Landslides and Engineered Slopes. Experience, Theory and Practice – Aversa et al. (Eds)
ISBN 978-1-138-02988-0

Assessment of Lidar-derived DTMs for landslide susceptibility mapping: Application in the Brazilian subtropical forest

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ABSTRACT: The efficiency of two sets of Digital Terrain Model (DTM), one based on LiDAR data, and the other on traditional contour lines method were assessed for landslide susceptibility mapping at 1:2000 scale. To evaluate the DTMs, we used the shallow slope stability model, SHALSTAB. The tests were carried out in a basin affected by shallow landsliding caused by extensive rainfall during March 2011, in the urban area of Antonina city (Parana State), southern part of the Serra do Mar mountain range, in Brazil. The geotechnical data needed for the model consisted of two sets of values measured from 2011 landslide scars. In order to validate the landslide susceptibility maps, we compared the spatial pattern of instability classes predicted by SHALSTAB with the mapped landslide scars. The results showed significant difference between the DTMs, especially in the distribution of the most unstable classes.

1 INTRODUCTION

Mass movements caused more than 4,000 deaths in Brazil between 1928 and 2011. The majority of large-magnitude events occurred in big urban centers (e.g., Rio de Janeiro) and in the Serra do Mar (SM) mountain range. In this regions, significant mass movement episodes generally occur at an interval of 5 to 10 years during the rainy season (Nalon 2000). Since 1920s there have been records of these processes, mainly debris flows and shallow landslides that caused casualties and partially or totally destroyed local industrial plants.

The topography of the SM greatly influences the rainfall distribution along its elevation profile as well its extent, with average values exceeding 3,000 mm/year. Some parts of SM, around an altitude of 600 m, have registered over 4,000 mm of annual precipitation (Milanesi & Galvani, 2012).

In Paraná, the SM is very mountainous, with its escarpments facing the coast due to the reactivation of NE and NNE trending faults. The parallel alignments of small mountains and isolated hills form a series of steps with altitudes between 20 and 900 m. The altitudes of this stretch vary between 800 and 1,300 m, with peaks above 1,800 m having granitic massifs of alkaline granite, and the steepest terrain being underlain by andesite and diabase dikes of alkaline microcline-biotite-granite (Maack 1947, Bigarella et al. 1978, Santos et al. 2006).

The research area (Figure 1) is located on the Southern part of the Serra do Mar mountains in the municipality of Antonina (Parana State). Portions of the area were affected by landslides that occurred during extensive rainfall in March 2011, causing severe damages to the local community (Figure 2).

Physically based mathematical models are considered the most objective to identify susceptible areas for landslides, due to the direct application of the equations that describe physically relevant processes, and no reliance on researcher's subjective opinions. In addition, they can predict landslide susceptibility under different scenarios (e.g., land use), regardless of whether those processes have taken place (Guzzetti et al. 1999; van Westen 2004).

One such model, SHALSTAB, calculates the critical steady-state rainfall necessary to trigger slope instability at any point in a landscape (Montgomery & Dietrich 1994, Montgomery et al., 1998). The model considers subsurface flow parallel to the surface, and the hydraulic conductivity and soil thickness, which generally are treated as uniform for the whole basin.

The introduction of LiDAR (Light Detection and Ranging) technology to acquire topographic

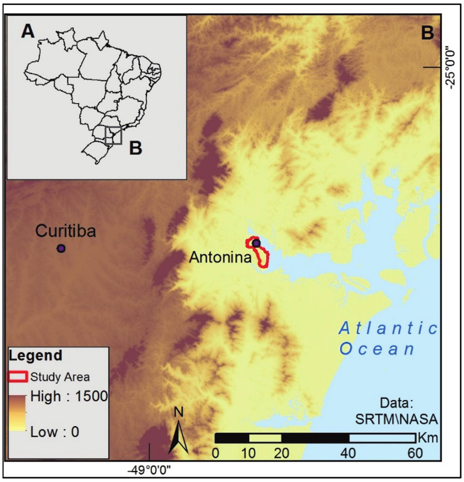

Figure 1. Study area, located in Antonina City, Parana state in South Brazil.

Figure 2. a) Urban area of Antonina at the foothills of Serra do Mar; b) Area affected by landslide on March, 2011.

data opens new avenues to prepare the Digital Terrain Model (DTM). This research aims to analyze the effects of using different Digital Terrain Models (DTMs) on shallow landslide susceptibility maps generated from the deterministic physically-based model SHALSTAB.

2 MATERIAL AND METHODS

In order to carry out the research we used topographical contours lines with intervals of 1 meter, on 1:2000 scale maps, and the raw LiDAR points. These data sets provided two different DTMs (DTM-Contour and DTM-LiDAR), both generated in ArcGIS 10 platform with 1-meter grid size.

The LiDAR points were filtered using the Las Dataset tool (ESRI 2015) that allowed only the selection of the ground points (last return). Next, we converted the points into raster format using the Natural Neighbor interpolation method, based on the discussion of the algorithm efficiency for LiDAR data interpolation provided by Bater & Coops (2009).

The SHALSTAB model was then applied on the Laranjeira basin that still has the landslides scars from 2011. To validate the results we produced a map of landslide scars generated based on the data from field verification and previous studies (MINEROPAR 2013, Martins et al. 2015). The geotechnical data needed for the model was obtained from literature: based on these data sources we adopted a saturated soil bulk density of $\rho_s = 2{,}600$ kg/m, and a soil friction angle of $\phi = 31°$ (Lopes 2013). We adopted zero for cohesion value for the soil, as field data indicated that reasonably approximated conditions at 1 meter depth, and this would result in the largest potential unstable area. We ran SHALSTAB in the GIS platform following Dietrich & Montgomery (1998).

Performance of both DTMs, was evaluated using two indices: (1) Scar Concentration (SC), the ratio of the number of cells in each susceptibility class affected by shallow landslides to the total number of cells in the basin; and (2) Landslide Potential (LP), the ratio of the number of cells in each susceptibility class affected by the shallow landslides to the total number of cells in the same susceptibility class. For both the models we also produced the Frequency (F) histogram for the number of cells of each susceptibility class: the ratio between the number of cells in each susceptibility class to the total number of cells in the basin.

3 RESULTS AND DISCUSSIONS

The maps of susceptible areas for landslides provided by SHALSTAB, based on the two different DTMs, are presented in Figure 3.

Using the DTM-Contour the model classified 13% of the basin as Unconditionally Unstable, 38% at the class Log q/T > –2,2 and 49% at the Unconditional Stable class. The four intermediary classes together accounted for less than 1% of the cells.

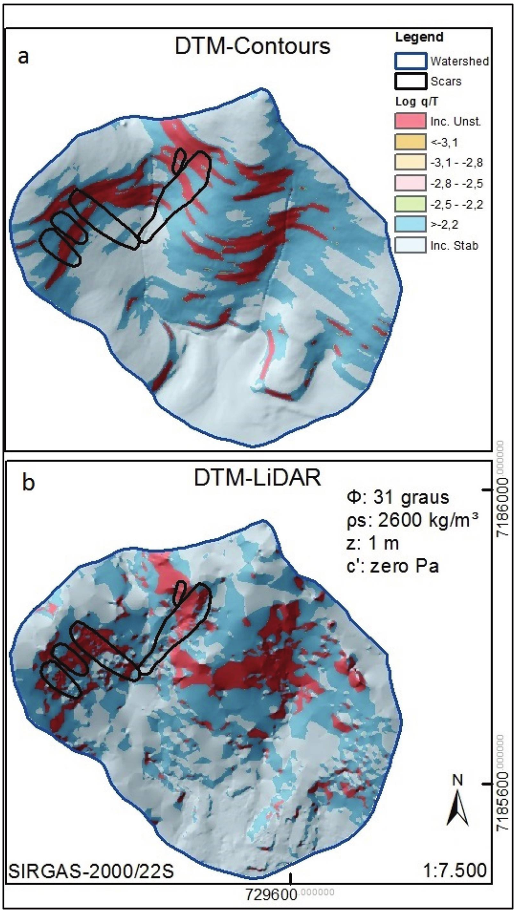

Figure 3. Maps of susceptible areas for landslides provided by SHALSTAB to the Laranjeira basin; a) results based on DTM-Contours, b) results based on DTM-LiDAR.

The Scar Concentration (SC) ranged from 32% that befell at the Unconditionally Unstable class and 66% at the two most stable classes. For the Landslide Potential (LP), the Unconditionally Unstable class recorded 15% and the two most stable accounted for 7% and 2%. The other classes vary from 4% to 12%.

Considering the DTM-LiDAR, 16% of the basin was classified as Unconditionally Unstable, and around 50% of the scars occurred in the same class. Altogether, the two most stable classes (Log q/T > –2.2 and Unconditionally Stable) recorded 84% for F and 50% of the scars were concentrated for those two classes. Null values were registered in the others classes regarding F.

For the LP, the Unconditionally Unstable class recorded 18% and among four intermediaries classes only Log q/T –3,1 – –2,8 registered any values (around 15%). The last two classes (Log q/T > –2.2 and Unconditionally Stable) recorded less than 8% together.

Based on the values presented by the two sets of DTM it is noticeable that the DTM-Contour registered values for all classes, whereas the DTM-LiDAR presented null values for some of the intermediary classes. On other hand, the DTM-LiDAR registered the highest value of SC for the most unstable class. In short, the DTM-Contour registered less value on the Unconditionally Unstable class compared to the DTM-LiDAR, and higher values for the two most stable classes. The four intermediaries' classes do not appear on both maps due to the small amount of cells within those classes.

Both DTMs recorded similar values for the LP (15% and 17%) for the Unconditionally Unstable class. In addition, the major occurrence of the same class happened to be along the middle slope, followed by the upper slope. It is important to mention that on the DTM-Contour map smooths out the zones of high hazard, whereas in the DTM-LiDAR map seems to better captures the actual slides. This can be explained because the LiDAR survey it was made 2 years after the landslide, and some of the scars are still visible.

The very low values, or even null values registered on the intermediate classes on both DTMs, can be explained by the slope morphometry, which according to the literature (MINEROPAR, 2013) are not concave slopes. In some part of the study, all the slopes mapped within the Laranjeira basin are of convex shape.

The LiDAR derived DTM still need further investigation for the precision and accuracy to represent the terrain. Another important issue is the number of ground points. In the present case the ground points obtained after the filtering process are relatively low compare to other works (Bater & Coops 2009, Guo et al. 2010) with a value of 0.06 points/square meter against about 2 points/square meter. This it is due to the dense canopy cover and for the lack of specific parameters predefined for the aerial LiDAR survey, in order to obtain a high ground point density.

The value of DTM derived from LiDAR data for different analyses has been extensively discussed in the literature and the results may differ especially due to the number of grounds points per square/meter and due to the complexity of the terrain (Liu 2008). Previous workers have mentioned the precision and accuracy of LiDAR points provided by the same apparatus used here, identifying 15 cm error on the altimetry value, and more systematic error under dense canopy cover (Becker & Centeno 2013). Thus, as is the case for other remote sensing data, LiDAR derived DTMs have certain limitations on some specific analyses, such as hydrological modeling (Barber & Shortridge 2005), or, as presented here for susceptibility maps for landslides, using physically-based models.

4 CONCLUSION

In Brazil most of the mass movements, especially shallow landslides that occur in the Serra do Mar mountain range, are triggered by intense rainfall. Since early 2000's many researchers has applied physically based models, such as SHALSTAB, to identify areas potentially susceptible to landslides with successful results. With the advancement of tools to collect topographical data and generate LiDAR-derived DTMs, it is important to analyze the influence of the topographical data on model performance.

This research has identified differences between DTM from contour lines and a DTM derived from LiDAR applying SHASLATB. LiDAR derived DTM still need further investigation about the minimum requirements in order to elaborate a precisely terrain representation.

ACKNOWLEGMENTS

The authors are thankful to CAPES (Processo BEX 5188/14-8) and FAPESP (Processo 2014/10109-2) who provided the financial funding for this research. The authors also want to convey their thanks to Harvey Greenberg and Dr. Lopamudra Dasgupta of the GIS Lab of the Department of Earth and Spaces Sciences, University of Washington, Seattle.

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