Susceptibility and Vulnerability to Landslides - Case Study: Basin of River Bengalas - City of Nova Friburgo - Brazil

Silva, L. T. [1]
Sampaio, E. P. F. F. M. [2]
Corte-Real, J. A. M. [3]
Rodriguez, D. A. [4]
Carnaúba Medeiros, F. C. [5]
Moraes, B. E. [6]
França, D. G. M. [7]

1, 4, 6 and 7 - National Institute for Space Research
Rodovia Pres. Dutra, Km. 40 - 12630-970 - Cachoeira Paulista - São Paulo, Brazil
luiz.tadeu@cptec.inpe.br
+ 55 12 3186-9527 and + 55 12 98828-2678

2, 3 and 5 - ICAAM and University of Évora
Largo dos Colegiais 2 - 7004-516 - Évora, Portugal
ems@uevora.pt; jmcr@uevora.pt; and carnauba.fabiana@gmail.com
+ 351 266-740-800

Abstract

Landslides have frequently occurred in last years, due to the disorderly growth of the cities and the occupation of risk areas by the poor population, causing social, environmental and economic impacts. Urban areas in expansion move to geologically unstable areas and topographically inclined, such as the River Bengalas Basin, located in the city of Nova Friburgo, mountainous region of the State of Rio de Janeiro, Brazil. This article aims to present the model developed and used to evaluate the susceptibility and vulnerability of the River Bengalas Basin to landslides, which in January 2011, with the occurrence of heavy rains, caused landslides that impacted in the death of 429 people in city of Nova Friburgo. For the case study, several investigations have been made related to the areas of the basin, such as slope, soil conditions, lithology, land use and cover, vertical curvature, horizontal curvature, and precipitation data. With this study it was possible to understand how the natural and anthropics elements of the basin are related to the local dynamics of the disasters regarding to their interferences in the induction of landslides; evaluate the effectiveness of the guidelines of the Plano Diretor Participativo do Município de Nova Friburgo regarding the landslides; identify the susceptible and vulnerable basin areas to landslides and calculate the rates of susceptibility and vulnerability to landslides from new calculation model proposed..

Keywords: Index; Susceptibility, Vulnerability, Landslides

1 – Introduction

Humankind has been challenged by the occurrence of extreme natural events, responsible for large amounts of material damage and for innumerous fatalities. Since 1970, with the increasing frequency and intensity of disasters, the scientific community and international institutions like the United Nations (UN), were mobilized to worry about this issue. In Brazil, this concern is due to the increase in the number of fatalities in the 1960s, 1970s and 1980s, associated with rapid urban growth and the disordered occupation of unsuitable areas for urbanization in the country. Year after year natural disasters result in a large number of dead and wounded, besides the costly economic losses. According to UNDP report (2004), 75% of the world population lives in areas that were affected at least once by cyclones, floods, droughts and earthquakes between the years 1980 and 2000, causing numerous deaths, impacts on agriculture, on water resources, in health, in economy etc. (Braga et al. 2006).

2 – Objective

Create indexes of susceptibility and vulnerability to landslides, from the survey of environmental data and the precipitation occurred on January 12, 2011 in the River Bengalas Basin, city of Nova Friburgo, State of Rio de Janeiro, Brazil. These indexes and the methodology here created taking into account the conditions of environmental variables and the precipitation of the area of study, can be used universally for research centers and other active institutions in the prevention, monitoring and forecasting of landslides.

3 - Methodology

For each variable (declivity, pedology, lithology, use and cover of land, vertical and horizontal curvature) were adopted weights according to their classes, ranging from 0.00 to 1.00, while those closer to 0.00 indicate classes of low relationship with the susceptibility to landslides, while those closer to 1.00 indicate classes of high relationship. The interaction of information plans of these variables is based on studies of Tricart (1977), with the principles of ecodynamics that establishes a gradation between the morphogenesis, prevailing the modifiers erosive processes of the soil's forms, and the pedogenesis, where the forming processes of soils prevail. Several studies have been conducted, such as: Survey of all the points of landslides which triggered the disasters in the River Bengalas Basin, in January 2011; Analysis to understand how the natural and man-made elements of the study area are related to the local dynamics disasters, regarding to their interference in the induction of landslides; Compilation of georeferenced data of the study area to treat them through Geographic Information System (GIS) so that the spatial information represents the best way possible its susceptibility / vulnerability to landslides; Calculation and analysis of the group of indicators of physical environmental susceptibility of the study area, based on the characteristics of the physical environmental of declivity, pedology, lithology, use and land cover. It is emphasized that on this new model the geomorphometrics variables "vertical curvature" and "horizontal curvature" were included in the calculations and analysis, besides the calculation of the areas' susceptibility of the basin were done according to the proportionality of 183 landslides; Survey and evaluation of precipitation data; Development of equation to the new methodology of calculating the vulnerability to landslides from data of the indicators of susceptibility and of the precipitations occurred in the Basin.

The method adopted in this work is based on the study of the Empirical Analysis of the Fragility of Natural and Anthropogenic Environments proposed by Tricart (1977), with adaptations of the Authors, which systematizing a nominal hierarchy of weakness represented by nominal values or weights, named in this work as "Classes of Susceptibility / Vulnerability and their Indexes", adapted by the Author. They are: very low (0.00-0.19), low (0.20 0.39), medium (0.40 to 0.59), high (0.60 to 0.69) and very high (≥ 0.70).

Those classes with "very low" or "low" susceptibility / vulnerability are the areas that present lower risks to landslides, while "medium", "high" and "very high" are the areas that have, respectively, medium, high and very high susceptibility / vulnerability to landslides. The criteria of observation and analysis adopted for this work in relation to the variables of the Basin were adapted from Tagliani (2002), and the declivity variable had as analysis criteria the angle of the terrain; the pedology the thickness and density of the soil; the lithology the typology of rocks, the use and cover of the land the types of soil protection, and the vertical and horizontal curvatures of the forms of terrain.

4 - Results

The weights assigned to the classes of the variables, as shown in Table 4.1, were introduced into the Equation 1 below, created specifically in this work to calculate the indexes of susceptibility (S) of the River Bengalas Basin to landslides.

$$S = \left(\frac{\sqrt{Vdc} + \sqrt{Vpd} + \sqrt{Vli} + \sqrt{Vus} + \sqrt{Vcv} + \sqrt{Vch}}{NVA} \right) \qquad (1)$$

Where S is the susceptibility; $\sqrt{Vdc}$ is the square root of the declivity variable; $\sqrt{Vpd}$ square root of the pedology variable; $\sqrt{Vli}$ square root of the lithology variable; $\sqrt{Vus}$ square root of the use and cover of the soil; $\sqrt{Vcv}$ square root of the vertical curvature; $\sqrt{Vch}$ square root of the horizontal curvature; and NVA is the number of variables (6). So, from the calculation of the susceptibility of the River Bengalas Basin, its own map was generated.

Weights ranging from "0.00" to "1.00", calculated proportionally to the number of landslides occurred in the Basin, were assigned to classes of the studied variables to calculate the susceptibility of it and are shown in Table 4.1

Variables	Indexes Used	Variables	Indexes Used
Declivity		**Pedology**	
< 5%	0.02	Argisols	0.00
5 a 12%	0.03	Neosols	0.00
12 a 30%	0.38	Rocky Outcrops	0.00
30 a 47%	0.41	Cambisols	0.13
> 47%	0.16	Urban Area	0.20
Lithology		Latosols	0.68
Igneous Rock		**Use and cover of the soil**	
Gabbro	0.00	Lakes	0.00
Gneiss	0.00	Rocky Outcrops	0.00
Granite. diorite and granodiorites; and Metadiorite, metatonalite, metagabbro and gneiss granulítico.	0.65	Agriculture	0.01
		Degraded Areas	0.01
Quartzite	0.00	Eucalyptus and Pines	0.01
Granitic composition of Orthogneiss.	0.14	Forest (Atlantic Forest)	0.04
Metamorphic Rock		Pastures and Forages	0.19
Amphibole Gneiss	0.00	Forest Home and Media	0.26
Biotitic Gneiss	0.04		
Sedimentary Rock		Urban Area	0.48
Colluvial; and Alluvial and Colluvial Sediments.	0.17		
Vertical Curvature		**Horizontal Curvature**	
Very Convex	0.03	Very Divergent	0.10
Convex	0.08	Divergent	0.10
Flat	0.27	Flat	0.19
Concave	0.39	Convergent	0.33
Very Concave	0.23	Very Convergent	0.28

Table 4.1 Classes of susceptibility/vulnerability to landslides and its weights
Source: Tricart (1977) and Ross (1994), adapted by the Author.

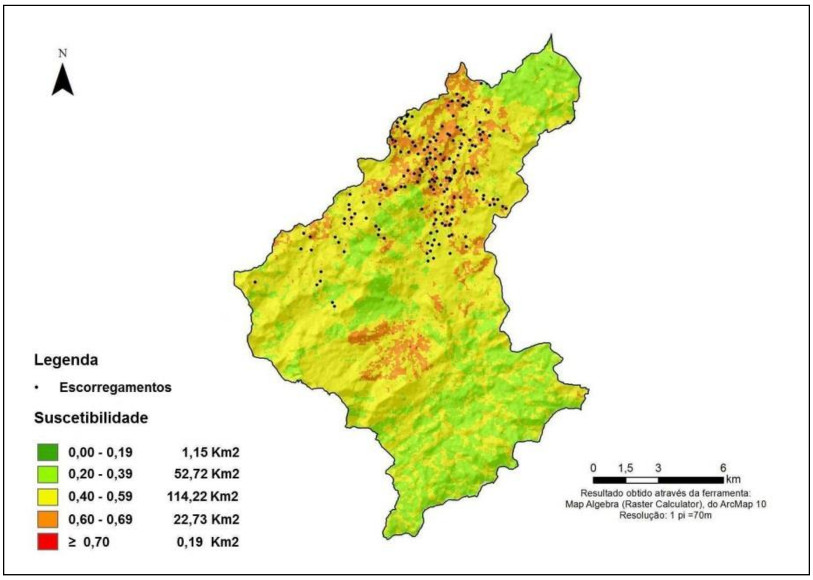

Figure 4.1 Map of Susceptibility of the River Bengalas Basin to Landslides

The generated map (Figure 4.1) shows that from the areas of the Basin, 114.22 Km² are classified as medium susceptibility, 52.72 Km² of low susceptibility and 22.73 Km² of high susceptibility to landslides. Imperceptible on the map, 1.15 Km² of the Basin are areas of very low susceptibility and 0.19 Km² of very high susceptibility to these types of disasters.

The methodology created to calculate the vulnerability to landslides of the Basin was developed from the calculation of the susceptibility (S), in other words, we calculate the susceptibility and then, with the inclusion of calculation involving several indicators related to the "precipitation of rains", according to the Equation 2 below, the vulnerability was calculated.

$$V = \frac{\left(\frac{\sqrt{Vdc} + \sqrt{Vpd} + \sqrt{Vli} + \sqrt{Vus} + \sqrt{Vcv} + \sqrt{Vch}}{NVA}\right) + \sqrt{\left[\frac{\left(\frac{PD}{CPC}\right) + \left(\frac{PA5}{MAXPA5}\right)}{2}\right]}}{2} \qquad (2)$$

Where V is vulnerability; $\sqrt{Vdc}$ is the square root of the declivity variable; $\sqrt{Vpd}$ square root of the pedology variable; $\sqrt{Vli}$ square root of the lithology variable; $\sqrt{Vus}$ square root of the use and cover of the soil; $\sqrt{Vcv}$ square root of the vertical curvature; $\sqrt{Vch}$ square root of the horizontal curvature; NVA is the number of variables (6); PD is the daily precipitation; CPC is the coefficient of critical precipitation (70 mm/24 hours); PA5 is the cumulative precipitation for five days; MAXPA5 is the maximum cumulative precipitation for five days in the historical series 01/01/1995 to 03/19/2013.

From this historical series, four dates (01/19/2005, 01/04/2007, 01/12/2011, and 03/18/2013), here called a "day of the event" had their data separated for analysis, because these were recorded in the city of Nova Friburgo a daily precipitation exceeding 80 mm.

On 01/19/2005 the 5-day cumulative precipitation (PA5) was 117.5 mm and the previous day (01/18/2005) was 32.8 mm, with no occurrence of landslides: On 01/04/2007 the PA5 was 176.3 mm and the previous day (01/03/2007) was 88.6 mm, causing 350 landslides; On 01/12/2011 the PA5 was 219.9 mm and the previous day (01/11/2011) was 85.0 mm, causing 183 landslides**,** and on 03/18/2013 the PA5 was 131.6 mm and the previous day was 26.8 mm, with no occurrence of landslides.

It was observed that the events occurred on 01/04/2007 and on 01/12/2011, there were respectively 350 and 183 landslides, due to the rain precipitation started one day before (01/03/2007 and 01/11/2011) to the days of the events, with its elevation and continuity in the days events. However the events of 01/04/2007 and 03/18/2013, the high rain precipitation occurred only on these dates, insufficient for the occurrence of the landslides. Hence the importance of analyzing the PA5, in case of prediction of landslides, always for a minimum of two (2) days.

The vulnerability maps of the Basin were generated by the software ArcGIS ® 10, with the overlay of the map's variables "declivity, pedology, lithology, use and cover of land, vertical and horizontal curvature", with their related information, including the vulnerability indexes of the Basin calculated from Equation 2.

The map generated for the vulnerability of the River Bengalas Basin to landslides (Figure 4.2) is identical to the 5th, 4th and 3rd preceding day of the day event, respectively the days 7, 8 and 9 January, 2011. The figure 4.3 presents the map of vulnerability of the Basin generated for the day January 10, 2012 (2 days before the day of the event). The vulnerability map generated for 1 day prior to the event (01/11/2011), as well as for the event day (01/12/2011), when there were 183 landslides in the Basin, also was identical. It was observed in this map that the applied methodology indicated two major classes of vulnerability - very high and high - which correspond respectively to 136.18 Km² and 54.63 Km² of the River Bengalas Basin. However, the indexes adopted for the classes of vulnerability standardized in this study (Table 3.1) do not allow for a more detailed observation and analysis of which areas of the River Bengalas Basin are more vulnerable to landslides. The first impression is that the entire study area has the same characteristic. Therefore, the technique of algebra maps applied from the weighting of all the thematic maps results in continuous numeric values that allow other ways to categorize the vulnerability, if it is necessary to assess the areas more or less critical of the Basin. Thus, it was decided to reclassify the vulnerability indexes to landslides calculated for the days 11 and 12 January, 2011, from the slicing of these indexes so the analysis could be more detailed.

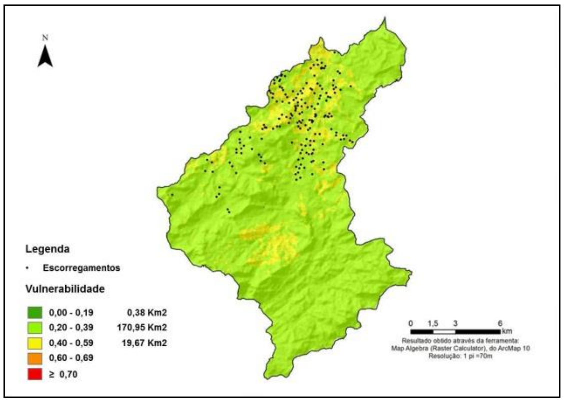

Figure 4.2 Vulnerability Map of the River Bengalas Basin to landslides for the days 7, 8 and 9 January, 2011, respectively the 5th, 4th and 3rd day before the day event

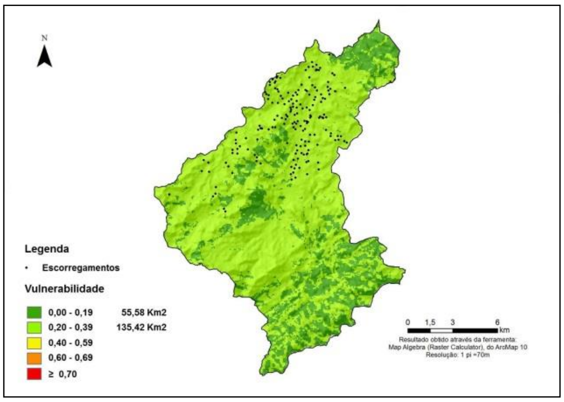

Figure 4.3 Vulnerability Map of the River Bengalas Basin to landslides for the day 10 January, 2011, 2nd before the day event

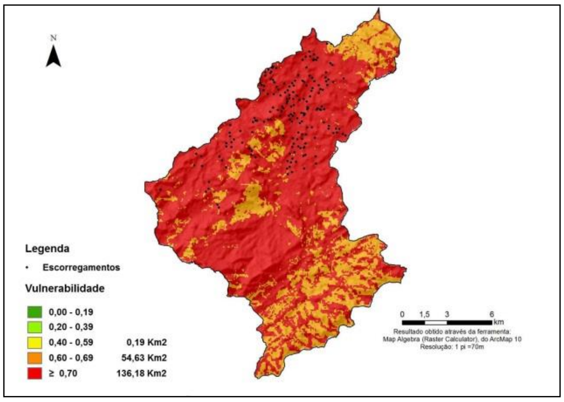

Figure 4.4 Vulnerability Map of the River Bengalas Basin to landslides for the days 11 and 12 January, 2011 respectively the 1st day before the day event and the day event

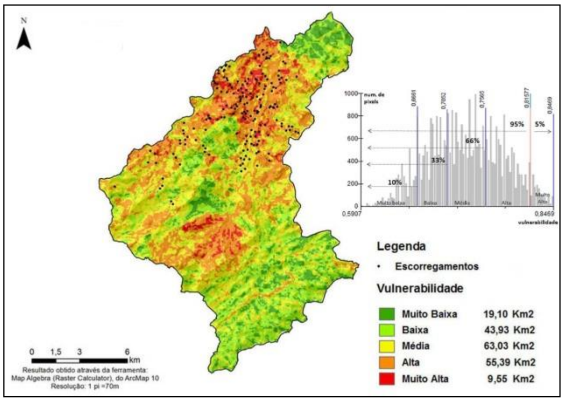

Figure 4.5 Vulnerability Map of the River Bengalas Basin to landslides for the days 11 and 12 January, 2011, representing the more critical 5% of the Basin

Figure 4.5 shows the alternative to the case, which deals with the division of vulnerability classes from percentages found in the resulting histogram of algebra maps for the days 11 and 12 January 2011. This type of classification is done for various phenomena of the nature, which seeks to define a critical threshold that, from this, there is the occurrence of extreme/rare considered events (spatial and temporarily). This occurs, for example, in the precipitation data analysis. In this case, the temporal distribution of the rains over a given period (annual or decadal) is statistically evaluated, so the rains that corresponds to the 99% percentile are called as very extreme events. In other words, they are rains that don’t occur 99% of the times in a region during a determined period.

For the vulnerability case to landslides, aimed to draw such percentages in order to define the areas of River Bengalas Basin that represents a very critical situation, that is, very high vulnerability to these types of disasters. In the literature, there are several validated studies that indicate that the most critical vulnerability class, normally, occupies between 3.5% and 8.0% of the analyzed basins (Kayastha et al. 2013; Bai et al. 2009; Ayalew et al. 2004; and Akinci et al. 2011).

So, the limit for the vulnerability class "very high" was traced to the 95% percentile, as option of viewing of the results shown on the vulnerability map of the River Bengalas Basin to landslides (Figure 4.5). This means that the vulnerability class "too high" is over 95% from the values found within the River Bengalas Basin, representing the 5% more critical from the Basin in relation to landslides. It is noteworthy that other classes of vulnerability - very low, low, medium, and high - were also traced based on the values found in the literature, so the less critical class represents 10% and the other classes were placed equidistant each other, according to the result presented in Figure 4.5.

It was counted 35,318 pixels on the vulnerability map of the River Bengalas Basin to landslides. Given that the class "very high" represents the most critical 5% from the Basin, such class has 5% of the total pixels, that is, has

1,766 pixels. Sarkar and Kanungo (2004), in a study conducted in Darjeeling, a mountainous region of the Himalayas, India, the frequency of landslides per Km² and from calculated classes by them were "very low: 0.00"; "low: 0 , 16, "" moderate: 0.50 ", and" high: 1.79 ".

Conclusion

With the development of this work, it was possible to create a specific methodology capable of creating indexes of susceptibility and vulnerability to landslides, that can be universally used for research centers and other institutions active in the prevention, monitoring and forecasting of landslides. Also, it proved effective regarding the concepts, tools, techniques, and applicability, having been applied to four (4) events of high rain precipitation that occurred in the city of Nova Friburgo, being efficient in the four (4) situations and proving that it is a methodology that can be used universally for research centers and other institutions active in the prevention, monitoring and forecasting of landslides. It was observed that when the vulnerability index to landslides is greater than or equal to 0.70 (critical threshold) for two (2) days in a row, as proposed in this study, the incidence of these types of disasters is "very high." Moreover, it is highlighted the importance of analyzing the 5-day Accumulated Precipitation (PA5) of at least two (2) days. From the analysis of pixels of the vulnerability map to landslides, if the frequency of these disasters per Km² calculated in this work for the class "high: 2.57", is compared to the frequency obtained from the class "high: 1.79" from the work validated by Sarkar and Kanungo (2004), it is concluded that the results found here is above compared to the found by the authors, so that this type of classification by the percentiles is able to represent well the critical situation which corresponds to landslides.

References

Akinci, H.; Doğan, S.; Kiliçoğlu, C. Temiz, M. S.; Production of landslide susceptibility map of Samsun (Turkey) City Center by using frequency ratio method. Geomatics Engineering, Ondokuz Mayis University, 55139, Kurupelit/Samsun, Turkey. Kavak Vocational School, Ondokuz Mayis University, Kavak/Samsun, Turkey. International Journal of the Physical Sciences Vol. 6(5), pp. 1015-1025, 4 March, 2011. DOI: 10.5897/IJPS11.133. Academic Journals. 2011.

Ayalew, L.; Yamagishi, H.; Ugawa, N.; Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. DOI 10.1007/s10346-003-0006-9. School of Natural Resources. University of Arizona. 2004.

Bai, S-B.; Wang, J.; Lü, G-N.; Zhou, P-G.; Hou, S-S.; XU, S-N.; GIS-Based and Data-Driven Bivariate Landslide-Susceptibility Mapping in the Three Gorges Area, China. College of Geography Science, Nanjing Normal University, Nanjing 210097 (China). China Institute of Geo-Environment Monitoring, Beijing 100081 (China). ELSEVIER. Vol. 19, Issue 1, February 2009, Pages 14–20.

Braga, T.M.; Oliveira, E.L.; Givisiez, G.H.N. Avaliação de metodologias de mensuração de risco e vulnerabilidade social a desastres naturais associados à mudança climática. São Paulo em Perspectiva, São Paulo, Fundação Seade, v. 20, n. 1, p. 81-95, jan./mar. 2006.

Kayastha, P.; Dhital, M. R.; Smedt, F.; Evaluation and Comparison of GIS based Landslide Susceptibility Mapping Procedures in Kulekhani Watershed, Nepal. Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussels, Belgium. Mountain Risk Engineering Unit, Tribhuvan University, Kirtipur, Kathmandu, Nepal. Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. JOURNAL GEOLOGICAL SOCIETY OF INDIA. Vol.81, February 2013, pp.219-231.

Sarkar, S.; and Kanungo, D.P.; An Integrated Approach for Landslide Susceptibility Mapping Using Remote Sensing and GIS. American Society for Photogrammetry and Remote Sensing (ASPRS). PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING. Vol. 70, No. 5, May 2004, pp. 617-625.

Tagliani, C.R.A. 2002. Técnica para avaliação da vulnerabilidade ambiental de ambientes costeiros utilizando um sistema geográfico de informações. Galeria de artigos acadêmicos. Disponível em: www.fatorgis.com.br. Acesso em: 10 jan. 2012.

Tricart, J. Ecodinâmica, Rio de Janeiro: IBGE-SUPREN, 1977, 91p. (Recursos Naturais e Meio Ambiente).

UNDP - Reducing disaster risk: a challenge for development, a global report. UNDP Bureau for Crisis Prevention and Recovery. New York: UNDP, 2004.