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January 2011: the extreme landslide disaster in Brazil

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Abstract: This work describes the extreme event of landslides occurred in January 2011 in the Rio de Janeiro mountainous region and discusses its relationship to the spatial and temporal variation of critical and prior rainfall. Interviews in the field let us establish the landslide initiation timing around the automatic pluviometer stations which supply detailed data on the rainfall intensity. The study concludes that the accumulated rainfall during the last months associated with high rainfall levels over 24 hours, along with local conditions like the direct impact of lightning and tremors resulting from landslides, formed the relevant conditions for thousands of landslides.

Keywords: landslides, accumulated rainfall, lightning and sequential detonation.

Introduction

The disasters caused by landslides have been concentrated in the mountainous area of the southeast and south regions of Brazil, especially along the Serra do Mar, between the states of Espírito Santo and Santa Catarina (Fig. 1). Among the large magnitude disasters registered in the southeast region up to 2010, the events of 1966 in the city of Rio de Janeiro and, in 1967, in the Serra de Caraguatatuba (São Paulo state) and Serra das Araras (Rio de Janeiro state), stand out as indicated by Schuster et al. (2002). The 1966 and 1967 events in the state of Rio de Janeiro were described by Barata (1969), Costa Nunes (1969) and Jones (1973). The last author indicated that in 1967, strong storms occurred with intense electric discharges accumulating around 250 mm of rainfall in only 3 and a half hours, with an average intensity of around 100 mm.h^{-1}. Jones (1973) reports that the intense lightning and the collapse of slopes shook the region like an earthquake and tens of thousands of landslides replaced plant cover with exposed soil or rocks and drowned valley bottoms with extensive debris flows. Lacerda (1997) reinforced the possibility of an association between lightning and landslide detachment during the heavy summer storms.

In this paper, we present the extreme rainfall event occurred on January 12, 2011, which induced the detachment of thousands of landslides in the mountainous region of Rio de Janeiro state, with special attention to the municipality of Nova Friburgo. This event caused more than 1,500 deaths and severe damage to the urban and rural infrastructures. The focus of the study is the spatial and temporal analysis of critical rainfall and preceding conditions to evaluate the possible relationships with thunderstorms and other local control-factors of geological and geomorphological nature, as well the vegetation cover and land use.

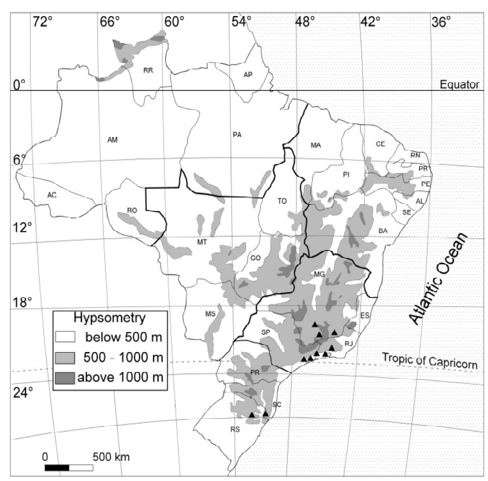

Figure 1 - Location of catastrophic landslides recorded in Brazil at Serra do Mar (Coelho Netto et al., 2010).

The study region

The region affected by landslides on January 12 includes the municipalities of Nova Friburgo (936 km^2; 182,000 inhab.), Teresópolis (771 km^2; 163,000 inhab.) and Petrópolis (774 km^2; 296,000 inhab.). The population of these municipalities is predominantly urban (~90%), and it is noteworthy for industry, although agriculture is also very present. It has a predominantly High-Altitude Tropical Climate with an average temperature of 16^{o}C. This area was originally the Tropical Atlantic Rainforest, but is currently fragmented and very degraded, especially around the urban areas.

Nova Friburgo is the most rainy area of the state with an average annual precipitation of around 2500 mm in the highest areas (from 1977 to 2000), decreasing progressively to the north up to 1300 mm; in Teresópolis the average annual precipitation also varies in the N-S direction from 2200 to 1500 mm and, in Petrópolis, from 1900 to 1000 mm (Coelho Netto et al., 2008). The rainiest period occurs between December and February when the average monthly rainfall varies between 340 and 240 mm in the southern highest altitudes, and between 240 and 150 mm to the north. Located in the summit area, Teodoro de Oliveira is the rainiest place in the region.

The critical rainfall and landslide occurrences

Rainfall records were obtained from 47 rainfall stations, of which four were automatic (Fig. 2). The spatial distribution of January 12th data were analyzed and interpolated by using the Kriging method. This interpolation was undertaken using the weighting parameters determined by the analysis of directional semivariograms expressing an anisotropy in the accumulated rainfall values. The isohyets map on January 12th in Fig. 2 shows that the rainiest cell (> 200 mm) occurred in the center of Nova Friburgo.

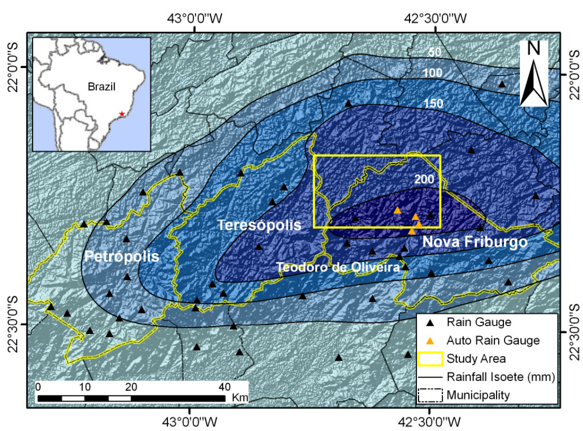

Figure 2 - Isohyets map of January 12th over the disaster region and location of the rain gauge stations (N=47); the rectangle indicates the detailed study area.

The landslide scars were mapped over the Geoeye image made on January 19th, 2011 available on Google Earth 6.0 program, using the "add polygons" tool. The polygons generated were saved in .kml format and imported into ArcGIS 9.3 with the X Tools Pro 7.1 extension. In Fig. 3 a spatial distribution of the landslide scars can be observed. It was noted that the main landslides occurred in the rainiest area. As the rainfall decreases, a progressive increase in the frequency of landslide scars of smaller sizes increases. Of the total number of landslides (N= 3622), it was verified that the frequency of landslide occurrence in isohyets varied in direct relationship with the rainfall size: only 2.7% between 140 and 160 mm; 22.7% between 160 and 180 mm; 34.6% between 180 and 200 mm and 40.0% in the area of rainfall >200 mm. The locations with the largest number of landslides were associated with Fazenda Mendes polygon (#3, N = 1174) and Sítio Santa Paula (#5, N = 1558), as presented in Tab. 1.

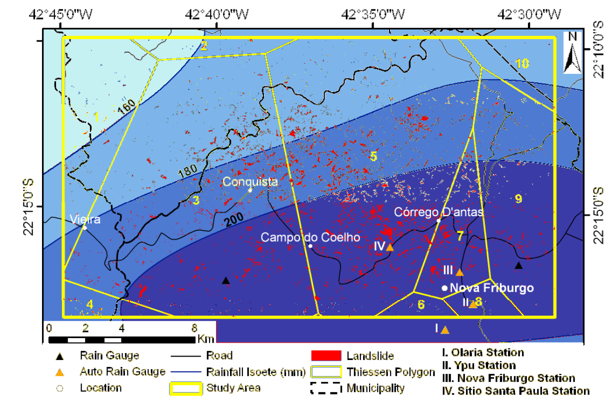

Figure 3 - Map of landslide scars within the rainfall isohyets and Thiessen polygons of January 12: 1- Córrego Sujo, 2-Sumidouro, 3-Fazenda Mendes, 4-Friburgo/INMET, 5-Sitio Santa Paula, 6-Olaria, 7- Nova Friburgo, 8-Ypu, 9-Vargem Grande, 10-Bom Jardim.

Table 1 – Number of different sized landslide scars in each Thiessen polygon and in its respective isohyet strip.

Thiessen Polygon	Isohyet (mm)	Number (N) (Total landslides = 3622)		
		< 5,000 m^2	5,000 to 20,000 m^2	> 20,000 m^2
1-Córrego Sujo	140-160	82	6	--
	160-180	56	3	1
	180-200	3	1	--
2- Sumidouro	140-160	8	--	--
	160-180	22	2	--
3-Fazenda Mendes	140-160	1	--	--
	160-180	354	53	14
	180-200	353	76	20
	200-220	228	66	9
4- Friburgo /INMET	180-200	13	11	--
	200-220	5	1	--
5- Sitio Santa Paula	160-180	259	46	5
	180-200	378	141	40
	200-220	514	139	36
6- Olaria	200-220	23	1	--
7- Nova Friburgo	180-200	2	10	2
	200-220	193	32	11
8- Ypu	200-220	17	--	--
9- Vargem Grande	180-200	148	43	2
	200-220	145	31	--
10- Bom Jardim.	160-180	7	--	--
	180-200	5	4	--
Sub-Total		2816	666	140

Tab. 1 summarizes the relationship between the rainfall and the size of the landslide scars. It was verified that of the total scars from landslides, 2,816 (77.8 %) were less than 5,000 m^2 and only 3.9% were greater than 20,000 m^2. Among these major scars, 85% occurred in locations where the rainfall was higher than 180 mm. The landslides smaller than 20,000 m^2 occurred from 140 mm. The largest landslide scars predominated (58%) in the rainiest polygon referred to the Sitio Santa Paula station (#5). In this polygon, a total number of 1558 landslides occurred with varying sizes close to the regional tendency (74% less than 5,000 m^2 and 5% greater than 20,000 m^2). Another polygon with a high concentration of landslides refers to the Fazenda Mendes station (#3), where 1174 landslide scars occurred. The polygons 5 and 3 concentrate 75.4% of the total of landslides, including 88.6% of the larger sized landslides (>20,000 m^2).

Rainfall characteristics and landslide initiation

Four automatic stations serve as a basis for the analysis of rainfall intensity on January 11-12th event. In addition, by interviewing local residents, it was possible to identify the location (by GPS) and time that the landslides occurred within a 1 Km radius of these pluviometer stations. All persons interviewed confirmed the occurrence of intense lightning and thunder during the storm, indicating the sensation of tremors associated with more intense lightning. However, it was not clear that these tremors referred to the lightning or the landslides. Landslides were also associated with strong noises and tremors as if they were “earthquakes”.

Tab. 2 indicates the number of landslides within a 1 Km radius around the Olaria (O), Ypu (Y), Nova Friburgo (NF) and Sítio Santa Paula (SSP) stations, as well as the number of interviews with local residents and the accumulated rainfall during January 11-12 event and in preceding months. In this table, it can be observed that the Nova Friburgo station, located in the city center, presented the lowest values for accumulated rain during the four time intervals considered; however, this was the area that presented the largest concentration of landslides. On the other hand, around Olaria and Ypu stations, which had high accumulated rainfall values, few landslides occurred: only one landslide in Olaria and 11 landslides in Ypu.

The rainfall data registered in these four stations between January 11 and 12 were analyzed for intensity distribution ($mm.h^{-1}$) at half hour intervals (Fig. 4). This figure shows the rainfall intensity histograms, along with the two accumulated rainfall curves: one refers to the critical event on January 11-12 and the other accumulates the previous event. During the continuous rainfall period from January 11-12th, a lower rainfall value was registered at the Nova Friburgo station (~140 mm); the other stations registered ~180 mm (Olaria); ~205 mm (Ypu) and, until it was destroyed at 5 am, the Sítio Santa Paula station registered ~190 mm. The rainfall intensity varied considerably in time and also between the four stations. The only landslide nearby the Olaria station occurred around two hours after the peak intensity (~15 $mm.h^{-1}$) and accumulated since the beginning of the event close to 115 mm along with the previous day totaling ~190 mm. Around the Ypu station, the first analyzed landslide occurred when the accumulated rainfall was ~70 mm and reached the maximum of ~60 $mm.h^{-1}$ and, after an accumulated rainfall around ~170 mm, two more landslides occurred. In the area around the Sítio Santa Paula station, three landslides occurred: under rainfall intensity of 10 $mm.h^{-1}$ and accumulated rainfall of 70 mm, with 135 mm accumulated the previous day; three others occurred under a rainfall intensity equal to 20 $mm.h^{-1}$, with 80 mm of accumulated rainfall and 145 mm accumulated the previous day and three others when the intensity reached the peak value with ~55 $mm.h^{-1}$ and accumulated rainfall of 107 mm that, accumulated the previous day reached 174 mm total. At the Nova Friburgo station, the rainfall was well distributed and the intensity prevailed around 20 $mm.h^{-1}$. The majority of the landslides occurred under rainfall intensity below 20 $mm.h^{-1}$. Even at the end of the rainfall, with a low intensity (~ 5 $mm.h^{-1}$), two more landslides occurred.

In Fig. 5 the landslide triggering time reported by local residents within a 1 Km radius of the Nova Friburgo and Sítio Santa Paula stations were plotted. We note the spatial and temporal variation of hours for the detonation of landslides between the two areas and within each. The grouping of cases with little difference in time, indicate certain sequencing in triggering landslides at both areas.

Table 2 – Number of landslides (Ls) and interviews (Iv) in a 1 Km radius around the rainfall stations and accumulated rainfall (R_{mm}) in different time intervals. O – Olaria, Y – Ypu, NF – Nova Friburgo, SSP – Sítio Santa Paula. *Partial data: SSP station was destroyed at 5:00 am.

Station	Ls (N)	Iv (N)	R_{mm} Jan 11-12th	R_{mm} Jan 2011 until 11th	R_{mm} Dec 2010	R_{mm} Nov 2010
O	1	1	177.4	119.6	271.8	418.2
Y	11	6	207.4	113.4	217.8	469.0
NF	41	30	141.6	86.8	196.0	314.6
SSP	36	18	190.0*	121.8	220.6	433.0

Environmental conditions around the landslides

The municipality of Nova Friburgo has its headquarters located at 846 m of altitude and encompasses the highest point of the Serra do Mar at 2,316 m (Pico Maior), configuring a great breadth of relief. Among the main basins that drain this area the Bengala and Grande basins can be included, which drain to Paraíba do Sul river, and the Macaé basin, that drains to the northeast coast.

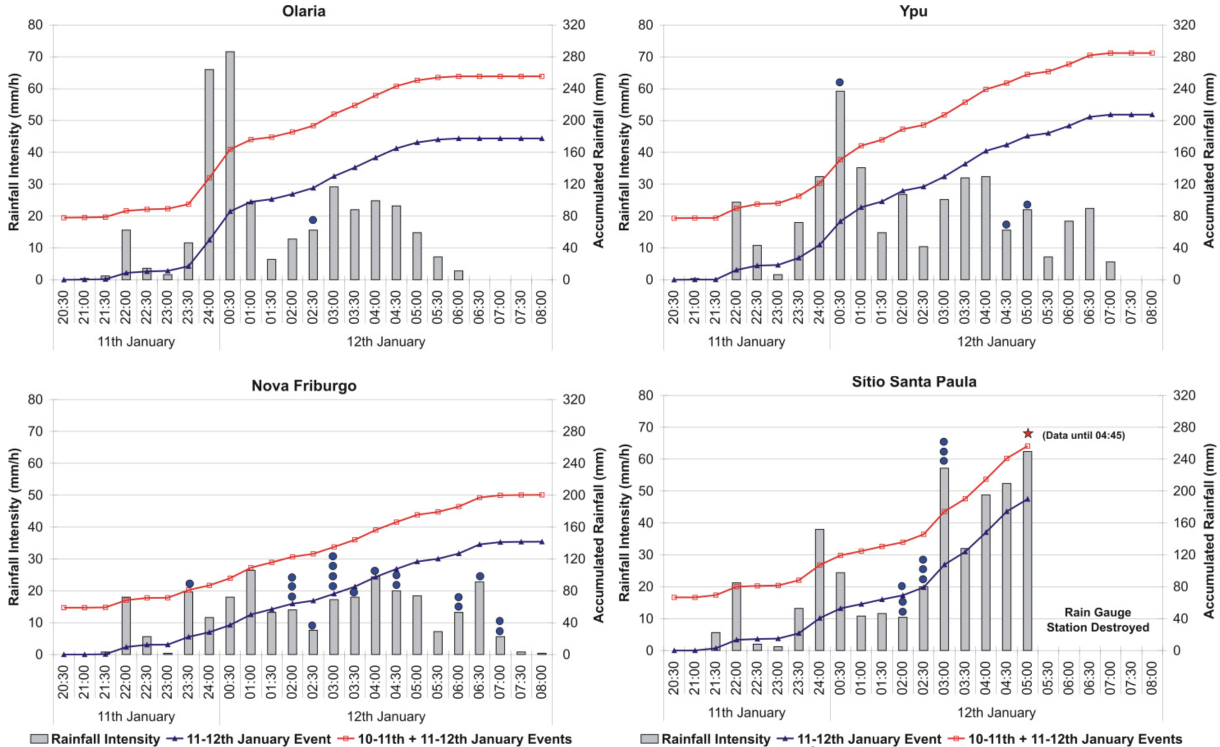

Figure 4 – Histogram of rainfall intensity distribution (mm.h^{-1}) during the January 11-12th event and accumulated rainfall curves during the same event as well as those accumulated on January 10-11th and 11-12th 2011 events. Blue dots indicate landslide occurrences.

Figure 5 – Landslides detonation time presented in fragments of Geoeye images from Google Earth within a 1 Km radius around Nova Friburgo station, in the city center of Nova Friburgo, and around Sítio Santa Paula station, in the rural area.

Geologic-geomorphological background

The studied area is dominated by post and sin-tectonic granite (63.0%) and migmatites (14.4%) as evident in Fig. 6 and Tab. 3. The table shows the largest density of landslides over post-tectonic granite although its area of occurrence is relatively more restricted in relation to sin-tectonic granites. The urban zone is part of the granite area and also presented a high density of landslides (7.6.km^{-2}). The high density of fractures that favor the formation of *in situ* blocks, provided the incorporation of a high load of blocks to landslide material. Older block rich colluvial deposits were also exhumed and incorporated into the mass of debris in valley bottoms. Materials mobilized on the slopes fed extensive avalanches rich in blocks and organic debris along the river valley bottoms forming torrents of great magnitude, in turn overflowing the canals and modifying the canal and the floodplain morphology. In these locations, all forms of human occupation (homes, agricultural areas, roads, among others) were destroyed or buried.

A digital elevation model (DEM) with 20 m resolution was generated from the 1:50,000 scale topographic maps from IBGE (Instituto Brasileiro de Geografia e Estatística). Then, the slope map and Topographic Position Index (TPI), as proposed by Jenness (2006), were obtained. Crossing the slope maps with the map of the classification of slope position, it was verified that the largest part of the landslides occurred on the ridge and upper slope positions (1982 cases or 55%); the rest occupied the middle and lower slopes, as illustrated in Fig. 7. Taking the total landslide area into account in these three positions (ridge+upper slopes=3.5 km^2; middle=6.5 km^2 and lower=5.7 km^2), it was shown that smaller landslides dominated at the highest parts of the slopes.

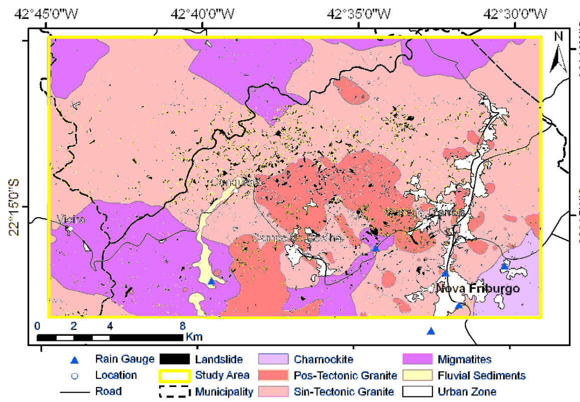

Figure 6- Geological map (1:50,000, DRM-RJ) and 2011 landslide scar map.

Table 3 – Distribution of landslides in the different types of rock. L_A: Landslides Total Area; L_D: Landslides Density.

Geology and Urban Site	Area (Km^2)	Landslides (N)	L_A (Km^2)	L_D (N/Km^2)
Charnockite	11.6	55	0.1	4.7
Pos-Tectonic Granite	54.1	644	4.3	11.9
Sin-Tectonic Granite	235.6	2235	9.4	9.5
Migmatites	97.5	523	1.9	5.4
Fluvial Sediments	3.9	24	0.1	6.2
Urban Zone	18.5	141	0.2	7.6
TOTAL	421.1	3622	16.0	8.6

The slope map indicates an average slope for the total mapped area of around 17°. The landslides occurred in slope segments with an average slope of 19° and maximum slope of 65°. Taking the quartile of 50% (median) into account, the slope varied little among landslides less than 5,000 m^2 (17.6°), landslides of between 5,000 and 20,000 m^2 (19.8°) in size and landslides larger than 20,000 m^2 (21.0 °).

Figure 7 – Panoramic view of the January 11-12th landslides in the rural areas of the Nova Friburgo municipality.

Vegetation and Land Use

A previous mapping of vegetation and land use at 1:50,000-scale (Madureira et al., 2008, in: Coelho Netto et al., 2008) was used to evaluate their possible interactions with the landslide spatial pattern. The legend was grouped into eight categories as Tab. 4 indicates. The forest cover (including all forest patches, independently of their succession stage or state of conservation) occupies a total area of 247.5 km^2 (59%) predominating around the different-sized landslide scars. It is worth pointing out that the field observations made along the roads, indicated that the majority of forest patches were of initial secondary succession stage, with shallow roots and variable stages of degradation. The second major cover is pastureland, which covers a total area of 122.6 km^2 (29%). In the urban area (18.5 km^2) there were no landslide of more than 20,000 m^2; the total area for intermediary and lesser-sized landslides only reached 0.4 km^2.

Table 4- Total area of land cover/use and area removed by landslides of variable sizes occurred in January 11-12 2011.

Land Cover/Use	Total Area		Landslide Area		< 5,000 m^2		5,000 to 20,000 m^2		>20,000 m^2	
	(Km^2)	(%)	Km^2	(%)	Km^2	(%)	Km^2	(%)	Km^2	(%)
Forest	230.9	54.8	10.2	64.0	2.6	57.9	4.1	65.3	3.5	67.5
Initial Secondary Forest	10.4	2.5	0.4	2.6	0.1	1.7	0.2	2.7	0.2	3.3
Reforestation	6.2	1.5	0.1	0.8	0.0	1.0	0.1	1.2	0.0	0.0
Pasture	122.6	29.1	3.9	24.7	1.3	30.0	1.6	24.4	1.1	20.4
Agriculture	24.6	5.8	0.4	2.8	0.2	3.9	0.2	2.8	0.1	1.8
Urban Area	18.5	4.4	0.4	2.3	0.2	4.1	0.2	1.9	0.0	1.2
Bedrock	7.9	1.9	0.5	2.9	0.1	1.4	0.1	1.5	0.3	5.7
TOTAL	421.1	100	16.0	100	4.4	100	6.3	100	5.2	100

Conclusions

Despite the fact that rainfall was spatially non-uniform during January 11-12th event, the accumulated volume in all stations of the region hit by the disaster reached values close to mean monthly rainfall in less than 10 hours. Preceding months were also rainy, but accumulated values from December and November 2010 were not far from mean values expected for this period.

Another relevant aspect to be considered is the temporal relationship between landslide trigger and rainfall intensity. Although some landslides were triggered during high intensity rain instances, many other landslides did not show a direct relationship with the intensity or time interval between the beginning of the rain and the trigger of landslide. However, frequent reports by local residents on the relationship between lightning and the immediate detachment of landslides called our attention and strengthened the pioneering ideas of Jones (1973) and Lacerda (1997). The lightning would have caused the vibrations and very strong sounds, which many people associate with "collapsing hills"; in fact, the rocky slopes and the high declivity (ridge and high slope positions) had lightning impact marks.

The time sequencing observed during landslides initiation also deserves our attention, mainly for cases of landslides that were triggered under low intensity and at the end of rainfall events with no association to lightning. These landslides, rich in rock blocks and organic debris, were also associated with strong sounds and local tremors of the earth, according to local residents. Just like seisms of tectonic nature, these earth tremors would have also induced the beginning of the landslides. However, it remains to understand how these effects propagated to adjacent slopes, and how this would affect the stability of saturated or near-saturated soil materials.

Among the local geological conditions, we cannot omit the role of water percolating into the fractured rocks, especially given the predominance of highly fractured granites and migmatites. The high concentration of rain and water saturation in the fractured environment also might favor discharges of superficial or subsuperficial flow able to induce other ruptures in the soil and/or fragments of rock, especially in the middle and lower slopes. When the forest vegetation is well preserved, it was shown that it was only able to inhibit the propagation of landslides. But, it was the urban area that showed the most vulnerability since, even with lesser proportions of rain, it presented a high landslide concentration. Without a doubt, this study is insufficient to make final conclusions, yet it allowed to raise an array of new questions which will certainly be guided by detailed future research, especially in the geological, geomorphological, geotechnical and geoecological interfaces.

Acknowledgments

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References

Barata F.E. (1969) Landslides in the tropical region of Rio de Janeiro, in: Proceedings, 7th Int. Conf. on Soil Mechanics and Foundation Engineering, Mexico City, Soc. Mexicana de Mecanica de Suelos, Vol. 2, 507-516.

Coelho Netto A.L., Avelar A.S., Fernandes M.C., Coutinho B., Freitas L. (2008) Technical Report o n Environmental Quality of Rio de Janeiro state (1:100,000): subsidies for the economic - ecological zoning, Environmental Secretariat of Rio de Janeiro State Government.

Coelho Netto A.L., Avelar A.S., Lacerda W.A. (2010) Landslides and Disasters in Southeastern and Southern Brazil, chapter 12, in: Latrubesse, E.M. (Ed.) Natural Hazards and Human-Exacerbated Disasters in Latin America, Volume 13: 223-241, Elsevier B.V., ISSN 0928-2025, DOI 10.1016/S0928-2025(08)10012-8.

Costa Nunes A.J. (1969) Landslides in soils of decomposed rock due to intense rainstorms, in: Proceedings, 7th Int. Conf. on Soil Mechanics and Foundation Engineering, Mexico City, Soc. Mexicana de Mecanica de Suelos, Vol. 2, 574-554.

Jenness, J. 2006. Topographic Position Index (tpi_jen.avx) extension for ArcView 3.x, v. 1.3a. Jenness Enterprises. Available at: http://www.jennessent.com/arcview/tpi.htm.

Jones F.O. (1973) Landslides in Rio de Janeiro and Serra das Araras escarpment, Brazil: U.S. Geological Survey Professional Paper 697, 42p.

Lacerda W.A. (1997) Stability of natural slopes along the tropical coast of Brazil". Symp. on Recent Develop. in Soil and Pavement Mechanics, COPPE-UFRJ, Rio de Janeiro, Almeida, M.S.S. (ed), Balkema: 17-40.

Madureira C., Sanches R., Bastos, R. (2008) Vegetation and land use map of Rio de Janeiro state (scale 1:100,000), in: Coelho Netto A.L., Avelar A.S., Fernandes M.C., Coutinho B., Freitas L. , 2008, Technical Report on Environmental Quality of Rio de Janeiro state (1:100,000): subsidies for the economic - ecological zoning, Environmental Secretariat of Rio de Janeiro State Government.

Schuster R.L., SalcedoD.A., Valenzuela L. (2002) Overview of catastrophic landslides in South America in the twentieth century, Geological Society of America, Reviews in Engineering Geology, Volume XV.