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Map of Mass Movement in a Region of the State of São Paulo, Brazil

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Abstract. In the past fifteen years, there has been a significant increase of the number of natural disasters on a world scale. Specifically in Brazil, this increase is mainly related to the growth of urbanization leading to unsuitable buildings and deforestation on hillsides causing social and economic problems. Hence, studies are needed to better understand the triggering factors and the communities' response capacity. The purpose of this paper is to come up with a hazard map of mass movement in the region of the Paraíba Valley and North Coast of the state of São Paulo, Brazil. The data of mass movement were managed according to Natural Disasters Database of Center of Meteorology, São Paulo State University (UNESP) considering the period between 1996 to 2016. All the occurrences were georeferenced allowing detailed study of the physical characteristics such as geomorphology, geology, geotechnics and land use. In order to do so, the data were analyzed statistically according to the occurrence numbers. The trigger rains analyses considered daily rains, 3 days and 7 days before the occurrence. The quantification of the hazard used a matrix that combined socionatural criteria with rainfall thresholds. Three maps were done based on daily rains, 3 days and 7 days and it was concluded that the 3 days rain were the most relevant.

Keywords. Mass movement map, natural hazard, triggering agent.

1. Introduction

Natural disasters can be defined as impacts of natural phenomena on inhabited areas that cause human, material and environmental damages. The magnitude of a disaster depends on the relationship between the intensity of the event and the degree of fragility of the affected society. [1].

The Hyogo Framework for Action was a global campaign endorsed by the United Nations Office for Disaster Risk Reduction (UNISDR) to build more resilient communities and is now complemented by the Sendai Framework (2015-2030) whose actions are being built on the experience gained in the previous period. The year 2015 was also highlighted by the adoption of Agenda 2030 for Sustainable Development, generating a document listing 17 Sustainable Development Goals (SDGs) with 169 targets; from which 10 goals and 25 targets are related to this subject.

Among them, the first target of 13th SDG encloses the aim of this paper: "Reinforcing resilience and adaptability to climate-related risks and natural disasters in

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all countries." [2]. Hence, modern society increasingly values knowledge of the physical environment, pointing to the integration of man and nature both for a more rational use of space and for the protection and preservation of the environment. Geotechnical mapping is an important tool in this context, since it tries to manage the occupation in a systematic and rational way.

In Brazil, the great majority of natural disasters originate due to the external dynamics of the Earth, such as storms, floods and landslides. [3] assembled a map of hazard of landslides for the State of São Paulo that highlights the eastern region with higher hazard scores. This map considered only environmental aspects applying attributes of the basic subdivision units (UBC) that reflect elements of the geologic-geomorphological-pedological substrate of the landscape.

The occurrences are related to the periods of higher rainfall [4]. In the South and Southeast regions of São Paulo State it occurs in the summer, mostly between October and March.

This paper purpose is to come up with a hazard map of mass movement in the region of the Southeast region of the state of São Paulo (called Paraíba Valley and North Coast), Brazil considering not only the physical characteristics, but also social vulnerability and the triggering agent.

2. Background

The negative impact of natural disasters has been shaped by several interrelated components including population growth, urbanization, increased global inequality, unsustainable practices, and increased risk exposure. Therefore, in this new global era, disaster risk management has become a challenge for the entire community interested in disaster prevention [5].

For mass movements in humid tropical environments, it is the intense rain, both the short duration and the long duration, the main trigger. The southeastern coast of Brazil is regularly affected by heavy rains that generate mass movements [6] and [7].

Gravitational mass movements, in the context of natural disasters, are usually triggered by rains that lead to infiltration of water into the soil, raising the pore-pressure, reducing shear strength and thus leading to mass instability. The combination of more intense summer rains and the lack of urban planning has been creating a high potential for catastrophes [8]. Hence, [9] inferred the hazard assessment and management need to be one of the main goals of public policies for developing countries and also in mountainous inhabited regions in different parts of the world. The safety target in areas affected by debris flows and falling barriers can only be achieved through a clear understanding of their cause, which differs in each site.

The International Strategy for Disaster Reduction - United Nations (UNSIDR) is concerned about the correct use of terms and is constantly updating the definitions. In its 2016 version [10], hazard has been defined as a dangerous human phenomenon, substance or activity that can lead to loss of life, injury, health impacts, property damage, loss of livelihood and services, social and economic disruption or environmental damage. Hazard can be related to natural or man-induced events. When events are the result of the combination of natural events with anthropogenic factors, according to [10], it can be classified as “socionatural”, which include environmental degradation and climate change.

The importance of the combination of rainfall thresholds and landslides susceptibility maps was highlighted by [11] since it allows: knowledge when and where a landslide can occur; assessment of its degree of danger allowing risk management; and refinement of the spatial resolution map to improve the alert zone system. The authors suggested that the hazard assessment needed to be dynamic with continually actualization of the rainfalls. The susceptibility map considered morphometric attributes and thematic maps (land use and lithology). The general classification for the hazard assessment is described in Figure 1.

To summarize, [12] highlighted the integration of different dimensions of knowledge, geospatial and statistical analyzes with the aim of improving emergency preparedness and response measures, not only in terms of location of potential man-made hazard sites, but also of plans to deal with it.

	S1	S2	S3
R1	H0	H1	H2
R2	H1	H2	H3
R3	H2	H3	H4

S1: low susceptibility
S2: medium susceptibility
S3: high susceptibility
R1: low rainfall
R2: medium rainfall
R3: high rainfall

H0: null hazard
H1: low hazard
H2: medium hazard
H3: high hazard
H4: very high hazard

Figure 1. Hazard Matrix. Adapted of [11].

3. Data and methods

The main concern of the application of this methodology is the use of data available in websites of government agencies in order to turn easy its utilization in other regions.

The frame of the hazard matrix considered the socionatural factors as susceptibility, and the rainfall thresholds as triggering factor.

The Southeast region of the state of São Paulo (called Paraíba Valley and North Coast), Brazil (Figure 2), was chosen because their high number of landslides. The IPMet/UNESP database recorded 167 days with mass movement between the years 1996 and 2016. Importantly, the database computes only those occurrences where the Civil Defense actuated.

3.1. Data

Firstly, the occurrences of mass movement were obtained of Natural Disasters Database of Center of Meteorology, São Paulo State University (IPMet/UNESP). The main information were: date; city; landslides type; geographical coordinates; number of victims.

The quantification of mass movements at the IPMet/UNESP database counted fall barrier, landslide and erosion. The date information were used to find the threshold rain by open data of the National Water Agency (ANA) and National Center for Monitoring and Alerting Natural Disasters (CEMADEN). The triggering agent study took in account the daily rains, 3 days, 7 days.

Spatialization of occurrences used open Geographic Information System (GIS), such as QGis and Terraview. Hence, geology, geomorphology and geotechnical of each place were characterized according to [13], [14] and [15].

For each city, the population data, such as population density and the elderly population, were obtained by the Brazilian Institute of Geography and Statistics (IBGE) using the 2010 census.

The poverty index is defined as the deviation between the per capita income of the municipality's poor and the poverty line. The calculation was made for the 2010 year, in order to correspond the last census realized in Brazil. As a result, the poverty line was U$1/day and for each city the per capita income was obtained by the Atlas of Human Development in Brazil, at http://atlasbrasil.org.br/2013/en/consulta/.

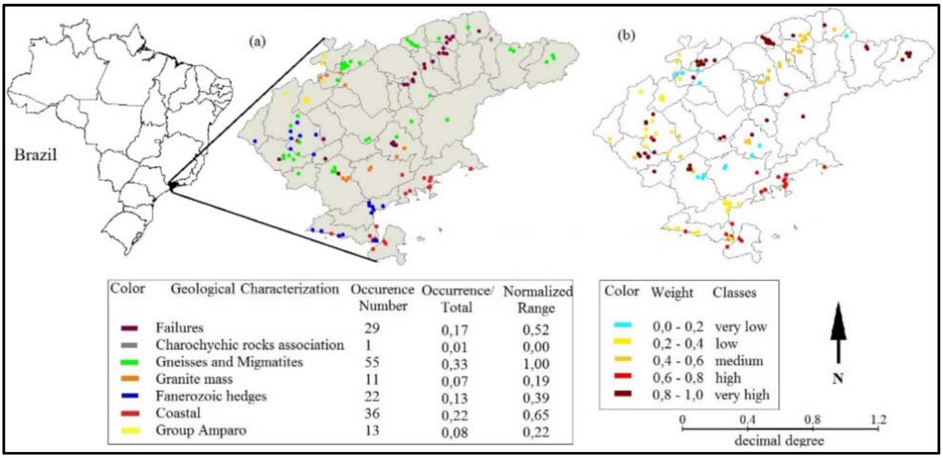
3.2. Susceptibility analysis

The landslide hazard assessment was classified using a square matrix based on the rainfall classes and susceptibility classes. The difference of [11] square matrix is that the susceptibility here was obtained by environmental criteria, Eq. (1), and anthropogenic criteria, Eq. (2).

$$C_{env} = C_{geol} + C_{geom} + C_{geot} \tag{1}$$

where C_{env} : environmental criteria; C_{geol} : geology characterization factor; C_{geom}: geomorphology characterization factor; and C_{geot}: geotechnical characterization factor.

For each dimension (C_{geol}, C_{geom} and C_{geot}), the occurrences were spatialized, and the weighting factor was calculated as function of the frequency of disasters that occurred in each class. For example, analyzing the geology in Figure 2a, the majority occurred in Gneisses and Migmatites rocks, 55 events of a total of 167, which correspond to 33 percent. These values were normalized applying Eq. (3) and classified in classes varying from very low to very high, Figure 2b. This procedure was repeated to the geomorphological and geotechnical factors. The sum of these values normalized resulted on the environmental criteria, Eq. (1).



Color	Geological Characterization	Occurence Number	Occurrence/ Total	Normalized Range
🟪	Failures	29	0,17	0,52
⬜	Charochychic rocks association	1	0,01	0,00
🟩	Gneisses and Migmatites	55	0,33	1,00
🟧	Granite mass	11	0,07	0,19
🟦	Fanerozoic hedges	22	0,13	0,39
🟥	Coastal	36	0,22	0,65
🟨	Group Amparo	13	0,08	0,22

Color	Weight	Classes
🟦	0,0 - 0,2	very low
🟨	0,2 - 0,4	low
🟧	0,4 - 0,6	medium
🟥	0,6 - 0,8	high
🟫	0,8 - 1,0	very high

Figure 2. Geological factor.

The anthropogenic criteria, Eq. (2), were also analyzed in three dimensions and each one had different unit of measure. In order to transform C_{DD} (inhabitant/km^2), C_{EP}

(inhabitant) and C_{PI} (%) at same magnitude, the dimension was normalized individually by Eq (3). After the sum of the three dimensions to each occurrence, C_{ant} were again normalized by Eq. (3).

$$C_{ant} = C_{DD} + C_{EP} + C_{PI} \tag{2}$$

Where: C_{ant}: anthropogenic criteria; C_{DD}: population density factor; C_{EP}: elderly population factor; C_{PI}: poverty index factor.

$$X_n = \frac{(X - X_{min})}{(X_{max} - X_{min})} \tag{3}$$

Finally, for every occurrence, the sum of Eq (1) and (2) resulted the susceptibility criteria, S of Eq. (4), and again the Eq. (3) were applied to normalize the values.

$$S = C_{env} + C_{ant} \tag{4}$$

3.3. Accumulated rainfall thresholds analysis

Firstly, data of daily rains, 3 days and 7 days were collected to all the cities with occurrence for the period of 1996 to 2016. The rain intervals were obtained by Sturges' rule.

Eq. (5) represents the weight of the accumulated rainfall thresholds, R, and means the ratio between the number of occurrences, O, and the total number of rains within the respective interval to years 1996 to 2016, N.

$$R = \frac{O}{N} \tag{5}$$

Unfortunately the complete rainfall data to the period did not exist to all the analyzed municipalities. Therefore, it was chosen two cities with a complete series of rain: São José dos Campos to Paraíba Valley and Caraguatatuba to North Coast.

The daily rains, 3 days, 7 days received the weighting using the same procedure of Eq. (5).

3.4. Hazard matrix

All normalizations of susceptibility and rainfall thresholds resulted in 5 classes from 0 to1, Table 1. The Matrix Hazard, Table 2, lead to 9 classes and it was used at the spatialization of the all the occurrences of mass movement.

Each geographical coordinate received a hazard weight, H_i, and generated 3 maps for daily rainfall, accumulated rain of 3 days and 7 days before the event.

Table 1. Classes to susceptibility and rainfall thresholds.

Range	Classes	Susceptibility	Rainfall Tresholds
0.0 – 0.2	very low	S1	R1
0.2 – 0.4	low	S2	R2
0.4 – 0.6	medium	S3	R3
0.6 – 0.8	high	S4	R4
0.8 – 1.0	very high	S5	R5

Table 2. Combination of susceptibility and rainfall thresholds into hazard matrix. Modified of [11].

	S1	**S2**	**S3**	**S4**	**S5**
R1	H0	H1	H2	H3	H4
R2	H1	H2	H3	H4	H5
R3	H2	H3	H4	H5	H6
R4	H3	H4	H5	H6	H7
R5	H4	H5	H6	H7	H8

4. Results

The Figure 3 shows the environmental criteria as a result of the sum the geology, geomorphology and geotechnical factors. The spatialization of the 167 disasters showed 147 located in urban territory and only 20 in rural territory, 8 of which were found on road slopes, Figure 4.

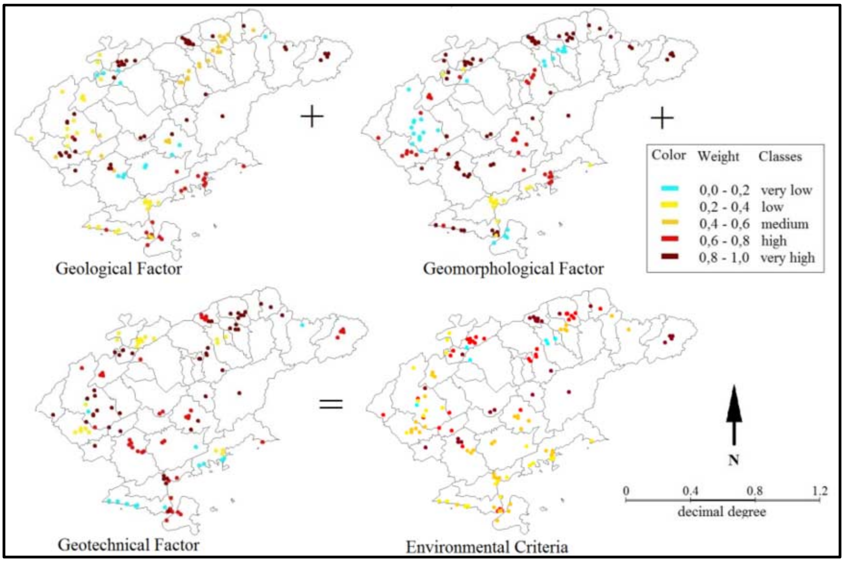


Figure 3. Environmental criteria.

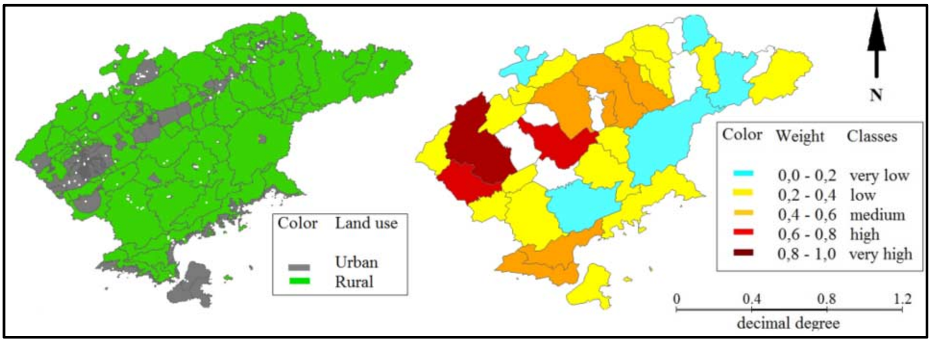


Figure 4. Social criteria.

Hence, the urban density was considered to better report the reality of the anthropogenic criteria even so the available data of poverty index and elderly population being municipal. The addition of Figure 3 and 4 resulted on Figure 5, called susceptibility criteria.

Figure 6 shows the combination between the susceptibility criteria and the accumulated rainfall. In the coastal region, the accumulated rainfall of 3 days before seems to have a tendency to be more dangerous than daily and accumulated of 7 days.

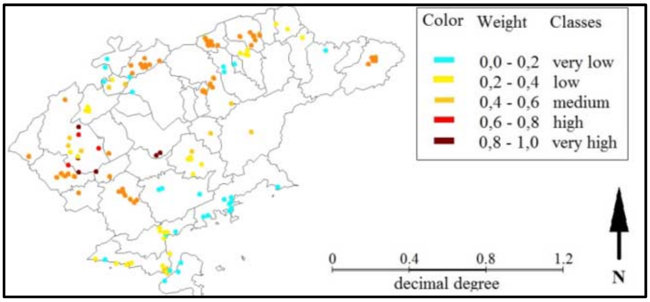


Figure 5. Susceptibility criteria.

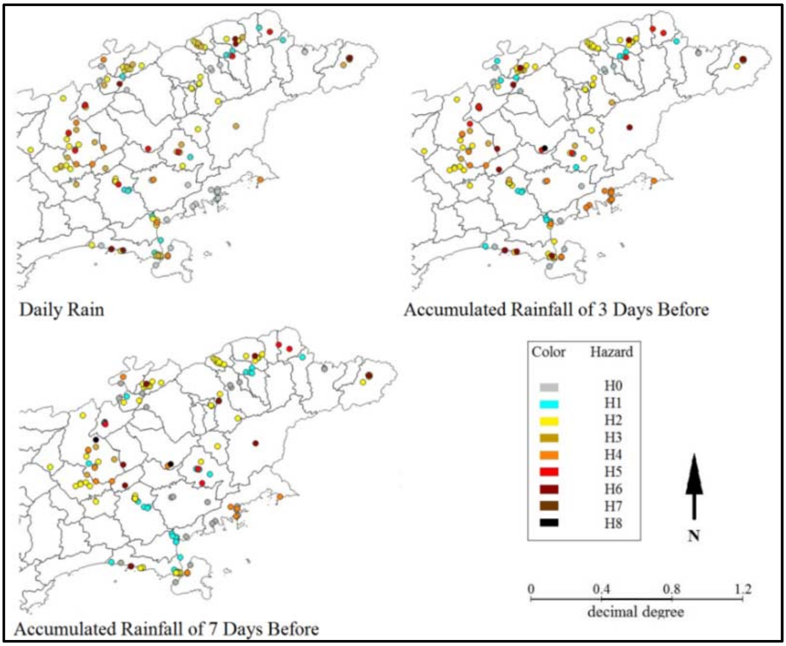


Figure 6. Hazard maps according accumulated rainfall.

5. Conclusions

The majority of mass movements occurred in inhabited regions pointing the strong influence of the anthropic factors. In addition, the quantification of the accumulated rains and their corresponding probability of occurrence showed that the rains of 3 days associated to the anthropic and environmental factors were those that presented higher hazard classes. Hence, the inclusion of social and meteorological aspects at the analyses as well as environmental factor emphasized the importance of these considerations in the construction of maps of mass movements.

Finally, the achievement of the methodology was highlight at the use of only data available on the web and thus making it possible to replicate in other regions.

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