Anuário do Instituto de Geociências
Universidade Federal do Rio de Janeiro
https://revistas.ufrj.br/index.php/aigeo/

ISSN 0101-9759
e-ISSN 1982-3908

Assessment of the Potentiality to the Debris-Flow Occurrence from Physiographic and Morphometrics Parameters: a Case Study in Santo Antônio Basin (Caraguatatuba, São Paulo State, Brazil)

Avaliação da Potencialidade à Ocorrência de Corridas de Detritos a Partir de Parâmetros Fisiográficos e Morfométricos: Estudo de Caso na Bacia Santo Antônio (Caraguatatuba, SP)

Claudia Vanessa Santos Corrêa[1], Fábio Augusto Gomes Vieira Reis[1], Lucilia do Carmo Giordano[1], Victor Carvalho Cabral[1], Marcelo Fischer Gramani[2], Beatriz Marques Gabelini[1], Beatriz Guzzo Duz[1] & Vinicius Queiroz Veloso[1]

[1]São Paulo State University (Unesp), Institute of Geosciences and Exact Sciences, Geology Department, Rio Claro, São Paulo, SP, Brazil
[2]IPT – Institute for Technological Research, São Paulo, SP, Brazil
E-mails: claudia.correa@unesp.br; fabio.reis@unesp.br; lcg@ecogeologia.com.br; victor.carvalho@unesp.br; mgramani@ipt.br; beatriz.gabelini@unesp.br; b.duz@unesp.br; viniciusqveloso@gmail.com

Abstract

This work aims to evaluate the potential for the debris-flow triggering from Santo Antônio hydrographic basin, located in the Serra do Mar region on North Coast of the State of São Paulo, Brazil, based on physiographic attributes, rainfall data, and morphometric parameters. For this purpose, hydrographic basin techniques were applied, assessing the vulnerability to the debris flow from geomorphological, geological, climatic, and anthropic aspects, and morphometric parameters relevant to the triggering of these processes in watersheds were calculated. Seven physiographic units were identified, which supported the understanding of geological and geomorphological aspects of the basin: coastal plains; river plains; colluvium and talus ramps; escarpments of Serra do Mar; upland of Paraitinga; mountainous relief and hillocks domain. The sub-basins located in steep sections of the relief, with high slopes, valleys, and channels docked, high drainage densities present higher values in the morphometric parameters, indicating a greater potential for triggering and occurrence of debris-flow processes. The joint analysis of physiographic compartmentalization with the identification of relief features, slope, amplitude, valley, slope shapes and morphometric parameters, is extremely relevant to recognize hydrographic basins susceptible to debris flows, as it integrates, and correlates aspects of the physical environment considered to trigger in the occurrence of these processes.

Keywords: Hydrogeomorphological processes; Serra do Mar; Physical environment attributes

Resumo

O objetivo deste trabalho foi avaliar a potencialidade à deflagração de corridas de detritos da bacia hidrográfica Santo Antônio, situada na região de Serra do Mar no Litoral Norte do Estado de São Paulo, Brasil, a partir de atributos fisiográficos, dados pluviométricos e de parâmetros morfométricos. Para tal, foram aplicadas técnicas de compartimentação fisiográfica, avaliada a vulnerabilidade à corrida de detritos sob à ótica dos aspectos geomorfológicos, geológicos, climáticos e antrópicos e adicionalmente foram calculados parâmetros morfométricos relevantes à deflagração desses processos em bacias hidrográficas. Foram identificadas na área de estudo sete unidades fisiográficas, que subsidiaram o entendimento dos aspectos geológicos e geomorfológicos da bacia: planícies costeiras; planícies fluviais; rampas de colúvio e tálus; escarpas da Serra do Mar e espigões digitados; planalto de Paraitinga; relevo montanhoso e mares de morro. As sub-bacias situadas em porções escarpadas do relevo, com altas declividades, vales e canais encaixados, elevadas densidades de drenagem apresentam maiores valores nos parâmetros morfométricos, indicando uma maior potencialidade à deflagração e ocorrência desse processo. A análise conjunta da compartimentação fisiográfica com identificação de feições do relevo, como a declividade, a amplitude, as formas do vale e da encosta e os parâmetros morfométricos possui extrema relevância na identificação de bacias hidrográficas suscetíveis a corridas de detritos, por integrar e correlacionar aspectos do meio físico considerados deflagradores na ocorrência desses processos.

Palavras-chave: Processos hidrogeomorfológicos; Serra do Mar; Atributos do meio físico

1 Introduction

The debris flows are hydrogeomorphological processes characterized by their high erosive capacity and with a large volume of water in their flow, capable of mobilizing materials of different compositions and dimensions during their trajectory. Kang & Lee (2018) highlight that because they can cross long distances and reaching high speeds, the threat of debris flows is greater than other geodynamic processes. In general, these processes are characterized by a movement in the form of flow, involving generally dense fluids, composed of coarse material and fine material, as well as plant remains and varying amounts of water (Ni & Wang 1990). Due to these characteristics, added to its high range, even in flat areas, high speeds and high peak flows, the debris flows have a high capacity of erosion and impact force, which give them great destructive power, and, therefore, are classified as high-risk factor processes, which can cause loss of life and considerable physical damage to infrastructure and the environment (Downling & Santi 2013; Kang & Lee 2018).

The occurrence and triggering of the debris flows are favored by a set of physiographic conditions that allow their formation and development, summarized in general to an abundant source of particles and debris from unconsolidated soil and/or rock, to the presence of slopes or thalwegs steep (above than 25^0), the abundant water source and the sparse vegetation (Jakob & Hungr 2005; Takahashi 2014).

As the debris flows have a hydrodynamic character, the morphometric characteristics of the hydrographic basins are also configured as important factors in the magnitude, potential, and triggering of these processes (Jakob 1996; De Scally & Slaymaker & Owens 2001; Wilford et al. 2004; Chen & Yu 2011). Other authors also emphasize the characteristics of land use as a factor that potentiates and accelerates the triggering of debris flows, as human activities such as deforestation, excavations, and construction of artificial drainages are generally aggravating factors that they contribute to the development of landslides, a type of process that is a source of materials to be mobilized in the debris-flow event (Rivera Pomés 1994; Gramani 2001).

Due to these characteristics, the phenomenon occurs naturally in mountainous regions, usually associated with high rainfall (Gramani 2001; Takahashi 2014). Collins & Znidarcic (1997) point out that in tropical and coastal areas mass movements in the form of rapid debris flows are common, causing enormous destruction in their trajectory, involving different types of soils and geological environments.

In Brazil, the area's most susceptible to its occurrence are those located at the foothills of the Serra do Mar, Serra da Mantiqueira and Serra Geral (Gramani 2001). In the municipality of Caraguatatuba, on the northern coast of São Paulo State, on March 18, 1967, one of the most expressive mass movements recorded in the State and Brazil occurred, caused by heavy rains that devastated the region, associated with the escarpment relief of Serra do Mar, causing significant social, economic, and environmental damage, with many losses of human lives (Cruz 1974; Gramani 2001). An accumulated rainfall of 586 mm in 3 days triggered widespread landslides on the slopes of the hills and Serra do Mar escarpment, whose materials reached numerous drainages and generated debris-flow processes in the urban area of Caraguatatuba city (Cruz 1974). Due to population growth, disorderly occupation, and current climate change scenario, the debris-flow occurrence has increased in Brazil in recent years, especially in mountainous areas, which requires greater knowledge about the factors that trigger these processes (Kobiyama et al. 2010).

Liu & Lei (2003) highlight that the evaluation of an area concerning its potential to generate debris-flow processes is the most effective method in the scope of awareness since it precedes real disasters and makes the diagnosis of the site in its physical and socio-economic aspects given the factors that trigger these processes. In this sense, the analysis of physiographic attributes, combined with rainfall data and morphometric parameters of a hydrographic basin, makes it possible to assess which factors control debris-flow processes, allowing to identify which places have the greatest potential for their occurrence (De Scally & Slaymaker & Owens 2001; Wilford et al. 2004; Chen & Yu 2011; Cerri et al. 2018).

Based on these premises, this work aims to evaluate the potential of debris-flows processes generation from the Santo Antônio hydrographic basin, in the Serra do Mar region of the coast of São Paulo State, Brazil (Figure 1), based on physiographic attributes, rainfall data, and morphometric parameters, to identify the places that are risks to human life. The region stands out in the Brazilian scenario for being an area where there are important highways that connect the upland to the coast, seaports, railways, pipelines, and industries, in addition to being currently in the process of urban expansion and attracting a large annual flow of tourists.

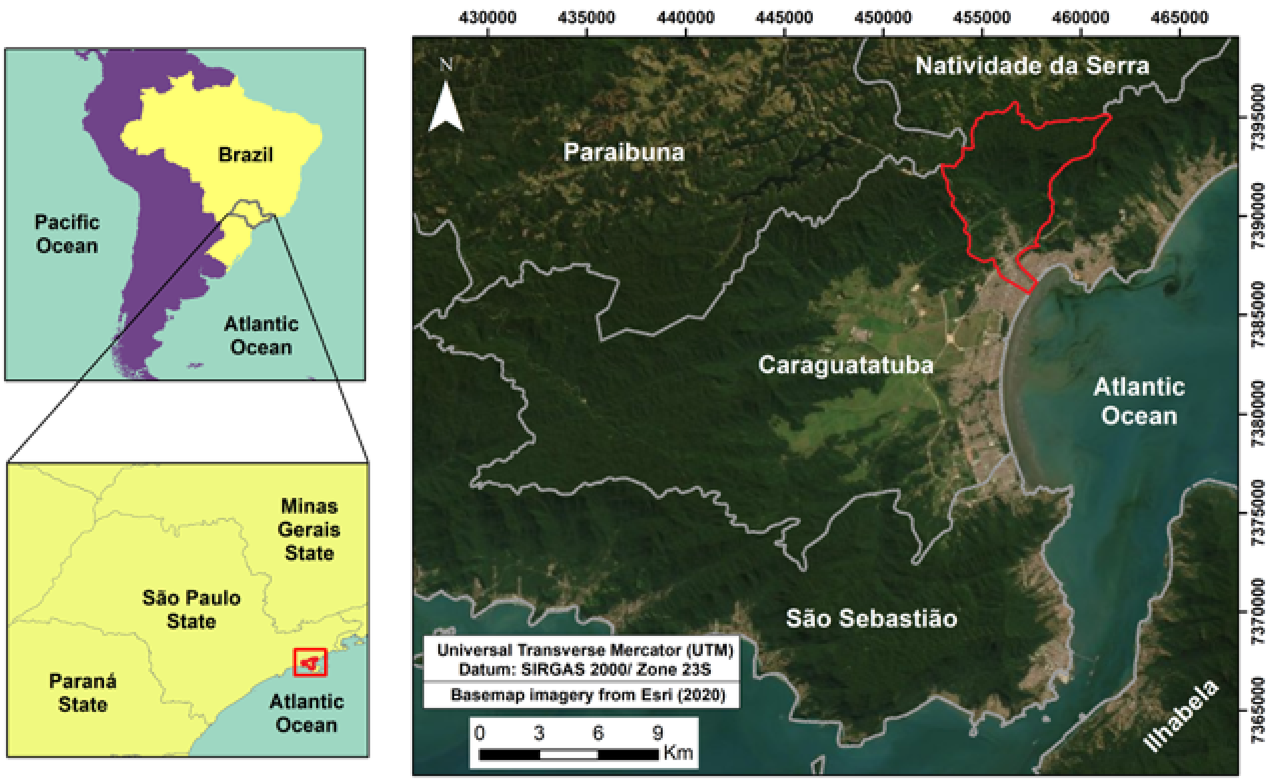

Figure 1 The geographic location of the study area (highlighted in red).

2 Methodology

For the study area, the assessment of the potential to the debris-flow occurrence was based on the premise that its triggering is closely related to the physiographic characteristics of the terrain, incidence of high rainfall, morphometric parameters, past occurrences of these processes, and the anthropic intervention (Jakob 1996; Kanji et al. 1997; De Scally & Slaymaker & Owens 2001; Wilford et al. 2004; Kobiyama et al. 2010; Chen & Yu 2011; Takahashi 2014; Cerri et al. 2018). Thus, three steps were used: the physiographic compartmentalization, the assessment of the vulnerability of sub-basins to the debris-flow processes and the use of morphometric parameters.

As for the cartographic base, the Caraguatatuba topographic chart (SF-23-YD-VI-1) (IBGE 1974) was used at a scale of 1: 50,000. In addition, the geological map at 1: 50,000 scale of Caraguatatuba sheet (CPRM 1982) was used to subsidize the steps of physiographic compartmentalization and assessment of vulnerability to debris-flow process basin in question.

As for the remote sensing data, orthophoto images from Emplasa (Paulista Metropolitan Planning Company) (2011) were used at a scale of 1: 10,000 and aerial photographs from 1973 at a scale of 1: 25,000, and high-resolution images from *Google Earth Pro®* platform were used also, to get more updated information on the land use in the region. Google Earth (GE) was launched in 2005 and has since become one of the most popular virtual globes, with wide use for teaching and research in Geosciences, mainly in studies of landscape forms and processes (Boardman 2016). It is a simulation of a virtual terrestrial globe that uses elevation data and satellite imagery from a variety of sources.

The rainfall aspects were based on accumulated hourly on 03/18/1067 in the respective watershed as related by Vargas (1999). In a GIS environment (ArcGIS 10.2.2), the respective contour lines and the drainages of the Caraguatatuba topographic chart were georeferenced and incorporated into the digital database as well as the geological map, whose lithological units have been vectorized. From the contour lines the Digital Elevation Model (DEM) and the slope map were created, which helped in the delimitation physiographic units and in the calculation of morphometric parameters.

The current land use map in the basin was prepared with the help of the remote sensing data listed above, and the identification of the classes followed the guidelines of the IBGE (2013). Also, to assist the analyzes involving the morphometric parameters, the mapping of the deposits and their respective thicknesses of the Santo Antônio Basin was prepared, which corresponds to the areas with deposits of debris-flow event from the 1967 year. Such mapping was based on the application of photointerpretation techniques in aerial photographs from 1973, whose recognition of deposits was based on their morphology, tonality, and location (Vandine 1985; Van Steijn 1996).

2.1 Physiographic Compartmentalization

The physiographic compartmentalization method adopted in this work is based on the photogeological analysis of Zaine (2011) and includes fundamental geomorphological and geological criteria that contribute to the triggering of debris-flow processes, such as drainage density, altimetric amplitude, slope, shape of the valley and shape of the slope, characteristics of the mantle of alteration and runoff/infiltration ratio, which allows the identification of areas with a greater possibility for these processes to occur.

The delimitation of the physiographic units was performed on the 1: 50,000 scale with the orthophoto images of Emplasa – 2011, the Digital Elevation Model (DEM), the slope map, the geological map, and the cartographic base in a GIS environment.

2.2 Assessing the Vulnerability to the Debris-Flow Processes

The vulnerability to debris-flow processes assumes the combination of the following factors: unconsolidated materials that can be removed by heavy rains, critical inclinations of the slopes and drainage channels, and land use (Gramani 2001; Kanji & Gramani 2001).

The steepness of the slopes is a relevant factor, as are the origin of landslides, which are configured as input materials for the drainage channels. For Kanji & Gramani (2001), slopes with 30º to 45º are considered extremely critical for the debris-flow trigger. The channel slope is also an important source of sediment and is defined as the area in which the flow establishes its trajectory and development during a debris-flow event. According to Kanji & Gramani (2001), values of the order of 15^0 to 20^0 are sufficient for the movement of the materials deposited in the riverbed.

As for the geological aspects, Kanji & Gramani (2001) point out that there is a greater frequency of debris-flow events in environments that present thick residual soils, colluvial and talus deposits, alluviums, and alluvial terraces, which occur especially in areas of tropical climate due to intense weathering (Kanji & Gramani 2001).

Heavy rains are responsible for triggering debris-flow events, and daily rainfall rates above 250-300 mm appear to be responsible for large mass movements, with widespread landslides occurrence followed by debris-flow processes (Guidicini & Ywasa 1976; Gramani 2001). According to Kanji & Gramani (2001), human activity is an aggravating factor that contributes to profound changes in the environment, and in the case of superficial dynamic processes, deforestation can increase its frequency and intensity.

Initially, the Santo Antonio River Basin was divided into sub-basins, to assess which sectors are most vulnerable to the debris-flow occurrence. In GIS environment, each sub-basin was measured in area (km^2) and the analysis of morphological parameters (altimetric amplitude, drainage slope, and slopes). The anthropic factor was evaluated by the current land use map in the region and the rainfall aspects were based on accumulated hourly on 03/18/1067 in the respective watershed (Vargas 1999).

Thus, the vulnerability assessment followed the guidelines of Gramani (2001) and Kanji & Gramani (2001), who considered the factors mentioned above and established different values for each attribute, divided into regular intervals, admitting the value 10 for the most critical case and the score 0 for the least critical (Table 1). The final score, which ranges from 0 to 100, is calculated by the sum of the partial notes of each class multiplied by their respective weights (Eq. 1):

$$\sum PS \ x \ W \qquad (1)$$

Gramani (2001) and Kanji & Gramani (2001) established degrees of the vulnerability of the terrain to the respective processes, based on the final score obtained (Table 2).

2.3 Morphometric Parameters

The debris-flow occurrence is closely related to the morphometric conditions of a watershed (Jakob 1996; Wilford et al. 2004). Such parameters seek to characterize the hydrographic basins in terms of their morphometric characteristics, which are related to aspects of the physical environment (Cerri et al. 2018). In this work, the

Table 1 Factors, weights, classes, attributes, and partial scores used to assess vulnerability to debris-flow processes. Source: Gramani (2001) and Kanji & Gramani (2001). G1 = residual soils; colluvial and alluvial materials; a large amount of material available for mobilization after rainy events (on the slopes and channels); G2 = intermediate condition between G1 and G3; G3 = small-expression colluvial packages; small thickness of residual soils; G4 = sedimentary rocks; soils with high shear strength and low erosion; little material available in drainage channels.

Factors	Classes	Weight	Attributes	Partial score
Rainfall (R) (mm/h)	R1	3	>80	10
	R2		60 – 80	6.6
	R3		30 – 60	3.3
	R4		<30	0
Slope (S) (º)	S1	2.5	>45	10
	S2		45 – 30	6.6
	S3		15 – 30	3.3
	S4		<15	0
Drainage slope (D) (º)	D1	0.5	>25	10
	D2		15 – 25	6.6
	D3		10 – 15	3.3
	D4		<10	0
Area of the watershed (A) (km^2)	A1	1	<5	10
	A2		5- 10	6.6
	A3		10 – 20	3.3
	A4		>20	0
Height of the slope (H) (m)	H1	1	>750	10
	H2		500 – 750	6.6
	H3		200 – 500	3.3
	H4		<200	0
Vegetation (V) (% of deforested area)	V1	0.5	90 – 100	10
	V2		50 – 90	6.6
	V3		30 – 50	3.3
	V4		<30	0
Geological aspects (G)	G1	1.5	G1	10
	G2		G2	6.6
	G3		G3	3.3
	G4		G4	0

Table 2 Vulnerability degrees to debris-flow processes. Source: Gramani (2001) and Kanji & Gramani (2001).

Debris-flow vulnerability ranges (according to Table 1 results)	Designations
80 – 100	Very high
60 – 80	High
40 – 60	Medium
20 – 40	Low
0 – 20	Very low

morphometric parameters used to evaluate the potential of a hydrographic basin to debris-flow occurrence were the Circularity index, the Drainage density, the Roughness index, the Relief ratio, the Melton ratio, and the Sinuosity index (Table 3). The calculation of the respective parameters was subsidized by the DEM (Digital Elevation Model), by the slope map, and by the hydrography of each hydrographic sub-basin. Also, debris-flow deposits from the 1967 event in the region were mapped, to identify which sub-basins were most affected by these processes.

Table 3 Morphometric parameters used and their applications in the assessment of the debris-flow potential in watersheds.

Morphometric parameters	Formula	Units	Description	Relationship with debris-flow triggering
Circularity index (CI)	CI = A/Ac	dimensionless	A = area of the watershed Ac = area of the circle corresponding to the same perimeter of the watershed	*(IC) < 0.51* – indicates that the watershed tends to be more elongated favoring runoff; *IC = 0.51* – indicates a moderate level of runoff *IC >0.51* – indicates that the watershed tends to be more circular, favoring the occurrence of flooding
Drainage density (Dd)	Dd = Tl/A	km/km^{-2}	Tl = total length of stream channels A = area of the watershed	The higher the Dd index, the lower the water infiltration capacity within the watershed. Thus, the higher the Dd, the faster the water reaches the drainages, intensifying floods and, consequently, contributing to the increase in the potentiality and intensity of debris-flows events
Roughness Index (Ri)	Ir = H x Dd	dimensionless	H = elevation amplitude Dd = Drainage density	Rougher (higher Ri) watersheds tend to have a higher sediment production rate and, consequently, greater availability of sediment for transport during debris-flow events
Relief ratio (Rr)	Rr = H/Wl	m/km	H = elevation amplitude Wl = watershed length	An index that describes the distance, trajectory, and magnitude of debris flows. The higher the value of Rr, the greater the distance traveled by the flow, gaining greater its velocity.
Melton ratio (M)	M = H/√A	dimensionless	H = elevation amplitude A = area of the watershed	This parameter defines susceptible areas to processes of debris flow including general flows (flows, mudflows or earth flows)
Sinuosity index (Si)	Si = Cl/Dv	dimensionless	Cl = Length of the channel Dv = Vector distance	The higher the Si value, the slower the outflow velocity will be, resulting in a smaller influence on the sub-watershed downstream floods

3 Results and Discussions

3.1 Physiographic Compartmentalization

Seven physiographic units on a scale of 1: 50,000 were identified, which supported the assessment of the geological and geomorphological aspects of the Serra do Mar region regarding their potential for debris-flow processes (Figure 2). Distributed in Planalto Atlântico and Serrania Costeira geomorphological provinces, the delimited physiographic units were:

1. *Unit IA – Coastal plains*: fluviomarine sediments in plains, predominantly flat areas, with low drainage density and open valleys. Places with low potential for landslides and medium debris-flow potential, representing the distal deposition areas.
2. *Unit IB – River plains:* fluvial deposit sediments in plains, predominantly flat areas, low drainage density and open valleys. Places with low potential for landslides and high debris-flow potential, constituting the main areas of rocky debris deposition.
3. *Unit II – Colluvium and talus ramps:* colluvial sediments and talus deposits on the low slope, medium declivity, low drainage density, and convex slopes. High potential for landslides and debris-flows processes.
4. *Unit III – Escarpments of Serra do Mar*: granites and gneisses in escarpment relief, medium to high drainage density, high slopes, closed valleys, and concave to straight slopes. Places with high potential for landslides and medium potential for debris-flow processes.
5. *Unit IV – Upland of Paraitinga*: migmatitic gneisses in hills relief, medium drainage density, medium slopes, closed valleys, concave slopes, and rounded

tops. Medium potential for the development of landslides and low potential for the debris-flows occurrences.

6. *Unit V – Mountainous relief***:** migmatitic gneisses in mountainous relief, medium drainage density, medium slopes, closed valleys, concave to straight slopes, and rounded to angular tops. Medium potential for the development of landslides and medium potential for the debris-flows occurrence.
7. *Unit VI – Hillocks domain***:** Granites and gneisses in relief of hills, medium drainage density, medium slopes, closed valleys, concave slopes, and rounded tops. Locations with medium potential for the development of landslides and medium potential for the debris-flow occurrences.

3.2 Assessing the Vulnerability to the Debris-Flow Processes

The factors analyzed to assess the vulnerability of the Santo Antônio River Basin were climatic aspects (hourly rainfall data), morphological aspects (hypsometry, slope, and drainage slope), watershed and the percentage of deforested area, and geological aspects (Table 4).

According to Cruz (1974) and Vargas (1999), the rain gauge located in the Santo Antônio River Basin registered on March 18, 1967, accumulated rainfall of 211 mm/h. Such indexes were responsible for the liquefaction of the alteration soil mantle that covered the slopes along the Tamoios Road (SP-99), whose material quickly went to the drainage channels and triggered debris-flow generalized processes in the respective basin (Cruz 1974; Vargas 1999).

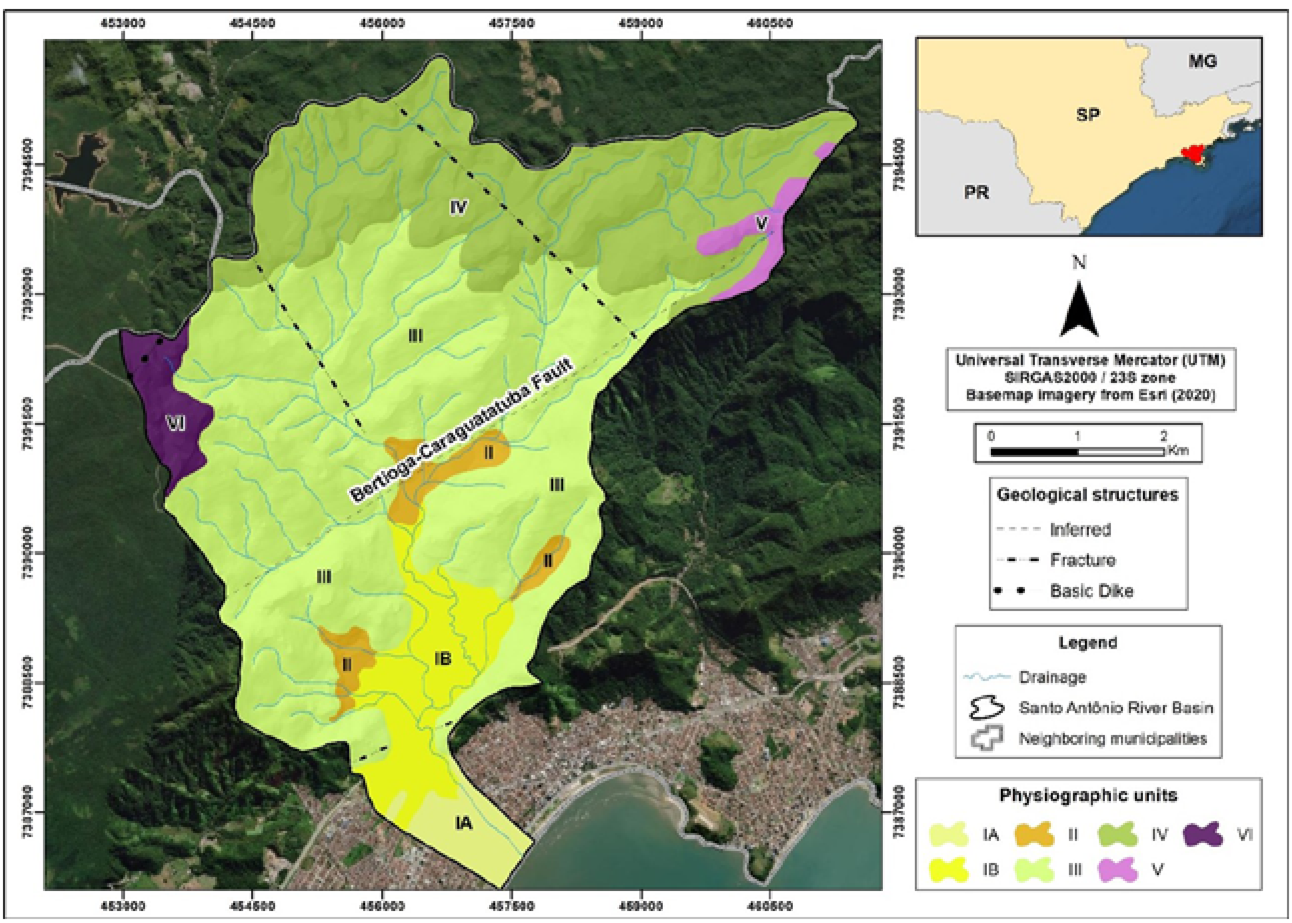

Figure 2 Physiographic units of the study area.

Table 4 Factors, weights, classes, attributes, and partial scores of the sub-basins of the Santo Antônio watershed. *cumulative rainfall reported by Vargas (1999); ** G1 = residual soils; colluvial and alluvial materials; a large amount of material available for mobilization after rainy events (on the slopes and channels); G2 = intermediate condition between G1 and G3; G3 = small-expression colluvial packages; small thickness of residual soils; G4 = sedimentary rocks; soils with high shear strength and low erosion; little material available in drainage channels.

Sub-basins	Rainfall (R)*	Slope (S)	Drainage slope (D) (º)	Area of the watershed (A) (km²)	Height of the slope (H)	Vegetation (V) (% of deforested area)	Geological aspects (G)**
1	211 mm/h	<15º	8.6º	12.9	more than 900 meters	Less than 30%	G2
2	211 mm/h	15º to 30º	8.4º	10.9	more than 900 meters	Less than 30%	G2
3	211 mm/h	15º to 30º	16.4º	3.9	200 to 500 meters	Less than 30%	G2
4	211 mm/h	15º to 30º	9.8º	2.1	less than 200 meters	Less than 30%	G1
5	211 mm/h	15º to 30º	13.6º	1.7	200 to 500 meters	Less than 30%	G1
6	211 mm/h	15º to 30º	11º	2.3	200 to 500 meters	Less than 30%	G2
7	211 mm/h	15º to 30º	14.2º	0.6	less than 200 meters	Less than 30%	G1
8	211 mm/h	<15º	2.8º	3.7	less than 200 meters	50% to 90%	G1

As for the slopes, sub-basins 2, 3, 4, 5, 6, and 7 register the highest inclination on their slopes. Sub-basin 1, which encompasses a large part of the upland of the Rio Santo Antônio Basin, and sub-basin 8, which comprises the large river plain of the area, correspond to the areas that have the smallest slopes (Figure 2) (Table 4). Sub-basins 3, 7, and 5 showed the highest slopes in the drainage channels (Table 4). According to Gramani (2001) and Nettleton et al. (2005), the inclination of the channels influences the erosion capacity and the mobilization of the deposited material along with the drainage network. Thus, the greater the average slope, the greater the current flow and, consequently, the greater the potential for debris-flow generating. Gramani (2001) points out that the 15º threshold for the inclination of the channels is considered a critical value for the mobilization of materials along the drainage.

Concerning the area, basins of up to 19 km² are the most likely to trigger debris-flow processes (Slaymaker 1988). There is a consensus among the authors that the larger the area of a basin, the greater the magnitude of debris-flow process (Jakob 1996; Wilford et al. 2004). In this sense, sub-basins 1 and 2 presented the largest extensions in area (Table 4). The amplitude of the slope, as well as influences the generation of landslides, is also considered a source of energy for development of flow and is related to the production of sediment from a watershed (Wilford et al. 2004). Sub-basins 1 and 2 presented the highest amplitudes, while sub-basins 7 and 8 registered the lowest values of the respective factor (Table 4).

Anthropic interference through the deforestation can initiate the process of mobilizing a large amount of soil, creating conditions for the debris-flows development (Rivera Pomés 1994). As a large part of the study area is in the Conservation Unit of the Serra do Mar State Park, only sub-basin 8 presented a percentage between 50 to 90 % of deforested area (Table 4).

The geological aspects are the factor with the third-highest weight in the assessment of watershed debris-flows vulnerability (Gramani 2001; Kanji & Gramani 2001). The sub-basins exhibited materials of colluvial and alluvial origin and many materials available for mobilization along the slopes and drainage channels during high rainfall events (Table 4).

Thus, the use of the method by Gramani (2001) and Kanji & Gramani (2001) revealed that, in general, the Santo Antônio River Basin is highly vulnerable to debris-flow processes (Table 5) (Figure 3). Sub-basins 1 and 8, which showed medium vulnerability, correspond, respectively, to areas located on the upland and the fluvial-coastal plains of the Rio Santo Antônio Basin. According to Cruz (1974) and Gramani (2001), these places recorded during the event of 03/18/1967 mainly landslides and mudflow processes.

3.3 Morphometric Parameters

The morphometric parameters used to assess the potential of Santo Antônio basin to debris-flow processes were Circularity index (Müller 1953), Drainage density (Horton 1945; Langbein 1947; Jakob 1996), Roughness index (Jakob 1996), Relief ratio (Schumm 1956), Melton ratio (Melton 1957) and Sinuosity index (Schumm 1956) (Table 6).

Concerning the Circularity index (Ci), in general, the values were high, indicating a more rounded shape of the basins. Ci values less than 0.50 are linked to basins with an elongated shape, which, according to Crozier (1986), indicate greater susceptibility to the debris-flow occurrence. However, for Augusto Filho (1993), watersheds with a rounded shape, and Ci greater than 0.50, are the most susceptible to the occurrence of these processes. It is noteworthy that in this work the highest Ci values were found in sub-basins that showed no debris-flow deposit related to the event that occurred on the site on 03/18/1967 (Figure 4). On the other hand, sub-basin 8, which has the lowest Ci value in the whole area, has large debris-flow deposits (Table 6, Figure 4). Cerri et al. (2018) pointed out that this index is very debatable, and Nery (2017a) pointed out that sub-basins with values close to 1 have a low concentration-time and, therefore, indicate a greater probability of drainage flooding. This can contribute to the secondary debris-flow occurrence, whose triggering is not related to landslides.

High values of Drainage Density (Dd) are expected to represent more intense debris-flow processes and with greater magnitudes and intensity (Gartner et al. 2008). In this work, sub-basin 5 showed the highest value of Dd, while sub-basin 8 showed the lowest value for the same index (Table 6). However, it should be noted that in sub-basin 5, as mentioned above, no evidence of debris-flow deposits related to the 1967 event was found, unlike sub-basin 8, which had the largest extension in deposits (Figure 4). It is important to note that several authors portrayed the subsequent occurrence of debris-flow, mudflow, and flooding processes in the sub-basin, in which the main drainage of the basin is (Santo Antônio

Table 5 Vulnerability degrees to debris-flow processes in the Santo Antônio Basin (Caraguatatuba, State of São Paulo, Brazil).

Sub-basins	(R)	(S)	(D)	(A)	(H)	(V)	(G)	Partial score	Debris-flow vulnerability
1	30	0	0	3,3	10	0	9,9	53,2	Medium
2	30	8,25	0	3,3	10	0	9,9	61,45	High
3	30	8,25	3,3	10	3,3	0	9,9	64,75	High
4	30	8,25	0	10	0	0	15	63,25	High
5	30	8,25	1,65	10	3,3	0	15	68,2	High
6	30	8,25	1,65	10	3,3	0	9,9	63,1	High
7	30	8,25	1,65	10	0	0	15	64,9	High
8	30	0	0	10	0	3,3	15	58,3	Medium

Table 6 Morphometric parameters of the Santo Antônio Basin (Caraguatatuba, State of São Paulo, Brazil). (Ci) = Circularity index; (Dd) = Drainage density (km/km2); (Ri) = Roughness index; (Rr) Relief ratio; (M) Melton ratio; (Si) = Sinuosity index (Si).

Sub-basins	(Ci)	(Dd)	(Ri)	(Rr)	(M)	(Si)
1	0,479235892	2,418865348	1935,092278	161,1994776	0,222799576	1,284800032
2	0,475965872	2,444254808	1955,403846	138,4606184	0,242523867	1,112099645
3	0,591208832	2,476476653	1981,181322	351,0753525	0,400866608	1,200242044
4	0,558160756	2,070199907	828,0799626	195,5837196	0,278597674	1,19400922
5	0,653093936	2,910894386	1746,536631	306,6442847	0,458159324	1,223722461
6	0,60295235	1,623307382	811,6536912	197,5308642	0,330615964	1,079327049
7	0,369158498	1,949196656	584,7589967	289,9005007	0,384067513	1,322563641
8	0,19768017	1,695123963	508,537189	75,48542435	0,157052479	1,459041019

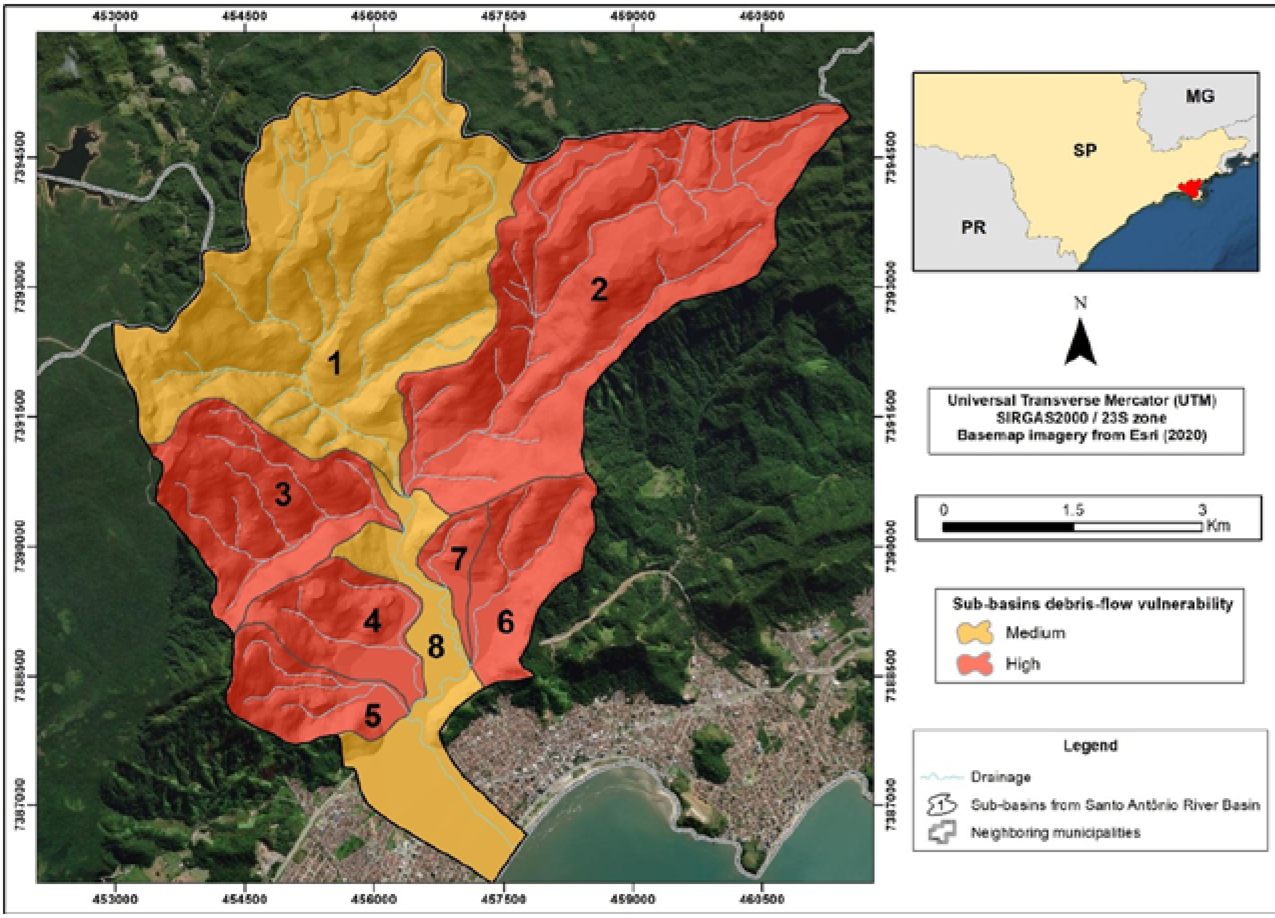

Figure 3 Vulnerability degrees to debris-flow processes in the Santo Antônio Basin (Caraguatatuba, State of São Paulo, Brazil).

River) (Cruz 1974; Gramani 2001; Vieira & Gramani 2015; Vieira et al. 2019).

The Roughness Index (Ri) is considered a parameter proportional to the Drainage Density (Cerri et al. 2018). The sub-basins 1, 2, 3, and 5 exhibited the highest values for this index, and evidence of the debris-flow occurrence in basins 1, 2, and 3 was found (Table 6, Figure 4). However, sub-basin 5 does not show deposits from the 1967 debris-flow process, although it also shows high values of Drainage Density. However, sub-basins 1, 2, and 3 also have high Dd values (Table 6).

The Relief Ratio (Rr) expresses the watershed's capacity to transport and store sediment (Cerri et al. 2018). Therefore, the higher this index, the greater the potential for debris-flow processes. The highest Rr values were found in sub-basins 3, 5, and 7 (Table 6). It is noteworthy again that there was no evidence of debris-flow processes in sub-basin 5; however, deposits were mapped in the other basins (3 and 7) (Figure 4).

The highest values for the Melton Ratio (M) were found in sub-basins 3 and 5 (Table 6). From this parameter, it is possible to define areas susceptible to processes that involve flows, such as the debris-flow phenomenon (Cerri et al. 2018). M values greater than 0.3 indicate basins with greater susceptibility to the occurrence of these processes (Melton 1957). Thus, sub-basins 3, 5, 6, and 7 are the most susceptible to the debris-flow occurrence, although deposits of these processes have not been found in basins 5 and 6 (Figure 4).

The Sinuosity Index (Si) is related to the speed of the flow, and, consequently, to the type of material to be transported (Alves & Castro 2003). The values found for Si in this work are intermediate, and the channels are framed as sinuous (Table 6). If debris-flow processes occur, possibly materials of varying diameters will be transported in the flow over long distances (Nery 2017b). Fieldwork at the site revealed this dynamic, especially in the flatter sections of the basin (Figure 5).

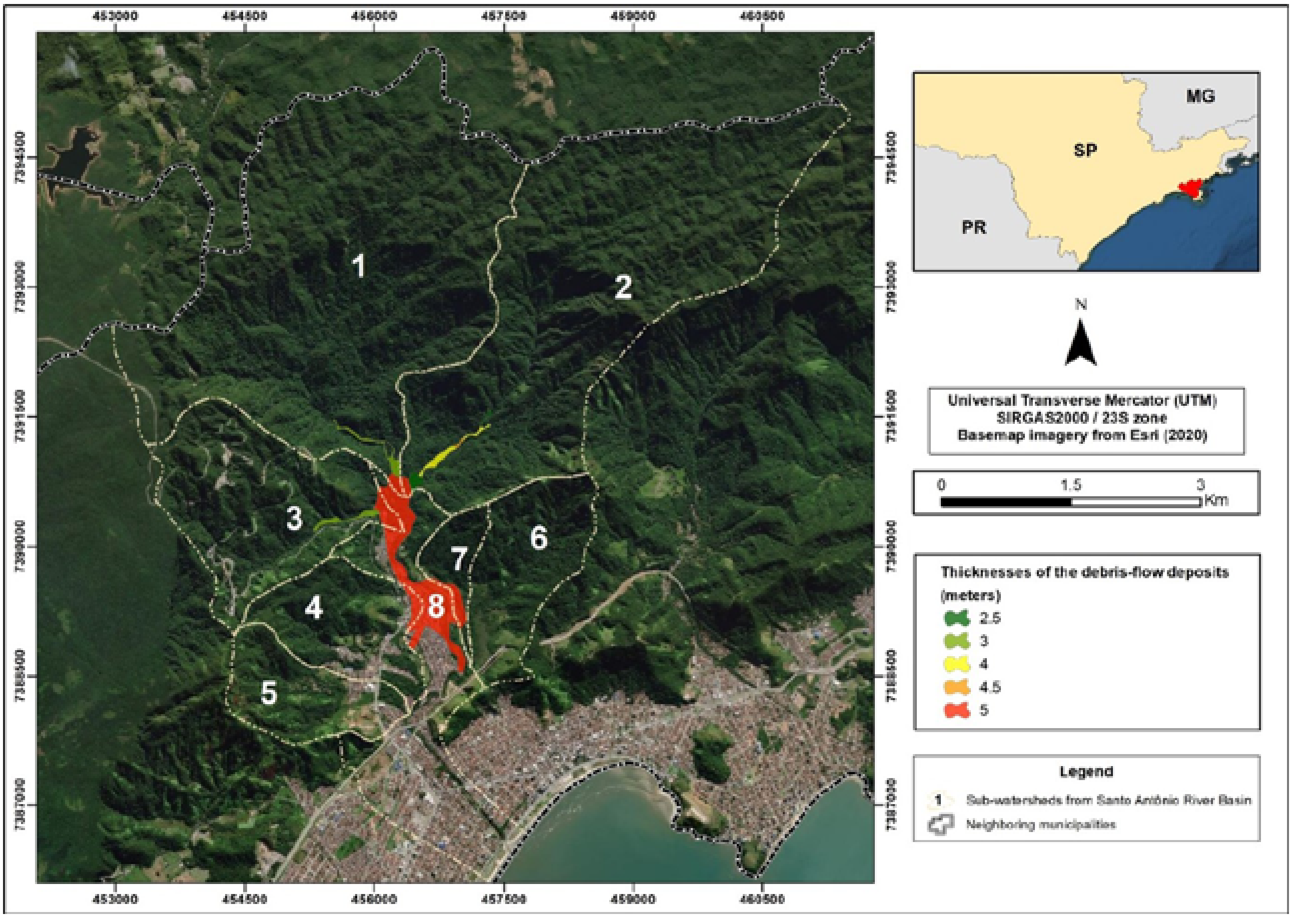

Figure 4 Map of debris-flow deposits from the event occurred in 1967 in the Santo Antônio Basin region (Caraguatatuba, State of São Paulo, Brazil).

Although several methods are used in the assessment of the debris-flow potential in watersheds, the techniques used proved to be advantageous for allowing the integrated and joint analysis of different aspects of the physical environment, both in the morphological and in the morphometric attributes. Specifically, the physiographic compartmentation enables the grouping of the physical environment elements (geology and geomorphology) and, through remote sensing techniques, geological and geotechnical properties are induced in each established unit. This characteristic makes it possible to infer which locations are most susceptible to debris-flow processes. Besides, the vulnerability assessment considered, in addition to the attributes of the physical environment, the rainfall data, considered one of the main agents in the debris-flows triggering. The use and calculation of the morphometric parameters added relevant metrics aspects of hydrographic basins, which, as explained, significantly contribute to the magnitude, production of sediments and debris, impact force, and potentiality of these processes. Therefore, these methods and techniques, used in an integrated and joint way, make it possible to evaluate with greater criteria and parameters the debris-flow potentiality in hydrographic basins, which makes it possible to replicate them in other places.

4 Conclusions

The physiographic compartmentalization method, with the analysis of vulnerability and morphometric parameters, made it possible to assess the components of the physical environment in an integrated way concerning the potential of the Santo Antônio Basin to the triggering of debris-flow processes. Thus, the contribution of the morphological variables of the hydrographic basins and drainage channels is evident.

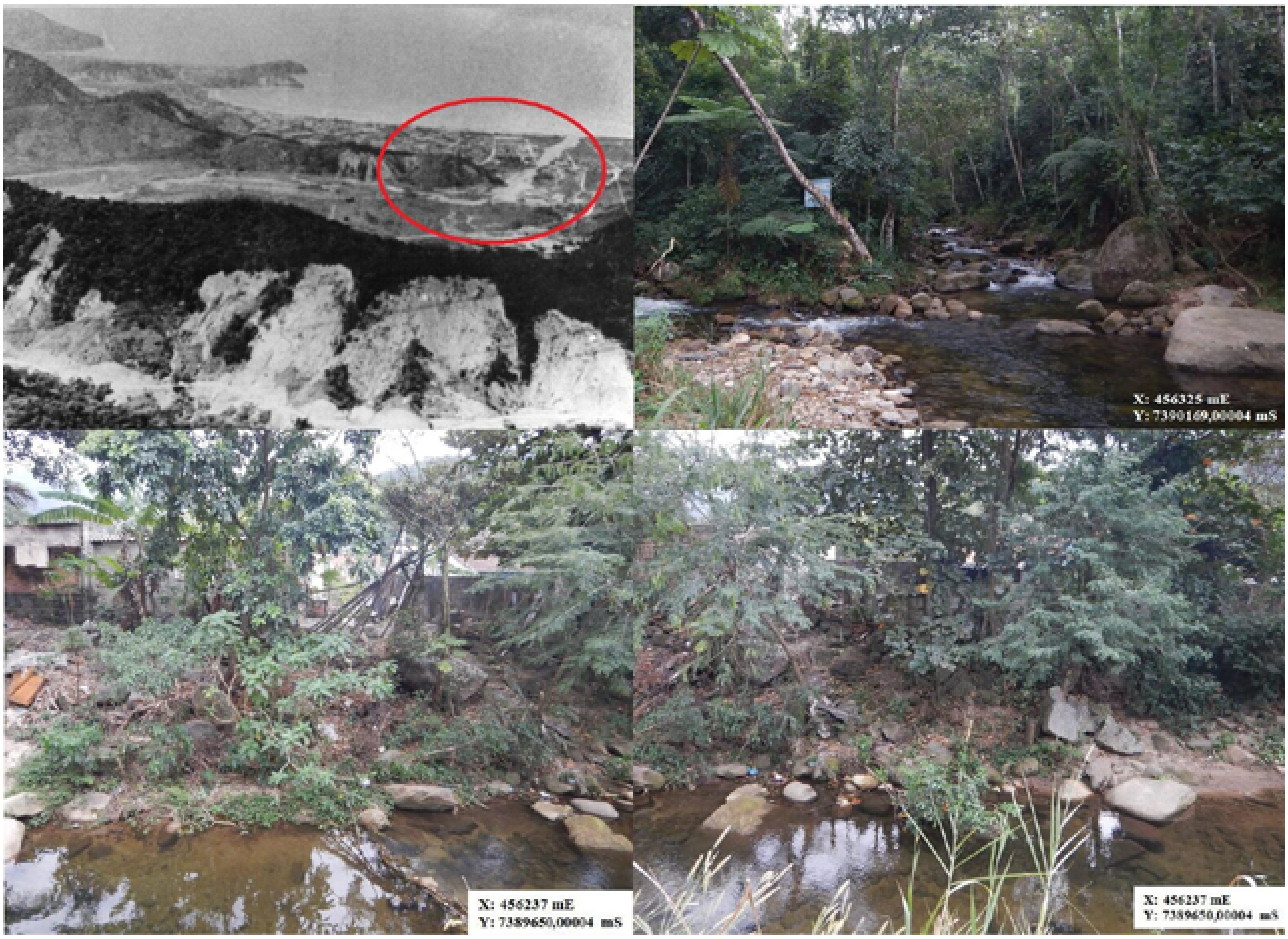

Figure 5 Evidence of occurrence debris-flow processes in the Santo Antônio Basin (Caraguatatuba, State of São Paulo, Brazil). (A) Zone of deposition of landslides and generalized debris-flows that descended the slopes of the Serra do Mar and the drainage channels, reported by Cruz (1974); (B, C e D) Rocky blocks deposited on the bed of the Santo Antônio River and its banks, indicating the current occurrence of the process. Source: (A) Cruz (1974); (B), (C) and (D) Personal files of the authors.

By the method of physiographic compartmentation employed, the sub-basins located in the escarpment sector of the relief, with high slopes, closed valleys, and rectilinear channels, high drainage densities present higher values in the morphometric parameters, which indicates a greater potential for deflagration and debris-flow occurrence.

Based on the geomorphological, geological, climatic, and anthropic aspects of the watershed, the vulnerability assessment method showed that all the sub-basins in the area in question have a medium to high vulnerability to these processes if similar rainfall accumulated on the day 03/18/1967 reach the region again.

In summary, the integrated analysis of physiographic compartmentalization with the identification of relief features, such as slope, amplitude, valley, and slope shapes is extremely relevant in the identification of watershed debris-flow susceptibility. Furthermore, as this technique incorporates these aspects with geotechnical attributes, its application becomes relevant compared to the use of morphometric parameters, which only consider superficial aspects of a hydrographic basin.

The use of morphometric parameters of a hydrographic basin in the assessment of the potentiality to the debris-flow processes is especially interesting to prioritize preventive actions to these processes, in a preliminary way. These, in turn, specifically focus on superficial attributes of the basin, and not subsurface ones, such as physiographic compartmentalization.

Still, it is worth noting that the use of morphometric parameters can help in the potential of the basin to the debris-flow generation and development, as it makes it possible to define which are the source-areas of these processes. Moreover, this technique makes it possible to establish which locations have the greatest potential for deposition of the flows, helping to define risk areas.

5 Acknowledgments

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support, and the Laboratório de Geologia de Engenharia e Meio Ambiente (GEMA/ UNESP) for technical and scientific support.

6 References

Alves, J.M.P. & Castro, P.T.A. 2003, 'Influência de feições geológicas na morfologia da bacia do rio do Tanque (MG) baseada no estudo de parâmetros morfométricos e análise de padrões de lineamentos', *Revista Brasileira de Geociências*, vol. 33, no. 2, pp. 117-24.

Augusto Filho, O. 1993, 'O estudo das corridas de massa em regiões serranas tropicais: um exemplo de aplicação no município de Ubatuba, SP', *Proceedings of Congresso Brasileiro de Geologia de Engenharia e Ambiental*, pp. 63-72.

Boardman, J. 2016. 'The value of Google Earth™ for erosion mapping', *Catena*, vol. 143, pp. 123–7. https://doi.org/10.1016/j.catena.2016.03.031

Cerri, R.I., Reis, F.A.G.V., Gramani, M., Gabelini, B.M., Zaine, J.E., Sisto, F.P. & Giordano, L.C. 2018, 'Análise da influência de atributos fisiográficos e morfométricos na definição da suscetibilidade de bacias hidrográficas à ocorrência de corridas de massa', *Geologia USP (Série Científica)*, vol. 18, pp. 35-50. https://doi.org/10.11606/issn.2316-9095.v18-133737

Chen, C.Y. & Yu, F.C. 2011, 'Morphometric analysis of debris flows and their source areas using GIS', *Geomorphology*, vol. 129, pp. 387-97. https://doi.org/10.1016/j.geomorph.2011.03.002

Collins, B. & Znidarcic, D. 1997, 'Triggering Mechanisms of Rainfall Induced Debris Flows'. *Proceedings of Pan-American Symposium on Landslides*, pp. 277-86.

Companhia de Pesquisa de Recursos Minerais 1982, 'Geological map of Caraguatatuba Sheet', 1:50,000 scale.

CPRM – vide Companhia de Pesquisa de Recursos Minerais.

Crozier, M.J. 1986, 'The climate-landslide couple: A southern hemisphere perspective' in Matthews et al. *Rapid Mass Movement as a Source of Climatic Evidence for the Holocene: Palaeoclimate Research*, Gustav Fischer Verlag, Stuttgart, vol. 19, pp. 333-54.

Cruz, O. 1974, 'A Serra do Mar e o litoral na área de Caraguatatuba-SP – contribuição à geomorfologia litorânea tropical', PhD Thesis, Universidade de São Paulo, São Paulo.

De Scally, F., Slaymaker, O. & Owens, I. 2001, 'Morphometric Controls and Basin Response in the Cascade Mountains', *Geografiska Annaler*, vol. 83A, pp. 117-30. https://doi.org/10.1111/j.0435-3676.2001.00148.x

Dowling, C. & Santi, P., 2013, 'Debris flows and their toll on human life: a global analysis of debris flow fatalities from 1950 to 2011', *Natural Hazards*, pp. 1–25.

EMPLASA – vide Empresa Paulista de Planejamento Metropolitano S/A.

Empresa Paulista de Planejamento Metropolitano S/A 2011, 'Projeto Mapeia São Paulo – Vale do Paraíba e Litoral Norte: Orthophotos 2011', 1:10,000 scale.

Gartner, J.E., Cannon, S.H., Santi, P.M. & Dewolfe, V.G. 2008, 'Empirical models to predict the volumes of debris flows generated by recently burned in the western U.S.', *Geomorphology*, vol. 96, pp. 339-54. https://doi.org/10.1016/j.geomorph.2007.02.033

Gramani, MF. 2001, 'Caracterização geológica-geotécnica das corridas de detritos ("Debris Flows") no Brasil e comparação com alguns casos internacionais', Marter Thesis, Universidade de São Paulo.

Guidicini, G. & Ywasa, O.U. 1976, *Ensaio de Correlação entre Pluviosidade e Escorregamento em meio tropical úmido*, IPT, Publicação 1080, São Paulo.

Horton, R.E. 1945, 'Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology', *Geological Society of America Bulletin*, vol. 56, no. 3, pp. 275-370.

IBGE – vide Instituto Brasileiro de Geografia e Estatística.

Instituto Brasileiro de Geografia e Estatística 1974, 'Caraguatatuba Sheet: SF-23-Y-D-VI-1', 1:50,000 scale.

Instituto Brasileiro de Geografia e Estatística 2013, *Manual Técnico de Uso da Terra,* IBGE, Rio de Janeiro.

Jakob, M. 1996, 'Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia', PhD Thesis, University of British Columbia.

Jakob, M. & Hungr, O. 2005, 'Introduction', in Jakob, M. & Hungr, O. (eds), *Debris-flow hazards and related phenomena*, Springer-Praxis, Chichester, pp. 1–7.

Kang, S. & Lee, S.R. 2018, 'Debris flow susceptibility assessment based on an empirical approach in the central region of South Korea', *Geomorphology*, vol. 308, pp. 1-12. https://doi.org/10.1016/j.geomorph.2018.01.025

Kanji, M.A., Cruz, P.T., Massad, F. & Araujo-Filho, H.A. 1997, 'Basic and Common Characteristics of Debris Flows', *Proceedings of Panamerican Symposium on Landslides*, pp. 223- 31.

Kanji, M.A. & Gramani, M.F. 2001, 'Metodologia para determinação da vulnerabilidade a corridas de detritos em pequenas bacias hidráulicas' *Proceedings of Conferência Brasileira de Estabilidade de Encostas*.

Kobiyama, M., Goerl, R.F., Correa, G.P. & Michel, G.P. 2010, 'Debris flow occurrences in Rio dos Cedros, Southern Brazil: meteorological and geomorphic aspects' in D. Wrachien & C.A. Brebbia (eds), *Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows III*, WIT Press, Southampton pp. 77–88.

Langbein, W.B. 1947, 'Topographic characteristics of drainage basins', *Geological Survey water-supply*, vol. 968, no. C, pp. 125-57.

Liu, X. & Lei, J. 2003, 'A method for assessing regional debris flow risk: an application in Zhaotong of Yunnan province (SW China)', *Geomorphology*, vol. 52, pp. 181-91. https://doi.org/10.1016/S0169-555X(02)00242-8

Melton, M.A. 1957, 'An analysis of the relations among elements of climate, surface properties and geomorphology', PhD Thesis, Columbia University.

Müller, C.V. 1953, *A quantitative geomorphic study of drainage basins characteristic in the Clinch Mountain area*, Department of Geology, Columbia University.

Ni, J., Wang, G. 1990, 'Some aspects of the mechanism of debris flow' in R.H. French (ed.), *Hydraulics/Hidrology of Arid Lands (H2AL)*, pp. 422- 27.

Nery, T.D. 2017a, 'O uso de parâmetros morfométricos como potencial indicador de ocorrência de fluxos de detritos no litoral norte de São Paulo', *Geosul*, vol. 32, no. 63, pp. 179-200.

Nery, T.D. 2017b, 'O uso de parâmetros morfométricos na avaliação do potencial a geração de corridas de detritos na Bacia do Rio Santo Antônio', *Revista Brasileira de Cartografia*, vol. 68, no. 9, pp. 1819-935.

Nettleton, M.I., Martin, S., Hencher, S., Moore, R. 2005, 'Debris flow types and mechanisms', in M.G. Winter, Macgregor & F. Shackman (eds), *Press. Scottish road network Landslides study summary report*, Scottish, p. 1-19.

Rivera Pomés, C.H. 1994, 'Desenvolvimento de um modelo conceitual para simulação de uma avalanche de detritos (Debris Flow) qualquer', PhD Thesis, Universidade de São Paulo.

Schumm, S.A. 1956, 'Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey', *Geological Society of America Bulletin*, vol. 67, no. 5, pp. 597-646.

Slaymaker, O. 1988, 'The distinctive attributes of debris torrents', *Hydrological Sciences*, vol. 33, no. 6, pp. 567-73.

Takahashi, T. 2014, *Debris flow: mechanics, prediction and Countermeasures*, Taylor & Francis Group, London.

Van Steijn, H. 1996, 'Debris-flow magnitude-frequency relationships for mountainous regions of Central and Northwest Europe', *Geomorphology*, vol. 15, no. 3-4, pp. 259-73. https://doi.org/10.1016/0169-555X(95)00074-F

Vandine, D.F. 1985, 'Debris flows and debris torrents in the Southern Canadian Codillera', *Canadian Geotechnical Journal*, vol. 22, no. 1, pp. 44-68.

Vargas, M. 1999, 'Revisão histórico-conceitual dos escorregamentos da Serra do Mar', *Revista Solos e Rochas*, vol. 22, no. 1, pp. 53-83.

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*, vol. 1, pp. 61-6. https://doi.org/10.1007/s10346-003-0002-0

Vieira, B.C., Gramani, M.F., 2015, 'Serra do Mar: the most "tormented" relief in Brazil' in B.C. Vieira, A.A.R. Salgado & L.J.C. Santos (eds), *Landscapes and Landforms of Brazil*, World Geomorphological Landscapes, Springer, p. 285-97.

Vieira, B.C., Matos de Souza, L., Alcalde, A.L, Dias, V.C. Bateira, C & Martins, T.D. 2019, 'Debris flows in southeast Brazil: susceptibility assessment for watersheds and vulnerability assessment of buildings', *Proceedings of 7th International Conference on Debris-Flow Hazards Mitigation*, pp. 597-604.

Zaine, J.E. 2011, 'Método de fotogeologia aplicado a estudos geológico-geotécnicos: ensaio em Poços de Caldas, MG', Professorship Thesis, Universidade Estadual Paulista.

Received: 24 April 2021

Accepted: 29 July 2021

How to cite:

Corrêa, C.V.S., Reis, F.A.G.V., Giordano, L.C., Cabral, V.C., Gramani, M.F., Gabelini, B.M., Duz, B.G., & Veloso, V.Q.. 2021, 'Assessment of the Potentiality to the Debris-Flow Occurrence from Physiographic and Morphometrics Parameters: a Case Study in Santo Antônio Basin (Caraguatatuba, São Paulo State, Brazil)', *Anuário do Instituto de Geociências,* vol. *44*:43313. https://doi.org/10.11137/1982-3908_2021_44_43313