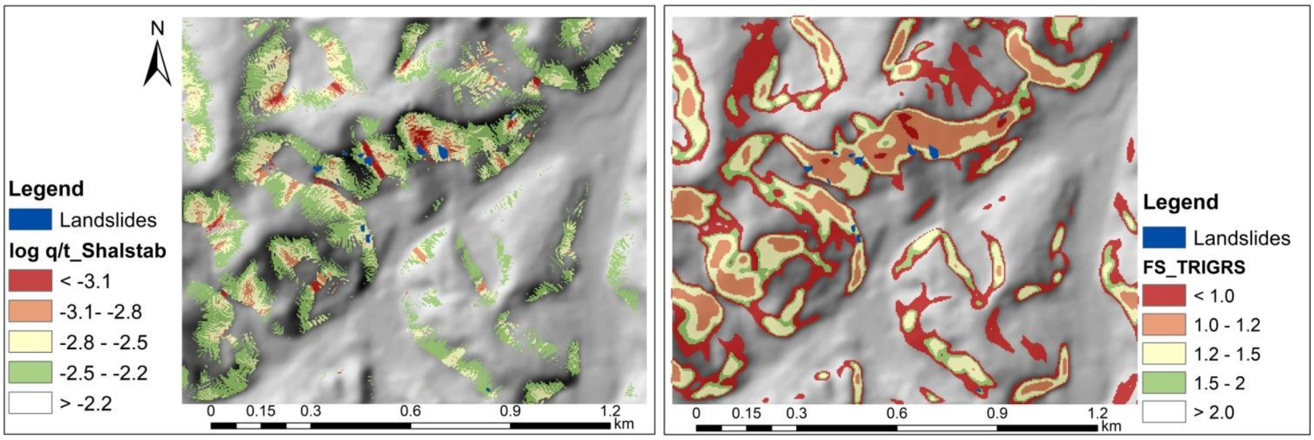

Figure 3. Landslide susceptible areas.

Analyzing

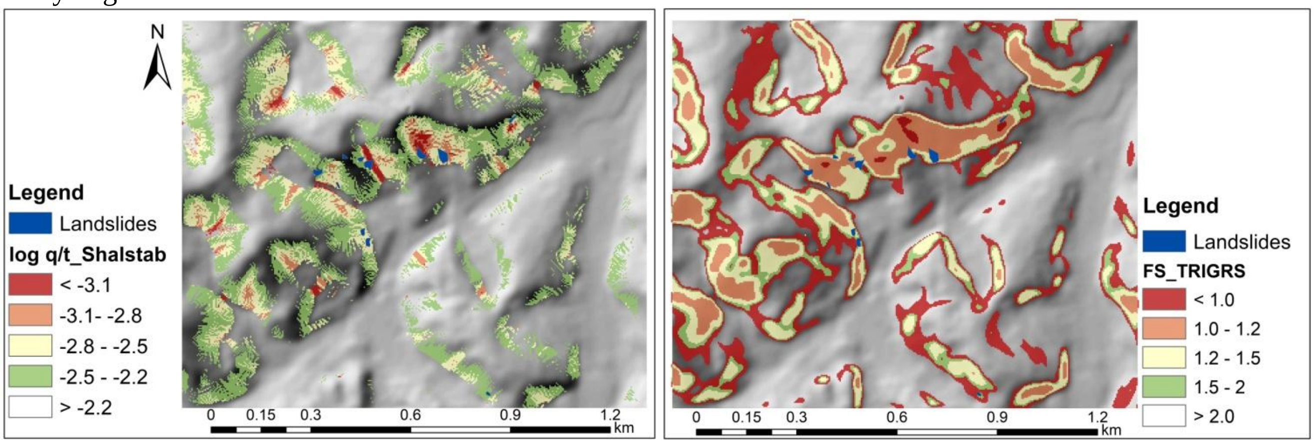

Figure **3**, it is possible to assume that both models show satisfactory results for identifying the most landslides-susceptible areas. Regarding Shalstab results, 30% of the landslides scars are in unstable areas (log q/t < -3,1), 60% in areas with medium susceptibility (-3,1 > log q/t > -2,5) and 10% in stable class (-2,5 > log q/t > -2,2).

Otherwise, in TRIGRS results, 20% of the landslides happened in areas with Factor of Safety (FS) < 1,0 and 80% occur in areas with FS 1,0 – 1,2. A further analysis indicate that TRIGRS model compute 14.96% of instability classes with FS < 1,0, while Shalstab identified 0,57 % (log q/t < -3,1). Table 3 present the unstable areas identified by both models.

Table 3. Unstable areas identified by both models.

Shalstab		**TRIGRS**	
Instability Class	% of area	Factor of Safety	% of area
< -3,1	0.57	< 1.0	14.96
-3,1 - -2,8	1.84	1.0 -1.2	6.39
-2,8 - 2,5	7.77	1.2 - 1.5	9.09
-2,5- -2,2	15.13	1.5 - 2.0	5.70
> -2,2	74.69	> 2.0	63.86

TRIGRS identified more unstable areas than Shalstab and, as previously mentioned, it is very sensitive to the initial conditions, especially with those related to the initial depth of the water table. Despite of that, this study demonstrates that both models have effective results identifying the landslide-susceptible areas.
It is important to highlight that the studied section is an urban area, with several manmade standards, causing changes in steep slopes, changing the soil properties and inducing landslides (König et al. 2019, Mendes et al. 2018a,b, Prieto et al., 2017).

These mathematical models identify the susceptible areas considering the soil properties and the total amount of rainfall infiltration. The Shalstab is very useful in the assessment of the initial groundwater conditions, and TRIGRS, due to the capability of analyses the changes in transient pore-pressure; provide good results identifying the most landslides susceptible areas.

4. Conclusion

Landslides are a recurrent phenomenon, especially in tropical countries, such as Brazil. It might become a disaster when affect the population. Then, identification and monitoring of landslides-susceptible areas are very important to avoid disasters. Mathematical models have been widely used to modeling the unstable areas. Thus, the applied approach was to compare the performance of two mathematical models which assumed different hydrological models, for the identification of the most landslides susceptible areas.
Despite the difference of the models physics, the results of both models are satisfactory. Landslides scars were used to validate the models results through a comparison between the unstable areas identified by the models and the areas where landslides were registered.
Some areas identified as medium landslide-susceptibility, present landslides scars. It corroborates with the assumption that anthropic changes and environmental degradation of steep slope areas, modify the soil properties and might induce landslides.
The authors recommend the use of these models to monitor and map landslide susceptible areas, improving the safety of those who live in such high risk slope areas.

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