SHALSTAB APPLICATION TO IDENTIFY THE SUSCEPTIBLE AREAS OF SHALLOW LANDSLIDES IN CUNHA RIVER WATERSHED, RIO DOS CEDROS CITY, SC, BRAZIL

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ABSTRACT:

The increased occurrence of natural disasters and the impacts they have caused society, especially in developing countries draws the attention of researchers so that mitigation measures consistent with the economic realities of the countries affected are adopted. Brazil has been suffering from disasters often associated with hydrological conditions, among which are the mass movements. The prediction of these phenomena is not a simple task, however, computer modeling combined with remote sensing techniques can aid in the understanding. This work employs the computational model SHALSTAB to identify areas susceptible to mass movements in the Cunha River Watershed in the municipality of Rio dos Cedros, in the state of Santa Catarina, Brazil. These areas were characterized in relation to soil use, occupation and the slope of the land by means of satellite images and planialtimetric maps. The methodology consisted of; mapping the scars resulting from movements in the study area, the determination of physical parameters and soil resistance, the development of a digital terrain model and its derivatives (slope and contribution area) and in the preparation of the map use and land cover. This study obtained data consistent with the reality of the area, where there is an evident predominance of native forest in the basin and in unstable areas, especially present in slopes between 20 ° and 30 °, and mapped the movements considered in this use as natural origin. Thus, this methodology can be applied in other regions and serve as an aid for public agencies to avoid these disasters.

1. INTRODUCTION

In Brazil, mass movements have often caused large losses to the population, especially those on low-incomes that normally live in unstable areas like steep hillsides. This situation is evident not only in large towns but also in rural areas.

Although these phenomena are recurrent in Brazil, the country is not prepared to act structurally in predicting these phenomena. The prediction is often limited by an insufficient climatic and hydrological database. Furthermore, there are insufficient databases that limit the study of relevant topographic details of the land required for analyzing these phenomena. In most cases these phenomena are represented on small scale maps.

Globally, mathematical models have been developed in order to assist in identifying hazard areas due to mass movements. Among them, the SHALSTAB (Shallow Landsliding Stability Model) proposed by Dietrich and Montgomery (1998) has been widely used with cartographic databases at various scales in many countries.

To identify areas susceptible to shallow landslides, the SHALSTAB model basically integrates slope stability and hydrological models into a geographic information system (GIS) (MONTGOMERY and DIETRICH, 1998). According to Guidicini and Nieble (1964), the shallow landslides are associated with the occurrence of debris flows, corresponding to places where soil rupture occurs. This loose material, when in contact with a certain amount of water, can acquire aspects of debris flows causing damage of catastrophic proportions.

The model uses topographic, hydrologic, physical soil and mechanical parameters (MONTGOMERY and DIETRICH, 1998). As a result the model provides a map of landslide susceptibility values at each pixel. Based on this map, possible predictions of unstable areas can be developed. The performance of this model can be seen by comparing the prediction map with the scars of mass movements in the area.

While employing this model, several studies were conducted to investigate the mass movements. For example, Dietrich and Montgomery (1998) in the western United States and Meisina and Scarabelli (2007) in Italy.

In Brazil, studies with this model in a watershed can be found in the pioneering work carried out in Rio de Janeiro (Guimarães, 2000; FERNANDES et al., 2004), which also verified the accuracy of the model using different scales of topographic maps (GOMES et al., 2004). In the state of Minas Gerais, Ramos et al. (2002) showed that the mapping of areas carried out by SHALSTAB were satisfactory, even though the scale data (1:50,000) was considered too small for that purpose, being more suitable for preliminary studies (Gomes et al., 2004). Therefore, since there is no planialtimetric data available in any scaled detail for all regions of Brazil, this tool can be used as an aid in mapping areas susceptible to mass movements.

Although SHALSTAB, did not consider human factors in the conditioning of landslides, it was used in urban watersheds to determine the use and occupation of land in unstable places, specifically with the works of Zaidan and Fernandes (2009), in Minas Gerais and Santa Catarina of Caramez et al. (2011).

The identification of the types of land use and land cover present in places defined as unstable by the model is relevant in the characterization of these areas by the presence or absence of vegetation. It is known, that human actions related to inadequate soil conditions can aggravate the occurrence of mass movements. Hesites, for example, removal of natural vegetation cover, exposing the soil to the physical weathering, creating cracks, crevices and hence landslide (SESTINI, 2000). For Rodrigues (1992), vegetation protects the soil from the action of rain, reducing runoff and water infiltration into the soil, minimizing the occurrence of erosion and mass movements.

The use of satellite imagery to characterize the physical environment has been widely used in several studies in order to obtain data for land use and land cover in a distributed way. Among these, we highlighted the work of Hoff et al. (2008) who used the software Idrisi Andes in the processing of Landsat TM 5 images, obtained from the maximum likelihood method and used a map of land cover for the Municipality of Cambará do Sul, in Rio Grande do Sul, Brazil .The aim of this study was to assess the degree of environmental degradation in the area resulting from improper use and occupation of the ground, offering low cost geo-technological quick responses to resolve the environmental damages.

Castro (1998) co-related the type of soil cover with sites affected by mass movements through the intersection of maps and found that the slopes formed by vegetation (forest and fallow) were the most affected by degradation, forming areas of instability.

In this context, this paper aims to identify spatialized areas subject to mass movements in the Cunha River basin and the influence of environmental factors such as slope, soils, hydrology, land use and soil processes in the destabilization of slopes. In this study we used the Cunha River basin, located in the rural municipality of Rio dos Cedros / SC, due to the occurrence of mass movements of great magnitudes in this area, classified as a debris flow (CEPED, 2009) and triggered by the extreme rainfall event in November 2008. For this, we used the mathematical model and software SHALSTAB Idrisi Andes and ArcGis 9.2.

2. MATERIALS AND METHODS

2.1 Location of study area

The Cunha River Watershed (16.2 km2) belongs to the southwestern portion of Rio dos Cedros, in the state of Santa Catarina, Brazil (Figure 1), which is among the municipalities declared as a state of emergency in the environmental disaster that occurred in November 2008 (Mattedi et al., 2009).

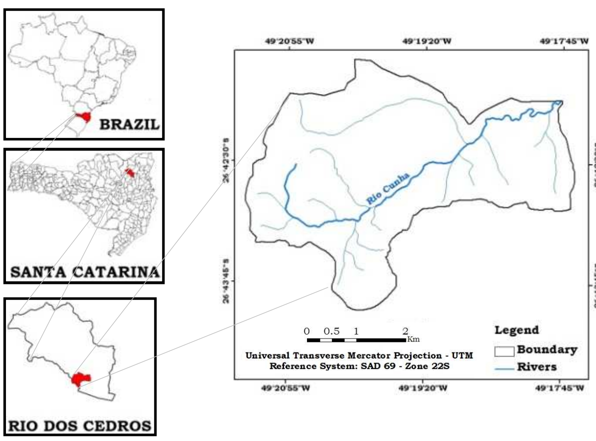

Figure 1.Location of Cunha River Watershed

Rio dos Cedros city suffers frequently from the occurrence of mass movements, evidenced mainly in rural areas due to rainfall intensity and declivous landscape of the sites, which impairs their economic and social development.

The Cunha River Watershed is predominantly covered by native forest belonging to the Atlantic Forest biome. The activities in the area focus on planting annual crops (Santa Catarina, 1986). The basin is dominated by Argisols (26%) and Cambisols (74%) (IBGE, 2003). The areas affected by mass movements are composed predominantly of Cambisols.

2.2 Modeling with SHALSTAB

For the stability analysis of the Cunha River Watershed, we used the algorithm developed by Montgomery and Dietrich (1998) and SHALSTAB from the GIS software ArcView 3.2a. According to these authors, the models associate the theories of infinite slope, where the strength of soil share at the discretion of rupture of Mohr Coulomb, with the hydrological model O'Loughlin (1986), resulting in equation (1).

$$\log\frac{Q}{T} = \frac{sen\theta}{a/b}\cdot\left[\frac{c'}{\rho_W\cdot g\cdot z\cdot\cos^2\theta\cdot tg(\varphi')} + \frac{\rho_S}{\rho_W}\cdot(1-\frac{tg\theta}{tg\varphi'})\right] \quad (1)$$

where Q= rainfall [mm]
T = soil transmissivity [$m^2\cdot dia^{-1}$]
θ = slope [°]
a = contribution area [m^2]
b = is the contour length across which flow is accounted for [m]
c’ = soil effective cohesion [kPa]
ρ_s = density of the soil [$kg\cdot m^{-3}$]
ρ_w = density of the water [$kg\cdot m^{-3}$]
g = gravitational acceleration [m·s-2]
z = soil thickness [m]
φ’ = soil effective friction angle [°]

In general terms relation Q • T^{-1} indicates the ratio of the amount of rainfall and the transmissivity of the soil required to create an unstable area. This ratio is directly proportional to the instability of local area and is used in the classification of pixels according to the classes of stability illustrated in Table 1.

Classes SHALSTAB	Interpretation of Class
Chronic instability	Unconditionally unstable and unsaturated
Log $Q{\cdot}T^{-1}$< -3,1	Unconditionally unstable and saturated
-3,1<Log $Q{\cdot}T^{-1}$< -2,8	Unstable and saturated
-2,8<Log $Q{\cdot}T^{-1}$< -2,5	Unstable and unsaturated
-2,5<Log $Q{\cdot}T^{-1}$< -2,2	Stable and unsaturated
Log $Q{\cdot}T^{-1}$> -2,2	Unconditionally stable and unsaturated
Stable	Unconditionally stable and saturated

Table 1. Classes defined stability SHALSTAB
Source: modified from Montgomery and Dietrich (1998)

In equation (1) the variables, a and θ, corresponding respectively to the hydrological and topographic attributes of the basin, are obtained from maps derived from the Digital Terrain Model (DTM), which spatialized these data in modeling. The data ρs, φ, c ', z and soil parameters involved, as well as ρw and b are constant for the entire area. The ρw is equal to 1000 kg•m^{-3} and b, related to the pixel size and was set to 15 meters in the drafting of the DTM.

2.2.1 DTM and its derivatives: the DTM is of fundamental importance in analyzes of areas susceptible to mass movements and in this study is directly related to the efficiency of modeling. For the Cunha River Watershed the DTM was generated using digital contour lines obtained from 1:50,000 scale topographic maps with contour intervals of 20 m, provided by the Company for Agricultural Research and Rural Extension of Santa Catarina (EPAGRI/CIRAM) at http://ciram.epagri.sc.gov.br/mapoteca/. The DTM was drafted using the Topo to Raster tool, which uses the algorithm ANUDEN for interpolation of the data (ESRI, 2006). This algorithm has been developed especially for use in models facing the hydrological analysis.

The DTM was generated with a spatial resolution of 15 m, consistent with the accuracy of the scale and the pixel size of the ASTER image (Spacebourne Advanced Thermal Emission and Reflection Radiometer) and is used in the preparation of the statement of use and occupation.

The maps of slope and contribution areas were prepared from DTM, the program ArcWiew ArcGIS 9.2 and 3.2a, respectively. The first map was drawn in degrees and represents the distribution of relief in the basin and is also related to the processes governing the instability of slopes and occupation. When characterizing the areas, this map was classified into intervals of slope of 10° to 10°. In turn, the contribution of the area map was made through the tool Shaltopo (Contributing Area) of SHALSTAB, which uses an algorithm based on the methodology to Quinn et al. (1991) which calculates the area contribution of each cell (pixel) distributed by the flow method (GUIMARÃES, 2000).In this algorithm, the upstream water flow is distributed to downstream cells corresponding to their slope. The parameter input area is related to the drainage system of the basin and the model incorporates in SHALSTAB the influence of the concave portions of the relief in the ways in which the water flows, which are identified as potential sites of saturation, and thus instability.

2.2.2 Soil parameters: variables, effective cohesion (c'), effective friction angle (φ), density (ρs) and soil thickness (z) are relevant soil data in this modeling. In determining these parameters, except oz, we carried out direct shear tests (CD) in ten undisturbed soil samples which were collected in nearby areas of disruption, ie, the top two landslides present in the study area. The tests were carried out in CD flooded and three vertical pressure levels: 32, 76 and 124kPa. Some samples were also submitted to a pressure of 250kPa.

The thickness of the soil was verified by probing into the field using an auger. The drilling or boring of the soil was also run on top of a mass movement, to achieve the bedrock, identifying in this way, the vertical depth of the soil (z). However, due to the difficulty of access to the study site, it was not possible to achieve the bedrock and the value employed for the variable (z) corresponds to the depth reached in the survey and not the total depth of the soil.

Several samples were tested as CD, increasing in this way, the accuracy of data. However, average values were used for modeling, since the model assumes a constant value over the whole area.

2.2.3 Landslides mapping: this mapping corresponds to the delineation of mass movements in the Cunha River basin, set off after heavy rainfall occurred in November 2008. The model SHALSTAB simulates places where there is a breakdown of the material, called zones of disruptions. Therefore, for modeling we only considered the demarcation of disruption areas of debris flows.

The identification of these sites were based on visual interpretation of aerial photography on a scale of 1:5.000, obtained in 2010 and field surveys with the aid of GPS navigation, Garmin 76CSx model, with an accuracy of 10 meters. The demarcation of the points of mass movement occurrence was made by ArcGis 9.2, through polygons representing the scars evidenced. From these procedures it was possible to determine the spatial distribution of mass movements in the watershed and to see if they were in areas of instability, defined by SHALSTAB. This statement aims to compare the results of the model with the real situation in this field.

2.3 Types of ground cover

Map and land use was developed with ASTER images obtained, for the month of April 2006, using the bands of the visible and near infrared, with a resolution of 15 meters. The day data images were obtained, the region was affected by low cloud cover.

The image processing was done in software Idrisi Andes and consisted of the steps geo-referencing, enhancement using a combination RGB-234, cutting the area of interest and classification.

The ASTER images were geo-referenced using the reference co-ordinate system Universal Transverse Mercator (UTM) in the 22S zone, SAD-69 horizontal Date and vertical Imbituba / SC. For this purpose, we used the polynomial method (first degree) to adjust the points and the nearest neighbor to the re-sampling of the raw image pixels. The average square error was 0.834 pixels, compatible to the resolution of 15 meters.

The next step was the classification of images, in order to obtain the statement of uses and land cover. For this study we defined six classes of uses and land cover: native forest, pasture, forestry, agriculture, bare soil (no cover) and water (rivers, lakes and ponds), identified in the field inspections carried out during year 2010. The classification method used was maximum likelihood. According INPE (2009), this method sets similar regions in accordance with the spectral information of each image pixel. Thus, we obtained training samples representative of each use and land cover.

To assist in the identification, 50 training samples were collected with GPS navigation, corresponding to different uses and land cover, as shown in Table 2. We also used the vectors of roads and waterways, obtained from a 1:50.000 scale topographic map corresponding to the classes of exposed soil and water, respectively. It should be noted that the roads in the basin are not paved, which explains its association with the class of exposed soil. Finally, the accuracy of mapping was confirmed by further in-field inspections, where the generated map was confronted with the actual situation and adjusted.

Classes of use and occupation	Number of samples
Native forest	11
Pasture	13
Reforestation	12
Agriculture	7
Bare soil (absence of cover)	5
Water (Watercourses, lakes and ponds)	2

Table 2. Types of soil covering the Cunha River Watershed

The map of land use was crossed with the susceptible and slope maps using the Raster Calculator tool (Spatial Analyst) of ArcGIS 9.2. Thus, we identified the percentage of each land use, classes of stability and its steepness in the basin.

3. RESULTS

3.1 Map of susceptibility to landslides

Based on DTM, slope maps were prepared (Figure 2) and the contribution area (Figure 3), which were used as input data on the SHALSTAB model for calculating the degree of susceptibility to translational slip of the basin.

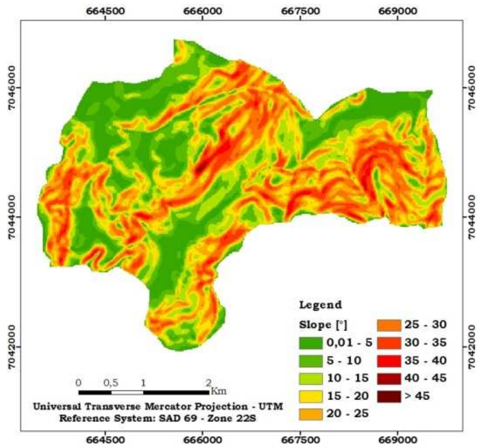

Figure 2. Slope map

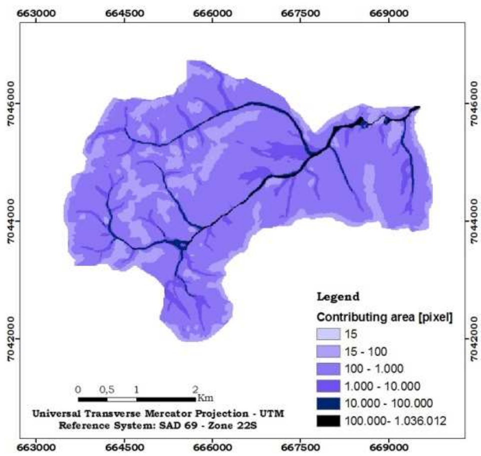

Figure 3. Map of contribution area

In Figure 2, note that the area has places with steep slopes reaching above 30°, above which the restriction of use and occupation of land, being intended for permanent preservation, according to the current master plan of the municipality of Rio dos Cedros since 2006. Please note that places with steep slopes are more likely to have occurrence of mass movements.

In the map of the contribution area (Figure 3) it was established that the flux concentration areas are located in the basal portions of slopes. Usually, the relief has a concave shape, suggesting the presence of drainage channels. It was also found that sites with the largest contribution correspond to the main channel of the watershed and its tributaries, classified according to the Strahler method, as first and third order, respectively.

Besides these variables, the soil depth was calculated equal to 12 meters and the soil properties shown in Table 3.

Considering these factors, the degree of susceptibility was determined and represented in the form of a map with spatial resolution of 15 meters, sorted by seven stability classes defined by SHALSTAB (Figure 4). Superimposed on this map are the scars of mass movements, used to verify the results of modeling.

Sample	c'	φ’	ρ_s
	kPa	degrees	kg/m³
1	15	29	1720
2	9	34	1420
3	5	30	1500
4	11	30	1740
5	14	33	1690
6	11	30	1680
7	12	27	1660
8	15	33	1750
9	18	32	-
10	10	34	1530
Average	12	31	1630

Table 3. Soil parameters

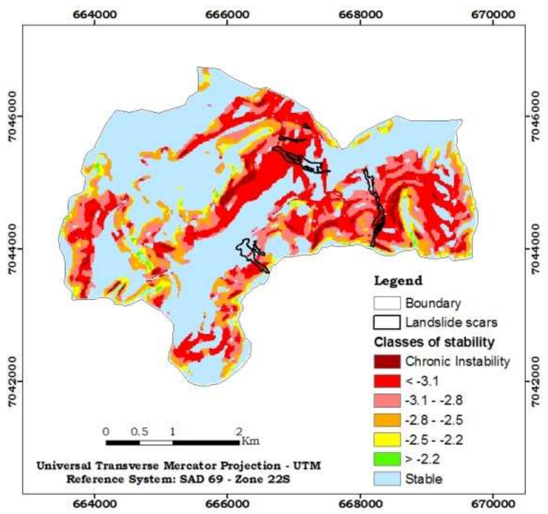

Figure 4. Map of landslide susceptibility to translational movements

Based on the susceptibility map (Figure 4) it was found that 54% of the Cunha River Watershed was classified as stable, of which 50% was classed as unconditionally stable and saturated. This class suggests that even with regolith in saturation, it is not likely to occur as mass movements of the translational type. The embossed stable areas are characterized by the maximum slope of 30°, however, 30% have gradients less than 10°, 22% between 10° to 20° and 4% between 20 and 30°.

The rest of the watershed (46%) was classified as unstable, and others classed as unconditionally unstable and saturated (21%). Moreover, 14% of unstable areas belong to the class unstable and saturated, 9% unstable unsaturated and 2% to unconditionally unstable and not saturated. In unstable areas, the terrain is more sloping in relation to stable areas, at a slope

between 10° to 40°, and 27% of the area has slope between 20° and 30°.
In addition to Figure 4, it is possible to observe that the mass of movement scars mapped in the watershed, present in the areas classified as unstable by SHALSTAB, showed good results from the simulation with the reality.

3.2 Map of use and occupancy of soil

The map of land use, illustrated in Figure 6, allowed the determination of human influence on the instability of the slopes of the study area. This map represents types of use and land cover of the Cunha River Watershed and the percentage that each type represents in relation to the total area of the basin and the control samples used in their preparation.

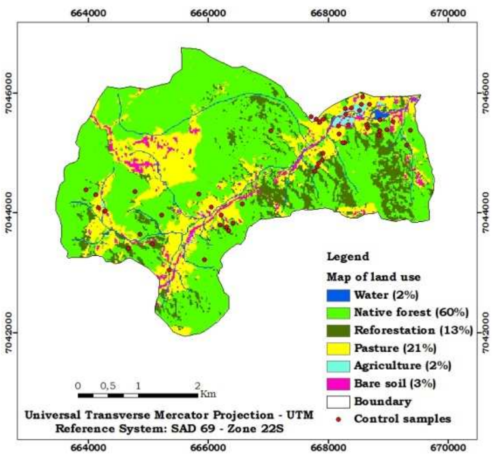

Figure 6. Map of use and occupancy of soil

Based on the map use and land cover it was verified that 60% of the area covered by native vegetation is primary, 21% pasture, reforestation and the remaining 13% represented by bare soil, water and agriculture. In this mapping, the predominance of primary vegetation (native forest) in the basin is consistent with the observations in the field, from which, it was also evident that most of the debris flow was initiated at the sites of primary native forest, and then considered as natural in origin. The mechanism of instability in this case had no human influence, causes were related to the slope of the hillside area of contribution of the watershed, geological and geotechnical conditions and rainfall. Additionally, it was also observed that debris flows in areas of pasture and reforestation of pine added to deforestation and causes of instability.
The comparison between land use classes and stability, also showed the presence of native forest (33%), forestry (9%) and pasture (4%) in unstable areas, reinforcing the correspondence of the model with the actual situation of the watershed study. These uses, in unstable areas, are predominantly in slopes between 20° and 30°.
While the classes, agriculture, bare soil and grass (17%) present in locations where relief has predominant slopes of up to 10°, in stable areas, there also happens to classes, native wood (27%) and forestry (4%), located in slope regions, especially 0-20°.

4. CONCLUSIONS

The model SHALSTAB, although considering the constant variables related to soil properties have been developed for areas where soil characteristics are usually different from those found in tropical countries, yet the associated scale used in this study generated data consistent with the reality found in the study area, identifying the unstable places in the watershed. However, especially in view of the scale, the susceptibility map generated by the model comprises a preliminary survey, serving as a basis for more detailed mapping of risk areas. According to this map approximately half the area was classified as likely locations of the occurrence of mass movements of the translational type, which, together with heavy rainfall can trigger debris flow.
The surface of the watershed consists predominantly of native forest, which was also observed in unstable areas in agreement with observations in the field, where it was noted that most of the debris flow occurred naturally.
In this mapping, the predominance of native vegetation in areas of instability is associated mainly due to the slope where the areas are predominantly between 20° and 30°. It is clear that in much steeper places, where the terrain is more susceptible to the occurrence of mass movements and processes of environmental degradation, the difficulty of cultivating the soil promotes the conservation of vegetation and its development.
Thus, the simulations in SHALSTAB have identified that the processes of destabilization in the Cunha River Watershed are specifically related to environmental factors such as soil type, rainfall, slopes and contribution area of the land.
The methodology employed in this work, especially in determining areas of instability, with GIS tools, data mapping on a small scale, along with soil and hydrological data, provided results that can assist in low cost preliminary and emergency planning of land use and occupation and compatible with the existing data available, for several regions in Brazil.

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