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Potential fragility of the Caeté catchment, municipality of Alfredo Wagner, Santa Catarina State, Brazil, to landslides occurrence

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ABSTRACT. Natural disasters associated with land mass movements in Brazil have become more frequent in recent years, with significant human loss and material damage. An alternative to reduce such natural disasters will occur when landslides-susceptible areas are mapped, with restrictions or conditions for the occupation of areas with natural fragility to landslide occurrences. Current analysis determines the slopes´ potential degree for the occurrence of landslide susceptibility in the Caeté catchment, municipality of Alfredo Wagner, in the highlands of the state of Santa Catarina, Brazil. The Shallow Stability model (SHALSTAB) identified the slopes´ instability index by hydrological factors, hillside stability and soil. Results revealed areas with high degree of hillside instability and the need for preventive and relieving actions. In fact, areas with very high potential fragility susceptible to the occurrence of mass movement in the Caeté catchment are more than 30% of the basin´s total area.

Keywords: SHALSTAB, landslide susceptibility, risk area.

Fragilidade potencial das vertentes à ocorrência de deslizamentos na bacia hidrográfica do Caeté, Alfredo Wagner, Estado de Santa Catarina, Brasil

RESUMO. Nos últimos anos no Brasil, os desastres naturais associados ao movimento de massa vêm sendo mais frequentes, com maiores danos materiais e humanos. Uma das alternativas de redução deste tipo de desastre natural dar-se-á a partir do mapeamento das áreas suscetíveis a deslizamentos e da determinação de restrições ou de condições para a ocupação de áreas que possuam fragilidade natural à ocorrência a deslizamentos. O presente artigo teve por objetivo determinar o grau de potencialidade das vertentes à ocorrência de deslizamentos na bacia hidrográfica do Caeté, município de Alfredo Wagner, região serrana de Santa Catarina. O modelo SHALSTAB (*Shallow Stability*) foi empregado para a identificação do índice de instabilidade das vertentes, a partir de fatores hidrológicos, de estabilidade da encosta e do solo. Os resultados demonstram a presença de áreas com elevado grau de instabilidade das encostas e a necessidade de ações preventivas e mitigadoras, uma vez que as áreas com fragilidade potencial muito alta e extremamente alta à ocorrência de movimento de massa na bacia hidrográfica do Caeté compreenderam mais de 30% da área total da bacia.

Palavras-chave: SHALSTAB, suscetibilidade a deslizamento, área de risco.

Introduction

Landslides, continuous natural phenomena that form landscapes, are the result of an association of hydrogeomorphic, geological and anthropologic factors. According to Guerra (1993), landslides may be defined as soil mass movement on a water-saturated foundation. They depend on several factors, such as the slope angle, rainfall intensity and frequency, vegetation cover, soil consolidation and others.

The potential fragility to landslides occurrence is considered to be a natural vulnerability and depends on their physical characteristics such as slope, rainfall and soil type.

Landslides are notable and significant processes in slope evolution and are characterized by fast movements (CUNHA, 1991). They may also be intensified by human activities and are similar to floods, draughts and other phenomena that cause natural disasters.

In Brazil, natural disasters associated with land mass movements have became more and more frequent, especially in the 1990s and 2000s, with 454 registered events affecting more than two million people (CEPED, 2012). Natural disasters caused by landslides in Brazil spatially occur in greater numbers in southeastern and southern Brazil, in the Atlantic Rainforest, and temporally they are abundant during the summer and late spring, especially in December, January and February. Their occurrence in the Atlantic Rainforest is mainly conditioned by steep slopes, relief (high altitude) and proximity to the ocean (more moisture). Further, the summer and late spring periods are characterized by heavy rainfall events.

In the Caeté catchment, municipality of Alfredo Wagner, a mountainous region in the state of Santa Catarina, Brazil, agricultural activities have provided a decrease in water infiltration into the soil especially in areas with steep slopes and deforested hillsides and riverbanks. There was a subsequent increase in overland flow which sometimes triggered a torrential flow under heavy rain. These factors have altered soil erosion processes and created favorite conditions for the destabilization of slopes by triggering landslides and mudslides. In fact, the town of Alfredo Wagner has undergone land mass movement and floods for a long time (HERRMANN, 2007).

The prior knowledge on the most susceptible areas for the occurrence of landslides (hazard areas) allows preventive and mitigating actions which may be implemented to reduce physical damage and human loss. Computer modeling has been of great service in the prevention of disasters.

One of the computational models to predict areas susceptible to landslides is the SHALSTAB which involves both hydrological (BEVEN; KIRKBY, 1979) and slope stability concepts (MONTGOMERY; DIETRICH, 1994) to determine the index of slope stability. SHALSTAB has been used successfully in numerous studies conducted mainly in the western USA (GORSEVSKI et al., 2006) and in southern Europe - Italy (GULLÀ et al., 2008; MEISINA; SCARABELLI, 2007), all of which have a temperate climate.

Meisina and Scarabelli (2007) compared the two models SHALSTAB and SINMAP (Stability Index Mapping) proposed by Pack et al. (1998), by applying them to measure data from shallow landslides in an area north of the Alps, Italy. Results obtained by SHALSTAB were more realistic for non-extreme events. The authors emphasized that the index of slopes stability shown in both models should not be interpreted as absolute numbers but an index indicating potentially dangerous areas.

In Brazil, studies with SHALSTAB also gave satisfactory results in the *Quadrilátero Ferrífero* region, state of Minas Gerais (RAMOS et al., 2002) and in the *Maciço da Tijuca* region, state of Rio de Janeiro (FERNANDES et al., 2001, 2004), both of which have a tropical climate. After comparing simulated and observed data, Fernandes et al. (2001) obtained 95% efficiency with this model. Furthermore, Michel et al. (2012) applied this model and SINMAP to the town of Rio dos Cedros, Santa Catarina State, Brazil, and compared the models' performance in terms of identification of susceptive areas. These authors concluded that SHALSTAB is more suitable for landslide hazard mapping.

In this context, it may be said that SHALSTAB is highly applicable to Brazilian conditions. The rate of the stability index calculated by SHALSTAB is transformed to the degree of landscape fragility for landslides, which may be very useful for the planning and environmental management. In fact, the procedure was applied to other mountainous region in the state of Santa Catarina.

Current study determines the potential fragility of the Caeté catchment for landslide occurrences by employing the Shallow Landslide Slope Stability Model (SHALSTAB) proposed by Dietrich and Montgomery (1998).

Material and methods

Study Area

The Caeté catchment (163 km^2) lies in the municipality of Alfredo Wagner in the mountainous region of the State of Santa Catarina, between latitudes 27° 52' 43" S and 27° 41' 49" S and longitudes 49° 20' 45" W and 49° 11' 17" W (Figure 1).

The catchment is formed by the Caeté and Santo Anjo rivers with sources at altitudes 1,140 and 1,600 m, respectively. Rivers´ densities (1.54 river km^{-2}) and average drainage (1.95 km km^{-2}) of the catchment indicate a well-drained area. The waterways have a several small and big waterfalls as well as a large number of headwaters (VESTENA et al., 2011).

The terrain is dissected by steep slopes and structural valleys where inappropriate usage activities have made the land more susceptible to erosion processes. The dissection is represented by mountainous steep relief and hills. Alluvial-colluvial deposits lie in the basin, mainly comprised of sandy-clay sediments with granules and pebbles with predominantly quartzite lithology deposited in torrential flow regimes (HERRMANN; ROSA, 1991). The V valleys are characterized by tight drainage system with high runoff velocity and energy (VESTENA et al., 2011).

Climate in the Caeté catchment is Cfb and the mean annual temperature is around 19ºC, with fluctuations ranging between -2° (winter) and 30ºC (summer), with the occurrence of frosts during the winter.

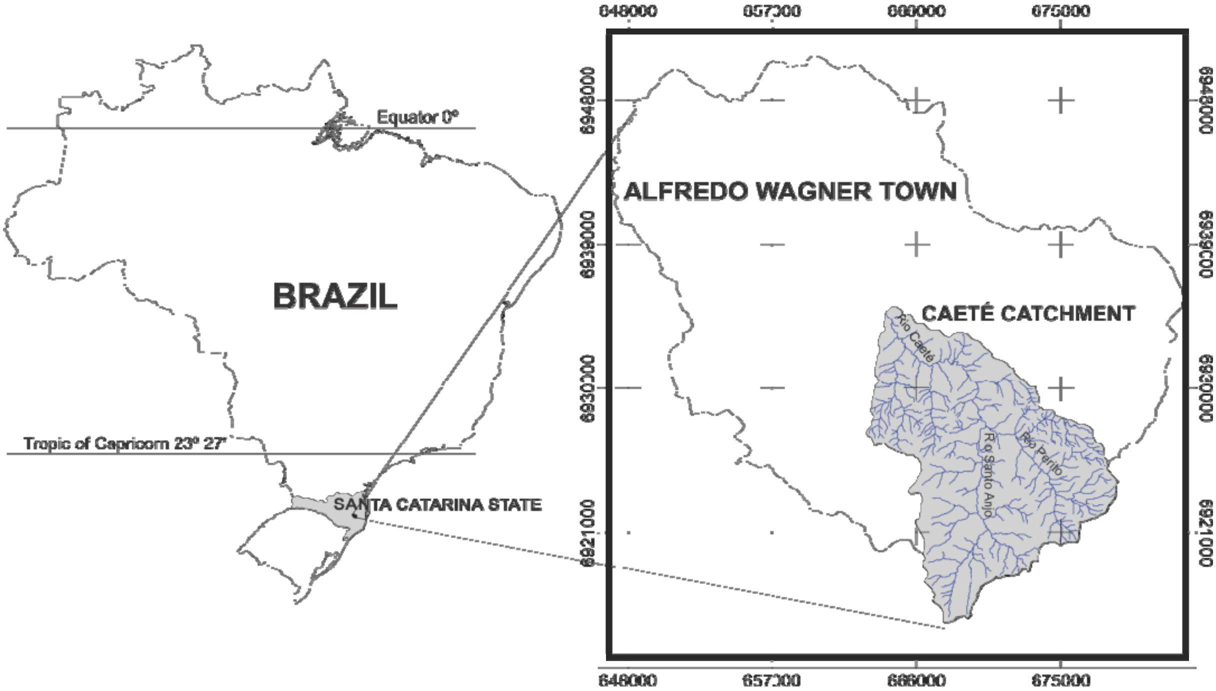

Figure 1. Location of the study area.

Mean relative air humidity is 85% (SANTA CATARINA, 1986), with high rainfall rates (1,660 mm year^{-1}) distributed throughout the year, without a specific dry period (MONTEIRO, 1963). However, the rainy season comprises December (165 mm), January (202 mm) and February (189 mm); the less rainy season comprises April (92 mm), May (109 mm) and June (97 mm) (VESTENA, 2009).

The Caeté catchment geology consists of nearly horizontal layers of sandstone, siltstones, mudstones and shales which belong to the Paraná Basin (SHIMIZU et al., 1995a). The soils covering the catchment are mainly Cambisols and Neosols which have very low natural fertility due to their high alkalinity (Figure 2).

According to Sachet (1994), the Cambisols in the catchment have incomplete sequence of horizons with little differentiation between them, or rather, with a well drainage system and high water retention. Neosoils normally occur in hilly areas associated with rock exposures.

Land usage is characterized by native forests, grasslands, exposed soils and cash crops. The main agricultural activity is the production of onions, beans and corn mainly on small farms.

SHALSTAB theory

SHALSTAB integrates hydrological and geomorphic aspects to determine the slopes´ degree of instability. The hydrological model establishes the relationship between the water concentration and soil transmissibility to define saturation conditions (BEVEN; KIRKBY, 1979; O'LOUGHLIN, 1986) (Equation 1).

$$W = \frac{h}{z} = \frac{Q}{T} \cdot \frac{a}{b \sin \theta} \qquad (1)$$

where:

W is the soil moisture content, expressed as the ratio h/z (dimensionless) in which being z is the soil thickness (m) and h the water height (m) in the subsoil; Q is the effective rainfall intensity (m/day), T is the soil transmissibility (m^2 days^{-1}); a is the contribution area (m^2); b is the contour length (m); and Θ is the local slope (°).

The ratio Q/T corresponds to the hydrological control whereas the ratio $a/b \sin \Theta$ corresponds to the topographic control (DIETRICH et al., 1993). Thus, the saturation zones occur wherever the upstream flow exceeds the capacity of the soil to transmit this flow. In the concept initially proposed by O'Loughlin (1986), the topography discretization is carried out by irregular polygons that are defined by the intersection with the contour lines of maximum gradient (Figure 3). The upstream region from the analyzed locality with counter length b, bounded by lines of higher gradient, perpendicular to the contour lines, is called the contribution area (a) for a given cell.

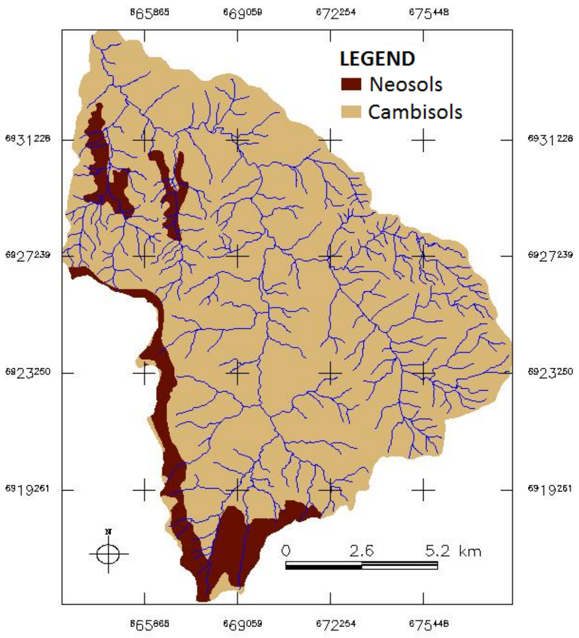

Figure 2. Soil classification (SHIMIZU et al., 1995b).

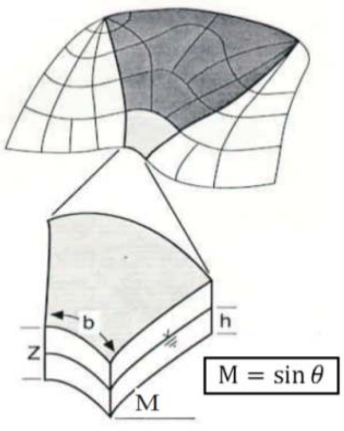

Figure 3. Hydrological concept of a contribution area. Note: The shaded area (contribution area) refers to the accumulated upstream drainage area (*a*) passing through the unit contour length (*b*).
Source: Guimarães et al. (2003).

The slope stability model is based on the infinite slope theory which simulates the degree of stability:

$$\frac{h}{z}=\frac{C'}{\rho_w g z\cos^2\theta\tan\phi}+\frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right) \quad (2)$$

where C' is the soil cohesion (kPa); g is the gravitational acceleration (9.81 m s^{-1}); ρ_s is the saturated soil bulk density (kg m^{-3}); ρ_w is the water density (kg m^{-3}); Θ is the slope angle (°); and ϕ is the soil friction angle (°).

Equation (2) expresses the ratio of the column of saturated soil on the total soil in an instability occurrence, which may vary from zero, when $\theta = \phi$, to the value of ratio ρ_s / ρ_w, when $\theta = 0$ (RAMOS et al., 2002). The failure plane is parallel to the surface slope plane, with ratio *h/z* varying between 0 and 1.

Figure 4 shows the slope condition with regard to *h/z* and *tan* θ rates under conditions $\varnothing = 45°$ and $\rho_s = 2.0$ g cm^{-3}. The limits shown in this figure are defined by the following conditions: (i) Unconditionally unstable – when $\Theta > \varnothing$, the right side of Equation (2) is less than zero; then the region proves to be unstable even though the soil is dry; in other words, $h/z = 0$. These regions are characteristic of rocky walls, in which all existing soil under these conditions has already been removed. In this case, the limiting slope, equal to the angle of friction, is 45°. (ii) Unconditionally stable – if tan θ is less than or equal to tan $(1-(\rho_s/\rho_w))$, even when fully saturated, since there is no place for sliding conditions. (iii) Stable and Unstable – Equation (2) defines the threshold for the stable and unstable zones.

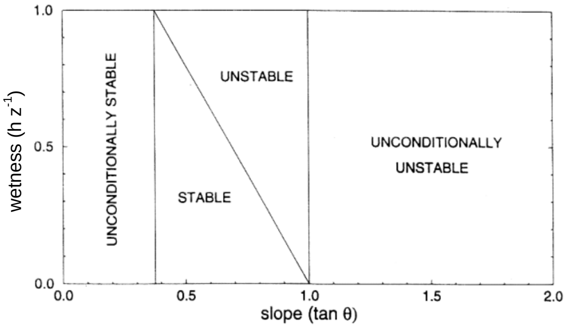

Figure 4. Relationship between the proportion of saturated soil column (*h/z*) and slope, expressed by tan Θ, to $\varnothing = 45°$ and $\rho_s = 2.0$ g cm^{-3}.
Source: Montgomery and Dietrich (1994).

The combination of the hydrological model (Equation 1) and the slope stability model (Equation 2), when soil cohesion is not considered, is defined as follows

$$\frac{Q}{T}=\frac{\sin\theta}{(a/b)}\left[\frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\right] \quad (3)$$

$$\frac{a}{b}=\frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\frac{T}{Q}sen\theta \quad (4)$$

The topographic parameters (θ and *a/b*) are obtained from a digital terrain model (DEM). Soil characteristics (ρ_s, $\varnothing$ and *T*) are measured in the field or estimated indirectly from the catchment conditions. According to Montgomery and Dietrich (1994), these characteristics are considered to be constant within the entire catchment. Q must be simulated for different rates of water discharge.

Figure 5 shows the relationship between the ratio *a/b* and the slope. The dashed line represents the saturation limit and the dotted one is determined from the rates obtained by Equation (4). The letters A to G are the portions of the graph representing the stability conditions shown in Table 1.

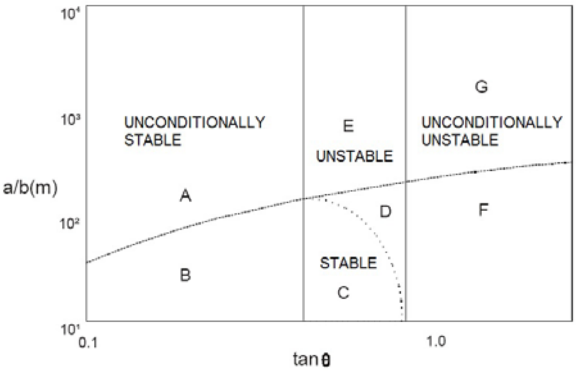

Figure 5. Ratio *a/b* as a function of tan θ.
Source: Ramos et al. (2002).

SHALSTAB Application

The software ArcView 3.2a was used to integrate the data into a Geographic Information System (GIS). The extension SHALSTAB (Shalstab.avx), was used to model the degree of the slopes' instability.

The topographic parameters were automatically computed from the DEM, generated from the topographic data (contour lines and elevation points), with 20 x 20 m resolution. The base map was obtained from the Brazilian Institute of Geography and Statistics (IBGE) topographic maps, with 20 m-equidistance between contours (Table 2).

The degree of slope stability was obtained by the relation *Q/T* from the grids of the contribution area and slope.

Table 2. Description of the topographic maps.

Map Index	Nomenclature	Name	Editor	Scale
2908-1	SG.22-Z-D-IV-1	Alfredo Wagner	IBGE	1:50,000
2908-2	SG.22-Z-C-IV-2	Rancho Queimado	IBGE	1:50,000
2908-3	SG.22-Z-C-IV-3	Bom Retiro	IBGE	1:50,000
2908-4	SG.22-Z-C-IV-4	Anitápolis	IBGE	1:50,000

Since the predominant soil in the catchment was Cambisoils (Figure 2), current study adopted the rate of the friction angle at 33.6° obtained in a catchment with predominant cambisols which is very similar to soils of the presente study. The rates of the saturated soil bulk density and the friction angle were 1,400 kg m^{-3} and 33.6°, respectively, due to clay soils in the catchment under analysis and to data from the literature. Furthermore, soil cohesion was not taken into account in current study.

In general, the soils in the Caeté river basin, predominantly clayey, are not deep and rarely exceed one meter in floodplains. They are mainly Dystrophic Haplic Cambisol (Tb), according to Embrapa classification (EMBRAPA, 1999), with low-active clay and low saturation in most of the first 100 cm of the B horizon. They are mainly friable and have low colloidal activity.

Figure 6 shows the flowchart summary of the methodological procedures adopted in the current study. The map elaborated by SHALSTAB was compared with the observed data by GPS-conducted field survey in which the landslide occurrences in the Caeté catchment were localized.

The result of the spatial degree of natural fragility of the natural areas to landslides, obtained from the SHALSTAB, was validated by comparing data points of landslide events observed during field work.

Table 1. Slope stability classes by *a/b* and tan θ.

Stability class Field	Condition
A – Unconditionally stable and saturated	$a/b > (T/Q)\sin\theta$; $\tan\theta \le \tan\phi(1-\rho_w/\rho_s)$
B – Unconditionally stable and unsaturated	$a/b < (T/Q)\sin\theta$; $\tan\theta \le \tan\phi(1-\rho_w/\rho_s)$
C – Stable and unsaturated	$a/b < (T/Q)\sin\theta$; $\tan\phi > \tan\theta^3 \tan\phi(1-\rho_w/\rho_s)$; $\frac{a}{b} < \frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\frac{T}{Q}\sin\theta$
D – Unstable and unsaturated	$a/b < (T/Q)\sin\theta$; $\tan\phi > \tan\theta^3 \tan\phi(1-\rho_w/\rho_s)$; $\frac{a}{b} \ge \frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\frac{T}{Q}\sin\theta$
E – Unstable and saturated	$a/b > (T/Q)\sin\theta$; $\tan\phi > \tan\theta^3 \tan\phi(1-\rho_w/\rho_s)$; $\frac{a}{b} \ge \frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\frac{T}{Q}\sin\theta$
F – Unconditionally unstable and unsaturated	$\tan\theta > \tan\phi$; $a/b > (T/Q)\sin\theta$
G – Unconditionally unstable and unsaturated	$\tan\theta > \tan\phi$; $a/b < (T/Q)\sin\theta$

Source: Dietrich and Montgomery (1998).

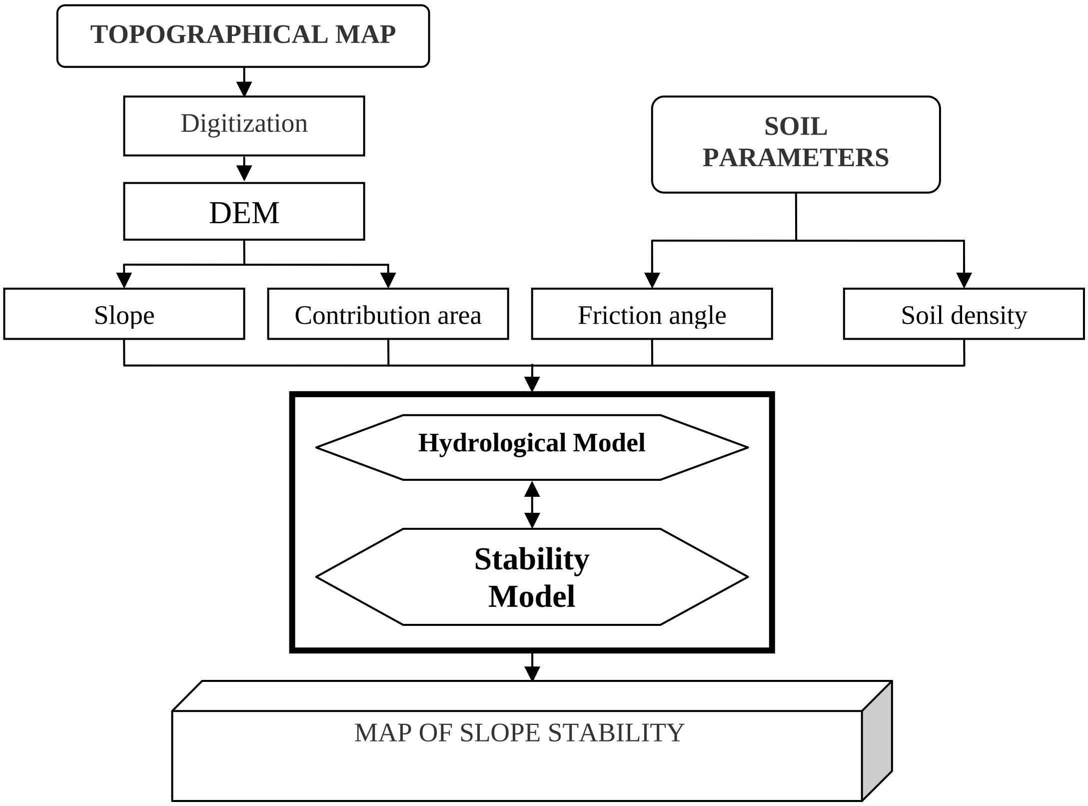

Figure 6. Flowchart of slope stability mapping in the Caeté catchment.

Results and discussion

The results of topographic analysis with data obtained from the DEM (resolution 20 x 20 m) show that the slopes are steep, mainly on the southern and southwestern sides of the Caeté catchment basin, especially at the headwaters of the Santo Anjo River (Table 3, Figure 7). Approximately one fifth of the catchment has over 45% slopes which intensifies the erosion processes and increases the catchment's susceptibility.

Table 3. Slope classes of the Caeté catchment.

Slope	Area (km^2)	% Total catchment
0 – 3%	10.52	6.4
3 – 8%	6.68	4.1
8 – 20%	43.79	26.7
20 – 45%	70.43	43
45 – 75%	24.57	15
> 75%	7.96	4.8
Total	163.95	100

Further, SHALSTAB simulation elaborated a map of areas susceptible to landslides in the Caeté catchment (Figure 8), where the stability-instability level is expressed by the ratio log(*Q*/*T*), taking into consideration a mean friction angle and a soil density of 33.6° and 1,400 kg m^{-3}, respectively. Results show a strong influence of the slope on landslide occurrences. However, the importance of the contribution area in this context should be emphasized, since the areas with the highest degree of instability have a large contribution area.

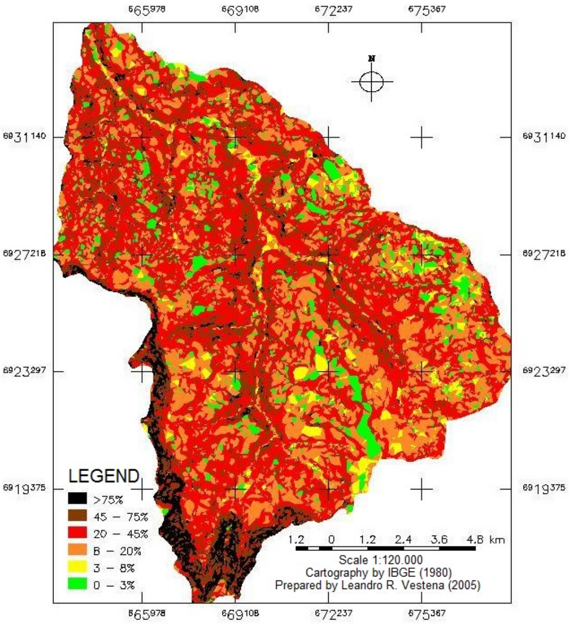

Figure 7. Slope distribution in the Caeté catchment.

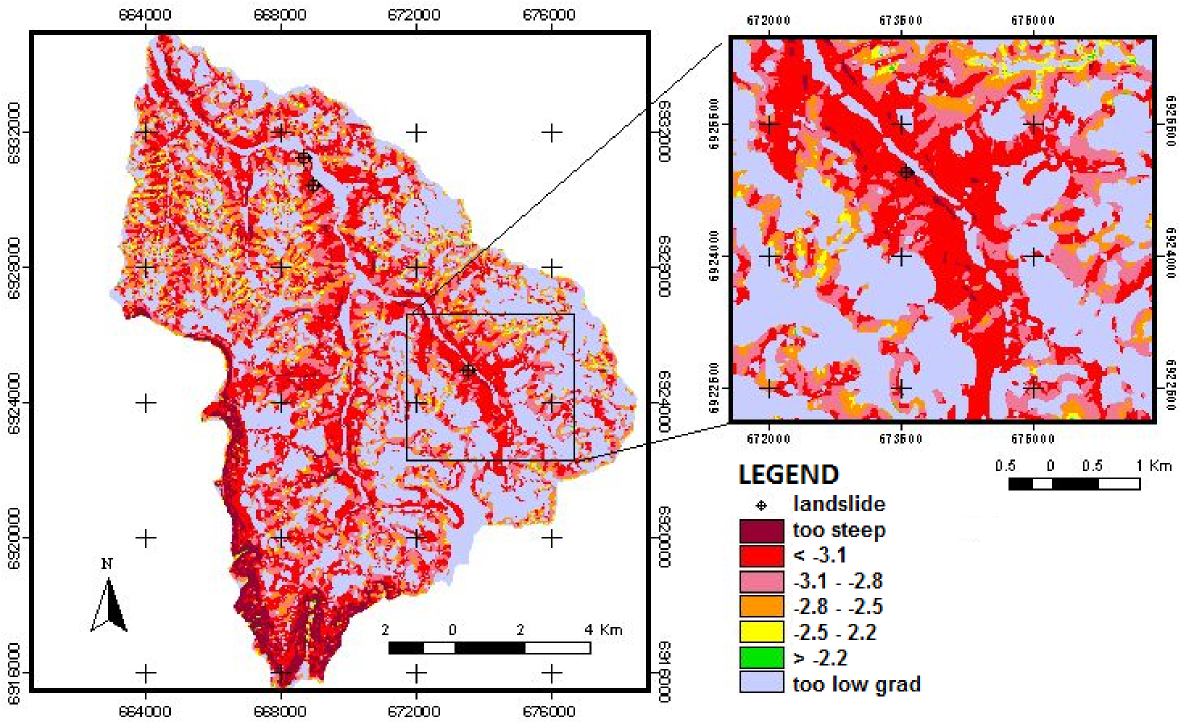

Figure 8. Slopes' potential fragility to landslides (*log (Q/T)*).

Figure 8 also shows three landslide occurrences located by UTM coordinates (673538; 6925020), (668997; 6931277) and (669041; 6930441) characterized respectively by a steep slope, an agricultural area (production of onions) and pasture.

Figure 9 shows landslide occurrence in a pastureland. The landslide occurred in an area characterized by high natural fragility to landslides, coupled to degrading land use, or rather, animal movements (cattle trampling). In these locations, surface boulders deposited on less steep areas may be observed. The comparison between field observation and SHALSTAB simulation concludes that the landslides occurred in regions potentially susceptible to landslides and that the model used produced satisfactory results for the identification of landslides-prone areas.

Figure 9. Shallow landslide in the Caeté catchment.

Log (*Q/T*) rates may be employed to classify the potential fragility of areas in the Caeté catchment. In fact, current study proposes 7 classes of fragility (Table 4). It should be noted that the stable regions, i.e., non-fragile regions, are only 39.3% of the total area of the Caeté catchment. Approximately half of the total area of the catchment is identified as extremely, very or highly fragile areas, which requires more precise land-use planning in the catchment. Any human intervention on the landscape, such as vegetation removal, road construction and agricultural practice, may induce landslide occurrences.

Table 4. Potential fragility classes in the Caeté catchment.

Stability class (log(*Q/T*))	Area (km^2)	% Catchment	Potential fragility classes
-9.9 a -10.1 –Chronic instability	8.39	5.2	Extremely high
-3.1 a -9.9	42.42	26.2	Very high
-2.8 a -3.1	25.88	16.0	High
-2.5 a -2.8	17.22	10.6	Moderate
-2.2 a -2.5	4.09	2.5	Low
9.8 a -2.2	0.43	0.2	Very low
9.8 a 10.1 - Stable	63.77	39.3	No
Total	162.2	100	

In general, the Caeté Catchment has a high potential fragility to landslides, especially its extreme south and southwest areas, near the main sources of the Caeté river. Since the watercourses lie in the catchment´s narrow valleys, there is a strong geomorphic connectivity. In other words, landslide occurrences significantly increase the quantity of sediments in the rivers. Analyzing the landslide influence on discharge and turbidity in a river in the municipality of Joinville, Santa Catarina State, Brazil, Kobiyama et al. (2011) reported that the landslide occurrence damaged the city´s water supply operation system. This type of water supply problem would be very common in the town of Alfred Wagner because the Caeté river provides for its principal water resources.

Conclusion

The computer model SHALSTAB was applied to identify landslide-susceptible areas in the Caeté catchment, municipality of Alfredo Wagner SC Brazil. The use of data observed through field survey showed that the landslides occurred in potentially susceptible regions which were calculated by the model. Moreover, the model was satisfactory for the identification of landslide-prone areas. The model simulation confirmed that the fragile areas to landslide occurrence are normally on steep slopes and on large contribution areas.

The Caeté catchment supplies water to the town of Alfredo Wagner, with a downtown area which requires adequate land-usage planning and management. The SHALSTAB identified that fragile areas to landslide are approximately one half of the Caeté catchment. Since these areas are naturally unstable, human activities should be avoided.

The SHALSTAB model is easily implemented and is a relevant tool in identifying the degree of fragility to landslides. Certain parameters such as soil parameters (hydraulic conductivity, friction angle, and soil density) should be determined by soil samplings to improve the model´s performance. Furthermore, soil cohesion shall be incorporated to the model since the soils in the Caeté catchment are so clayey that the cohesion characteristic cannot be ignored.

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