Debris flows in a tropical environment: relation between magnitude, deposits and watershed morphometry

Vivian Cristina Dias[1], Marcelo Fischer Gramani[2], Rebeca Durço Coelho[1], Helen Cristina Dias[1], and Bianca Carvalho Vieira[1]

[1]University of Sao Paulo, Sao Paulo, Brazil;

[2]Institute of Technological Research of Sao Paulo State, Sao Paulo, Brazil.

Corresponding author: vivian.cristina.dias@usp.br

Abstract

Debris flows are one of the most destructive type of mass movement causing social and economic losses when occur in areas densely occupied. Serra do Mar is a mountain range that extends through about 1.500 km in southeast coast of Brazil and is the most susceptible area to the occurrence of debris flows and landslides due its geology, geomorphology and climate. In recent Brazil history there are several disasters related to those process, highlighting Caraguatatuba, 1967; Rio de Janeiro, 2011; and Itaoca, 2014. In this way, this study aimed to contribute to the investigation of debris-flows occurrence in tropical environment focusing in the magnitude and morphological evaluation of a past event and its relationship with morphometric characteristics of watersheds. To fulfill this objective, it was selected four watersheds with register of debris flows; the determination of debris-flows deposits, morphology and magnitude; and the mapping of morphometry of watersheds. The results showed that the morphology of the deposits presented the main features also identified by literature in other occurrences, majorly in temperate environment. The magnitude classification and potential consequences of each standard was compatible with real damages registered in the watersheds. Also, morphometric analysis presented critical values in all areas, however, the altimetric gradient of longitudinal profile was significantly higher in the watershed classified with higher magnitudes, showing the importance of this parameter. This study can help in the mitigation action by government and in the understanding of main triggering factors.

1 INTRODUCTION

Debris flows are among the most destruction types of mass movements, causing a lot of damage and casualties when occurs in areas densely occupied. As major characteristics, debris flows have its potential to transport a high volume of different material through long distances, and for being a viscous plastic saturated flow, which favor the transport of large boulders. These characteristics are presented after the occurrences, in the form of deposits, which shows some features that indicate if it is a debris flow or other type of process. Some of these characteristics are inverse grading, presence of levees and large boulders (Johnson, 1970; Costa, 1984; Znamensky & Gramani, 2000; Jakob, 2005; Dias et al., 2019).

Several conditioning factors are related to the occurrence of debris flows, highlighting the watersheds dynamics and its morphometric characteristics (Thurber Consultants Ltd., 1983; Vandine, 1985; Slaymaker, 1990; Johnson et al., 1991; Jakob, 1996; De Scally et al.; 2001; Chen & Yu, 2011). The morphometry of watershed has been largely studied in the evaluation of debris flows in several aspects, such as susceptibility and magnitude analysis. It may help to evaluate a watershed predisposition to produce and transport sediments, for example, which can indicate its high or low susceptibility, and also the magnitude of some processes, specially debris flows (Jackson et al., 1987; Jakob, 1996; De Scally et al., 2001; Kanji et al., 2001; Wilford et al., 2004; Welsh & Davies, 2010; Chen & Yu, 2011; Zhang et al., 2015; Dias et al., 2016; Picanço et al. 2016).

In “Serra do Mar”, a mountain range that extend for about 1.500 km through the south and southeast coastline region of Brazil, debris-flows occurrence is quite common due to relief and climate characteristics (Jones, 1973; De Ploey & Cruz, 1979; Jica, 1991; Kanji et al., 1997; Gramani & Augusto Filho, 2004; Vieira & Gramani, 2015; Vieira et al., 2019). The mostly known disasters in Brazil occurred in Serra do Mar, highlighting Caraguatatuba and Serra das Araras, in 1967; Rio de Janeiro Mountain Range Region and Serra da Prata, in 2011; and Itaoca, in 2014 (Avelar et al. 2011; Brollo et al., 2015; Gramani & Martins, 2016; Picanço et al. 2016) (Figure 1).

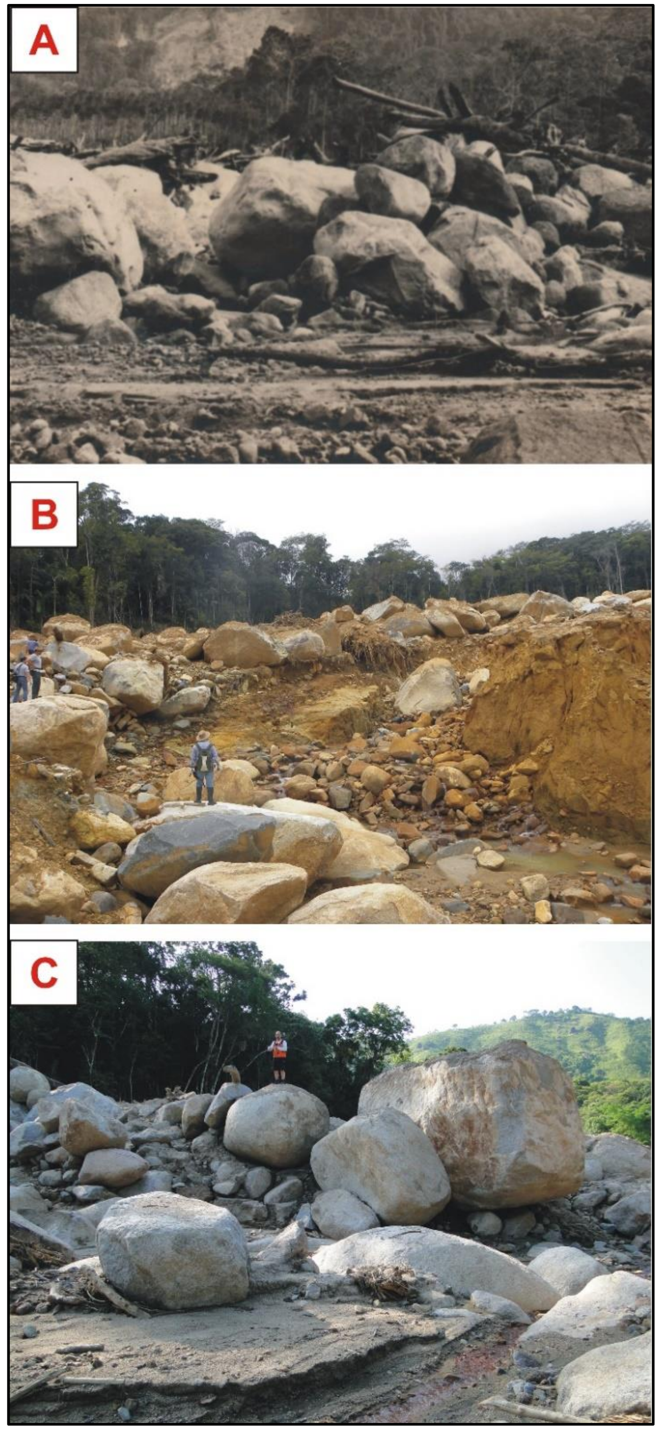

Figure 1. Debris-flows occurrences in Brazil. A: Caraguatatuba, in 1967; B: Serra da Prata, in 2011; and C: Itaoca, in 2014. Source: O. Cruz (A); GPMorfo (B); and M. Gramani (C).

Despite its frequency and potential damage, there are still a lack of studies about debris flows in Brazil. In this way, this study aimed to fill some gaps about the process occurrence in a tropical environment, focusing in the magnitude and morphological evaluation, and morphometric characteristics from watersheds. As study areas it was chosen four watersheds in Caraguatatuba, that presents register in landscape of debris-flows occurrence from the 1967 event.

2 STUDY AREA: THE 1967 DISASTER

Caraguatatuba, located in Sao Paulo State, in southeast coast of Brazil, is one of the many cities located along the Serra do Mar mountain (Figure 2).

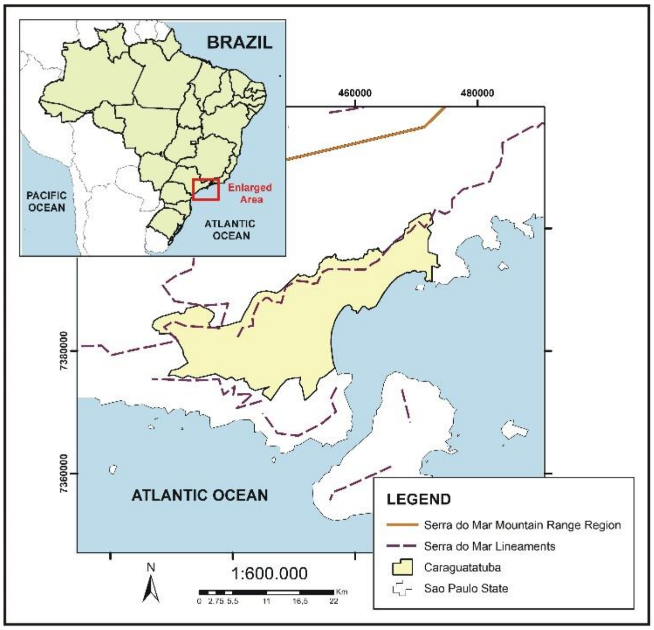

Figure 2. Location of study area.

In March of 1967 rained an average of 946 mm, with a critical value in days 17 and 18, when rained 586 mm in just 48 hours, triggering landslides and debris flows (Figure 3). About 2 million of tons of sediments and boulders were mobilized, reaching the urban area of the city, in the lowland, causing 120 deaths, the destruction of 400 houses and damaging the main highway to the city.

Almost all watersheds in the city were affected, both by landslides and debris flows. Debris flows were triggered by landslides whose materials (e.g. soil, boulder, vegetation) hit the channels already saturated by the large amount of rain, turning into a viscous plastic flow. One of the most affected watersheds was Santo Antonio, in which is located the downtown (Figure 4). At the time, most of the city was occupied by farms, which contributed to minor damages compared to the size of the disaster. Nowadays, most part of the territory it is occupied by the population, which increased the size of the urban areas. Also, recent occurrences with less impact (2017, single landslides without victims; 2020, landslide at Rio-Santos Highway without victims) highlighted the need for more studies about the occurrences in the area.

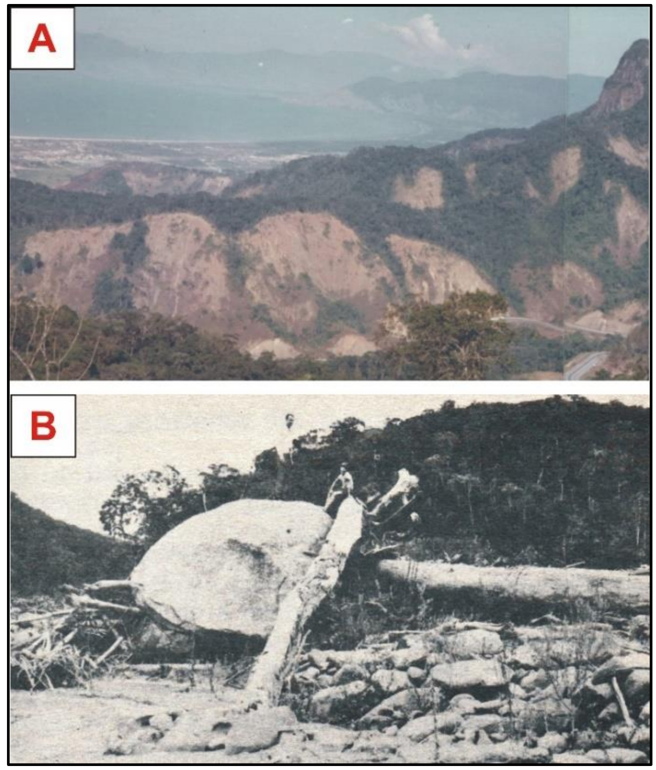

Figure 3. Caraguatatuba Disaster: landslides (A) and debris flows (B). Source: O. Cruz.

Figure 4. Destruction of a bridge in downtown. Source: Public Archive of Caraguatatuba.

3 METHODS

3.1 SELECTION OF WATERSHEDS

The selection of watersheds was carried out through field surveys and using the morphological map made by Cruz (1974; 1990) in which the author indicated the areas affected by mass movement, but without specify the typology of the processes. In the field, we identified features in landscape that indicated the occurrence of debris flows. It was selected four watersheds: Santo Antonio, Guaxinduba, Ribeirão da Aldeia, and Pau d'alho, which presented deposits still visible in the areas, despite increasing of human activities and occupation since 1967, in comparison to other watersheds.

3.2 DETERMINATION OF MORPHOLOGICAL CHARACTERISTICS OF DEBRIS-FLOWS DEPOSITS

During fields surveys it was identified both the presence of debris-flows deposits and its morphology. It was used a record (Figure 5) where we identified the presence of typical characteristics of debris-flows deposits, such as levees, inverse grading, and boulders very large, and other information. Also, it was verified the size of the boulders in the deposits, using a classification accord to the diameter in small, medium, large, and very large boulders.

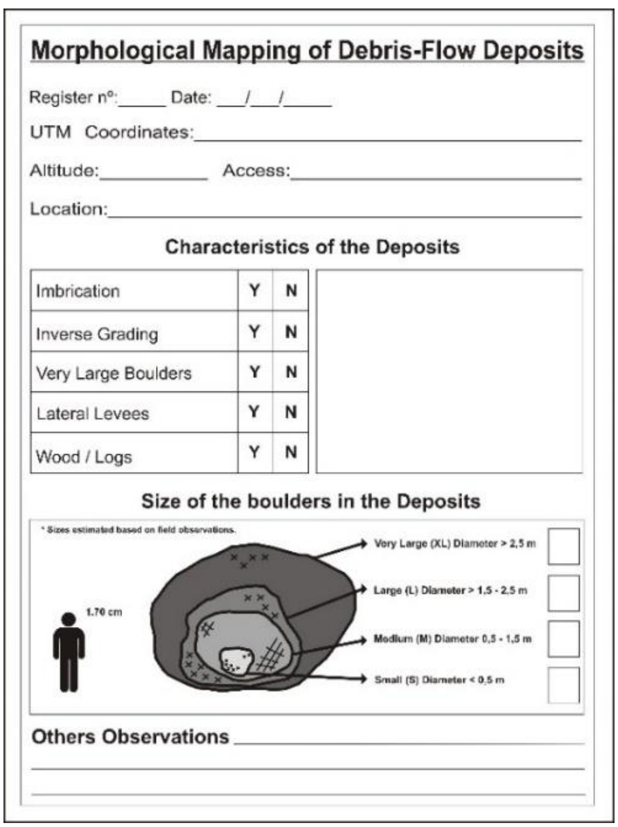

Figure 5. Field Record for morphological characterization of the deposits and size of the boulders.

3.3 DETERMINATION OF DEBRIS-FLOWS MAGNITUDE

The determination of debris-flows magnitude was carried out using the method propose by Jakob (2005) using the inundated area (m²) (Table 1). Also, it was used the mapping made by Cruz (1974; 1990) after the 1967 event to establish the inundated area by debris flows. Field surveys was also carried out in order to validate the previous mapping by identifying debris-flows deposits in the affected areas indicated by Cruz (1974; 1990).

Table 1. Magnitude classification of debris flow.

Level	Inundated area (m²)	Potential Consequences
1	$< 4 \times 10^2$	Very localized damage, known to have killed forestry workers in small gullies, damage small buildings.
2	$4 \times 10^2 - 2 \times 10^3$	Could bury cars, destroy a small wooden building, break trees, block culverts, derail trains.
3	$2 \times 10^3 - 9 \times 10^3$	Could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines.
4	$9 \times 10^3 - 4 \times 10^4$	Could destroy parts of villages, destroy sections of infrastructure corridors, bridges, could block creeks.
5	$4 \times 10^4 - 2 \times 10^5$	Could destroy parts of towns, destroy forests of 2km² in size, block creeks and small rivers.
6	$> 2 \times 10^5$	Could destroy towns, obliterate valleys or fans up several tens of km² in size, dam rivers.

Source: modified from Jakob (2005).

3.4 MAPPING OF MORPHOMETRIC PARAMETERS

The mapping of the morphometric parameters was made using a topographic map with 1:50,000 scale due to its availability in digitized format (source: Brazilian Institute of Geography and Statistics, from 1974) and SRTM (Shuttle Radar Topography Mission) from NASA, with 30 meters of resolution, in the software ArcGIS 10.1. The parameters were selected due its importance in literature to the occurrence of debris flows (Costa, 1984; Thurber Consultants Ltd., 1983; Vandine, 1985; Slaymaker, 1990; Johnson et al., 1991; Jakob, 1996; De Scally et al.; 2001; Chen & Yu, 2011; Dias et al., 2016). The parameters selected were Ruggedness number (RN), Relief ratio (RR), Drainage density (DD), Area above 25° (A25), Drainage hierarchy (DH) and Longitudinal profile (LP) (altimetric gradient of initiation and transportation/erosion).

4 RESULTS AND DISCUSSIONS

The mapping of debris-flows morphology showed that all main features related to the occurrence of debris flows (levees, inverse grading and large boulders) were founded in the four watersheds, highlighting Pau d'alho watershed, which presented deposits more preserved on riverbanks (Figure 6). These features are like the description of debris flows in literature from other climate zones, especially in temperate environment (Eisbacher & Clague, 1984; Ujueta & Mojica, 1995; Jakob, 2005).

Figure 6. Deposit of debris flow Pau d'alho watershed.

The magnitude classification using the Inundated area (m²) as a main attribute showed different levels in the four watersheds. Santo Antonio was classified with the higher magnitude, level 3, follow by Guaxinduba and Pau d'alho, both classified as level 2. Ribeirão da Aldeia presented the lowest classification, level 1.

Concerning to the morphometric characteristics, all watershed presented critical values to the occurrence of debris flows, highlighting the parameters ruggedness number, area above 25° and drainage hierarchy, as showed in Table 2.

Table 2. Results for the morphometric parameters in each watershed.

Parameters/ Watershed	**RN**	**RR (m/Km)**	**DD (Km/m)**	**A25 (%)**	**DH**	**LP (m)**
Guaxinduba	3444,1	77,76	3,41	31	52	320
Pau d'alho	2610,6	91,27	2,27	28	42	160
Ribeirão da Aldeia	2247,42	111,91	2,47	36	43	114
Santo Antônio	2054,8	94,34	2,2	30	62	326

Watersheds Santo Antonio and Guaxinduba, both classified with the higher levels of magnitude presented critical values for the parameter longitudinal profile (LP). In the case of Santo Antonio and Guaxinduba, the results show an altimetric gradient of 320 and 326 meters in each 1.000 meters, respectively. Pau d'alho and Ribeirão da Aldeia presented lowest values to LP, 160 and 140 meters, respectively, almost three times smaller than Santo Antonio. The values for LP indicate that the watersheds have a higher altimetric gradient, which favors the triggering, entrainment and range of the debris flows, once it is a process induce by gravity (Costa, 1984; Hungr et al., 2005).

The magnitude classification proposed by Jakob (2005) also indicate potential consequences related to each level of magnitude. Comparing with the damages registered in the 1967 event the potential consequences predicate was compatible with the reality. Santo Antonio, classified as magnitude level 3, had as main damages the destruction of bridges and the main highway to the city, which was very similar to the potential consequences, as follow "*could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines*". Guaxinduba and Pau d'alho, both classified as magnitude level 2 registered more local damage, as indicated by the classification "*could bury cars, destroy a small wooden building, break trees, block culverts, derail trains*". Lastly, Ribeirão da Aldeia classified with the lowest magnitude registered very located damage, also corroborate the potential consequences forecasted, as follow "very localized damage, known to have killed forestry workers in small gullies, damage small buildings".

5 CONCLUSIONS

This study produced results which corroborate the findings of a great deal of previous work in this field, highlighting here the deposition characteristics of debris flows and the potential consequences from the magnitude classification of the occurrences in the watersheds.

It was possible to verify a relation between the morphometry of watersheds and the magnitude of the occurrences, once the watersheds classified with higher magnitude showed critical values to some parameters, indicating its importance.

These findings enhance our understanding of debris flows and to the current literature, especially considering the occurrence of the process in tropical environment. However, more research is needed to better understand the specificities of debris-flows occurrence related to this specific climate zone.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge support for this project from São Paulo Research Foundation (FAPESP); Institute for Technological Research of São Paulo State (IPT); Coordination for the Improvement of Higher Education Personnel (CAPES); National Council for Scientific and Technological Development (CNPq) and the Graduate Program in Physical Geography from University of Sao Paulo (USP).

6 REFERENCES

Avelar, A. S., Coelho Netto, A. L., Lacerda, W. A., Becker, L. B., Mendonça, M. B. (2011). *"Mechanisms of the Recent Catastrophic Landslides in the Mountainous Range of Rio de Janeiro, Brazil"*. In: The Second World Landslide Forum, 2011, Roma. Landslide Science and Practice. Berlin: Springer-Verlag, vol.4. p. 265-270.

Brollo, M. J., Santoro, J., Penteado, D. R., Fernandes da Silva, P. C., Ribeiro, R. R. (2015). *"Itaoca (SP): Histórico de acidentes e desastres relacionados a perigos geológicos"*. In: 14° Simpósio de Geologia do Sudeste. Anais, Campos do Jordão – SP, 5p.

Chen, C.-Y. and Yu, F. -C. (2011). *"Morphometric analysis of debris flows and their source areas using GIS"*. Geomorphology, 129, 387 – 397.

Costa, J. E. (1984). *"Physical geomorphology of debris flows*". In: Costa, J. E., and Fleisher, J. P., eds., Developments and applications of geomorphology, New York: Springer-Verlag. p. 268 – 317.

Cruz, O. (1974). *"A Serra do Mar e o litoral na área de Caraguatatuba – SP. Contribuição à geomorfologia litorânea tropical"*. Tese de Doutorado. IG – Série Teses e Monografias nº 11, 181p.

Cruz, O. (1990). *"Contribuição geomorfológica ao estudo de escarpas da Serra do Mar"*. Revista do IG 11, p. 9 – 20.

De Ploey, J. and Cruz, O. (1979). *"Landslides in the Serra do Mar, Brazil"*. Catena 6: p. 111 – 122.

De Scally, F., Slaymaker, O. and Owens, I. (2001). *"Morphometric controls and basin response in the Cascade Mountains"*. Geografiska Annaler, 83 A (3), p. 117 – 130.

Dias, V. C., Vieira, B. C. and Gramani, M. F. (2016). *"Parâmetros morfológicos e morfométricos como indicadores da magnitude das corridas de detritos na Serra do Mar Paulista"*. Confins [Online], 29, p. 1 – 18.

Dias, V. C., Martins, T. D., Gramani, M. F., Coelho, R. D., Dias, H. C. and Vieira, B. C. (2019). *"The morphology of debris-flows deposits from a 1967 event in Caraguatatuba, Serra do Mar, Brazil"*. In: Jason W. Kean; Jeffrey A. Coe; Paul M. Santi; Paul M. Santi. (Org.). Debris-flow Hazards Mitigation: Mechanics, Monitoring, Modeling, and Assessment. 1ed.Golden: Association of Environmental and Engineering Geologists, v. 1, p. 645-652.

Eisbacher, G. H. and Clague, J. J. (1984). *"Destructive mass movements in high mountains: hazard and management"*. Geological Survey of Canada, 230p.

Gramani, M.F. and Augusto Filho, O. (2004) *"Analysis of the triggering of debris flow potentiality and the run-out reach estimative: an application essay in the Serra do Mar mountain range*". Landslide: Evaluation and Stabilization, Lacerda Ehrlich, Fountoura & Sayão (eds). 1477-1483.

Gramani, M. F. and Martins, V. T. S. (2016). *"Debris flows occurrence by intense rains at Itaoca city, São Paulo, Brazil: Field observations"*. In: Landslides and Engineered Slopes. Experience, Theory and Practice – AVERSA et al. (Eds), 9p.

Hungr, O., McDougall, S. and Bovis, M. (2005). *"Entrainment of material by debris flows"*. In: Debris-flow hazards and related phenomena (Eds. Jakob, M. and Hungr, O.). Springer, p. 135 – 158.

Jackson, L. E., Kostschuck, R. A. and Macdonald, G. M. (1987). Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. Geological Society of America. Rev. Eng. Geol. 7, 115 – 124.

Jakob, M. (1996). "*Morphometric and geotechnical controls on debris flow frequency and magnitude in Southwestern British Columbia*". Ph.D.

Dissertation, University of British Columbia, 232p.

Jakob, M. (2005). "*Debris-flow hazard analysis"*. In: Debris-flow hazards and related phenomena (Eds. Jakob, M. and Hungr, O.). Springer, p. 442 – 474.

Jica. (1991). *"The Study on the Disaster Prevention and Restoration Project in Serra do Mar, Cubatão"*. Region, S. Paulo. Jica International Cooperation Agency, January, vol. 2, 82p.

Johnson, A. M. (1970). "*Physical Processes in Geology. A method for interpretation of natural phenomena – intrusions in igneous rocks, fractures and folds, flow of debris and ice*". Freeman, Cooper & Company, San Francisco, Califórnia. 577p.

Johnson, P. A., Mccuen, R. H., Hromadka, T. V. (1991). *"Magnitude and frequency of debris flow"*. Journal of hydrology, 123. Elsevier Science Publishers B. V., Amsterdam, p. 69 – 82.

Jones, F. (1973). *"Landslides of Rio de Janeiro and the Serra das Araras Escarpments, Brazil"*. U. S. Geological Survey Professional Paper 697. United States Government Printing Office, Washington: 49p.

Kanji, M. A., Cruz, P. T., Massad, F., Araújo Filho, H. A. (1997). *"Basic and Common Characteristics of Debris Flows"*. In: II Panamerican Symposium on Landslides / II COBRAE, Rio de Janeiro, Brasil, 1:232-240.

Kanji, M. A., Gramani, M. F., Massad, F., Cruz, P. T. and Araujo Filho, H. A. (2000). *"Main Factors Intervening in the Risk Assessment of Debris Flows"*. Int. Workshop on the Debris Flow Disaster of Dec. 1999 in Venezuela, Caracas.

Picanço, J. L., Tanaka, M. J., Costa, V. V., Luiz, E. F. O., Lopes, A. B. B., Afonso, F. K., Pimenta, V. (2016). *"Debris flow hazard zonation in Serra da Prata range, Paraná State, Brazil: Watershed morphometric constraints"*. In: Landslides and Engineered Slopes. Experience, Theory and Practice – AVERSA et al. (Eds), 7p.

Slaymaker, O. (1990). *"Debris torrent hazard in Eastern Fraser and Coquihalla Valleys"*. Western Geography, Vol. 1, N. 1, Spring, p. 34 – 48.

Thurber Consultants LTD. (1983). "*Debris Torrent and Flooding Hazards, Highway 99, Howe Sound*". Report to Ministry of Transport and Highways, Victoria, British Columbia.

Ujueta, G. and Mojica, J. (1995). *"Fotointerpretacion y observaciones del flujo de escombros de Noviembre 13 de 1985 en Armero (Tolima, Colombia)"*. Geologia Colombiana, 1, p. 5 – 25.

Vandine, D. F. (1985). "*Debris flows and debris torrents in the Southern Canadian Cordillera"*. Canadian Geotechnical Journal, 22, p. 44 – 67.

Vieira, B. C. and Gramani, M. F. (2015). *"Serra do Mar: the most "tormented" relief in Brazil"*. In: Landscapes and Landforms of Brazil, World Geomorphological Landscapes, VIEIRA, B. C.; SALGADO, A. A. R.; SANTOS, L. J. C. (orgs.). Springer, p. 285 – 297.

Vieira, B. C., Matos, L. J., Alcade, A. L., Dias, V. C., Bateira, C. V. M., Martins, T. D. (2019). *"Debris flows in southeast Brazil: susceptibility assessment for watersheds and vulnerability assessment of buildings"*. In: Jason W. Kean; Jeffrey A. Coe; Paul M. Santi; Becca K. Guillen. (Org.). Debris-flow Hazards Mitigation: Mechanics, Monitoring, Modeling, and Assessment. 1ed.Golden: Association of Environmental and Engineering Geologists, v. 1, p. 597-604.

Welsh, A. and Davies, T. (2010). *"Identification of alluvial fans susceptible to debris-flow hazards"*. Landslides Volume 8, Issue 2, p. 183–194.

Wilford, D. J., Sakals, M. E., Innes, J. L., Sidle, R. C., Bergerud, W. A. (2004). *"Recognition of debris flow, debris flood and flood hazard through watershed morphometrics"*. Landslides, p. 61 – 66.

Zhang, H. Y., Shi, Z. H., Fang, N. F., and Guo, M. H. (2015). *"Linking watershed geomorphic characteristics to sediment yield: Evidence from the Loess Plateau of China*". Geomorphology 234, p. 19 – 27.

Znamensky, D. and Gramani, M. F. (2000). "*Debris-flow grain-size analysis, Debris-Flow Hazard Mitigation: Mechanics, Prediciton, and Assessment*". In: Wieczorek, G.F. and Naeser, N.D. (ed.). BALKEMA, 537-545.