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CALIBRATION OF PHYSICALLY BASED SLOPE-STABILITY MODELS: A CASE STUDY IN NOVA FRIBURGO (RIO DE JANEIRO, BRAZIL)

CALIBRAÇÃO DE MODELOS FÍSICOS DE ESTABILIDADE DE ENCOSTA: UM ESTUDO DE CASO EM NOVA FRIBURGO (RIO DE JANEIRO, BRASIL)

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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 11th and 12th January 2011 and impacted seven municipalities. These landslide events are considered the worst disasters in Brazilian history. This paper presents simulations with single and multiple calibration regions based on SINMAP (Stability INdex MAPping) in Nova Friburgo. The outputs obtained were further analysed to quantify the spatial discrepancy between the landslides triggered by the January 2011 event and the model results. The reliability of each simulation was also evaluated through ROC analysis and significant results are highlighted. Limitations in the availability of data, in particular, the lack of verified geotechnical parameters in some areas may have compromised the predictive performance of models.
Keywords: Shallow landslides, SINMAP modelling, Slope stability, Brazil.

RESUMO - Os movimentos de massa causam enormes danos econômicos e mortes em todo o mundo. O "Mega desastre" na região montanhosa do Rio de Janeiro ocorreu nos dias 11 e 12 de Janeiro de 2011 e atingiu sete municípios. Estes eventos de movimentos de massa são considerados o pior desastre da história brasileira. Este artigo apresenta simulações com regiões de calibração única e múltiplas com base em SINMAP (Stability INdex MAPping) em Nova Friburgo. Os resultados obtidos foram analisados para quantificar a discrepância espacial entre os deslizamentos provocados pelo evento de Janeiro de 2011 e as predições do modelo. A confiabilidade de cada simulação também foi avaliada através da análise ROC e os resultados significativos são destacados. As limitações na disponibilidade de dados, em particular, a falta de parâmetros geotécnicos verificados em algumas áreas podem ter comprometido o desempenho preditivo dos modelos.
Palavras chave: Movimentos de massa superficiais, Modelagem SINMAP, Estabilidade de encostas, Brasil.

INTRODUÇÃO

Landslides are a major natural hazard, causing significant damage to properties, lives and engineering projects in all mountainous areas in the world (Martha et al., 2010). Brazil has a complex scenario of threats, essentially as a consequence of its size, diversity, and heterogeneous natural and social environments. According to EM-DAT (The International Disaster Database) during the period from 1900 to 2016, Brazil recorded 224 disasters triggered by natural hazards, 58,9% of these being floods – representing the most common type of disaster in the country, followed by landslides (10,7%).

To prevent future impacts, it is essential to identify potentially affected areas. 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) and; 3) Process-based or deterministic modelling (slope stability factor) (Kuriakose, 2010).

Various terrain stability models have been created in such a way that they incorporate the effects of important processes that affects shallow landsliding. Before applying a spatially distributed physically-based model, parameter values are often calibrated to minimize the difference between observations and simulation results. One way of achieving this is to vary the model input parameter values in order to find optimum values or value ranges which yield a general agreement between observations and simulations (Zieher et al., 2017). The calibration procedure should be based on physical reasoning and only involve sensitive parameters (i.e. parameters with a distinct impact on the model's outcome) (Bathurst et al., 2005; Wagener & Kollat, 2007). Physically-based modelling SINMAP (Stability INdex MAPping) has been tested under different geological and hydrological conditions by several authors (Morrissey et al., 2001; Zaitchik & Van Es, 2003; Calcaterra et al., 2004; Silva, 2006; Tarolli & Tarboton, 2006; Meisina & Scarabelli, 2007; Nery & Vieira, 2012; Michel et al., 2014; Preti & Letterio, 2015; Terhorst & Jaeger, 2015; Abascal & González Bonorino, 2015; Rabonza et al., 2016, Cardozo et al., 2018) and it has proved to be highly reliable in predicting slope instabilities. The performance of SINMAP has also been compared against other models as SHALSTAB, TRIGRS, and SLIP, resulting in a similar global accuracy for all models (Zizioli et al., 2013).

Considering this findings, the aim of this study was to apply the physically-based modelling SINMAP adopting different calibration approaches in the Nova Friburgo municipality (Rio de Janeiro State, Brazil).

This paper is organized as follows: the next section presents a broad depiction of the 2011 Nova Friburgo disaster caused by landslides events. Then, features of Stability Index Mapping (SINMAP) method are described. The next section refers to the characteristics of the study area. Following that, details of the data sources and methodology are explained. Finally, results and conclusion are given at the end of the paper.

THE 2011 NOVA FRIBURGO DISASTER

The so called "megadisaster" in the mountainous region of Rio de Janeiro took place on 11th and 12th January 2011 (Figure 1) affecting 23 municipalities, seven from these ones were stated in public calamity situation (Vassoler, 2013): Areal, Bom Jardim, Nova Friburgo, São José do Vale do Rio Preto, Sumidouro, Petrópolis and Teresópolis.

Whole areas were covered by mud, hundreds of homes were swept away and hundreds of people were buried. Nova Friburgo, Teresópolis and Petrópolis municipalities recorded the greatest number of casualties. Government official numbers indicated 918 casualties, 22604 displaced and 8795 homeless (FREITAS et al., 2012); however, civil associations point out that the number of fatalities and missing people could be ten times greater. The divergence in numbers can be attributed, in part, to the fact that entire families disappeared and no one claimed for them (CARDOZO, 2018).

This catastrophe 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 implications

Figure 1 - Effects of 2011 landslide events in Nova Friburgo municipality (Cardozo et al, 2018).

on the quality of life of the survivors and on the economic activity of the entire region (World Bank, 2012). This hazardous event was triggered by extremely heavy precipitation.

During two rainstorm days, 241.8 mm were accumulated in a 24-h period (Dourado et al., 2012). Although it is considered the most destructive landslides ever registered in Brazil, some events had previously occurred in Rio de Janeiro in 1966, 1967, 1988, 1996 and 2010 (Barata, 1969; Costa Nunez, 1969; Jones, 1973) and particularly in the Nova Friburgo municipality in 1924, 1940, 1977, 1979, 2007 and 2011 (DRM-RJ, 2015).

Natural disasters do not affect people equally as if by an arbitrary stroke of nature. Instead, the disaster impact is contingent on the vulnerability of affected people, which can and often does systematically differ across economic class, ethnicity, gender and other factors (Neumayer & Plümper, 2007).

Cardozo et al. (2018) have carried out a broad assessment of human fatalities in the 2011 Nova Friburgo disaster. The authors pointed out that the total number of landslide-related deaths was 434 (205 women and 228 men). The cause of death for all the victims was mechanical asphyxia caused by burial.

The largest density of fatalities was concentrated in the Centre of the municipality, coincident with the urban area;while landslides were prone to occupy a larger area including both urban and rural zones (Figure 2).

The mean age of victims was 35 years old and the age range of affected people was 0 to 90 years old. Fatalities were linked to the existence of both intra-urban differentials in exposition and vulnerability, which also shaped differentials in response capacity of citizens. Nearby half of the people who lost their lives in this landslide-related disaster in Nova Friburgo were the youngest and oldest. Approximately 25% of the people who died were children and adolescents between 0 to 19 years old. On the other extreme, 19% of fatalities were persons 60 years old or older. These results are in concordance with Cutter et al. (2003), who pointed out that individuals at the extremes of demographic groups are the most affected by disasters.

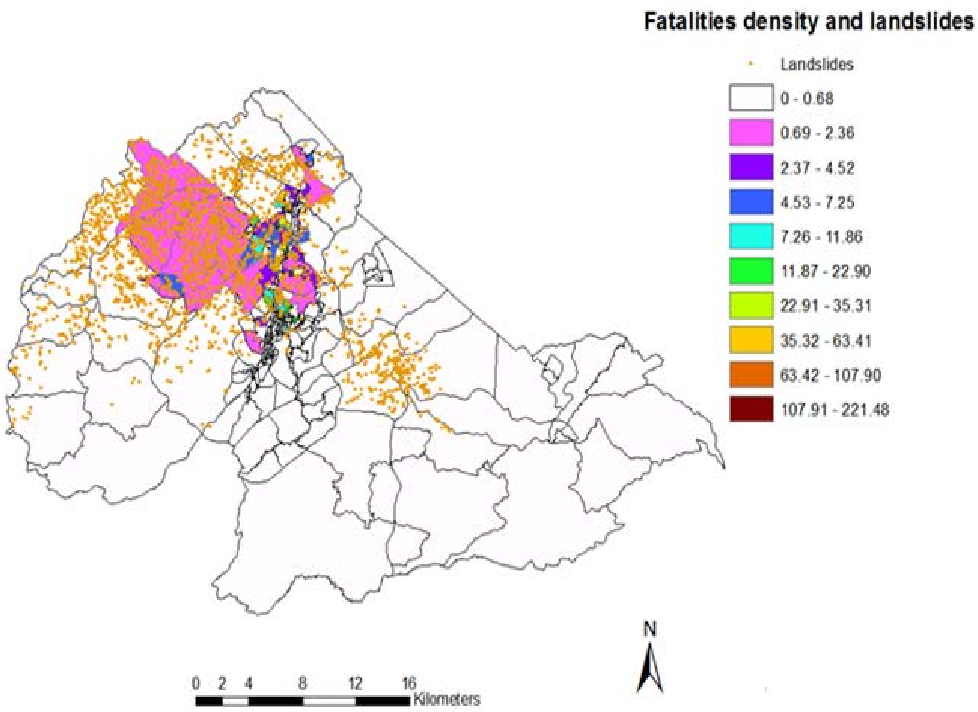

Figure 2 - Spatial distribution of the fatalities density (fatalities per km^2) and landslides location in the 2011 Nova Friburgo disaster (Cardozo et al., 2018).

THE STABILITY INDEX MAPPING MODEL

SINMAP (Stability Index Mapping) methodology published by Tarboton (1997) and Pack et al. (1999) 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 surface of the ground neglecting edge effects. SINMAP derives its terrain stability classification as a Factor of Safety (FS) 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; Meisina & Scarabelli, 2007) (Eq.1).

Each of these parameters is delineated on a numerical grid over the study area.

The Stability Index (SI) is the Factor of Safety that gives a measure of the magnitude of destabilizing factors (e.g. increased wetness due to road drainage, local loading, or local enhancement of pore pressures due to soil pipe effects) required for instability.

Figure 3 illustrates the geometry assumed in Equation 1.

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

where **FS** is Factor of Safety; $\mathbf{C_r}$ 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; $\boldsymbol{\phi}$ the internal friction angle of the soil [°]. The slope angle $\boldsymbol{\theta}$ is the arc tangent of the slope, **S**, expressed as a decimal drop per unit horizontal distance.

The stability classes adopted by SINMAP are shown in table 1.

The SINMAP's concept is based on field information for calibration; by consequence, the model's output depends heavily on accurate positioning of known landslides (Meisina & Scarabelli, 2007) and from other input parameters.

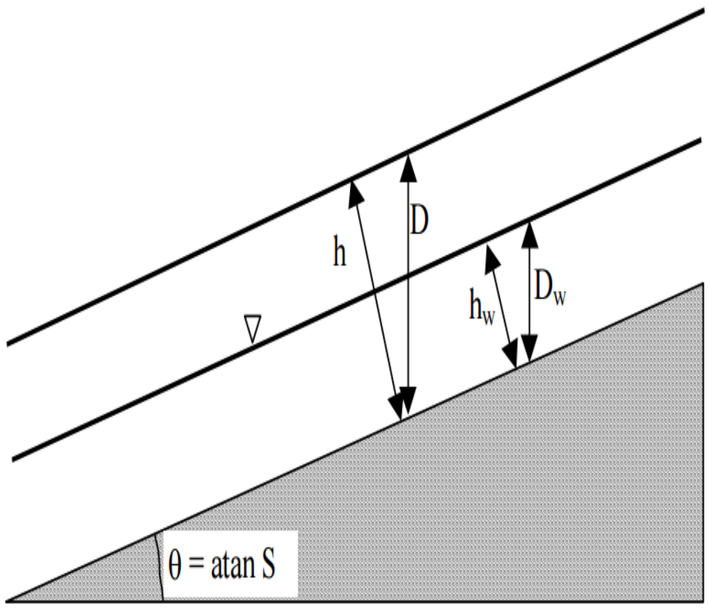

Figure 3 - Infinite slope stability model schematic. Soil thickness, **h** [m] and vertical soil depth, **D** [m] are related as follows, **h** = **D cos** $\boldsymbol{\theta}$ (Pack et al., 2005).

Table 1 - Stability classes in the SINMAP model (Michel et al., 2014).

Stability Index	**Stability classes**	**Parameter range**	**Possible influence of factors not modelled**
SI > 1.5	Unconditionally stable	Range cannot model instability	Significant destabilizing factors are required for instability
1.5 > SI > 1.25	Moderately stable	Range cannot model instability	Moderate destabilizing factors are required for instability
1.25 > SI > 1.0	Quasi-stable	Range cannot model instability	Minor destabilizing factors could led to instability
1.0 > SI > 0.5	Lower threshold of stability	Pessimistic half of range required for instability	Destabilizing factors are not required for instability
0.5 > SI > 0	Upper threshold of stability	Optimistic half of range required for instability	Stabilizing factors may be responsible for stability
SI < 0	Unconditional instability	Range cannot model instability	Stabilizing factors are required for stability

STUDY AREA

The municipality of Nova Friburgo is located in the mountainous region of the Rio de Janeiro State, Brazil (Figure 4) and covers a surface area of 933.415 km^2.

It is situated in “Serra dos Órgãos”, a local name that designates a higher portion of the mountains called “Serra do Mar”. The elevation ranges between 636 and 1587 m above mean sea level.

In 2010, the study area had a population of 182,082 inhabitants (195.07 inhabitants per kilometer square) (IBGE, 2010). According to Coelho Netto et al. (2011) about 90% lived mainly in the urban zones.

The zone has a predominately high-altitude tropical climate with an average temperature of 16°C. This area was originally the Tropical Atlantic Rainforest, but currently is fragmented and much degraded, especially around the urban areas.

Nova Friburgo is the rainiest area of the State with an average annual precipitation of around 2500 mm in the highest areas, decreasing progressively to the north up to 1300 mm (Coelho Netto et al., 2011). In this mountainous region of Rio de Janeiro, the valley bottoms are narrow and develop along persistent tectonic fractures in which only the larger rivers are able to generate fluvial deposits where the majority of the population is located.

Adjacent to these valleys, escarpments with rocky outcroppings and steeps slopes (more than 35 degrees) are common.

These can present deposits of talus or colluvium rich in rock blocks at the base. On the other hand, in the “Serra dos Órgãos” landscape, there are also many areas where intramontane hills grade to slopes of slighter declivity (between 15 and 35 degrees). In these areas the regolith are composed by thick saprolitic and colluvial deposits that together can reach up to 10 m in deep weathering profiles (saprolites) up to 50 m in thickness.

The predominant rock in much of mountainous region of Rio de Janeiro State is equigranular granite with grains between 3 and 5 nm, basically composed of quartz, K-feldspar and biotite (Avelar et al., 2011).

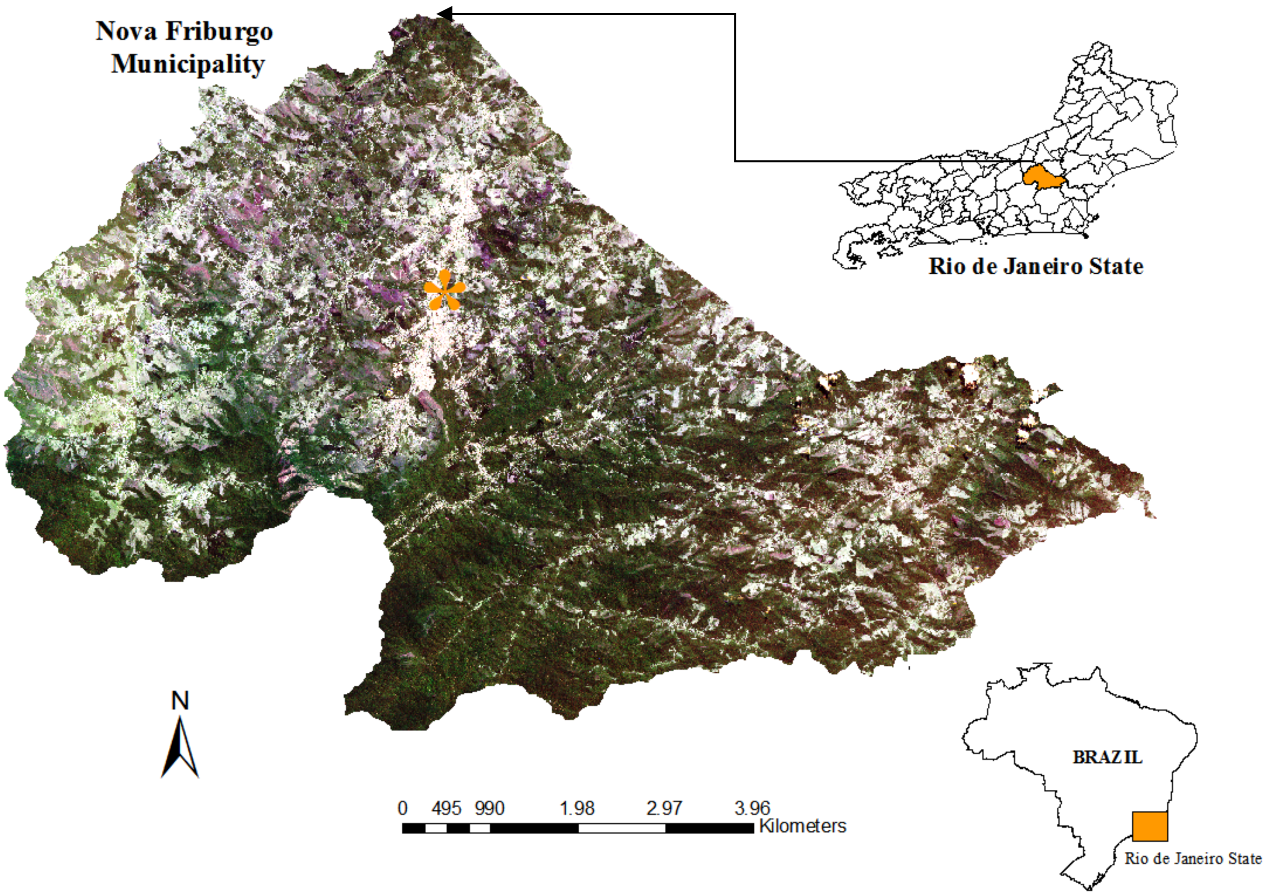

Figure 4 - Location map of the study area, Nova Friburgo-Rio de Janeiro State, Brazil.

DATA SOURCES AND METHODOLOGY

Figure 5 shows the generalized methodology adopted in this study. The testing was carried out in SINMAP 2.0 which uses ArcGIS software environment, version 9.0 or higher. To identify the most and least susceptibility zones, Stability Index (SI) was mapped based on six classes: stable, moderately stable, quasi-stable, lower threshold of stability, upper threshold of stability and defended. According to Pack et al. (2005) "lower threshold" and "upper threshold" characterize regions where, according to the parameter uncertainty ranges quantified by the model, the probability of instability is less than or greater than 50% respectively.

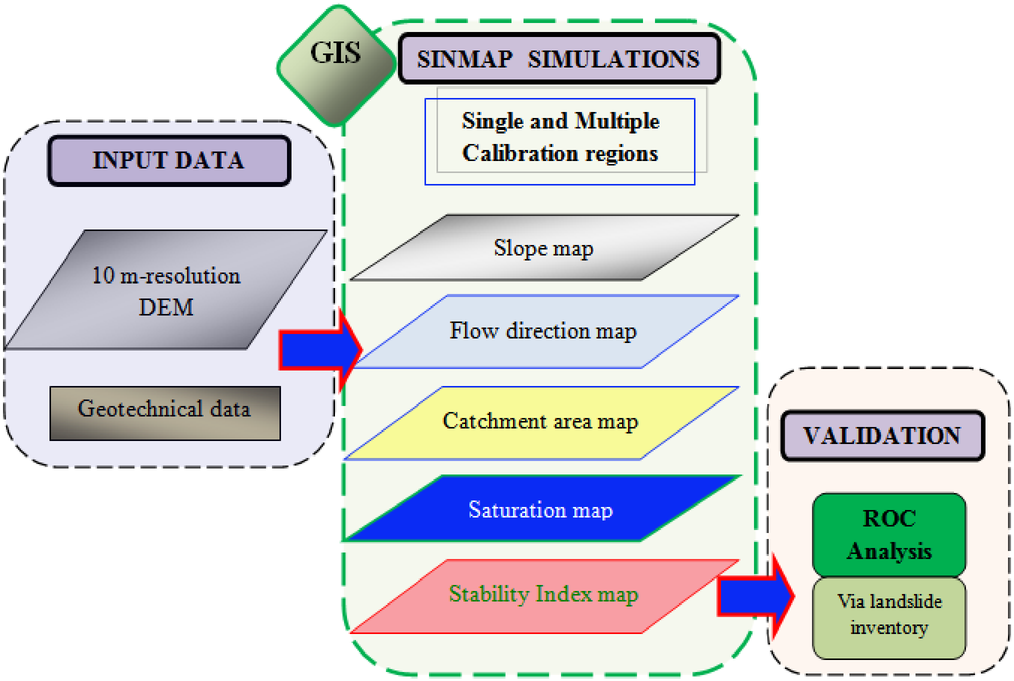

Figure 5 - Generalized methodology flowchart adopting different calibration approaches based on SINMAP (Stability INdex MAPping) model.

The calibration procedure has been carried out for the municipality as a whole (single calibration region - *SCR*) and for different sub-areas (multiple calibration regions - *MCR*), in which selected properties were assumed to be uniform enough for further analysis. Several calibration procedures (N=20) consisting in an iterative adjustment of the parameters were performed and evaluated in order to minimize the differences between observations and simulations results. This article presents the two best models (with single and multiple calibration approach) that showed the better predictive performance.

Topographic data and landslide inventory

The study used a 10 m-resolution digital elevation model (DEM) provided by the Brazilian Institute of Geography and Statistics (IBGE) from which the necessary input information was obtained (slope, flow direction, specific catchment area and saturation). Pits in DEM were eliminated using a "flooding" approach by raising the elevation of each pit grid cell within the DEM to the elevation of the lowest pour point on the perimeter of the pit (Pack et al., 2005).

A previous landslide inventory of 2011 had been completed for the study area using a Geoeye-1 satellite image of 2011 and a semi-automatic approach.

A total of 2272 fresh scars were recognized. According to the classification of Cruden & Varnes (1996), the landslides were classified as shallow "debris flow", "slides" and "debris slides". Landslides were observed in a slope range from 15 degrees to 72 degrees.

The highest landslide frequency was identified in slope angles between 15 degrees and 30 degrees (Figure 6). Since the SINMAP methodology applies to failure locations within a zone of initiation, in the present study the initiation point location of each landslide was identified. Consequently, this last inventory map was used to quantify the spatial discrepancy between the landslides and the model results. The reliability of each calibration was assessed with the receiver operating characteristic (ROC) analysis.

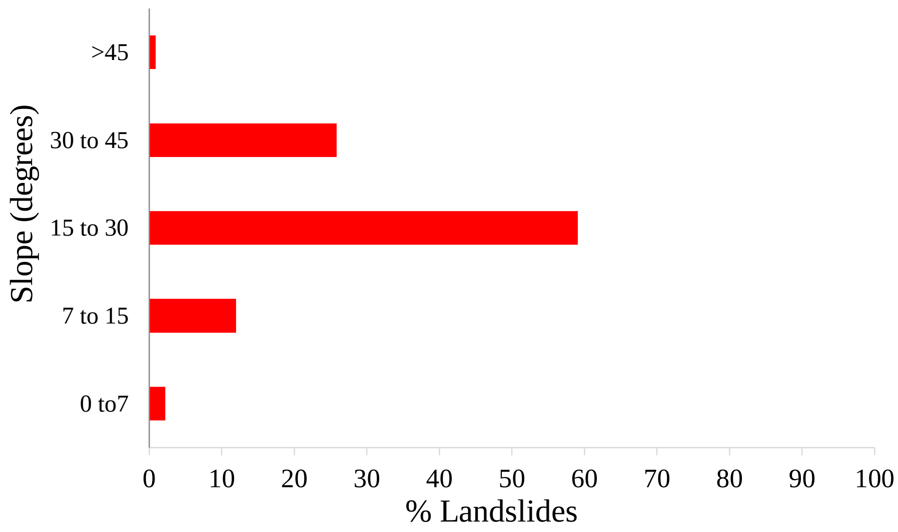

Figure 6 - Landslide frequency in each range of slopes angles in Nova Friburgo.

a zone of initiation, in the present study the initiation point location of each landslide was identified. Consequently, this last inventory map was used to quantify the spatial discrepancy between the landslides and the model results. The reliability of each calibration was assessed with the receiver operating characteristic (ROC) analysis.

When classifying a grid from the instability map, four outcomes are possible: *1)* If a computed unstable cell is inside the observed landslide area, it is counted as true positive (tp); *2)* if it is outside the observed landslide area, it is counted as false positive (fp); *3).*

If a computed stable cell corresponds to an observed landslide cell, it is counted as false negative (fn) otherwise, *4)* it is classified as true negative (tn). From these concepts, two quantities were calculated: *sensitivity* (true positive rate), defined as the ratio between (tp) and the sum of (tp) and (fn) and, *specificity* (false positive rate), defined as the ratio between (tn) and the sum of (tn) and (tf). A high sensitivity indicates a high number of correct predictions, whereas a high specificity indicates a low number of false positives (Zizioli et al., 2013).

The area under the ROC curve can serve as a global accuracy of the model. This statistic ranges from 0.5 (random prediction, represented by a diagonal straight line) to 1 (perfect prediction) and can be used for model comparisons (Cervi et al., 2010)

Geotechnical data

Since soil samples collection *in situ* and laboratory tests were outside the scope of this paper, soil and vegetation parameters were obtained from the literature values of different authors who worked in the mountain ranges "Serra do Mar".

As mentioned above, for the analysis a single and multiple calibration regions approaches were used. For the multiple calibration regions case, the study area was divided into three regions according to the lithological units of the simplified map proposed by DRM-RJ (2011) (Figure 7). In all simulations tested, a gravitational acceleration value equal to 9,81 m/s^2 and a wet soil density equal to 2000 (kg/m^3) were used. In addition, taking into consideration the values suggested by Marques et al. (2017), an average value of 1.25 m was assumed for soil thickness throughout the study area.

Uniform probability distributions with upper and lower bounds of parameters account for parameter uncertainty (Pack et al., 1999). The equation used to determine the dimensionless cohesion combines root and soil cohesion (Equation 2).

Theoretically, this is the ratio of the cohesive strength of the roots and soil relative to the weight of a saturated thickness of soil (Pack et al., 2005).

$$C = \frac{(Cr + Cs)}{\mathrm{h}\rho_s \mathrm{g}} \qquad \text{Eq. 2}$$

where $\boldsymbol{C}$ is cohesion; $\boldsymbol{C_r}$ is root cohesion [N/m^2]; $\boldsymbol{C_s}$ is soil cohesion [N/m^2]; $\boldsymbol{h}$ is soil thickness [m]; $\boldsymbol{\rho_s}$ is wet soil density [kg/m^3]; $\mathbf{g}$ is gravitational acceleration [m/s^2].

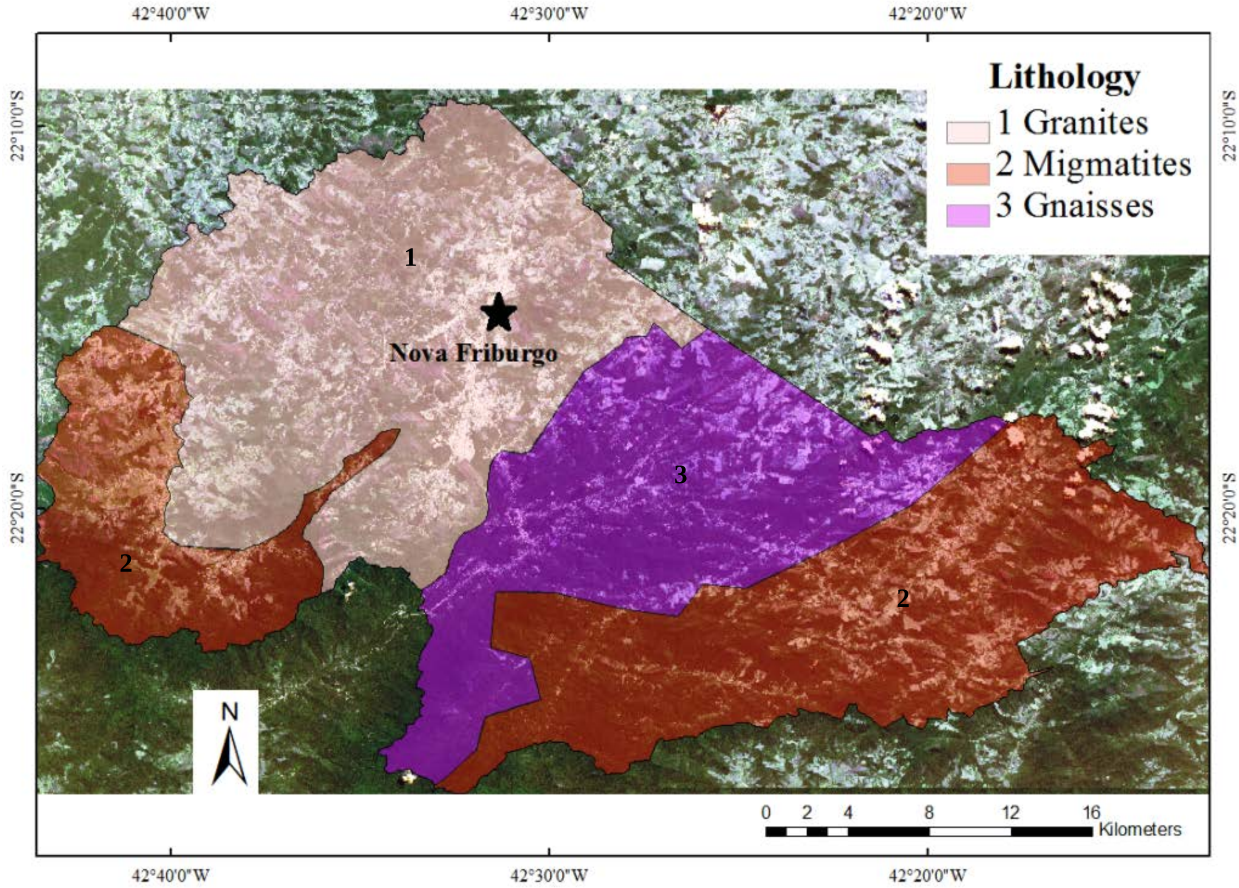

Figure 7. Simplified geological map of the study area (DRM-RJ, 2011).

Table 2 shows the values assumed for SINMAP simulations with a single and multiple calibration regions approaches. For the single calibration region case, average soil cohesion values were taken from the values cited by Wolle & Carvalho (1984), Amaral (2007) and Nery & Vieira (2012); while for multiple calibration regions, the values mentioned by Avelar et al. (2011) and Amaral (2007) were considered. Generally, root systems contribute to soil strength by providing an additional cohesion component. The vegetation in the area is mainly represented by forest with root systems that vary widely in time and space. Coelho Netto et al. (2011) indicated that exist forest patches represented by a secondary ecological succession of plants with shallow roots and variable degradation states. Due to the difficulty to find a specific root cohesion parameter for the study area, a value equal to 3 KPa was assumed (Wolle & Pedrosa, 1981).

Table 2 - Input data set used in the single and multiple calibration regions approaches.

Calibration	Region	***ϕ*** (°)		***C*** (N/m^2)		***T*** (m^2 h^{-1})		***R*** (m h^{-1})	***T/R*** (m)	
		min	**max**	**min**	**max**	**min**	**max**		**min**	**max**
Single -*SCR*-	-	30	45	0.001	0.004	-	-	-	68	213
Multiple -*MCR*-	1	38	42	0.000	0,020	0.027	0.142	6.56	0,004	0.022
	2	39	42	0.120	0.280	0.055	0.439	4.02	0.013	0.109
	3	32	42.5	0.220	0.330	0.044	0.095	5.57	0.007	0.017

Internal angle of friction is a measure of the shear strength of soil due to friction determined in the laboratory using direct shear strength or triaxial stress test (Rabonza et al., 2016). For the single calibration region approach, average internal angle friction values were taken from the values cited by Wolle & Carvalho (1984), Guimarães (2000), Lopes (2006), Mendes (2008) and Avelar et al. (2011). In the multiple calibration regions case, the values used from each zone were taken from Amaral (2007) and Avelar et al. (2011).

The T/R ratio combines both climate and

hydrogeological factors (Meisina & Scarabelli, 2007). It quantifies the relative wetness in terms of assumed steady state recharge relative to the soil's capacity for lateral drainage of water (Pack et al., 2005). For the single calibration region approach, the T/R parameter was assumed according to Nery & Vieira (2012).

The transmissivity T represents the water flow within the soil and it is derived from the hydraulic conductivity (minimal and maximal) measured in the field (Meisina & Scarabelli, 2007). For the three calibration regions, transmissivity was calculated considering the hydraulic conductivity values mentioned by Fraga et al. (2014) and Souza (2014).

The parameter R (steady state recharge rate) is difficult to measure; it is hard to evaluate the amount of infiltrated subsurface water from the total rainfall measurement. In fact, R is influenced by factors like rainfall intensity and duration (Meisina & Scarabelli, 2007). The recharge was assumed to be the effective precipitation. It means rainfall minus evapotranspiration and bedrock infiltration (Meisina & Scarabelli, 2007; Zizioli et al., 2013). Data suggest that rainfall was spatially non-uniform during January 11th and 12th in Nova Friburgo, for this reason different values of rainfall were assumed for each region according to Coelho Netto et al. (2011). The evapotranspiration data suggested by Cardoso et al. (2006) and the land use map allowed determining the water holding capacity necessary for the evapotranspiration calculation. The amount of infiltration depends on slope angle, so it was assumed that only ¼ of the water infiltrates in the substratum (Meisina & Scarabelli, 2007; Zizioli et al., 2013).

RESULTS AND DISCUSSION

The increased availability of thematic information in digital format, the improved ability to manage landslide and geomorphological information in geographical information systems have facilitated the preparation of predictive landslide models to prevent future impacts.

Different landslide susceptibility maps were created from the SINMAP simulations with a single and with multiple calibration regions. The outputs obtained were further analysed to quantify the spatial discrepancy between the landslides triggered by the rainfall of January 2011 and the model results. The reliability of each simulation was also evaluated through ROC analysis. According to Chung & Fabbri (2003), it is important to carry out the validation of prediction models. Without some kind of validation, the model's predictive capabilities would be unknown and it would be of little scientific value.

Single calibration region approach

Adopting this approach, 68% of the observed landslides were correctly identified (20% in the lower threshold class, 36% in the upper threshold class and 12% in defended class). Approximately, 63% of the considered area was estimated as unstable (35.40% lower threshold, 13.60% upper threshold and 14.6% defended). On the other hand, 37% was classified as stable terrain (19.2% stable, 7.6% moderately stable and 10.2% quasi-stable).

The largest landslide density was determined in the upper threshold (Figure 8-A) which represents 13.6% of the territory. The global accuracy represented by the area under the curve (AUC) - was equal to 0.65 (Figure 9). The predicted areas prone to landsliding were characterized by slope angles between 17 degrees and 59 degrees and catchment areas below 105 m2.

Multiple calibration regions approach

This simulation was quite successful in describing slope failure in the municipality of Nova Friburgo, identifying 90% of 2272 inventoried landslides (24% in the lower threshold class, 56% in the upper threshold class and 10% in defended class). About 75% of the considered area was estimated as unstable, that is, 61.64% was classified with a Stability Index (SI) below 1 (lower and upper threshold classes), which refer to conditions that are highly unstable and thus critical and, 13.36% of the area was classified as defended. A certain number of landslide locations (25%) fell within the stable, moderately stable and quasi-stable classes (with SI>1). The largest landslide density was found in the upper threshold class (Figure 8-B) which represents 20.5% of entire area. A higher performance was recorded for such scenario (AUC = 0.80) (Figure 9).

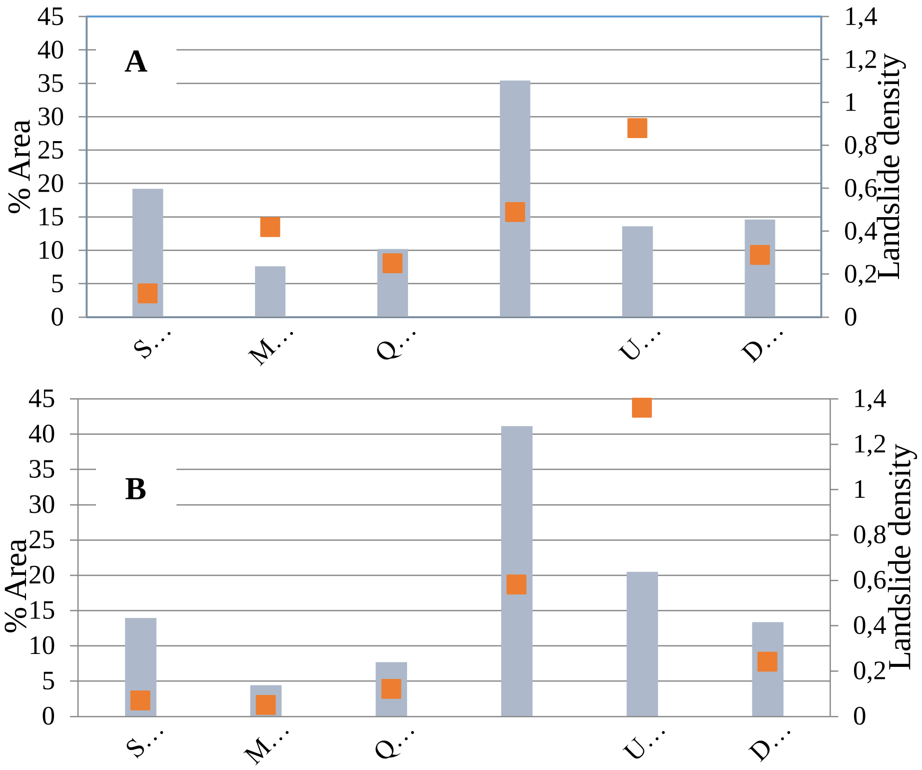

Figure 8 - Prediction accuracy of SINMAP models. A) Model with single calibration region;B) Model with multiple calibration regions (Red squares = landslide density; Light blue bars = area of the stability classes). (S = Stable, M = Moderately Stable, Q = Quasi-stable, L = Lower Threshold, U = Upper Threshold, D = Defended.

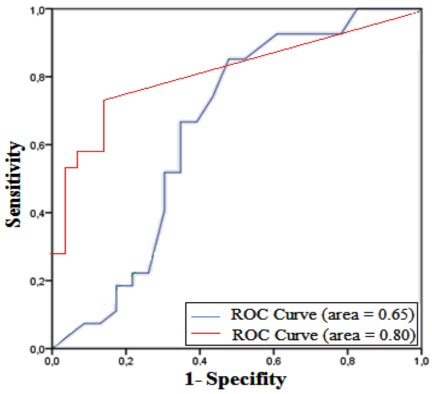

Figure 9 - ROC curves derived of SINMAP simulations with a single calibration region (blue) and multiple calibration regions (red).

The areas predicted to fail during the event of January 2011 included areas with slope angle between 15 degrees and 58 degrees (factor of safety below 1) and catchment areas below 10^5 m^2. These results are in agreement with Coelho Netto et al. (2011), who pointed out that landslides occurred in slope segments with an average slope of 19 degrees and maximum slope of 65 degrees. In the D'Antas creek basin -the area of Nova Friburgo most affected by the 2011 landslides- the average slope angle was 32 degrees (Coelho Netto et al., 2017). Likewise, other zones such as Riogandina and Conselheiro Paulino registered landslides on slopes steeper than 30 degrees (DRM-RJ, 2015).

The individual calibration regions contributed to the final result in different ways. The region 1 contributed the most. More than 70% of landslides were correctly predicted within this zone.

Regions 1 and 2 showed that a low proportion of the landslide-affected areas were located in areas for which high susceptibility was modeled. These findings probably are due to the limitations in the availability of input data, in particular, the lack of verified geotechnical parameters in regions 2 and 3.

Calibration procedure

Both SINMAP simulations showed that a certain number of landslide locations fell within the stable, moderately stable and quasi-stable classes (SI>1). According to Pack et al. (2005) the reasons for this may be twofold: 1) the bedrock, superficial geology and landslide processes are more complex and, 2) the DEM data fails to pick up many of the small but critical slopes. In addition, it also could be attributed uncertainties in the accuracy of landslide initiation locations previously delimited. In general, the landslides that were not well predicted showed mean slope equal to 26 degrees and did not evidence a spatial pattern.

On the other hand, stability index maps (Figure 10) obtained from both approaches also showed that many areas classified as unstable were not verified during the rainfall-induced landslides of January 2011.

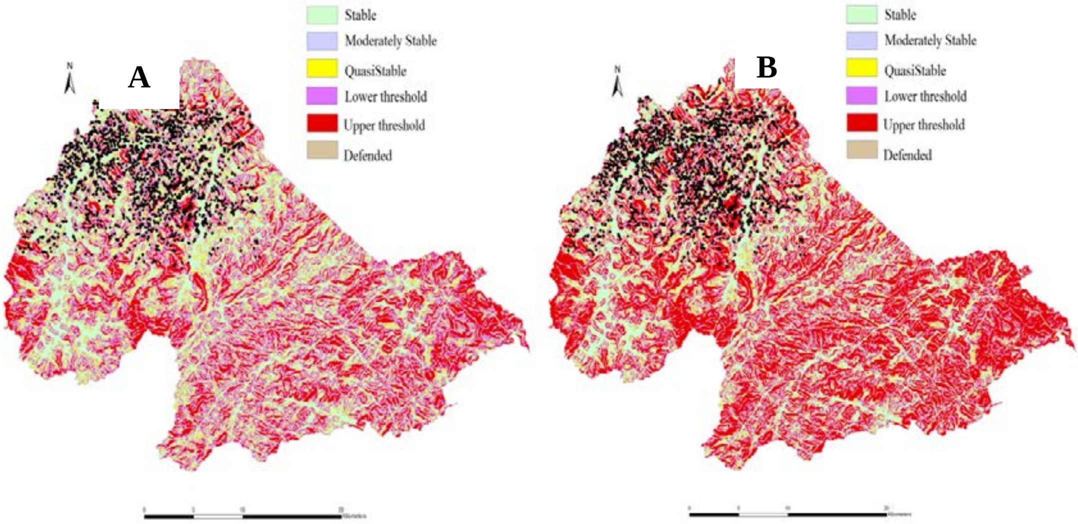

Figure 10 - Stability Index maps showing the classes of stability obtained by SINMAP calculations in: A) Single calibration region approach; B) Multiple calibration regions approach. (Black dots = location of inventoried landslides).

According to Bischetti & Chiaradia (2010), any attempt to increase the capability of the model to simulate as unstable the locations where landslides have occurred, then, inevitably leads to simulate all those cells with similar conditions as unstable. In the single calibration region case, this overestimation may be attributed to the range of parameter values used for the entire area; it had to be large enough to cover all different conditions. In order to overcome that condition, three calibration regions were assumed by dividing the territory in sub-regions and specific range of parameter values for each ones were assigned, limiting the effect of low values of parameters only to those areas where it was appropriate.

The findings revealed an improvement in the ROC curve of the multiple calibration regions approach, that is, a better ability of the model to correctly predict most landslides and non-landslides for a landslide-triggering rainfall event in January 2011. However, it seems that the geotechnical data used could not capture the spatial variability of the soil properties existing mainly in the Southeast and Southwest of the study area. More detailed geological and geotechnical assessments are necessary in the future in order to improve the predictive performance of the models.

Inevitably, there are uncertainties in the application of SINMAP simulations. In this study, uncertainties arose from the methodology applied and the input data used. According to Thiebes et al. (2016) topographic data represent the most important input for the SINMAP models. Results suggest that a 10 m-resolution DEM was useful to test the calibration procedure of the physically based slope-stability models in the study area.

Arguably, one of the most important limitations was given by the selection of geotechnical parameters which involved uncertainties. The T/R factor could not easily be determined and probably it has introduced some uncertainty. However, Thiebes et al. (2016) argued that the modification of this hydrological factor in the calibration procedures only produces small changes of the susceptibility classification. Results seem to show that the increase in the range of values of the friction angles resulted in a decrease in the fraction of the most unstable classes. This finding is in accordance with Zaitchik et al. (2003) who concluded that hydraulic conductivity and friction angle were the most sensitive parameters during the calibration.

Taking into account the considerations above mentioned, the multiple calibration regions approach proved to have an acceptable performance. Therefore, it could be considered as a preliminary susceptibility model for the Nova Friburgo municipality. Similarly, it could be used in future hazard and risk assessments, although it can still be and should be improved.

Further tests including field measurements should also be carried out.

CONCLUSIONS

In the present study, several SINMAP models were calibrated based on literature values and a detailed shallow landslide inventory. This article presents the two best models (with single and multiple calibration approach) that showed the better predictive performance. The scenario with three calibration regions was quite successful in describing slope failure in the municipality of Nova Friburgo, identifying 90% of inventoried landslides in areas classified as unstable. The inability of the model to correctly predict the remaining landslides may be in part related to the methodology and the input data used. Limitations in the availability of data, in particular, the lack of verified geotechnical parameters in some areas may have introduced uncertainties.

Results suggest that the internal angle friction probably had an important impact on the simulation outputs. However, further tests including field measurements should be carried out.

Model calibration is a difficult task, since it can be a very time-consuming process, therefore, future studies will seek the automatic optimization procedure in the study area.

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