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Assessment of the Influence of Rainfall and Landform on Landslide Initiation Using Physiographic Compartmentalisation

Análise da Influência da Distribuição da Chuva e do Relevo no Desencadeamento de Escorregamentos por Meio da Compartimentação Fisiográfica

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Resumo

A compartimentação fisiográfica é importante instrumento no planejamento urbano e na análise de riscos de áreas montanhosas, uma vez que identifica áreas onde processos erosivos naturais são mais suscetíveis a ocorrer de acordo com as características geológicas e geomorfológicas. A Serra do Mar é uma região naturalmente suscetível a ocorrência de movimentos de massa, especialmente escorregamentos, devido principalmente a seu relevo e clima, e, desta forma, estudos que correlacionam agentes controladores (relevo) e agentes desencadeadores (chuva) são fundamentais no desenvolvimento eficiente de programas de gerenciamento territorial e de risco. Nesse contexto, este estudo tem como objetivo a análise da suscetibilidade a escorregamento das bacias dos rios Mogi e Perequê, em Cubatão (São Paulo), por meio da compartimentação fisiográfica da região e da análise da influência do papel da chuva e do relevo no desencadeamento de escorregamentos, de acordo com os eventos de 1985 e 1994. As unidades fisiográficas foram separadas baseando-se em fotografias áreas, seguindo critérios geomorfométricos como densidade de elementos de drenagem e de relevo, amplitude e ângulo de encosta. A distribuição pluviométrica foi baseada em dados de cinco pluviômetros que abrangem a área de estudo. Como resultado, seis unidades fisiográficas foram individualizadas, sendo aquelas da vertente norte do rio Mogi as mais suscetíveis a escorregamentos, especialmente a região próxima à área urbana e industrial de Cubatão. Essa maior suscetibilidade pode ser atribuída a seu relevo, com alta declividade e solos rasos, à atividade antrópica e, principalmente, à concentração de chuvas. A compartimentação fisiográfica, portanto, é ferramenta importante no direcionamento de estudos de detalhe em áreas de grandes dimensões.
Palavras-chave: compartimentação fisiográfica; escorregamentos; Serra do Mar; distribuição de chuva; movimentos de massa

Abstract

Physiographic compartmentalisation emerges as an important instrument in urban planning and risk assessment of mountainous areas, identifying regions where natural erosive processes are more likely to occur based on landform features. The Serra do Mar escarpments are naturally prone to landslide occurrences, due to its landform characteristics and climate, and studies that correlate triggering (rainfall) with controlling (landform) factors are fundamental in the development of urban planning and risk assessment programmes. In this context, this study aims to assess the landslide susceptibility of the Perequê and Mogi River watersheds, in Cubatão (São Paulo), by compartmentalising the study area considering its physiographic features and discussing the role of rainfall and landform on landslide initiation, according to the 1985 and 1994's landslide events. Physiographic units were separated based on aerial photographs, following geomorphometric criteria such as water bodies and landform elements density, amplitude and slope. Rainfall distribution was based on pluviometric data from five rain gauges that cover the area. Six units were identified, as a result, and those at the northern slope of the Mogi River exhibit higher susceptibility to triggering landslides. This higher susceptibility can be attributed to steep slopes and thin soils, anthropic activities and, especially, rainfall concentration. Physiographic compartmentalisation, therefore, is an important auxiliary tool providing groundwork for more detailed studies in finer scales.
Keywords: physiographic compartmentalisation; shallow landslides; Serra do Mar; rainfall distribution; mass movements

1 Introduction

The physiographic compartmentalisation of mass movement prone areas emerges as an important instrument in urban planning and risk assessment of mountainous areas, since it identifies regions where these natural erosive processes are more likely to occur, based on geomorphological and geological features of the landform. The prediction of mass movements occurrences represents great challenge to the scientific community and, despite differences in analytical perspectives on these phenomena, rainfall is regarded as the main triggering effect in regions of tropical climate (Tatizana *et al.*, 1987; Crosta, 2004; Lopes *et al.*, 2007; Petley, 2012). Several studies associate shallow landslides and debris flows occurrences to short-term and long-term rainfall episodes (Lacerda, 2007; Chang *et al.*, 2011; Wilkinson *et al.*, 2012; Nikolopoulos *et al.*, 2015; Giannecchini *et al.*, 2016). It is, therefore, imperative more studies on landform response to triggering effects, identifying beforehand potential risks to avoid or mitigate socio-economic damages.

Geomorphological and geological features of the landform considerably affect slope stability and are regarded as the main controlling factors in landslides initiation (Gramani, 2001; Lopes *et al.*, 2007). At the Serra do Mar region, steep slopes that average 30-35° combined with intense rainfall rates make the region highly susceptible to mass movements occurrences (Tatizana *et al.*, 1987; Augusto Filho, 2001). The geology, comprised mainly of weathering resistant rocks such as migmatite and gneiss, influences the region's soil thickness, ranging from 1 to 2 m (Wolle, 1988; Wolle & Carvalho, 1994; Gramani, 2001). Shallow landslides and debris flows are the main erosive processes that naturally occur on the slopes of Serra do Mar, even in those that are not directly affected by anthropic impacts (Wolle, 1988).

Slope stability studies that correlate triggering factors, e.g. rainfall, with controlling factors are extremely relevant, since they provide the foundation for the development of risk assessment and risk prevention programmes in mass movements prone areas. In this context, this study aims to analyse the 1985 and 1994's landslides episodes that occurred in the Perequê and Mogi watersheds, in Cubatão (São Paulo State - Brazil), by compartmentalising the study area according to physiographic features and discussing how rainfall distribution and landform affected landslides initiation.

2 Study Area

The São Paulo state's portion of the Serra do Mar exhibits high rainfall index, especially during summer months (December to March) - averaging 2,630 mm annually (Lopes *et al.*, 2007). In Cubatão, annual precipitation can surpass 3,300 mm and, in localised small watersheds such as the Pedras basin, the precipitation may reach up to 4,000 mm (Kanji *et al.*, 2008). This high rainfall index is strongly associated with mass movements occurrences, which records are commonly observed in the region's history.

In January 1985, landslides in Perequê River's watershed caused intense mobilization of slope material into the river channel, which generated mud and debris flows that reached great distances and caused severe damages (Lopes *et al.*, 2007). Similarly, in February 1994, thousands of shallow landslides on Rio das Pedras' slopes, part of Mogi's watershed, originated debris flow that hit "*Presidente Bernardes*" refinery, from the Brazilian oil company Petrobras, causing a halt in the refinery activity and 40 millions US dollars in damages (Lopes *et al.*, 2007). Figure 1 shows the location of the study area, eastern part of Cubatão encompassing both Perequê and Mogi watersheds.

The region is at the transition of two Geomorphological Provinces: the Atlantic Plateau Province (*Província do Planalto Atlântico*) and the Coastal Province (*Província Costeira*) (Almeida, 1964). In the Atlantic Plateau, the Small Hills Landform is found (*Relevo de Morrotes*), where rounded landforms dominate, with amplitude of less than 50 m (Paula *et al.*, 2008). In the Coastal Province, there are two separate landform systems within the Serra do Mar Escarpments: Festooned Escarps (*Escarpas Festonadas*), that comprise the actual Serra do Mar escarpment, and Interdigitated Escarps and Peaks (*Espigões Interdigitados*), which resulted from fluvial erosion of the main escarpment (Festooned Escarps) and are interdigitated with the Atlantic Plateau Province (Ponçano *et al.*, 1981; Paula *et al.*, 2008).

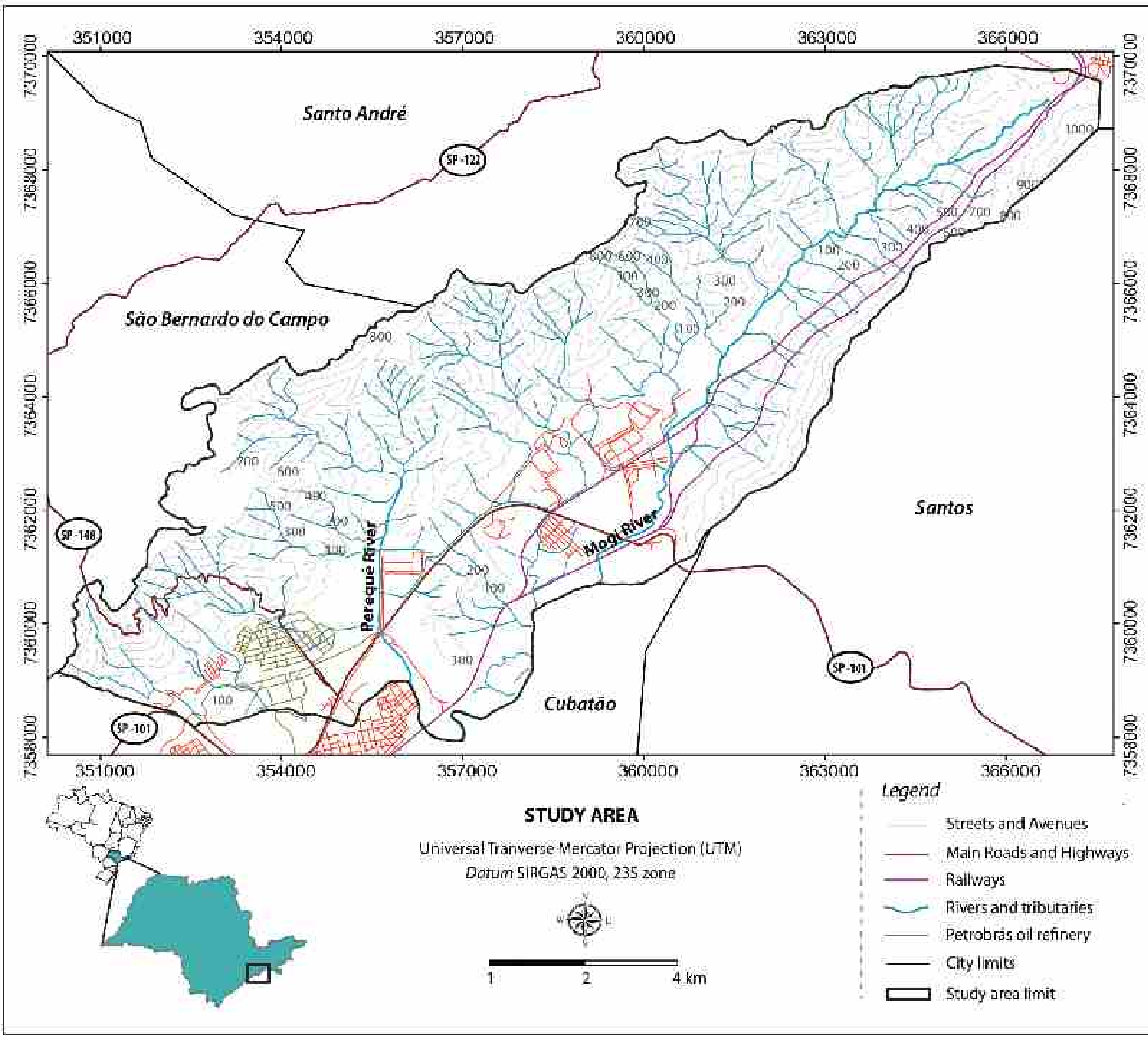

Figure 1 Location of the study region. UTM, datum SIRGAS 2000, 23S zone

Cubatão is located within the Mantiqueira province, which is divided into three Orogenic Belts – Araçuaí, Tijucas and Ribeira – and it is in the context of the Ribeira Belt that the study region is inserted (Hasui, 2012). The Ribeira Belt is comprised of two blocks: at north, Juquitiba Block, where the Açungui Group (Upper Proterozoic) dominates and, at south, Costeiro Block, with Costeiro Complex rocks (Archean), with the Cubatão shear zone separating the two blocks (IPT, 1986). Figure 2 shows the geological map of the study region, based on the mapping made by IPT (1986).

3 Materials and Methods

The materials employed in this study were: aerial photographs and ortophotos of the study area, Cubatão's topographic and geological maps (Table 1). The region's rainfall data were obtained from the Rainfall database of the Department of Water and Energy (DAEE – *Departamento de Água e Energia*) of the São Paulo State. The landslide scars extraction and physiographic compartmentalisation were based on the photoanalysis and photointerpretation methodologies.

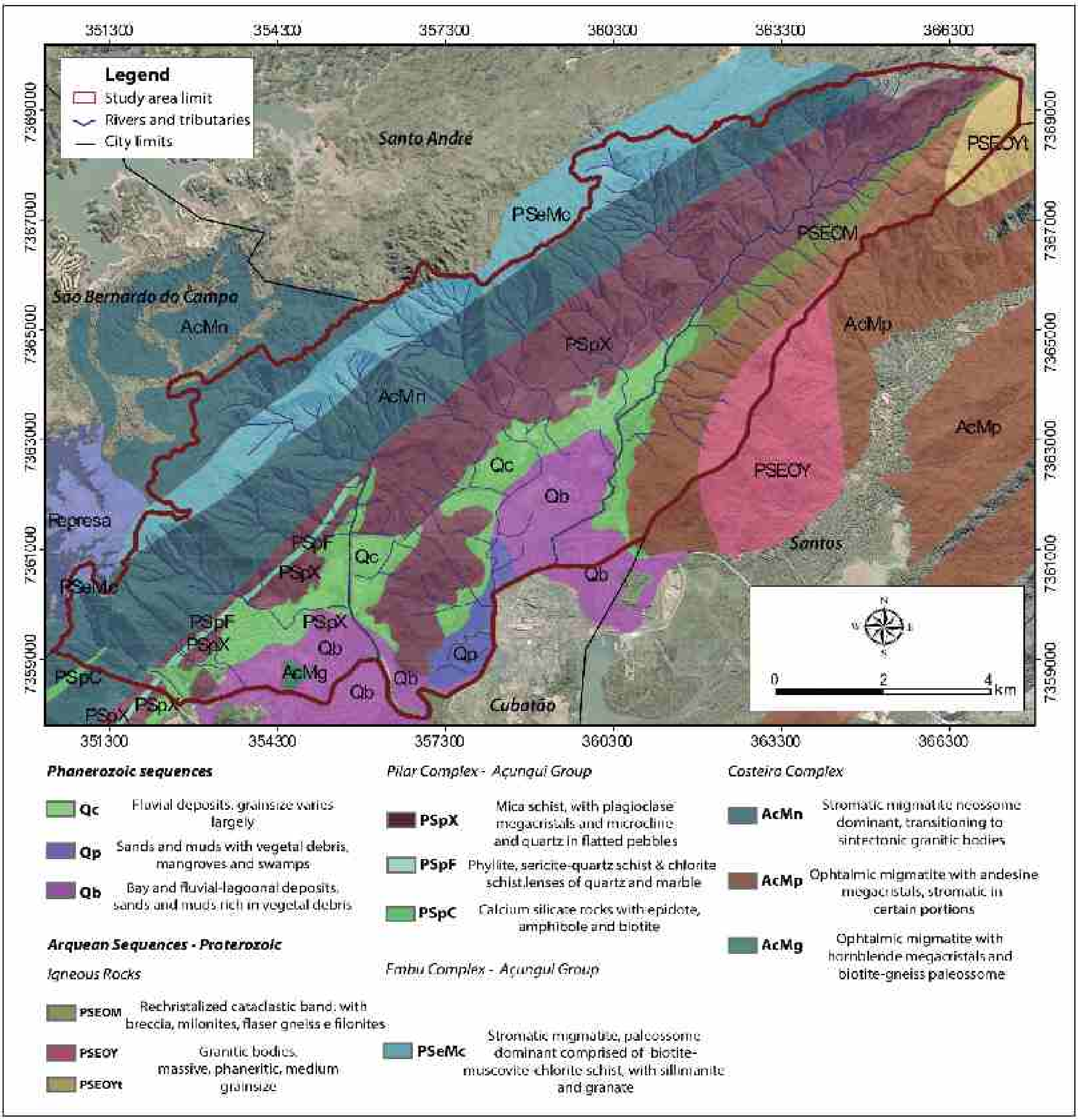

Figure 2 Geological map of the study region, based on IPT (1986). UTM, datum SIRGAS 2000, 23S zone.

3.1 Cartographic Products

Based on the topographic map with 20 m contours, the digital elevation model (DEM) was created with a resolution of 25 m (Hengl, 2006) in Universal Transverse Projection (UTM), datum SIRGAS 2000 - 23S zone. The ANUDEM interpolation method was used in DEM creation. In order to avoid errors due to the resolution of the data, sinks and peaks were addressed using the geoprocessing software's tool "Fill" of the extension "Spatial Analyst Tool". The DEM acted as the foundation for the creation of the curvature and slope maps. The slope map classi-

Material	Scale	Source	Year
Ortophotos	1:4,000	São Paulo State Metropolitan Planning Company (Empresa de Planejamento metropolitano do Estado de São Paulo - EMPLASA)	2011
Aerial Photographs	1:25,000	Technological Research Institute (Instituto de Pesquisas Tecnológicas - IPT)	1985 and 1994
Geological Map	1:25,000	Technological Research Institute (Instituto de Pesquisas Tecnológicas - IPT)	1986
Topographic Map	1:50,000	Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística - IBGE)	-
Rain Gauge Data	-	São Paulo State Water and Energy Department (Departamento de Água e Energia do Estado de São Paulo - DAEE)	1985 and 1994

Table 1 Material employed in this study.

fied the region into 5 slope range classes: 0° - 5°, 5° - 15°, 15° - 30°, 30° - 45° and 45° - 63°, which best represent the overall slope declivity distribution of the study region. The curvature map was created through "curvature" tool, classifying the region's slope into three types: concave, straight and convex.

The rainfall distribution map was constructed based on the data from seven rain gauges that cover the study region, analysing rainfall pattern of the 1985 and 1994 mass movements events. These maps were made using simple linear interpolation, classifying six different classes through natural breaks. The accumulated rainfall for January 22nd and 23rd, 1985, was 265 mm and for February 6th and 7th, 1994, was 377 mm. Curvature, slope and rainfall distribution maps were fundamental in the characterisation of the study region and, hence, in the physiographic compartmentalisation.

3.2 Photoanalysis and Photointerpretation

The identification of landform features and landslides scars of the landslides events was based on ortophotos and aerial photographs, respectively. The visual photointerpretative criteria in landslide scars recognition were: lack of vegetation, characteristic morphology (elongated, length superior to width) and drainage conditions of hill slopes (Soeters & Van Westen, 1996; Moine et al., 2010). 1679 and 542 landslide scars were extracted from the aerial photographs of the 1985 and 1994 events, respectively, as shown in Figure 3.

The physiographic compartmentalization is based on an integrated analysis of the landform, using landscape patterns as reference standards (Fernandes-da-Silva et al., 2010; Zaine 2011). Recent studies have applied physiographic compartmentalisation in environmental and territorial management (e.g. Cardoso et al., 2009; Silva et al., 2010; Zaine, 2011; Côrrea et al., 2014; Pilachevsky et al., 2015; Amaral et al., 2015). The procedures for the physiographic compartmentalisation in this study are based on Zaine (2011), which follows the steps of photoanalysis and photointerpretation.

Photoanalysis consists in the division of an area based on relief elements and the geology, which control the landform response to erosive processes. The analyses of the shape, texture, and structure of the landform elements were considered as reference for the delimitation of the different compartments, following the propositions of Zaine (2011) (Figure 4). The geological aspects used in the compartmentalisation are based on the geological map of Figure 2. Photointerpretation consisted on the assimilation of the data obtained from photoanalysis, judging their significance (Colwell, 1960) and, as a result, supporting the risk assessment of each compartment, according to mass movements susceptibility and socioeconomic damages.

The classification chart (Figure 4), based on Zaine (2011), considers the textural density (drainage and landform elements), form and slope characteristics, geological structures and complementary data, such as land-use and landform processes susceptibility. According to Soares & Fiori (1976), photoanalysis is the association and ordering of the observed features and photointerpretation is the assessment of the meaning, function and relationship between those features.

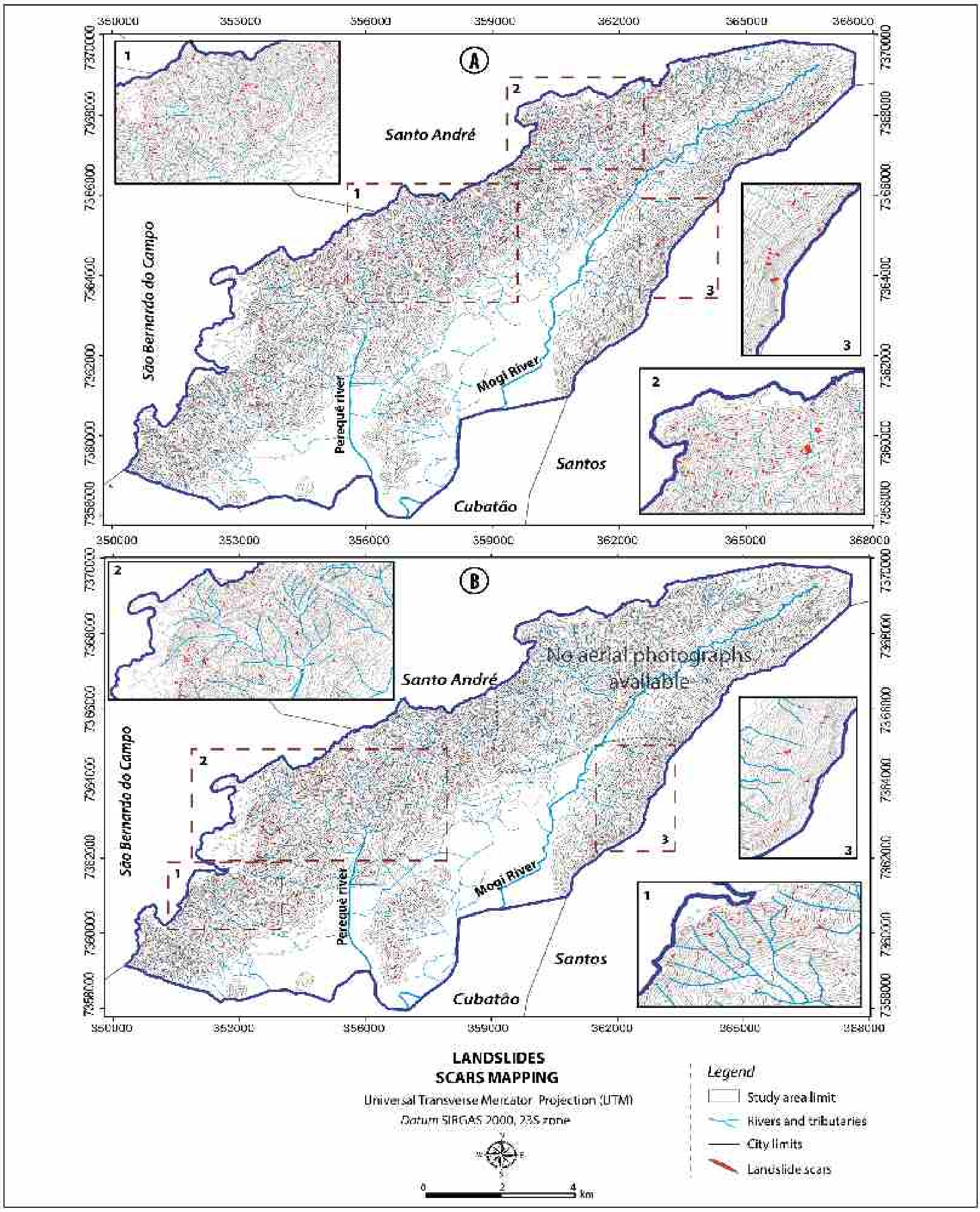

Figure 3 Landslide scars maps. A) Landslide scars extracted from aerial photographs post 1985 event. B) Landslide scars extracted from aerial photographs post 1994 event, where no aerial photographs are available at the northeastern portion of the area

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CRITERIA		CLASSES		
PHOTOANALYSIS	Drainage System Density	**Low**  (0 to 5/10 km²)	**Medium**  (5 to 50/10 km²)	**High**  (>20 km²)
	Landform Elements Texture Density	**Low** 	**Medium** 	**High** 
PHOTOINTERPRETATION	Permeability	**High**	**Medium**	**Low**
	Run-off/infiltration	**Low**	**Medium**	**High**
	Unconsolidated materials depth	**Deep**	**Medium**	**Thin / nonexistent**
PHOTOANALYSIS	Local Amplitude	**Small (0 to 100m)**	**Medium (100 to 300m)**	**Large (>300m)**
	Slope declivity	**Low (0 - 15%)**	**Medium (15 - 30%)**	**High (>30%)**
	Slope Form	**Convex** 	**Concave** 	**Straight** 
	Form of Valley	**unconfined** 	—	**confined** 
	Form of Peaks and Tops	**Plain**	**Rounded**	**Steep**
PHOTOINTERPRETATION	Bedrock depth	**Deep**	**Medium**	**Shallow/outcropping**
	Mass movements initiation potential	**Low**	**Medium**	**High**

Figure 4 Landform classification chart, adapted from Zaine (2011).

4 Results

4.1 Rainfall distribution

At the study region, rainfall plays a major role in landslide initiation. When comparing rainfall distribution of the 1985 and 1994's landslide events (Figures 5 and 6) with the landslide scars maps, it is evident the rainfall influence in triggering landslides. Rainfall distribution during January 22nd and 23rd, 1985, shows that rainfall was concentrated at the central and northeastern part of the study area, where the density of landslides scars is higher. Similarly, rainfall distribution from February 6th to 7th, 1994, shows higher rainfall index at the southwestern part of the study area, where landslide scars are also concentrated.

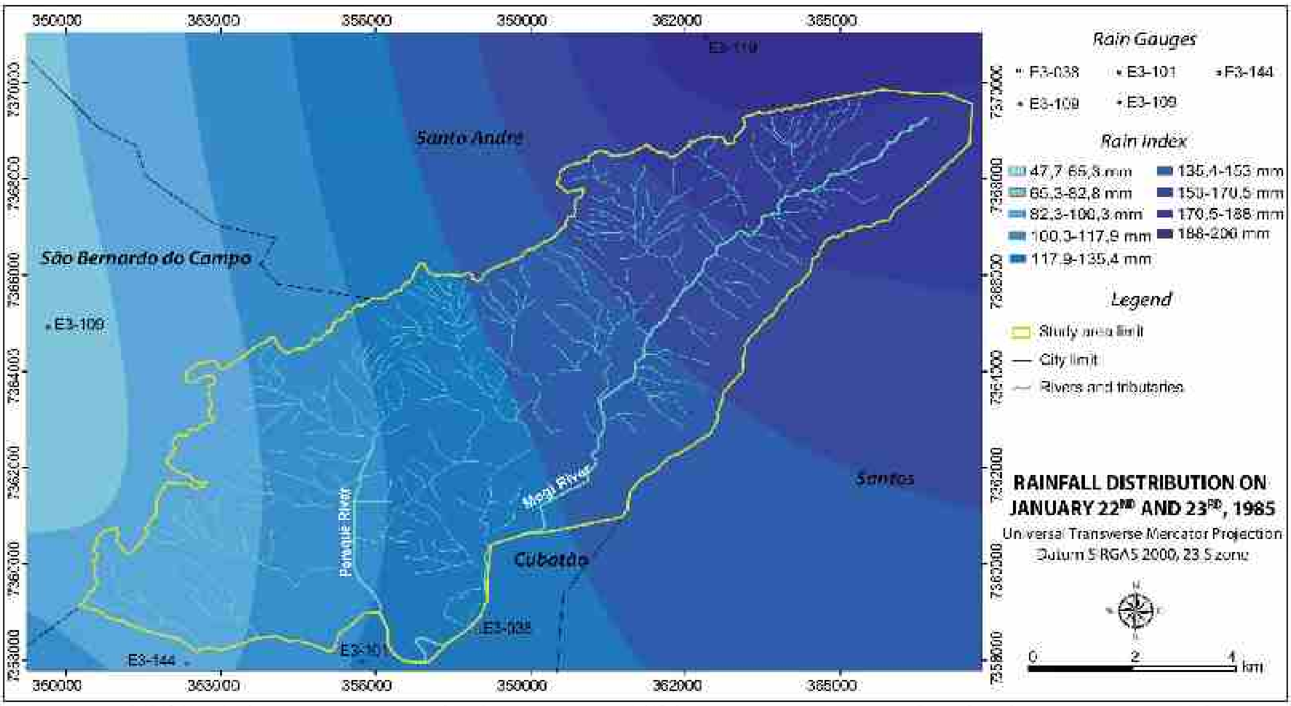

Figure 5 Rainfall distribution on January 23rd and 24th, 1985. Rainfall is concentrated at central and northeastern portion of the study area, where landslide scars are also concentrated.

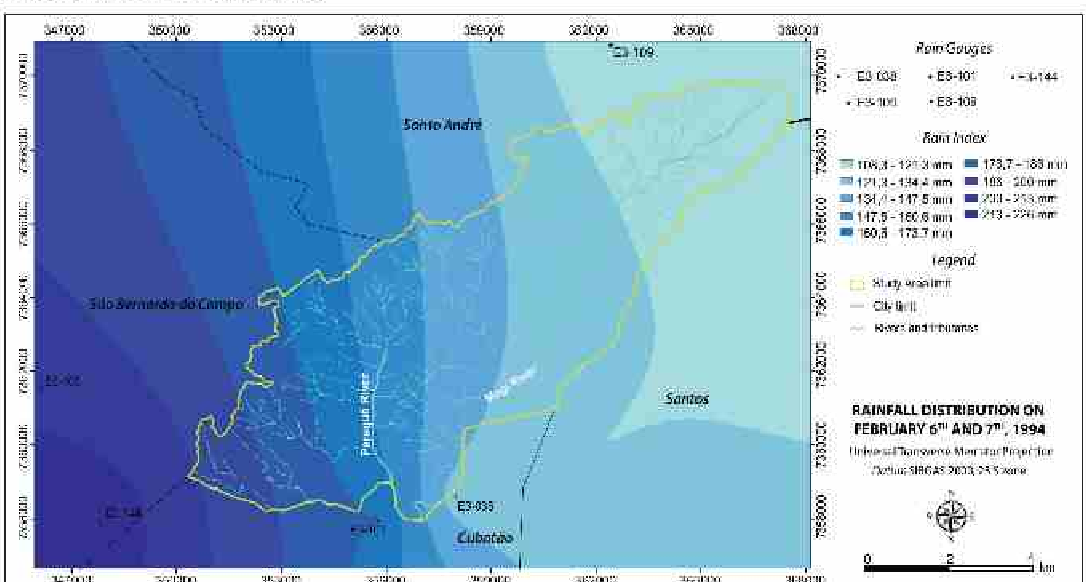

Figure 6 Rainfall distribution on February 6th and 7th, 1994. Rainfall is concentrated at southwestern portion of the study area, where landslide scars are also concentrated.

4.2 Physiographic Compartmentalisation

Six (6) physiographic units were identified (Figure 7), based on the criteria from Zaine (2011), and Figure 8 exhibits the photoanalysis and photointerpretation results that individualised each compartment. Moreover, Figure 9 shows the concentration of landslide scars according to each of the physiographic units. Unit 4 and, especially, unit 5 exhibit higher concentrations of landslide scars within the study region – both encompassing the northern slope of the Mogi River, within the Juquitiba Block.

In unit 1, the drainage density is medium to high, since it is on the pathway to the fluvial system discharge into the ocean, and landform elements texture density is low. The amplitude is very small, due to the lack of slopes or hills in the unit. Unit 1 is within the Coastal (*Costeira*) Geomorphological Province and the geology is comprised mainly of colluvial and alluvial deposits (Qc, Qb, Qp). Due to its plain relief, Cubatão's urban and industrial area is located within this unit, including Petrobras' oil refinery.

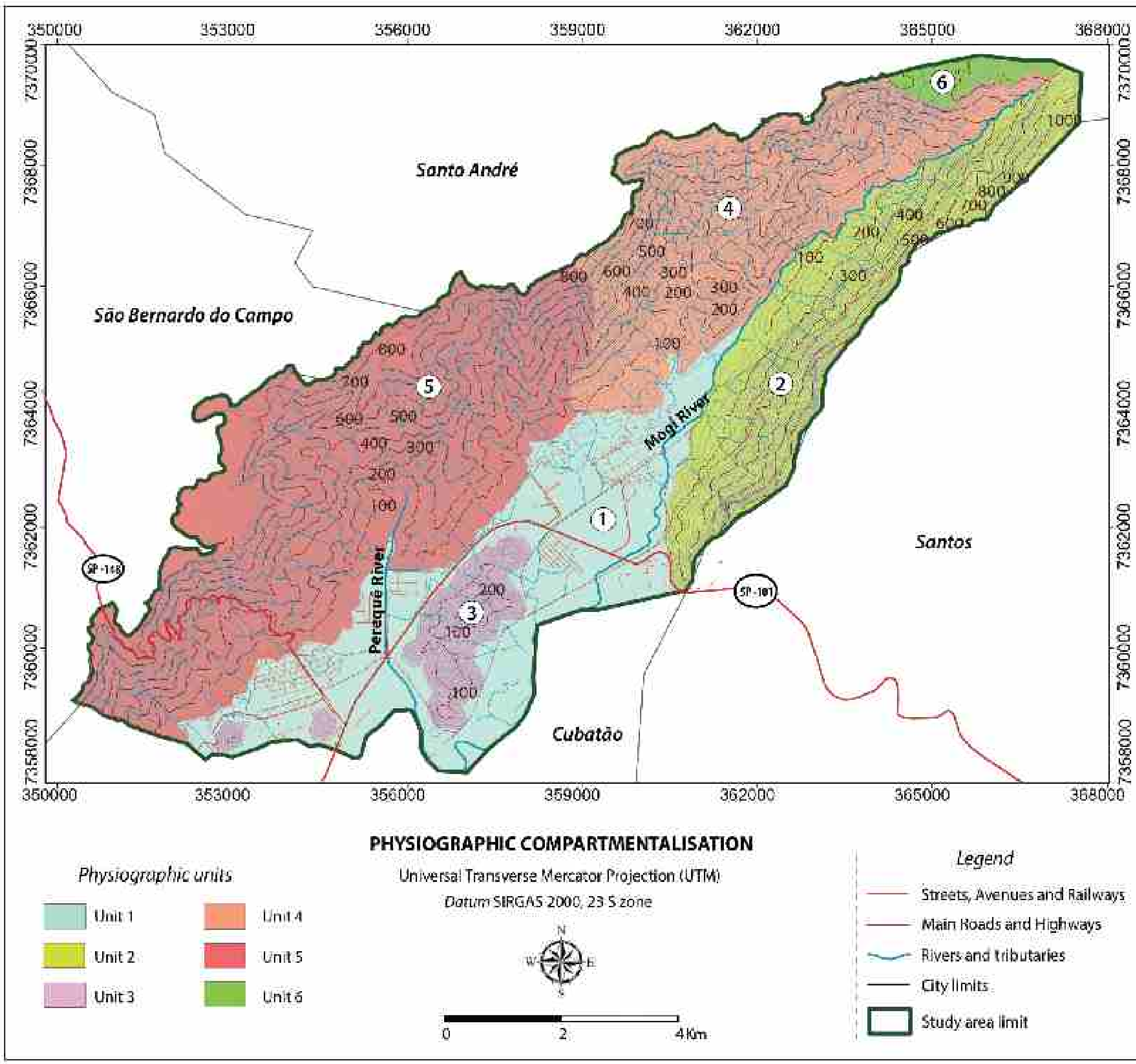

Figure 7 Compartmentalisation map of the study region.

Physiographic unit	Geology	Photoanalysis							Photointerpretation				
		Water body density	Landform elements texture density	Amplitude	Declivity	Slope form	Form of valley	Form of peaks and tops	Mass movement potential	Permeability	Run-off/ Infiltration	Bedrock depth	Unconsolidated Materials Depth
1	Alluvial deposits and detritic undifferentiated covers	High	Low	Small	Low	Plain	Unconfined	Plain	Low	High	Low	Deep	Deep
2	Granite and Migmatitic Gneiss	Medium	High	Large	High	Straight/ Convex	Confined	Steep	High	Low	High	Shallow	Thin
3	Banded Gneiss	Low	Low	Medium	Medium	Convex	Confined	Rounded	High	Low/ Medium	High/ Medium	Shallow	Thin
4	Ortogneiss, Milonite and Schist	High	Low	Large	High	Straight/ Convex	Confined	Steep	High	Low	High	Shallow	Thin
5	Milonite and Migmatitic Schist	High	High	Large	High	Straight/ Convex/ Concave	Confined	Steep	High	Low	High	Shallow	Thin
6	Ortogneiss, Milonite and Gneiss	Medium	Medium	Small	Low	Convex	Unconfined	Rounded	Low	Medium	Medium/ Low	Deep	Medium

Figure 8 Physiographic compartmentalisation criteria of each unit.

Unit 2 is within the Costal province and exhibits a medium to low drainage system density and landform features texture. Amplitude is very high, ranging from 100 m to 1000 m, and the form of slopes is mainly straight. Geology is comprised of igneous (PSEOY, PSEOYt) and metamorphic (AcMp, PSEOM) rocks. The potential for mass movements initiation is high, especially shallow landslides, due to steep (15° – 30°), straight slopes with thin layers of soil/unconsolidated materials. Within unit 2 is located the MRS logistics company's railway, as well as the abandoned *funicular* railway, that can be affected by these erosive processes.

Unit 3 comprises the isolated hills of the study area and exhibits low drainage system density and low landform elements texture density. Its amplitude is medium, ranging from 20 m to 220 m, with convex slopes and confined valleys. The unit is within the Coastal Province and the geology is comprised of metamorphic rocks (PSpX, AcMg). The potential for mass movements initiation is high and these processes can affect portions of urban and industrial areas, due to industries located at the foot of these isolated hills and the proximity to unit 1.

Unit 4, at the northern slope of the Mogi River, presents high density of drainage system and high landform elements texture density. With high amplitude (100 m to 900 m) and steep (30° – 45°), mainly convex slopes, its potential to mass movements initiation is very high. Unit 4 is also located within the Coastal Province and the geology is comprised of high-grade metamorphic rocks (AcMn, PSeMc). No industries, infrastructures or urban perimeters are located within this unit nor can be affected by the unit's erosive processes directly.

Similar to unit 4, unit 5 exhibits high drainage system density and landform elements texture, high amplitude and steep slopes. Slope forms are more varied, exhibiting convex, straight and concave slopes. It is also located within the Coastal Province and it is comprised of high-grade metamorphic rocks (AcMn, PSeMc, PSpC). Mass movements' initiation potential is very high and since several industries are located at the foot of this unit, as well as several infrastructures (pipelines, highways, hydroelectric power plant) within, unit 5 is highly susceptible to socioeconomic damages.

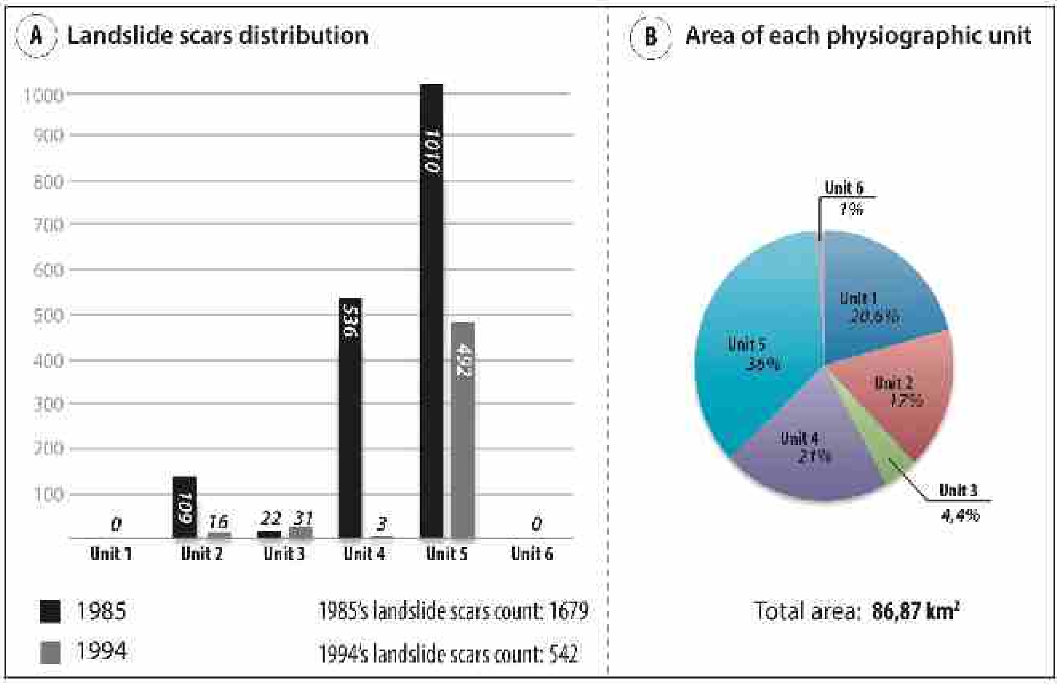

Figure 9 Landslide concentration according to physiographic units of the study region. Unit 5 concentrates landslide scars.

Unit 6 is the only physiographic unit within the Atlantic Plateau Province and it exhibits low drainage system density and landform elements texture. The amplitude is low, with convex slopes and confined valleys. It is the smallest unit of the region, at the head of the Mogi watershed, and is comprised of high-grade metamorphic rocks (AcMn). The potential for mass movements initiation is low and there are no urban or industrial areas within the unit.

5 Discussion

When analysing and comparing the distribution of rainfall and landslides scars from the 1985 and 1994 events, it is evident how rainfall plays a major role in landslide initiation in the Serra do Mar escarpments. The higher concentration of landslides scars in unit 4 and 5 are intrinsically related to rainfall patterns shown in figures 5 and 6. Unit 2, comprising the southern slopes of the Mogi River, exhibits a significantly lower landslide scars density than the northern slope units, even though it presents similar landform and geological characteristics and, hence, geotechnical behaviour.

The greater susceptibility of units 4 and 5 are also related to its landform features, identified and individualised using the photoanalysis and photointerpretation. Steep slopes, with straight/convex forms, high infiltration rate and thin soils contribute to landslides initiation susceptibility, though rainfall appears to play a more direct and intense role as a triggering factor. Unit 5 stands out in the region, due to the greater concentration of landslides scars and the presence of important industries and infrastructure.

The greater susceptibility of unit 5 can be related no only to rainfall patterns and landform features, but also to anthropogenic activities. Air pollution, for instance, can affect negatively the surrounding vegetation (Katz & Shore, 1955; Klumpp et al., 1996; 1998) that, in turn, can reduce soil's strength leading to slope failure. More detailed studies, therefore, must be concentrated at unit 5, considering anthropogenic influence on landslide susceptibility, as well as rainfall patterns encompassing a wider range of mass movements events.

Virtually almost all of the compartmentalised units are highly susceptible to mass movements' initiation, as shown in figure 8. Units 2 and 3 are also highly susceptible to mass movements, as is interpreted based on photoanalysis. The average depth of the Serra do Mar escarpments' soils are estimated at

1 to 2 m, according to Wolle & Carvalho (1994), and the measured total porosity of soils in the escarpments is 65% (Vieira et al., 2015), which is coherent with photointerpretation. If rainfall patterns, therefore, were concentrated at unit 2 or 3, the density of landslide scars in these units would be much higher.

Another parameter that greatly controls slope stability is water table depth (Morgenstern, 1963; Lane & Griffiths, 1967; Jia et al., 2009), which is difficult to identify using remote sensing techniques such as the physiographic compartmentalisation. However, the anisotropic and heterogeneous nature of soils, especially in tropical, admits many hydraulic discontinuities that significantly influences slope failure (Campos et al., 1992; Brugger et al., 1997; Terlien, 1997; Gerscovich et al., 2006), which even in situ geological-geotechnical mapping cannot account for.

The identification of different geotechnical characteristics of the landform using physiographic compartmentalisation is of great interest in different activities and applications, such as engineering design and slope stability studies. Studies based in photoanalysis and photointerpretation, however, must be considered starting points for more detailed studies. Through the physiographic compartmentalisation, there is a better understanding of the overall processes that occur in a region, according to particularities of the terrain.

6 Conclusions

Based on the criteria established by Zaine (2011), six physiographic units were identified, aiding the landslide susceptibility assessment of the Perequê and Mogi watersheds in Cubatão, São Paulo – Brazil. Most of the study area is naturally prone to mass movements initiation due to Cubatão's development at the foot of the Serra do Mar escarpments.

Nonetheless, when comparing the physiographic compartmentalisation with rainfall distribution patterns of the 1985 and 1994's landslide events, the northern slope of the Mogi River valley exhibits higher susceptibility, especially unit 5. This higher susceptibility of unit 5 can be attributed to its physiographic features, with steep slopes and thin soils, and anthropogenic activities, especially air pollution that can affect negatively soil's strength.

Landform characteristics, such as steep slopes with straight/convex forms, high infiltration rate and thin soils, contribute to landslides initiation susceptibility, though rainfall appears to play a more direct and intense role as a triggering factor. More detailed studies, therefore, must consider anthropogenic influence on landslide susceptibility, as well as rainfall patterns encompassing a wider historical range of mass movements events on unit 5.

An overview of how landform features and climate interact is very important when applying the physiographic compartmentalisation on landslide susceptibility studies. Physiographic compartmentalisation is an important instrument in urban planning and risk assessment of mountainous areas, providing an overview of the landform response to climate and erosive processes. It is, therefore, an auxiliary tool providing groundwork for more detailed studies.

7 Acknowledgments

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