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Identifying shallow landslide susceptibility in Nova Friburgo, Rio de Janeiro.

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Identifying shallow landslide susceptibility in Nova Friburgo, Rio de Janeiro

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Abstract. Landslides cause enormous economic damage and fatalities worldwide. The "Mega disaster" in the mountainous region of Rio de Janeiro took place on 11 and 12 January 2011 and reached seven municipalities. This landslides event is considered the worst disaster in Brazilian history. Landslide susceptibility zonation is one of the most important tasks in landslide risk assessment. The different approaches for landslide susceptibility modelling includes: 1) Heuristics (e.g., index-based approach and an analytical hierarchical process approach); 2) Statistical (statistical index, certainty factor, probability based methods, weight of evidence modelling, multiple linear regression and logistic regression analysis); 3) Process-based or deterministic modelling (slope stability factor). In this study, the process-based model SINMAP (Stability Index Mapping) was applied to determine landslide susceptibility in Nova Friburgo municipality (Rio de Janeiro State). The most common landslide processes in the study area are shallow triggered by rainfall. Entire database was incorporated in a GIS environment to compute the susceptibility index in a single-calibration mode. Results show that 13,94 % of area includes terrains with low susceptibility; 12,1 % includes moderate susceptibility and 73,96 % a high susceptibility. Validation showed that 89% of shallow landslides mapped occurred within the three highest susceptibility classes. Final susceptibility map can be used as a predictive model for future location of mass movements. The deterministic method proved to be a reliable technique for landslide susceptibility analysis. However it is necessary to test the sensitivity to different input data sets and geotechnical parameter values to have a holistic approach.

Key words: susceptibility zonation, SINMAP modelling, deterministic analysis, Brazil.

1. Introduction

Brazil has a complex scenario of threats, essentially as a direct result of its size, diversity, and heterogeneous natural and social environments. There were around 150 records of disasters caused by natural events during the period 1900–2013, whose associated impact is also alarming: 10,052 fatalities, 71 million people affected and a loss of about USD16 billion (EM-DAT, 2013). Floods were the most frequent events (57%), followed by mass movements (11%) (Camarinha et al. 2014). Between 2010 and 2011, over a thousand people died in many regions of Rio de Janeiro State, i.e., the disaster in Angra dos Reis municipality (52 fatalities), in the metropolitan region (166 fatalities) and in the mountainous zone (905 fatalities).

The "Mega disaster" in the mountainous region of Rio de Janeiro took place on 11 and 12 January 2011 and reached seven municipalities: Areal, Bom Jardim, Nova Friburgo, São José do Vale do Rio Preto, Sumidouro, Petrópolis and Teresópolis. This event is considered the worst disaster in Brazilian history, not only because of the human fatalities that it caused, but also because of the significant losses and economic damage with considerable negative important implications on the quality of life of the survivors and on the economic activity of the entire region (World Bank, 2012). This event was one of the largest mass movements widespread in the country, triggered by extreme conditions of precipitation: 241.8 mm accumulated in 24 hours, with a peak of 61.8 mm in one hour, and an accumulated precipitation of 573.6 mm between 11 and 12 January (Dourado et al. 2012). Although it is considered the most destructive landslides ever registered in Brazil, similar events had previously occurred in Rio de Janeiro in 1966, 1967, 1988, 1996 and 2010 (Barata, 1969; Jones, 1973: Lacerda, 2007; Coelho Neto et al. 2009) and particularly in Nova Friburgo municipality in 1924, 1940, 1977, 1979, 2007 and 2011 (DRM-RJ, 2015).

Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of local terrain conditions (Brabb, 1984). It is the degree to which an area can be affected by future slope movements, i.e., an estimate of "were" landslides are likely to occur (Guzzetti et al. 2006).

Landslide susceptibility zonation is one of the most important tasks in landslide risk assessment. The different approaches for landslide susceptibility modelling includes: 1) Heuristics (e.g., index-based approach and an analytical hierarchical process approach); 2) Statistical (statistical index, certainty factor, probability based methods, weight of evidence modelling, multiple linear regression and logistic regression analysis); 3) Process-based or deterministic modelling (slope stability factor) (Kuriakose, 2010).

This paper presents a landslide susceptibility zonation through a deterministic method: a SINMAP (Stability Index Mapping) approach (Pack, 2001).

2. Study area

The municipality of Nova Friburgo is located in the central mountainous region of Rio de Janeiro State, Brazil (Figure 1). Specifically, it is situated in “Serra dos Órgãos”, a local name that designs a higher portion of the mountains (Serra do Mar). Nova Friburgo has a population of 182,000 habitants (IBGE, 2010).

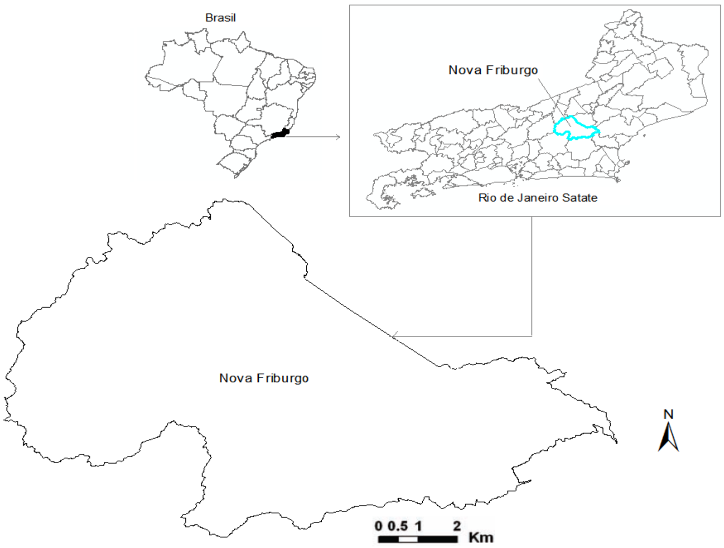

Figure 1. Location of Nova Friburgo, Rio de Janeiro State, Brazil.

3. Methodology and data set

SINMAP (Stability Index Mapping) methodology is based upon the infinite slope stability model that balances the destabilizing components of gravity and the restoring components of friction and cohesion on a failure plane parallel to the ground surface with edge effects neglected. SINMAP derives its terrain stability classification from inputs of topographic slope and specific catchment area and from parameters quantifying material properties (such as strength) and climate (primarily a hydrologic wetness parameter) (Pack et al. 2005) (Eq.1).

$$FS = \frac{C_r + C_s + \cos^2\theta[\rho_s g(D - D_w) + (\rho_s g - \rho_w g) D_w]\tan\phi}{D \rho_s g \sin\theta \cos\theta} \quad (1)$$

where $\mathbf{C_r}$ is root cohesion [N/m^2]; $\mathbf{C_s}$ is soil cohesion [N/m^2]; $\boldsymbol{\theta}$ is slope angle; $\boldsymbol{\rho_s}$ is wet soil density [kg/m^3]; $\boldsymbol{\rho_w}$ is the density of water [kg/m^3]; **g** is gravitational acceleration (9.81 m/s^2); **D** the vertical soil depth [m]; $\mathbf{D_w}$ the vertical height of the water table within the soil layer [m] and; **φ** the internal friction angle of the soil [-]. The slope angle **θ** is the arc tangent of the slope, **S**, expressed as a decimal drop per unit horizontal distance. Figure 2 illustrates the geometry assumed in Eq. 1.

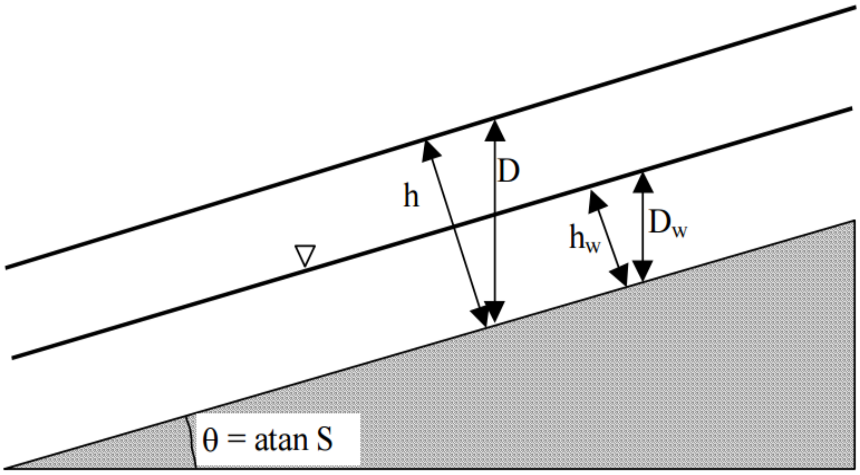

Figure 2. Infinite slope stability model schematic. Soil thickness, **h** [m], and vertical soil depth are related, **h** = **D cosθ** (Pack et al. 2005).

Geospatial and geotechnical data are necessary to compute the stability index in the SINMAP approach. For this study, DEM data were obtained from IBGE (Instituto Brasilero de Geografía e Estatística) and the geotechnical values were obtained from the bibliography (Table 1). In many articles, geotechnical soil parameters are mentioned in both conditions: saturated soil and natural wet. For the analysis were selected only the saturated soil parameters that reflects the conditions in which landslides occurred in this area of “Serra do mar”. The testing was carried out in SINMAP 2.0 which uses ArcGIS software environment, version 9.0 or higher.

Table 1. Input data set used in SINMAP model for Stability Index.

Data	References/Source	Value	Unit
Root cohesion	Wolle and Pedrosa (1981)	0,003	N/m^2
Minimum soil cohesion	Wolle and Carvalho (1994)	0,001	N/m^2
Maximum soil cohesion	Wolle and Carvalho (1994)	0,004	N/m^2
Gravitational acceleration	-	9,81	m/s^2
Minimum internal friction angle	Wolle and Carvalho (1994) De Campos et al. (1992)	28	degrees
Maximum internal friction angle	Wolle and Carvalho (1994)	39	degrees
T/R minimum	Nery (2011)	68	m
T/R maximum	Nery (2011)	213	m
Wet soil density	Pack (2001)	2000	kg/m^3
Slope angle	DEM (10 m resolution)	-	degrees

Landslides of 2011 event were mapped semi-automatically by creating a routine in object-based classification using the spectral, spatial and morphometric properties of landslides and by incorporating expert knowledge in Definiens Developer software environment (Cardozo et al., unpublished). A large number of landslides were recognized (2272 fresh scars). Later it was identified the zone of initiation of each landslide, defined for failure surface. This inventory map was used to test the accuracy and model prediction skill of SINMAP approach.

4. Results and Discussion

According to Rossi et al. (2010) advancements in computer technology, the increased availability of thematic information in digital format, the improved ability to manage landslide and geomorphological information in geographical information systems, and the possibility of exploiting remote sensing technology for landslide detection and mapping relevant environmental information have facilitated the preparation of landslide assessments.

Susceptibility zonation map reveals that 13,94 % of area includes terrains with low susceptibility (stable class in stability index); 12,1 % includes moderate susceptibility (moderately and quasi-stable classes) and 73,96% a high landslide susceptibility (lower/upper threshold and unstable classes) (Figure 3).

SINMAP model predicted correctly the largest number of landslides, that is, 89% of the shallow landslides occurred within the three highest susceptibility classes established (Table 2). Unstable and upper threshold stability classes had the highest landslide density in the zone (0,98 and 0,45 landslides/km^2 respectively). Despite of good results, a considerable number of landslides fell within the stable (83), moderately stable (43) and quasi-stable (114) classes. According to Pack et al. (2005) the reason for these results may be twofold: 1) the bedrock, surficial geology and landslide processes are more complex and, 2) the DEM data fails to pick up many of the small but critical slopes.

SINMAP routines also generate contributing area map (Figure 4), wetness map (Figure 5) and a slope-area chart (Figure 6). This last one product provides information about: 1) the mapped landslides; 2) the boundaries for regions within slope-specific catchment area space that have similar potential for stability or instability and, 3) the boundaries for regions within slope-specific catchment area space that have similar wetness potential.

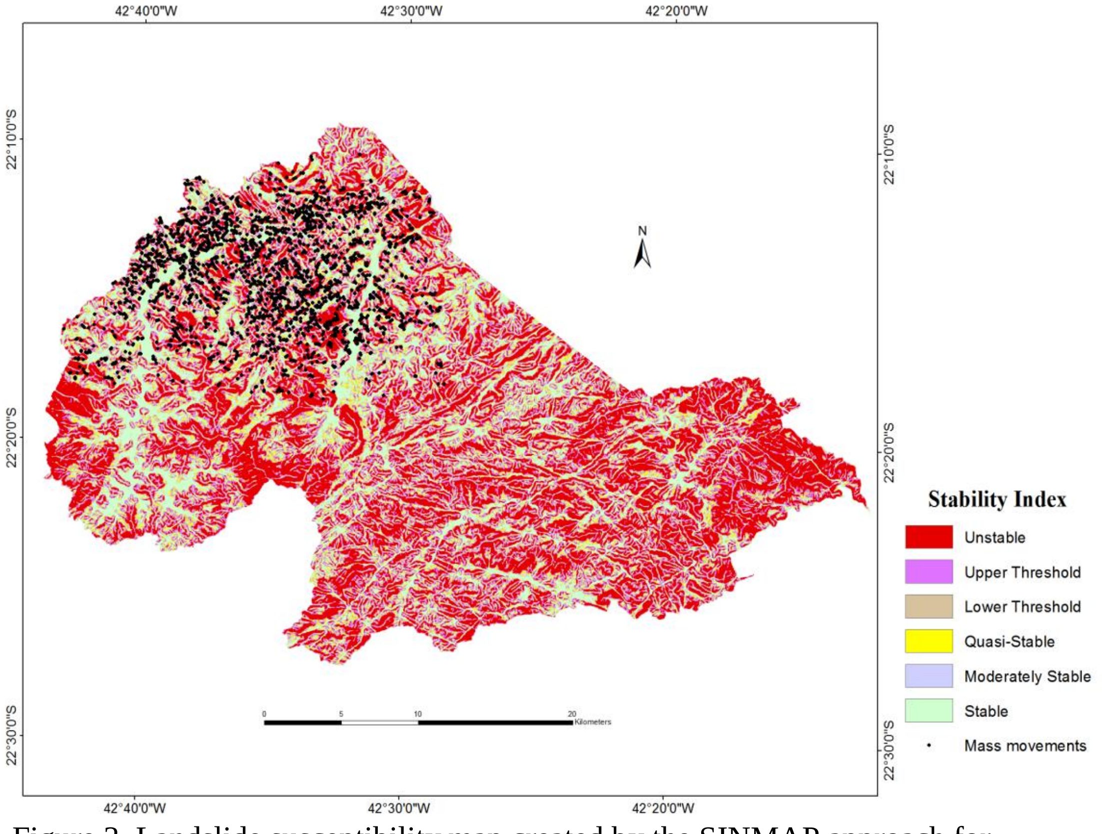

Figure 3. Landslide susceptibility map created by the SINMAP approach for Nova Friburgo municipality, Rio de Janeiro, Brazil.

Table 2. Summary statistics of SINMAP analysis in a single-calibration mode for Nova Friburgo municipality, Rio de Janeiro, Brazil.

	Stable	Moderately Stable	Quasi-Stable	Lower Threshold	Upper Threshold	Unstable	Total
Area (km^2)	176,13	56,00	97,13	168,78	264,64	500,43	1263,11
% of region	13,94	4,43	7,69	13,36	20,95	39,63	100,00
# Landslides	83	43	114	233	565	1234	2272
% Landslides	3,65	1,89	5,02	10,26	24,87	54,31	100,00
Landslide density(#/km^2)	0,07	0,03	0,09	0,18	0,45	0,98	1,80

Inspection of the S-A plot and wetness map reveal that most of landslides are located within the areas modelled as being wet.

Results suggest that susceptibility map can be used as a predictive model for future location of mass movements. However, it would be necessary to test other geotechnical parameters and to incorporate a multi-calibration analysis to consider the variability of lithology and soils in the study area and improve the quality of DEM data.

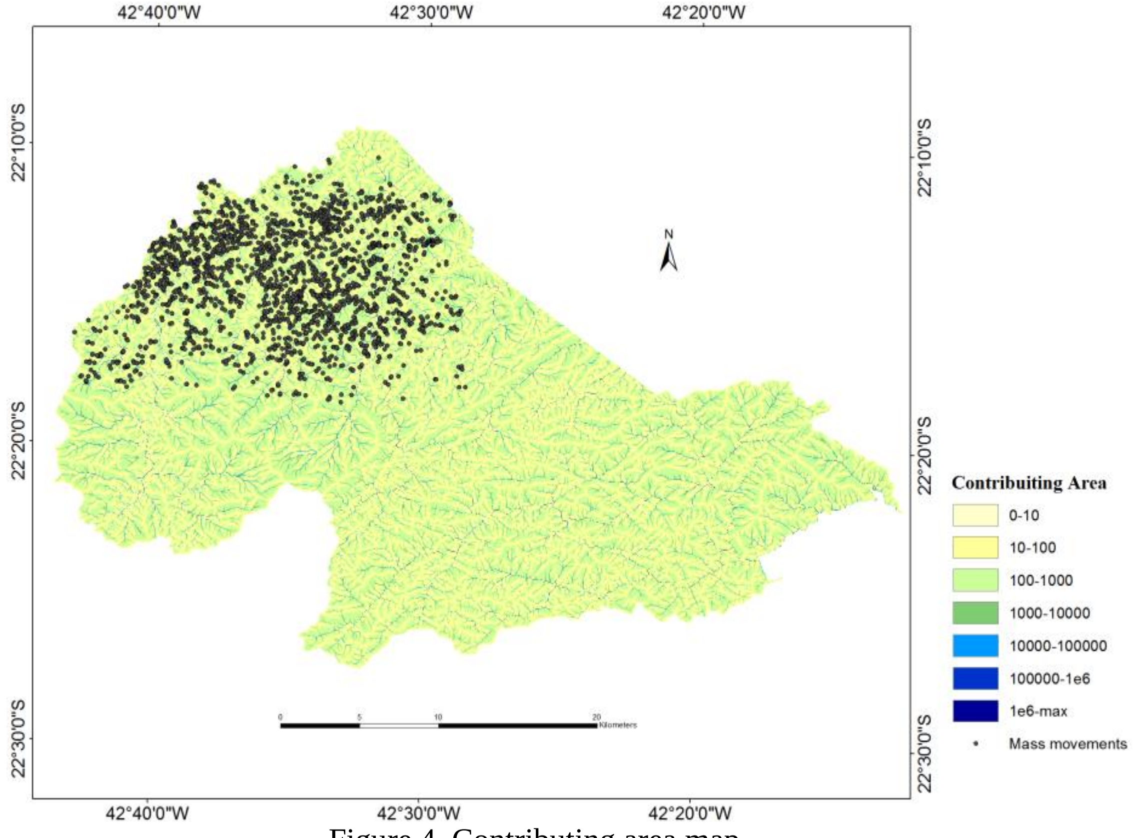

Figure 4. Contributing area map.

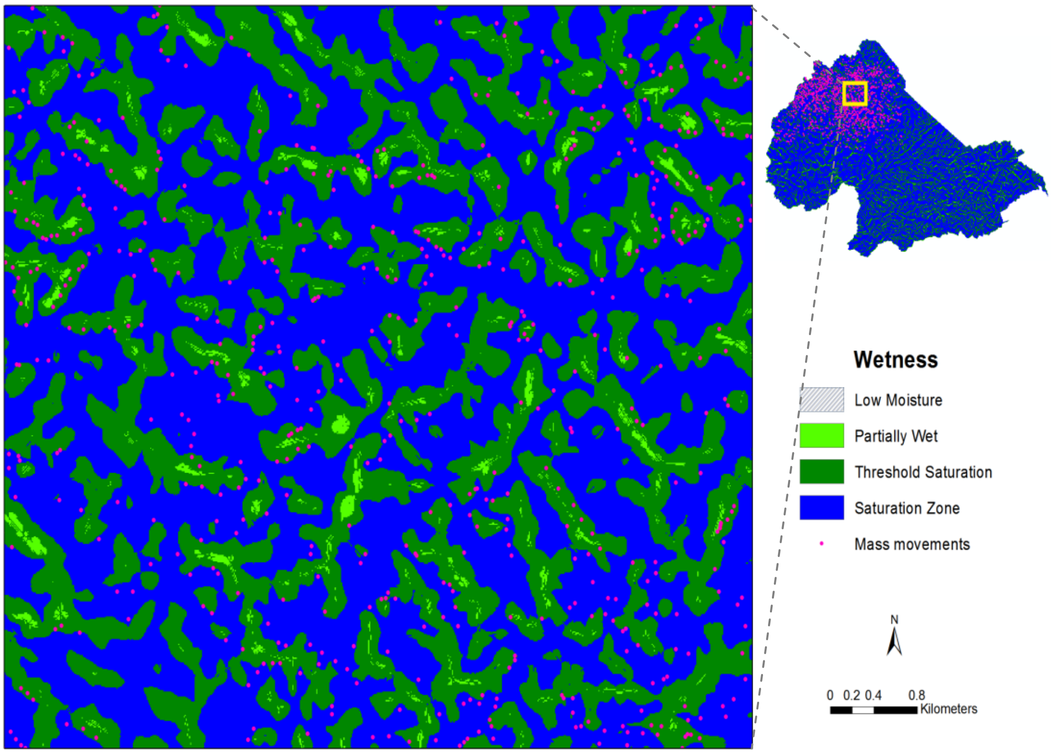

Figure 5. Wetness map.

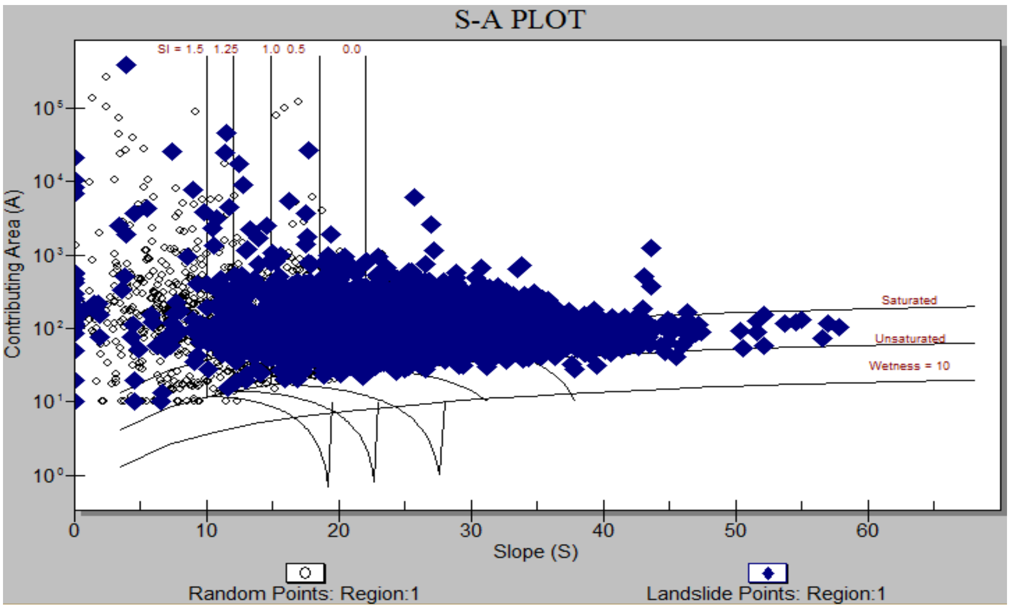

Figure 6. Slope-area plot for the single-calibration mode.

5. Conclusions

The susceptibility zonation map was obtained through SINMAP analysis. The model prediction skill were tested against the location of landslides occurred in 2011 event.

The deterministic method proved to be a reliable technique for shallow landslide susceptibility analysis with the dataset used, however it is necessary to test the sensitivity to different input data sets to have a holistic approach. This will be done in future studies.

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