Influence of DEM spatial resolution on the susceptibility mapping with SHALSTAB in the Rio Garcia hydrographic basin, municipality of Blumenau/SC

Influência de la resolución espacial del MDE en la cartografía de susceptibilidad con SHALSTAB en la cuenca hidrográfica del Río García, municipio de Blumenau/SC

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ABSTRACT
In translational landslide susceptibility analysis with SHALSTAB (Shallow Landsliding Stability Model), the resolution of the digital elevation model (DSM) is determinant for defining the type of mapping generated (preliminary or not). In this study, in order to verify the influence of the SDM scale on the SHALSTAB stability classes, susceptibility maps were prepared at two scales: 1:50,000 and 1:10,000. The study area was the Garcia River watershed, belonging to the municipality of Blumenau, Santa Catarina, affected by landslides in the 2008 catastrophe, which enabled the validation of the simulations with the scars mapped in the field. Thus, the influence of scale on the distribution of the model's stability classes and on its performance was verified. SHALSTAB performed better at the 1:10,000 scale, predicting 70% of the instabilities in a percentage of unstable area approximately three times smaller than at the 1,50,000 scale.

Keywords: SHALSTAB, Translational Sliding, Digital Elevation Model

RESUMO
Em análises de suscetibilidade a escorregamentos translacionais com o modelo SHALSTAB (Shallow Landsliding Stability Model) a resolução do modelo digital de elevação (MDE) é determinante para a definição do tipo de mapeamento gerado (preliminar ou não). Nesse estudo, com o intuito de verificar a influência da escala do MDE nas classes de estabilidade do SHALSTAB, foram elaborados mapas de suscetibilidade em duas escalas: 1:50.000 e 1:10.000. A área de estudos foi a bacia hidrográfica do Rio Garcia, pertencente ao município de Blumenau, Santa Catarina, afetada por escorregamentos na catástrofe de 2008, o que possibilitou a validação das simulações com as cicatrizes mapeadas em campo. Desta forma, verificou-se a influência da escala na distribuição das classes de estabilidade do modelo e no seu desempenho. O SHALSTAB obteve melhor desempenho na escala 1:10.000, prevendo 70% das instabilidades em um percentual de área instável aproximadamente três vezes menor do que na escala 1.50.000.

Palavras-chave: SHALSTAB, Escorregamentos Translacionais, Modelo Digital de Elevação

1 INTRODUCTION

Brazilian cities are being affected by an intense urbanization process, this implies on densification of already urbanized areas and most times in disorganized occupation of periphery areas. The lack of planning and territorial management in this occupation dynamics, where usually are unconsidered the conditions of the physical environment, cause serious social, environmental and economic problems triggering the surge of risk areas.

Zuquette (2004) defines risk areas as places where physics phenomena occurrence cause considerable economic, social and environmental damage, besides natural or anthropic origin. Thus, intrinsic actions to disorderly expansion characterize potential risk areas, such as occupation of erosion susceptible slopes and occupation of steep slopes susceptible to mass movement's occurrence.

Several catastrophes resulting from this problematic had been registered in some Brazilian capital cities. Cristo (2002) highlights the occurrence of mass movements in the cities of Salvador, Belo Horizonte, São Paulo and Rio de Janeiro and advises Santa Catarina state regarding the occurrence of natural disasters related mainly to intense rain episodes.

In particular, the rainfall event that took place between November 20-24 in 2008, caused a large amount of landslides and debris flows (more than 4000), especially in the rio Itajaí valley (DIAS, 2009). In this event, Epagri/FURB meteorological station located in Blumenau (SC), registered an accumulated precipitation larger than 200mm/day, with a 244mm peak on November 22 and a 251mm peak on November 23 (SEVERO, 2009).

According to the Defesa Civil report (SANTA CATARINA, 2018), more than 1.5 million inhabitants were affected in the state of Santa Catarina. Regarding the number of deaths, disasters caused deaths in 16 municipalities, the highest numbers occurred in Ilhota, Blumenau and Gaspar municipalities with 46, 24 and 21 deaths respectively.

In order to take effective preventive measures, it is necessary to identify the areas considered at risk, based on the phenomena understanding and the factors involved. Kobiyama et al. (2006) and Tominaga (2009) respectively mention the importance of understanding the mechanisms of natural phenomena and the study of their conditioning factors as subsidy for their prevention.

In last decades many forecasting methodologies have been developed. For example, geotechnical mapping associated with Geographic Information Systems (GIS) and remote sensing techniques, which generate subsidies to act on the prediction of unstable areas, helping in the individualization and characterization of factors related to instability. Works such as those by Mendonça et al. (1996) and Ahrendt (2005) determined places susceptible to the occurrence of landslides based on geotechnical units. Reginatto (2013) mentions the importance of geotechnical mapping in the elaboration of a database for environmental analyzes and more reliable modeling.

It is also observed the importance of mathematical modeling combined with a GIS in research studies on mass movements. Among the various models that compound the forecasting methodologies, the deterministic mathematical model SHALSTAB (Shallow

Landsliding Stability Model) has been used frequently in several regions of Brazil and at different scales for mapping susceptibility to translational landslides. For example, in hydrographic basins located in the Maciço da Tijuca in Rio de Janeiro at the 1: 10.000 and 1: 50.000 scales (GUIMARÃES, 2000; GOMES, 2006), in Minas Gerais at the 1: 50,000 scale (RAMOS et al., 2002) and in Santa Catarina on a scale of 1: 50,000 (REGINATTO, 2013; SBROGLIA, 2015).

SHALSTAB incorporates topographic parameters (slope, contribution area and contour length) and soil parameters (effective friction angle, effective cohesion intercept, specific weight and soil thickness) in its analyses. Soil parameters can be determined in field or in the laboratory, thereby increasing the representativeness of the environment. The data related to the relief (topographic parameters) are obtained from the Digital Elevation Model (DEM).

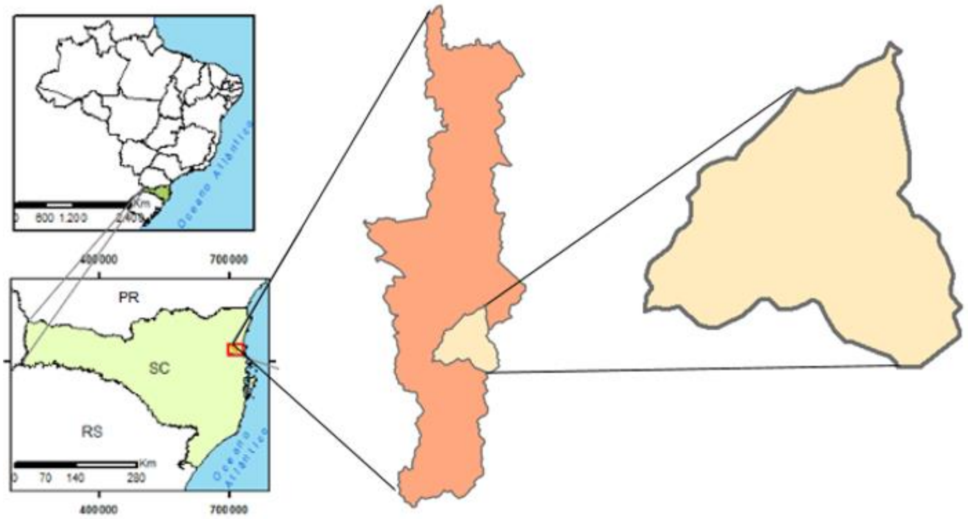
In modeling with SHALSTAB, Gomes et al. (2004) recommend the use of a DEM on a scale equal or greater than 1: 10,000 in order to obtain a better terrain representativeness. These authors emphasize that the 1: 50,000 scale should be used for preliminary mapping, since it can classify an area prone to landslides as stable. Not all Brazilian states where mass movements occur, have topographic data with the recommended accuracy by the mentioned authors, with data on the 1: 50,000 scale or less being more common. Therefore, it is important to check the performance of the SHALSTAB model at different cartographic scales.

This article aims to compare the results obtained in the mapping of susceptibility with SHALSTAB in the hydrographic basin of Rio Garcia, located in the municipality of Blumenau, using two different scales (1: 10,000 and 1: 50,000) on the elaboration of the DEM. In this area, the scars from the November 2008 landslides were mapped, which allowed the measurement of the results obtained in the modeling stage.

2 STUDY AREA

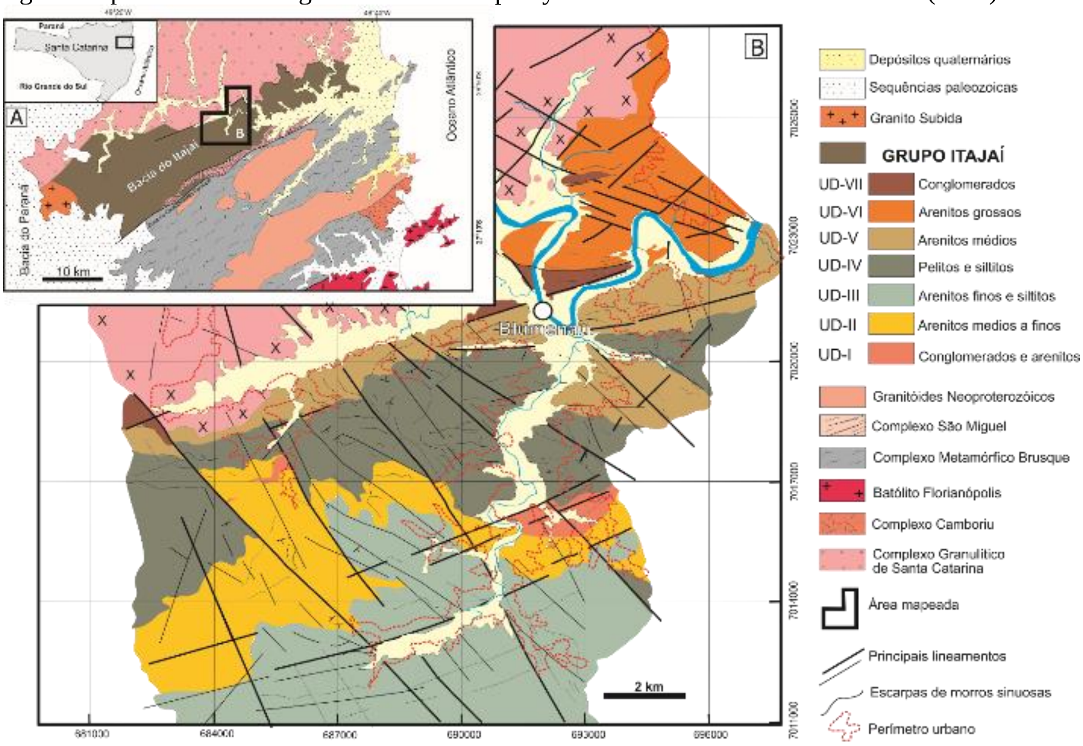
The hydrographic basin of the Rio Garcia, the place of study for this research, is located in the south of the municipality of Blumenau, in an area of urban expansion (Figure 1). Like many regions in the state of Santa Catarina, it was affected by landslides caused by intense and concentrated rainfall in November 2008.

Figure 1. Location of the Rio Garcia basin.



Regarding the geological aspects, according to Flores et al. (2018), the southern region of the urban perimeter of Blumenau is inserted in the tectono-sedimentary domain of the Rio Itajaí Basin. This basin is part of the northern portion of the Cinturão Dom Feliciano and has an NE-SW orientation, being limited to the south by the Itajaí-Perimbó Shear Zone, where it has contact with the Brusque Metamorphic Complex, to the north it is limited by the Santa Catarina Granulitic Complex, to the east it is covered by sedimentary sequences from the Paraná Basin, and to the west it is covered by quaternary deposits (Figure 2).

Figure 2. Geological context of the urban expansion area of Blumenau: (A) simplified geological map; (B) Geological map of the central region of the municipality of Blumenau. Source: Flores et al (2018).



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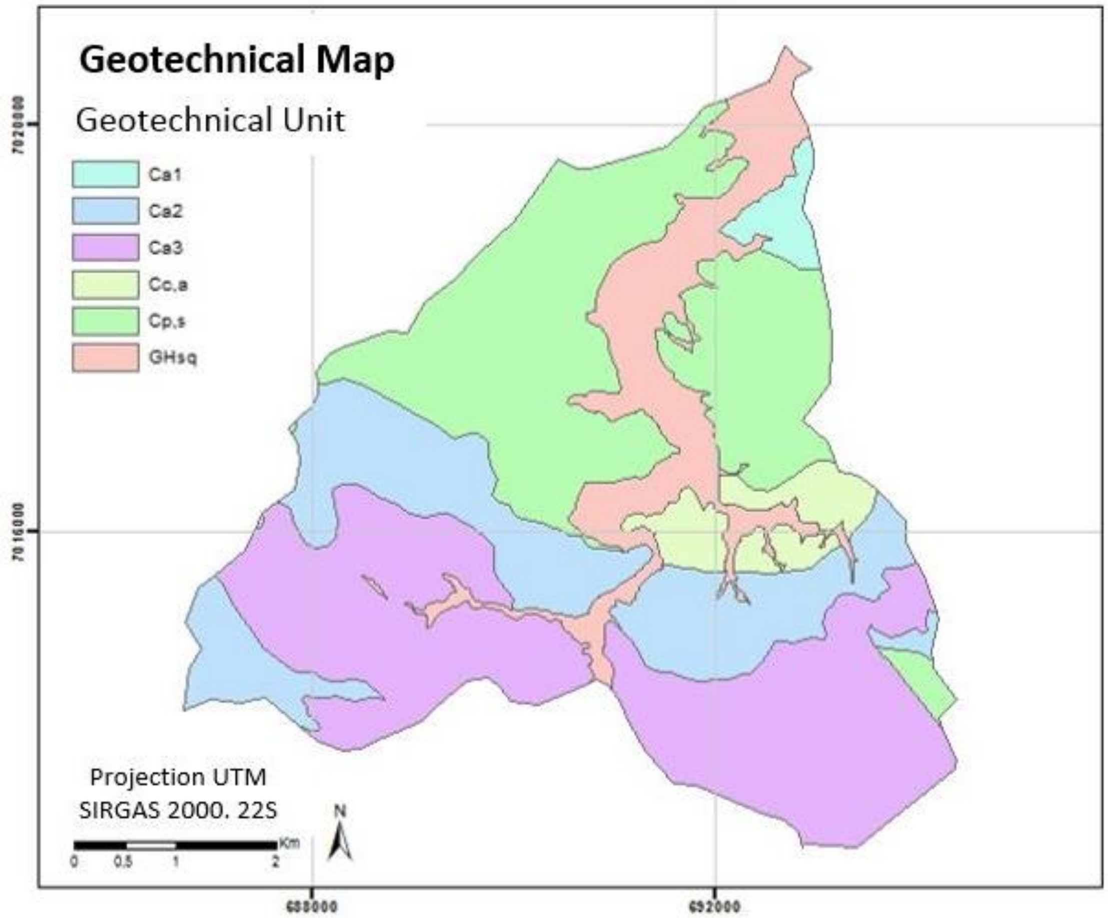
The basin of the Rio Garcia, as shown in Figure 3, is composed of the following residual geotechnical units: Ca1 (Cambisol substrate medium to fine sandstone), Ca2 (Cambisol substrate fine sandstone and siltstone), Cc,a (Cambisol substrate conglomerate and sandstone), Cp,s (Cambisol substrate pelites and siltstones) and by the sedimentary geotechnical unit: GHsq (Gleisole substrate alluvial quaternary sediments).

The geotechnical map was prepared by Flores et al. (2018), following the Geotechnical Mapping of Large Areas methodology, developed by Davison Dias (1987, 1995 and 2001). These authors prepared the geotechnical map of the entire urban expansion area in the Blumenau municipality, using the pedological map in 1: 100.000 scale, made available by the Projeto de Gerenciamento Costeiro (GERCO) of the Brazilian Institute of Geography and Statistics (IBGE, 2003) and the geological map in 1: 10.000 scale, they elaborated.

Figure 3. Geotechnical Map of Rio Garcia hydrographic basin. Source: Flores et al (2018).



3 METHODOLOGY

3.1 MODELING WITH SHALSTAB

The SHALSTAB model was developed by Montgomery and Dietrich (1994) and implemented in AML (ArcInfo Macro Language) by Dietrich and Montgomery (1998), for its use in geoprocessing software and spatial data analysis.

In this study, the ASA tool (Automatic SHALSTAB Analysis) was used, developed by Sbroglia et al. (2017), which is added to the Toolbox of the ArcGIS geoprocessing software, containing the automated routine of the SHALSTAB mathematical equation (equation 1). This tool automates the modeling processes (speeding up the results) and allows spatial variation of soil parameters, which, for the Rio Garcia basin was based on the geotechnical units polygons.

SHALSTAB, in order to quantify the terrain instability in terms of critical rain (necessary rain to trigger landslides), developed its mathematical base integrating two models: a hydrological one (with uniform state of recharge) and another of slope stability (based on the of infinite slopes theory), resulting in equation (1).

$$\frac{q}{T} = \frac{b}{a} \cdot sen\theta \cdot \left[\frac{c'}{\gamma_w \cdot g \cdot z \cdot \cos^2 \theta \cdot tg\varphi'} + \right] \left[+ \frac{\gamma_s}{\gamma_w} \cdot \left(1 - \frac{tg\theta}{tg\varphi'} \right) \right] \quad (1)$$

Where q is the intensity of the rain (mm); T the transmissivity of the soil (m2/ day); a is the contribution area (m²); b the unitary contour length (pixel size of the DEM) (m); θ is the slope (degrees); φ' is the effective friction angle of the ground (degrees); c' is the effective cohesion intercept (kPa); g is the acceleration due to gravity (m/s2); γ_s is the density of the soil (kg/m3); γ_w is the density of the water (kg/m3) and z the thickness of the soil (m).

In the present study, from the equation (1), the degree of susceptibility to translational slips was calculated for each pixel of the grids obtained from the DEM, in the spatial resolution of 1m and 10m. The results were expressed in the form of maps, classified from the values of log (q/T) according to the seven stability classes of the model, established by Dietrich and Montgomery (1998), which represent the conditions of stability and saturation from soil.

3.1.1 Obtaining Topographic Parameters

The maps related to the topographic parameters, slope (θ) and contribution area (a), were obtained from the DEM in the scales 1: 10,000 and 1: 50,000. They were elaborated in degrees and m2, respectively. The contour length (b) corresponds to the pixel size of the DEM and was defined as 1m for the 1: 10,000 scale and 10m for the 1: 50.000 scale.

The 1m spatial resolution DEM was made available by Secretaria de Desenvolvimento Social of Santa Catarina (SDS / SC). The 10m spatial resolution DEM was obtained from the level curves on the 1:50,000 scale, made available by the Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI / CIRAM). For data interpolation, Hutchinson's Anudem (Australian National University's Digital Elevation Model) (1998, 1999) algorithm was used, available on the topo to raster tool of ArcGis 10.5. In the elaboration of the DEM in the 10m resolution, the depressions generated erroneously in the interpolation of the data were removed with the help of the fill tool of Hidrology software.

3.1.2 Obtaining Soil Parameters

In determining soil parameters, different geotechnical units of residual soils present in the urban expansion area of the municipality of Blumenau were investigated, some of them located in the Rio Garcia watershed. The geotechnical map, as well as the soil data, were provided by Flores et al. (2018). Table 1 shows the geographic coordinates in Universal Transverse Mercator (UTM) of the points where soil samples were collected for the tests, and the valuesof the parameters obtained for each geotechnical unit.

Chart 1. Soil collection points and geotechnical tests data

Geotechnical Unit	Coordinates UTM*		Soil Parameters**		
	mE	mN	c'	°Ø	γ_{sat}
Cp,s	690696	7017519	9,9	26	15,4
Ca1	694198	7021907	7,8	32	18,4
Ca2	691187	7015810	10,8	21	13,7
Ca3	691495	7012393	15,8	22	15,8
Cc,a	695752	7025752	20,3	23	17,3

*Zone 22 (M.C. -51°); **c'(kPa); Ø (degrees); γ_{sat} (kN/m³)

According to Flores et al. (2018), soil shear strength parameters (effective friction angle and effective cohesion intercept) were determined from direct shear tests (DC) in the flooded condition, following the recommendations of the American Society for Testing and Materials (ASTM) (D3080/2011). The saturated specific weight (γsat), used in the modeling, was determined based on the natural specific weight (γnat), also determined in the direct shear tests. The soil thickness (z) was established as 5m, based on field observations.

3.2 VALIDATION OF MAPS

The validation of the susceptibility maps generated with spatial resolution of 1 and 10m was performed based on the spatial coincidence between the scars from the landslides mapped in the study areas (triggered in November 2008) and the model classes. Thus, it was possible to verify whether the scars were found in the lowest log values (q/T) (most unstable classes). For this, the inventory elaborated by Tomazzoli et al. (2012) was used, where 86 scars were identified in the Rio Garcia basin.

Bearing in mind that the validation must be carried out considering the slip rupture zone, and due to the difficulty in accurately identifying it, the SHALSTAB class with the lowest log value (q/T) was determined for each scar, which was used in the comparison with the unstable areas of the obtained maps. In determining the rupture zone, the ArcGis Zonal Statistics tool was used.

Then, the validation curves were elaborated for the maps generated in 1m and 10m spatial resolutions, following the guidelines of Remondo et al. (2003), from which the compatibility of the simulations with the real instability situation of the basin was identified.

According to these authors, the validation curve relates the percentage of accumulated area of each class in the basin (abscissa axis) with the accumulated percentage of the number of scars in each of them (ordinates axis). Both axes must present the sum of the accumulated percentage, starting with the most unstable class. The curve that moves away from the axis of the abscissa and reaches the proportion of 100% of the unstable pixels more quickly is the one that represents the scenario with the greatest predictive capacity. With this information, was possible to analyze the performance of the model using different scales.

4 RESULTS AND DISCUSSIONS

The influence of scale on the relief of the Rio Garcia hydrographic basin can be observed in the graphs presented in Figures 4 and 5, where are shown the percentage of occurrence of altitude and slope data in the spatial resolutions of 1m and 10m, respectively.

Figure 4. Altitude variation in spatial resolutions of 1m and 10m.

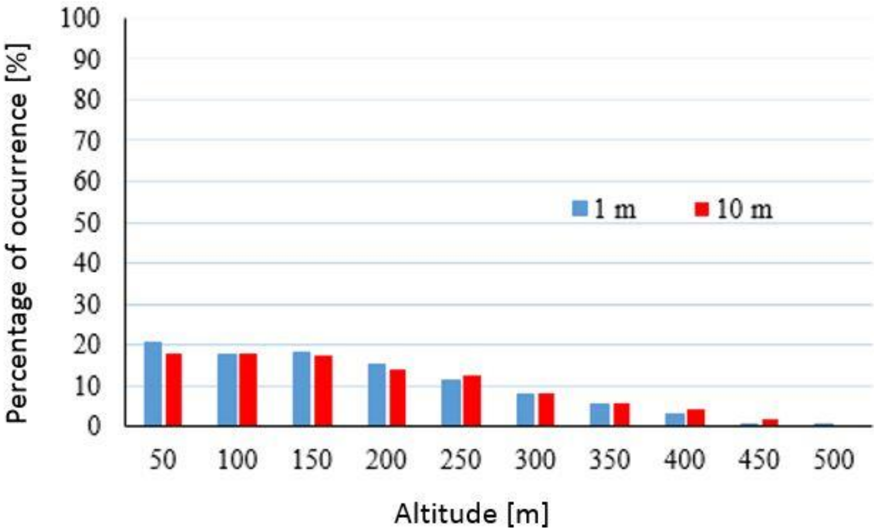
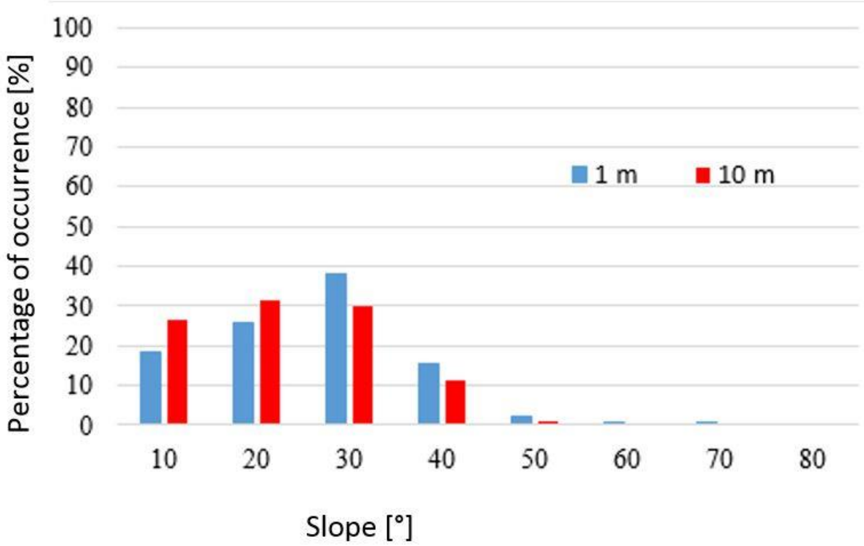


Figure 5. Slope variation in spatial resolutions of 1m and 10m.



As for the altitude data, it was observed that the values are similar in the two spatial resolutions. However, from the slope values, the relief of the relief was noted with the use of data on the 1:50,000 scale, as mentioned by Gomes et al. (2004), influencing the mapping of unstable areas. On the 1:50,000 scale, the occurrence of slopes between 10° and 20° increased by a maximum of 8%. Between 30° and 50° it decreased by a maximum of 8%. Slopes greater than 50° were not identified on this scale. Thus, it is possible to observe a better detail of the relief in the 1:10.000 scale.

In turn, the susceptibility maps to translational landslides in the Rio Garcia hydrographic basin, in the spatial resolutions of 1m and 10m, are shown in Figures 6 and 7, respectively.

Figure 6. Susceptibility map to translational landslides in the 1m spatial resolution.

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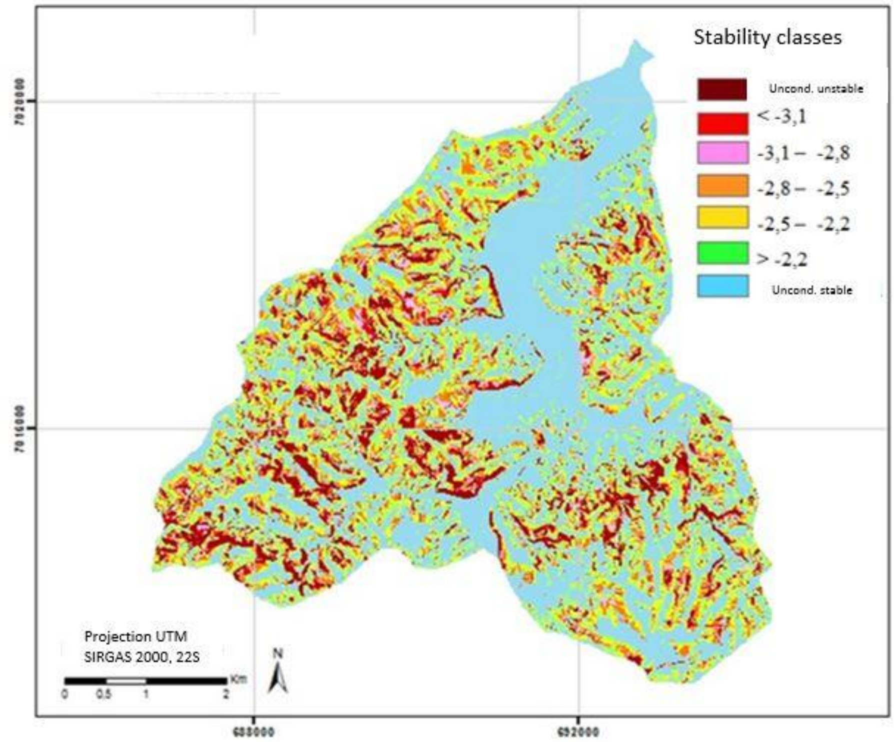
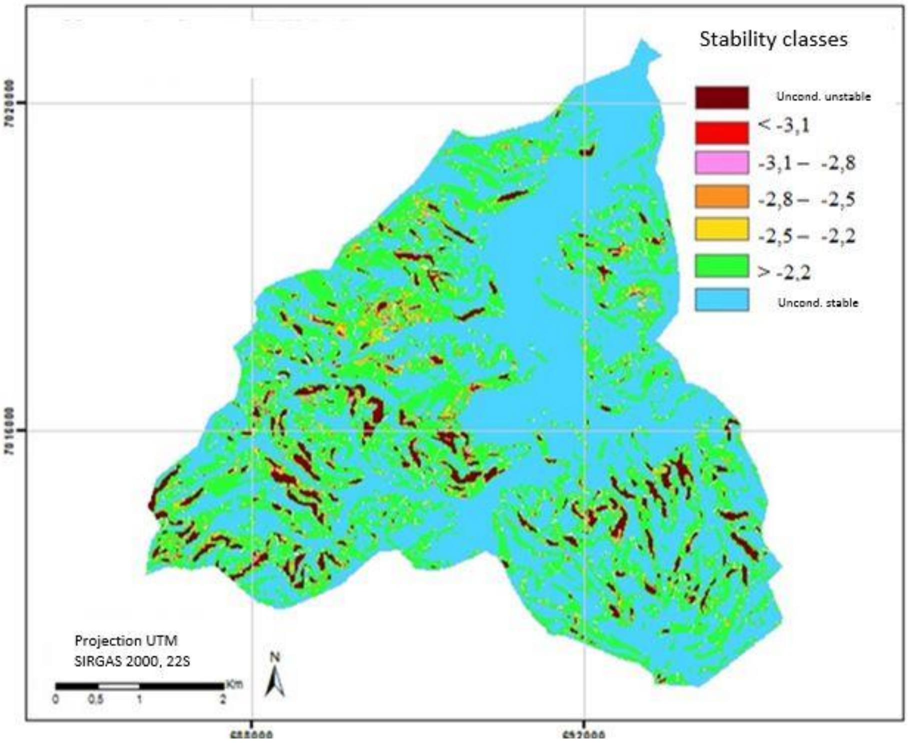
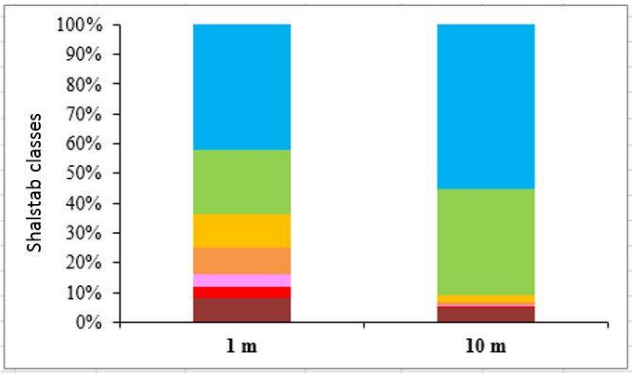


Figure 7. Susceptibility map to translational landslides in the 10m spatial resolution.



Based on the susceptibility maps, the graphs presented in Figure 8 were elaborated, which relate the percentage of occurrence of each SHALSTAB class with the different spatial resolutions.

Figure 8. Percentage of each SHALSTAB class area in the 2 different spatial resolutions.



According to Figure 8, it was observed that in the 10m resolution, the two most stable classes (Unconditionally stable and Log (q/T) > -2.2) stood out, representing approximately 90% of the area of the hydrographic basin. In the 1m resolution, these two classes also stood out, however they represented approximately 64% of the area. Therefore, as expected due to the smoothing of the relief, at a resolution of 10m a higher percentage of stable area was mapped.

In the two spatial resolutions, the class with the highest occurrence in the study area was the unconditionally stable (42% at 1m resolution and 55.4% at 10m resolution). In this class, the relief is so smooth that even the saturated soil will not cause instability.

In the 10m resolution, the occurrence of the intermediate classes (Log (q/T) = -2.5 to -2.2, Log (q/T) = -2.8 to -2.5, Log (q/T) = -3.1 to -2.8 and Log (q/T) < -3.1) totaled 4.3% of the area, representing 23.7% less than in the 1m resolution. Therefore, at the 1:50.000 scale, the occurrence of the intermediate classes was underestimated, making them little representative in the mapping.

The unconditionally unstable class, where the relief conditions provide instability to occur even though the soil is dry, had a higher occurrence in the 1m resolution (8.3%). In the scale with the lowest spatial resolution, the occurrence of this class was 4.8%. In order to verify the compatibility of the field situation of the basin under study with the generated susceptibility maps, the graphs of Figure 9 were elaborated, which show the number of scars in each SHALSTAB class for the spatial resolutions of 1m and 10m. To verify the performance of the model at the different scales used, the validation curves shown in Figure 10 were generated.

Figure 9. Number of scars in each SHALSTAB class at 1m and 10m spatial resolutions.

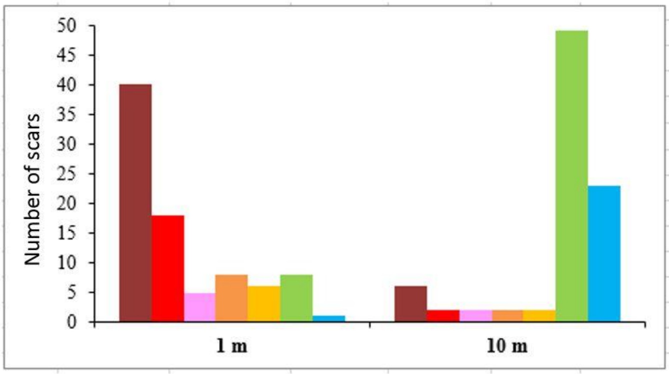
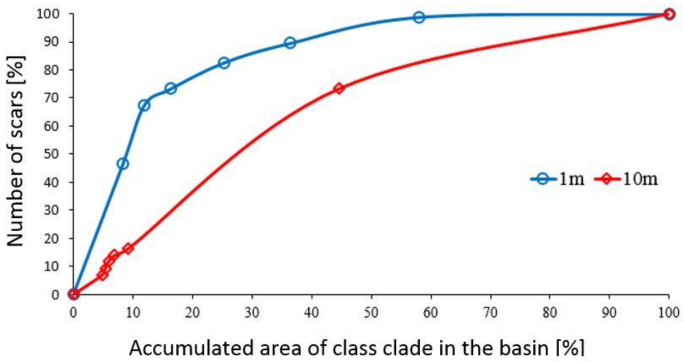


Figure 10. Validation curves in the 1m and 10m spatial resolutions.



Regarding the validation curves (Figure 10), it was found that the one referring to the spatial resolution of 1m was the one that identified a greater amount of landslides in a smaller percentage of unstable area of the basin, being then considered to have better predictive capacity. In this resolution, about 70% of the landslides were identified in 16.3% of the basin area (equivalent to the Log class (q/T) = -3.1 to -2.8). While, at the 10m resolution, about 70% of the landslides were identified in 44.6% of the area (equivalent to the Log class (q/T)> - 2.2), that is, in a percentage almost three times higher, involving areas classified as stable by SHALSTAB.

5 CONCLUSSION

In this study the mapping of susceptibility to translational landslides was carried out with the SHALSTAB model, in two different scales: 1.10.000 (equivalent to the spatial resolution of 1m) and 1.50.000 (equivalent to the spatial resolution of 10m), and distributing the parameters soil based on geotechnical units. Subsequently, the results were validated with the scars from the landslides that occurred in November 2008 in the watershed of the Rio Garcia, in the municipality of Blumenau / SC.

When comparing the susceptibility maps generated in the different spatial resolutions, it was found that on the 1.50,000 scale, due to the relief of the relief, the stable areas were overestimated (by approximately 27%), representing almost the entire area of the basin. At the 1m spatial resolution, although the stable areas represent more than half of the basin, there was a better distribution among the stability classes of SHALSTAB. Thus, it was possible to conclude that the two most stable classes in the model showed greater sensitivity due to the change in the scale (maximum variation of approximately 14% in the Log class (q/T)> - 2.2), followed by the most unstable class (Unconditionally Unstable). Based on the overlapping of the scars mapped in the basin to the susceptibility maps, it was concluded that on the 1.50,000 scale, the result obtained was not consistent with the field situation, since the majority of the scars (83.7%) were identified in areas classified as stable. The opposite occurred on the 1.10.000 scale, where, despite the large percentage of stable area, most scars were found in unstable areas.

The performance of the model at the different scales was also analyzed from the validation curves of Remondo et al. (2003). As expected, on the 1.10.000 scale, the predictive capacity of the model surpassed that obtained on the 1.50.000 scale, representing more consistently the slips that occurred in November 2008. The difference between the results was considerable, since, on the 1.10.000 scale, a large percentage of landslides (70%) were predicted and identified in the three most unstable classes of SHALSTAB, whose occurrence did not exceed 16.3% of the area. At the 1.50,000 scale, only 11.6% of landslides were predicted and mapped in the three most unstable classes. Therefore, in the scale of lower spatial resolution, most of the landslides were not predicted, since they occurred in stable areas.

This study demonstrates the importance of the DEM scale in the mapping of areas susceptible to translational landslides with the SHALSTAB model, which could be observed in the watershed of Rio Garcia in determining the percentages of occurrence of each stability class and mainly in the validation of the results with field data. However, it is noteworthy, again, that several Brazilian states with problems related to the occurrence of landslides present topographic data, available free of charge, at scales equal to or less than 1:50,000, which does not make the mapping unfeasible. In this case, it is suggested that it be used in preliminary analyzes, given the need for a more refined scale for determining critical areas. Another issue to be highlighted is the relevance of field data (scars from landslides) for the validation of maps and definition of the type of mapping generated.

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