Landslides
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Application of the debris-flow hazard index for pipelines in the context of the hydrogeological disaster of February 2023 in São Sebastião, Serra do Mar, Brazil

Abstract Debris flows are a type of natural disaster that poses great threat to infrastructure, humans and the environment. In Brazil, debris flows have caused significant damage, especially in the Serra do Mar Mountain region. The increasing frequency and intensity of extreme precipitation events in the country highlights the need for the development of effective landslide risk management strategies. In this study, we analyze the initiation and dynamics of a debris-flow event that occurred in the Toque-Toque Grande watershed based on numerical modeling, as well as the risk that debris-flow occurrences represent to pipeline crossings using the Debris-flow Hazard Index methodology. The Toque-Toque Grande watershed is located in São Sebastião, northern coast of the São Paulo state (Brazil), where in February 18–19, 2023, an unprecedent precipitation event triggered landslides and debris flows. The results revealed that the intensification of extreme precipitation frequency and volume over short periods demands a more in-depth analysis. Instantaneous events, occurring without prior accumulations, are becoming increasingly frequent. It becomes imperative to urgently comprehend their dynamics and their relationship with natural disasters, especially debris flows, and their impact on urban centers and strategic infrastructures along impact routes. The increasing frequency and intensity of extreme precipitation events highlight the need for adaptable risk management strategies focused on prevention to mitigate impacts on infrastructure, society, and the environment. Additionally, the study emphasizes the urgency of structural protection measures following the magnitude of the 2023 event, evidenced by meteorological and geomorphological assessments, highlighting the influence of physical environmental conditions on the formation of debris flows. Computational modeling aided in visualizing the dynamics of the flow, providing crucial understanding for its dynamics. The identification of high-risk areas and the implementation of containment measures, exemplified by the protection structure of Transpetro in the Toque-Toque Grande basin, highlight the importance of proactive structural measures in impact mitigation. Essentially, this study sought to demonstrate the complexity of debris flow risk management, advocating for multidisciplinary approaches, prevention strategies, emergency response, and infrastructure protection in the face of environmental and operational challenges.

Keywords Debris flow · Hazard assessment · Infrastructure resilience · Environmental risk management · Geomorphological influences · Multidisciplinary approaches

Introduction

In recent decades, numerous studies have addressed and attempted to understand the dynamics of debris flows, including their genesis, main triggering factors and, particularly, the increase in their frequency in various parts of the world (Varnes 1978; Takahashi 1991; Rickenmann and Zimmermann 1993; Hungr et al. 2014; Bernard and Gregoretti 2021; Veloso et al. 2023b). These highly destructive phenomena, characterized by high velocity and long runout distances, are generally associated with high intensity to extreme rainfall events in mountainous areas, such as the Serra do Mar mountain range in Brazil (Gramani 2001; Veloso et al. 2023b).

The Serra do Mar region has one of the highest rainfall indices in Brazil (Gramani 2001), with exceptional and extreme rains periodically occurring, such as those that recently hit the northern coast of São Paulo state in February 2023 (Marengo et al. 2024). The recurrence interval of debris flows is decreasing, as demonstrated by various studies and reports (Eybergen and Imeson 1989; Rebetez et al. 1997; Westra et al. 2014; Pereira Filho et al. 2018; IPCC 2022; Giardino et al. 2023; Cabral et al. 2023b; Giordano et al. 2023; Lopez et al. 2023). These studies highlight the urgency of better understanding the influence of climate variability on the frequency and magnitude of landslides and debris flows (Cabral et al. 2022).

The intense rains that struck the northern coast of São Paulo between February 18 and 19, 2023, especially in in the region of São Sebastião, are a recent example. The 683 mm/15 h rainfall triggered numerous landslides along the coast, resulting in 65 deaths in the Barra do Sahy neighborhood of São Sebastião (Marengo et al. 2024), over 1000 displaced individuals, and damages totaling USD $122.4 million, according to the municipal administration. According to official meteorological and natural disaster monitoring agencies such as the National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) and the National Institute of Meteorology (INMET), it was the largest rainfall event recorded in 24 h in the history of Brazil. This event was compared to the catastrophic event that destroyed the city of Zhengzhou in 2021 by Brazil's METSul meteorological agengy (Guo et al. 2023).

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Landslides and floods occurred in several areas along the coast of São Sebastião, including a debris-flow event in the Toque-Toque Grande catchment. This catchment is naturally prone to debris flows, as it is characterized by deeply incised channels and steep slopes. The high gradient of the main channel, coupled with abundant in-channel woody and rocky material, contributes to the accumulation of sediments resulting from previous landslides, which can, then, act as potential source areas for a debris-flow event. Moreover, in the region of the catchment, there is a high-density of residential areas, as well as a federal highway (BR-101) and an oil pipeline that are crucial logistic routes and that cross the main channel, within the impact zone limit of a potential debris-flow event.

Compared to other events described in the literature (Gramani 2001, Kanji et al. 2007; Manzolli et al. 2018; Corrêa et al. 2021; Veloso et al. 2023a; Cabral et al. 2023b), particularly in the Serra do Mar, this event exhibited a smaller magnitude, likely due to the smaller area of the hydrographic basin, which influenced the volume of material mobilized both on the slopes and by the flow of the main channel. Nevertheless, it exhibited a significant impact and destructive power due to its proximity to infrastructure and densely populated areas (Cabral et al. 2023a).

In this context, this study characterizes the debris-flow event in the Toque-Toque Grande catchment, with special attention to the section where the channel-crossing oil pipelines occur. For the hazard assessment of the pipelines, the authors developed and applied the Debris Flow Hazard Index. Combined with geomorphological and meteorological analyses, as well as numerical simulation using RAMMS:DF (Graf and McArdell 2008; Graf and McArdell 2011).

Study area

Serra do Mar is a geomorphological feature that extends along a large part of the Brazilian coast, stretching from the state of Espírito Santo to Santa Catarina (Fig. 1B). The mountain range is composed mainly of migmatitic, granitic, and gneissic rocks dating back to the Precambrian, and is characterized by a rugged terrain, with steep slopes exceeding 30° and altimetric gradients ranging between 850 and 950 m. The mountainous relief is responsible for blocking moisture coming from the Atlantic Ocean, which, when attempting to cross the topographic barrier, precipitates upon reaching higher elevations in the form of rain, characterizing orographic rains (IPT 1987).

The scarps of Serra do Mar also act as obstacles to the passage of air masses, resulting in meteorological conditions known as semi-stationary and stationary fronts, especially the cold fronts of polar air masses and the fronts originating from the South Atlantic Convergence Zone (ZCAS), which provide conditions for strong and continuous rains (three to four days), responsible for the high rainfall rates (IPT 1987), São Sebastião (Fig. 1C) is a coastal municipality with approximately 90 thousand inhabitants.

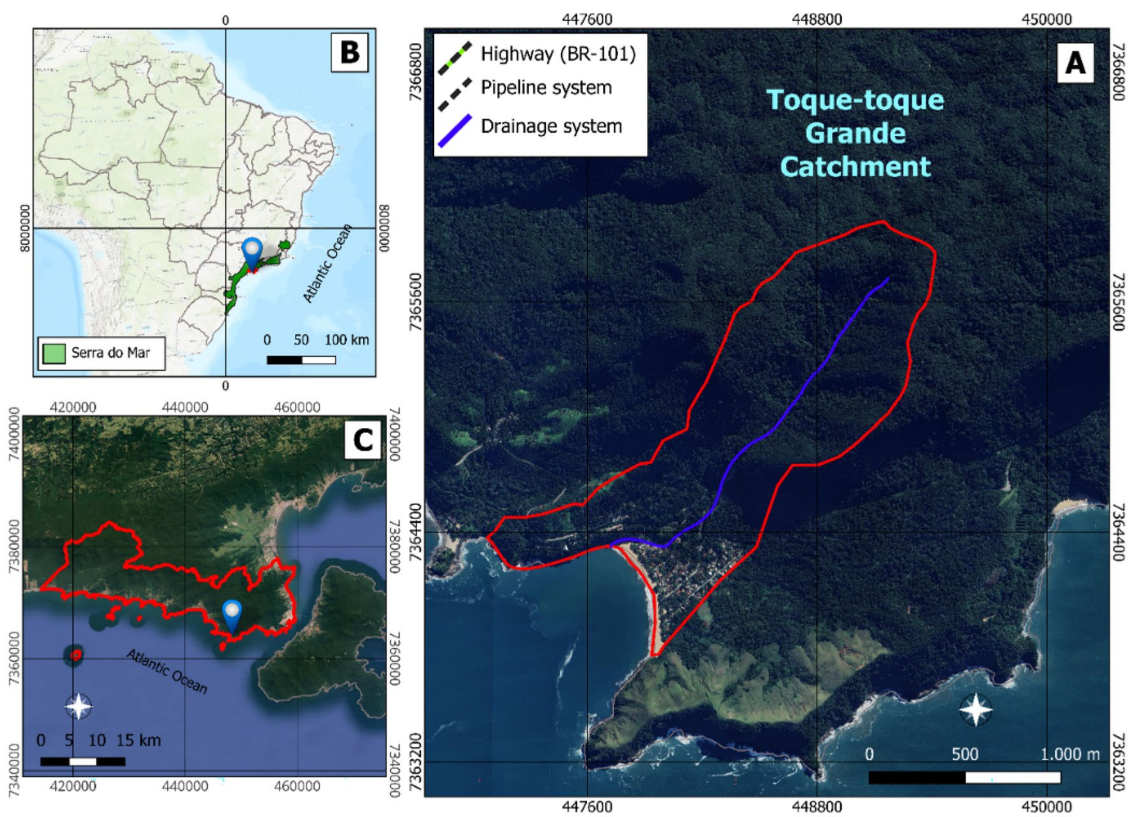


Fig. 1 Location of the study area. **A** Location of the Toque-Toque Grande watershed, São Sebastião—SP. **B** Location of the study area in the Brazilian territory. **C** Location of the study area in the municipality of São Sebastião—SP

In the local geological context (Fig. 2A), the São Sebastião peninsula is characterized by the predominance of paraderived gneisses, described as relatively homogeneous rocks that follow variations in the metasedimentary sequence (Dias Neto et al. 2009).

According to the Geomorphological Map of the State of São Paulo (IPT 1981), São Sebastião is divided into two morphostructural units: (i) Coastal Province and (ii) Atlantic Plateau. The coastal plains are characterized as low, flat terrain close to sea level, with sinuous streams and rivers. The Atlantic Plateau presents the subzones of Festooned Scarps and Digitate Spurs (i.e., the Serra do Mar mountain range), which are characterized by steep slopes (>30%), amplitudes exceeding 100 m, angular hilltops, rectilinear slope profiles, entrenched valleys, and high drainage density, which are fundamental elements in slope instability processes (Fig. 2B).

Materials and methods

The study was based on three steps: (i) evaluation of the meteorological and rainfall conditions that led to the initiation of the debris flow in the Toque-Toque Grande catchment; (ii) assessment of the geomorphological conditions affected by the debris flow, taking into account the main factors controlling their initiation; (iii) estimation of the hazard index for the occurrence of debris flows on highways.

Meteorological analysis

The analysis of the extreme rainfall event that triggered the debris flow on the São Sebastião Coast was conducted by combining data from the Geostationary Satellite (GOES 16) provided by the Center for Weather Forecasting and Climate Studies (CPTEC/INPE). This was conducted to better visualize the precipitation event specifically in the study area, while the rainfall intensity was estimated using data from twelve automatic rain gauges from CEMADEN, located along the coastline that recorded precipitation from February 15 to February 20, 2023 (Fig. 3).

The data was correlated to verify and determine where the most intense rainfall occurred, aiming at understanding the initiation of the debris flow and at assessing the influence of the orographic factor on the distribution and intensity of the rainfall.

Geomorphological analysis

The geomorphological characterization was conducted in two stages. The first stage involved a desktop analysis, during which maps were created using geoprocessing techniques, along with the acquisition of aerial images and topographic maps of the study area. In the second stage, which took place 9 months after the event (November 2023), a fieldwork was conducted with the purpose of identifying the geomorphological features resulted from the phenomenon, such as the main triggering factors related to the catchment.

Estimation of debris-flow hazard index in drainage crossing sections of pipelines

The estimation of the debris-flow hazard index is based on the correlation of two factors: (i) susceptibility and (ii) vulnerability. The susceptibility score is conditioned by the probability of debris-flow occurrence in a particular area, classified from 0 to 16, while vulnerability is classified from 0 to 10 (Fig. 4).

Susceptibility refers to the likelihood of an eventual debris-flow occurrence in the catcment and is directly dependent on triggering factors related to the geomorphology of the areas under evaluation. Its determination takes into account the main triggering factors of debris flows in tropical mountainous areas, such as channel slope, watershed length and area (Gramani 2001; Dias et al. 2016; Corrêa et al. 2021; Cabral et al. 2023b).

Each of the parameters applied in the susceptibility assessment is classified on a scale from 0 to 4, and the sum of all can vary from 0 to 16, where 0 represents a negligible probability of debris-flow occurrence, and 16 indicates the maximum possibility in the

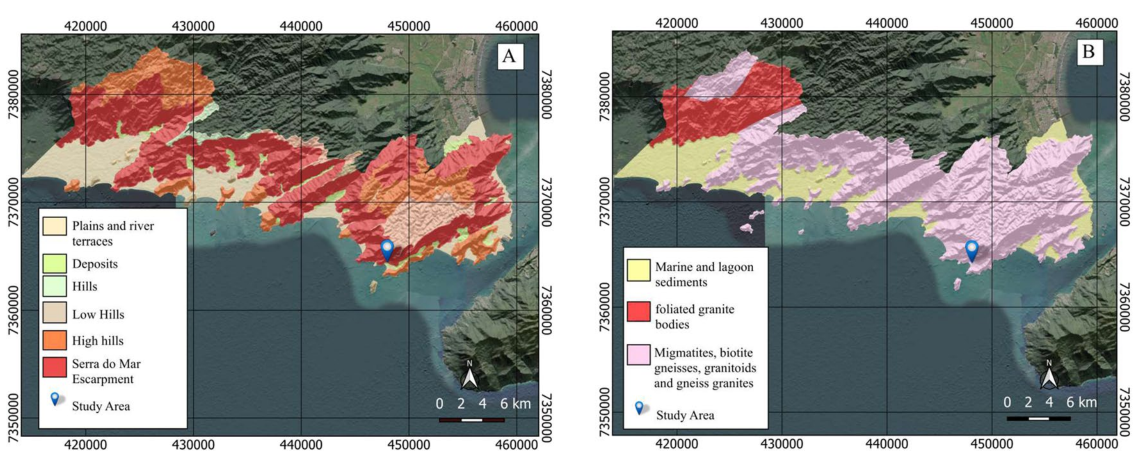


Fig. 2 **A** Geological context of São Sebastião. **B** Geomorphological context of São Sebastião

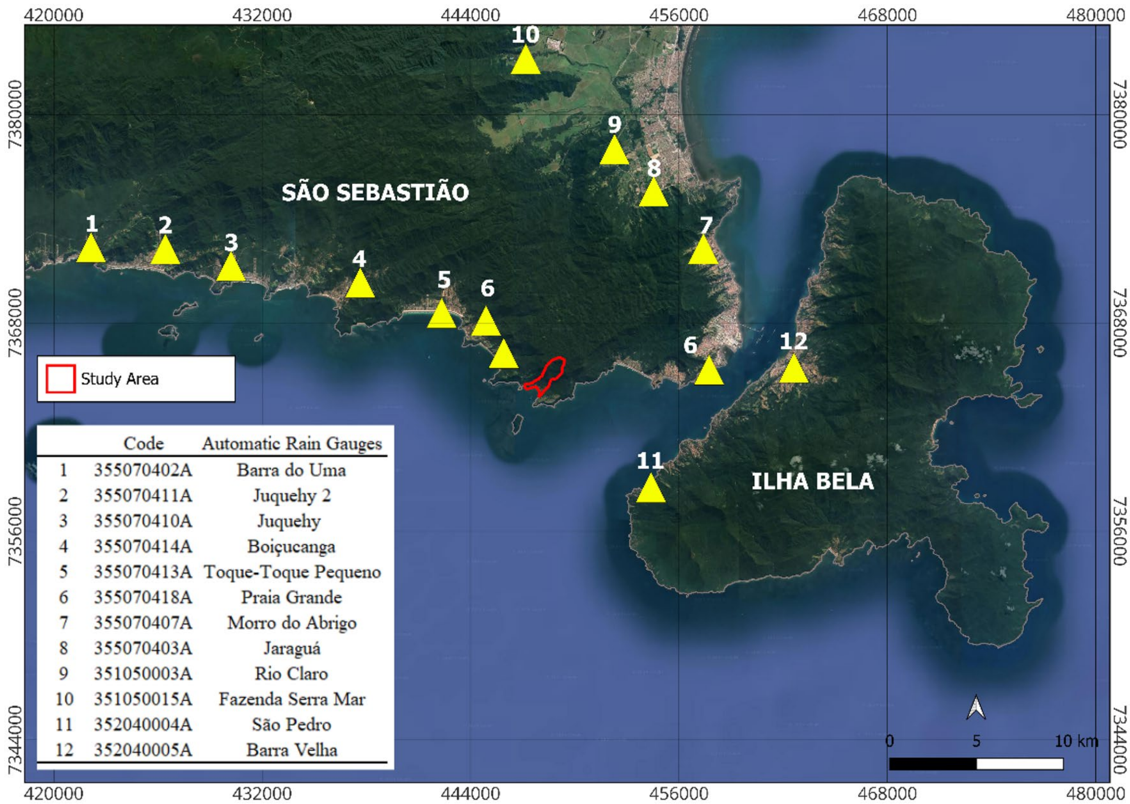


Fig. 3 Rain gauges used for evaluating the extreme event in the study area

case of extreme and localized rainfall in the considered catchment (Table 1).

Vulnerability, on the other hand, determines the damage that debris flows can cause to all mapped infrastructure in different risk scenarios, mainly the pipeline crossing. It is important to note that the vulnerability considered in this study takes into consideration only the physical vulnerability, not economic or social. Its classification was based on numerical computational modeling, where the runout

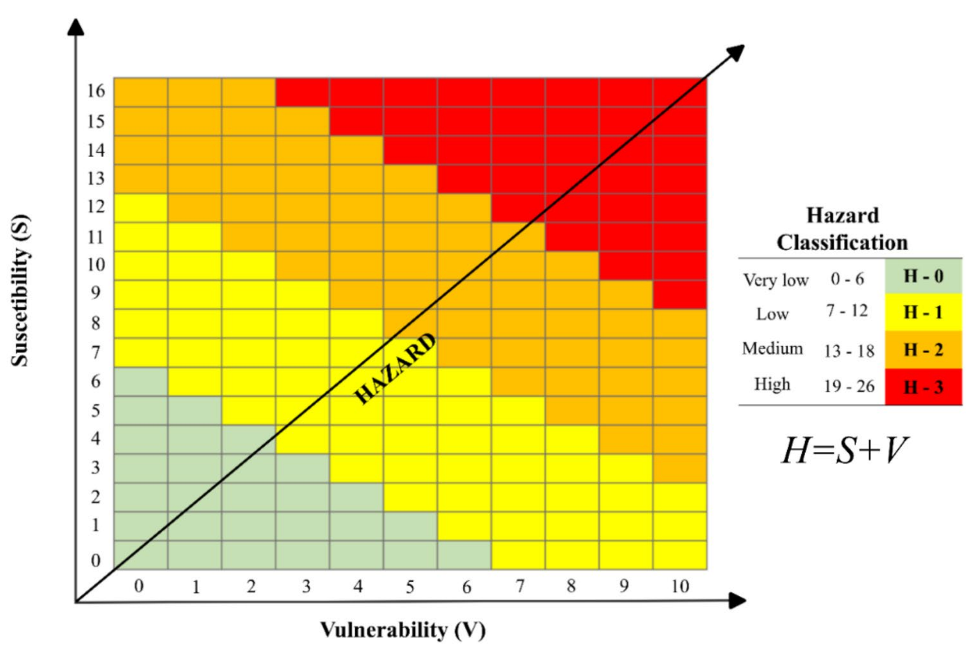


Fig. 4 Matrix of hazard classification for debris flow occurrence

Table 1 Parameters used for evaluating susceptibility to debris-flow occurrence

Susceptibility (16 points)	Hillside	Altimetric gradient (H) (m)	> 750	4
Geomorphological constraints			500–700	3
			200–500	2
			100–200	1
			< 100	0
	Drainage	Channel slope (D) (°)	> 25	4
			15–25	3
			10–15	2
			5–10	1
			< 5	0
		Length of the watershed (WL) (km)	> 4	4
			3–4	3
			2–3	2
			1–2	1
			< 1	0
	Watershed	Watershed area (A) (km^2)	< 5	4
			5–10	3
			10–15	2
			15–20	1
			> 20	0

distance of the debris flow was estimated, considering three crucial parameters: (i) distance traveled, considering the height of the flow (meters) and velocity (m/s) in the watershed areas where the main channel intercepts the pipelines; (ii) magnitude estimation based on the volume of mobilized material (m^3); and (iii) the method applied in the construction of the pipes (Table 2).

The numerical modeling was conducted using the RAMMS-DF, developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), which employs the Voellmy friction model for debris flows based on Voellmy's fluid flow law (Frank et al. 2017; Cabral et al. 2023b).

For model calibration, we adopted the methodological procedure of Schraml et al. (2015), where we compared the observed and simulated deposition areas using an approach like that of Carranza and Castro (2006), Scheidl and Rickenmann (2010), and Cabral et al. (2023b). Subareas Ax, Ay, and Az resulting from the overlay of the simulated areas were systematically compared (Eqs. 1–3).

Subsequently, a coverage index (Ω) is derived using Eq. (4), and the closer it is to 1, the more accurate the simulation results are:

$$\boldsymbol{\alpha} = \boldsymbol{A}\ \boldsymbol{x}/\boldsymbol{A}\ observed \tag{1}$$

$$\boldsymbol{\beta} = A\ y/\boldsymbol{A}\ observed \tag{2}$$

$$\boldsymbol{\gamma} = A\ z/\boldsymbol{A}\ observed \tag{3}$$

$$\boldsymbol{\Omega} = \boldsymbol{\alpha} - \boldsymbol{\beta} - \boldsymbol{\gamma} \tag{4}$$

Results and discussions

Meteorological analysis

The northern coast of the State of São Paulo exhibits particularities in terms of climate dynamics due to its geographical position situated between subtropical (polar) and tropical atmospheric fluxes. This positioning tends to favor, especially during summer, intense rainfall events. Additionally, the orographic factor plays a significant role in blocking warm and humid winds from the sea, as well as thick, highly saturated clouds, which induce condensation and precipitation (Sant'Anna Neto 2001; Costa 2023; Carvalho et al. 2022).

In this context, during the night of February 18th to the early morning of February 19th, an exceptional rainfall event occurred along the northern coast of the state of São Paulo, with elevated rainfall indices in the municipality of São Sebastião. The hourly-intensity peak in the study area was reached around 4:00 AM (UTC) on February 19th, with no significant accumulated precipitation prior to that time.

Table 2 Determination of vulnerability classes

Vulnerability (10 points)			
	Runoff		
	High	h > 1.0 m and v > 1.0 m/s	3
	Moderate	h < 1.0 m or v < 1.0 m/s	2
	Low	h < 0.4 m and v < 0.4 m/s	1
	Very Low	Non-affected areas	0
	Magnitude volume (m^3)	> 5000 m^3	4
		1000–5000 m ^{3}	3
		100–1000 m^3	2
		0–100 m^3	1
		No damage to the crossing section	0
	Constructive method		
		Aerial pipeline	3
		surface pipeline	2
		Underground pipeline	1
		pipeline with protection work	0

Between the night of February 18th and 9:30am (UTC) on the 19th, a rainfall volume of approximately 403 mm occurred in the Toque Toque Pequeno rain gauge, the nearest to the Toque-Toque Grande catchment, triggering landslides in its upper sections, which were concentrated in the main channel, breaking natural in-channel dams and initiating the first pulses of the debris-flow event (Fig. 5A and B).

According to Metsul, the phenomenon resulted from the collision between two different air mass systems. The equatorial Amazonian continental mass through the formation of the South Atlantic Convergence Zone (ZCAS) in displacement, which influences the precipitation in a large part of the Brazilian territory, met with a cold front advancing from the southern region over Serra do Mar, resulting in this unprecedented rainfall event (Fig. 6).

An important relationship was developed by Jones and Liebmann (2002) regarding the influence ZCAS and the occurrence of extreme events in the state of São Paulo. In this study, the Serra do Mar was characterized as one of the most important topographic factors influencing the regional distribution of rainfall in the state, responsible for the seasonal maximum precipitation along the coast, which decreases towards the inland areas. It has also been observed that when the activity of the South Atlantic Convergence Zone (ZCAS) is weaker, with a displacement towards the ocean, there is an association with the occurrence of extreme events, especially in areas along the Serra do Mar (Jones and Carvalho 2002; Goncalves 2015).

Therefore, when analyzing the precipitation responsible for triggering the debris flow, the focus was on seeking a pattern of concentration along the escarpments of the Serra do Mar, through the analysis of data from the CEMADEN rain gauges distributed along the coast. By interpolating the data from rain gauges, it is possible to observe the predominant role of the Serra do Mar in rainfall concentration.

The extreme precipitation was confined to the ridge line of the mountain range, concentrated in the Barra do Sahy region, with a rainfall index of 601 mm/24 h, with hourly peaks of 106 mm (Fig. 7).

Geomorphological analysis

At this stage, the analysis of the main geomorphological factors that trigger debris flows was performed (Fig. 8). The following are the results of slope and channel characterization, as well as magnitude estimation, based on the DEM with a spatial resolution of 10 m.

Slope conditions

Through fieldwork, it was possible to observe the extensive destruction caused by the debris flow. Overall, the catchment covers an area of 1.8 km^2, with an elevation range of approximately 680 m, length of 1.5 km, and channel slope averages at 24° up until the knickpoing of the Toque-Toque Grande waterfall, which is where the main channel the section where a topographic intersects the BR-101 highway (Fig. 9A).

Due to its small area, high altimetric gradient and steep slopes, rainfall has a tendency to occuring with higher average intensity per area in a more uniform manner in the catchment compared to larger ones, resulting in longer concentration times. Generally speaking, at Serra do Mar, smaller catchments exhibit steeper slopes and are more susceptible to orogenic effect, making them proner to triggering debris flows (Facuri and Picanço 2021).

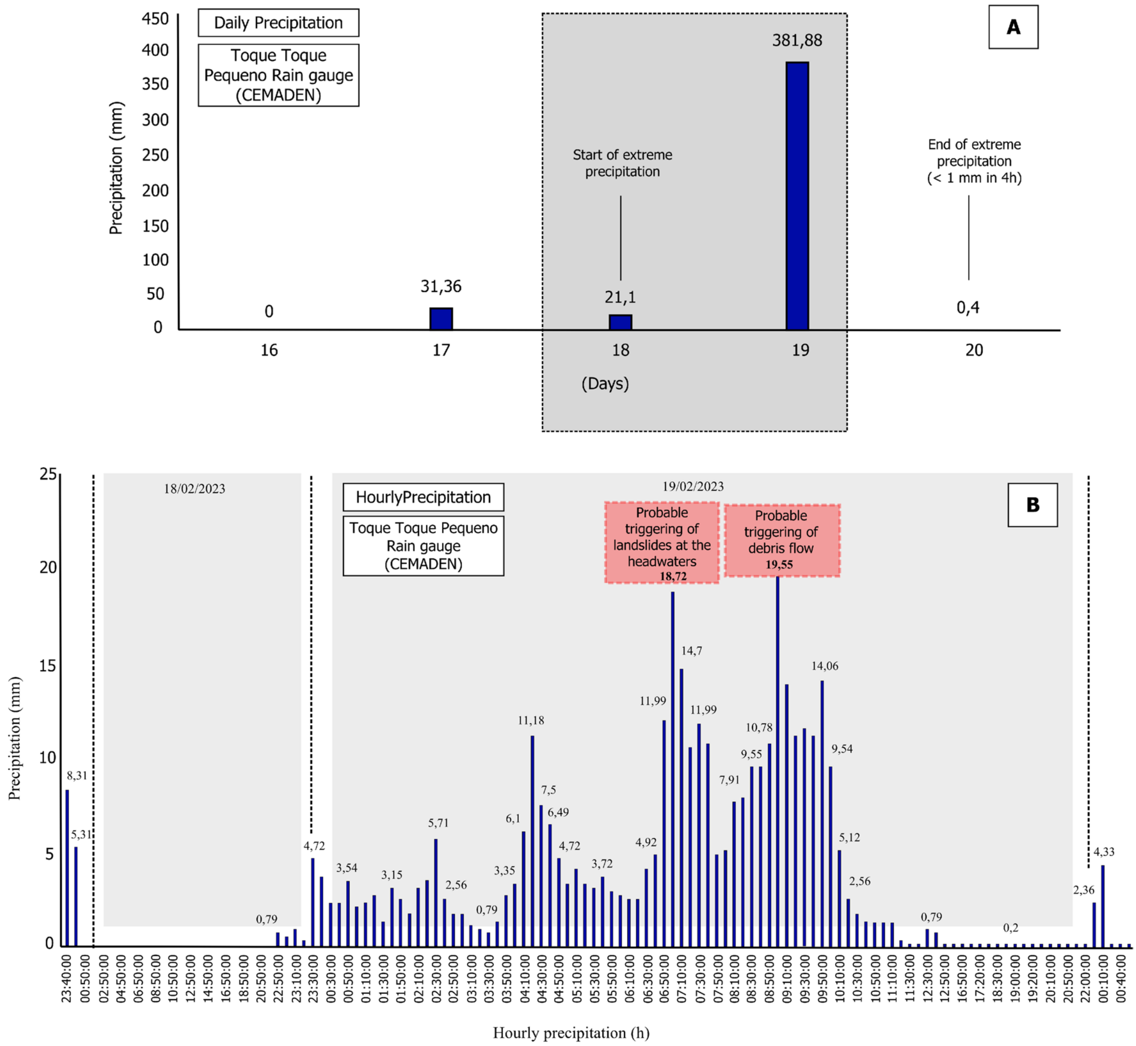


Fig. 5 **A** Daily precipitation analyzed for February 18th and 19th, 2023, for the Toque-Toque Pequeno rain gauge (closest to the study area, located 2.8 km away). **B** Precipitation recorded by the rain gauge between February 18th and 19th, indicating the onset of the main events responsible for triggering the debris flow

In this section, it was observed that the waterfall post-event was completely exhumed, meaning all dislodged or fractured material was transported downstream during the debris-flow event, indicating the impact force and erosive power of the event (Fig. 9A and B).

Regarding the catchment slope (Fig. 8), characteristics and factors favorable to destabilization processes (shallow translational landslides, rockfalls, erosion) were identified. Due to the difficulty of accessing the upper part of the Toque-Toque Grande waterfall and for safety reasons, we did not have physical access to the upper section of the catchment. However, through the use of drone imaging, it was observed that the vegetation is mostly well-preserved without signs of degradation, indicating that it was not the direct cause of the destabilization processes.

Rectilinear slopes predominate in the upper portions, with slopes exceeding 30°, which are considered the most critical for landslides (Cabral et al. 2023b). The slopes in the initiation zone located at the headwaters region are strong conditioned by geomorphological and structural factors, with valleys deeply incised in a "V" shape, featuring slopes ranging approximately from 74° to 63° at higher elevations, decreasing from 63° to 55° in the middle course, and reaching 35° in the deposition zone at the lower sections of the catchment (Fig. 10).

By analyzing Toque-Toque Grande's topographic profile a striking resemblance to other debris-flow prone catchments at Serra do Mar is observed, such as those in Cubatão (state of São Paulo), Itaoca (state of São Paulo) and Guaratuba (state of Paraná) (Massad 2002; Kanji et al. 2007; Massad et al. 2009; Veloso et al. 2023a; Cabral et al. 2023b). In these catchments, the main channel, due to high gradients and topographic discontinuities, is often associated with sections of high geological fracturing and shallow soils in the upper and middle courses, amplify the flows, increasing their transport load with rocky material and large wood.

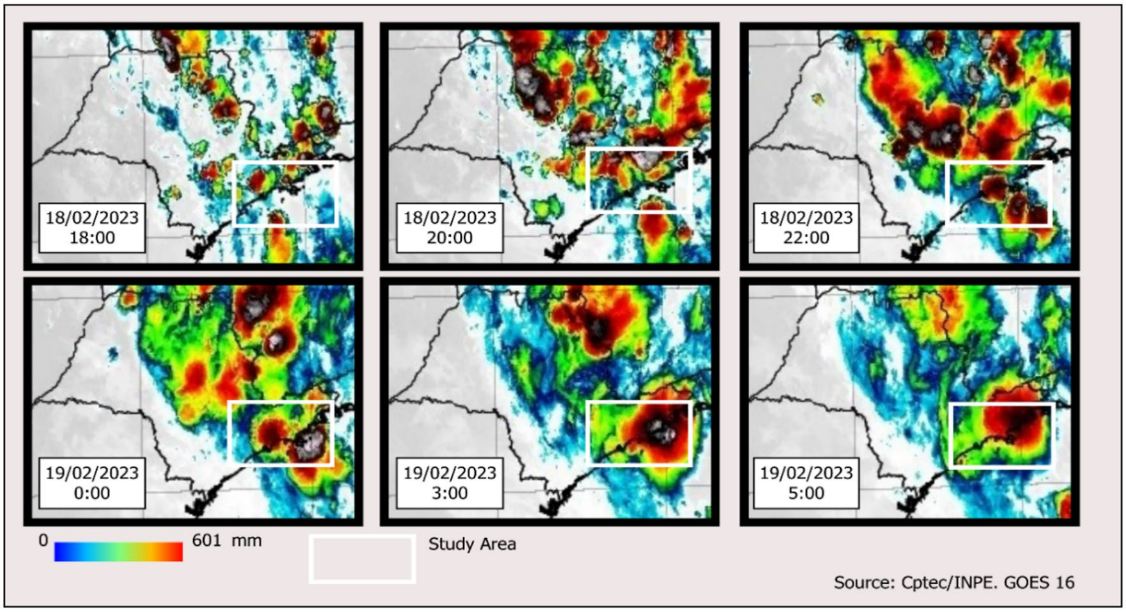


Fig. 6 Analysis of the phenomenon through GOES 16 satellite images

Channel conditions

A catchment's channel heavily influences the formation and development of a debris flow. The material mobilized by a debris flow along a channel does not solely originate from the slopes; a significant portion, especially coarser materials, is incorporated along the flow path, which, in some events, are also the primary sediment source (Scott 1971; Varnes 1978; Takahashi 2006; Hungr et al. 2014).

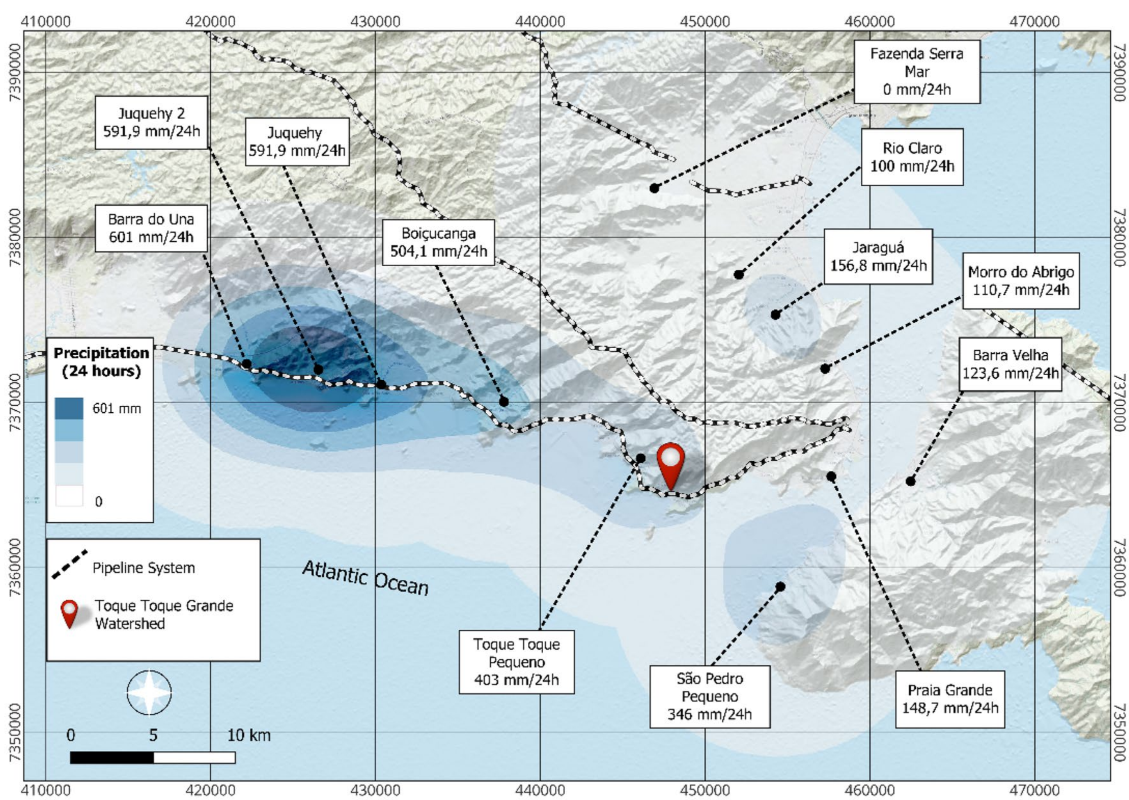


Fig. 7 Representation through interpolation of Cemaden's automatic rain gauges, highlighting the orographic factor in extreme precipitation in São Sebastião, SP

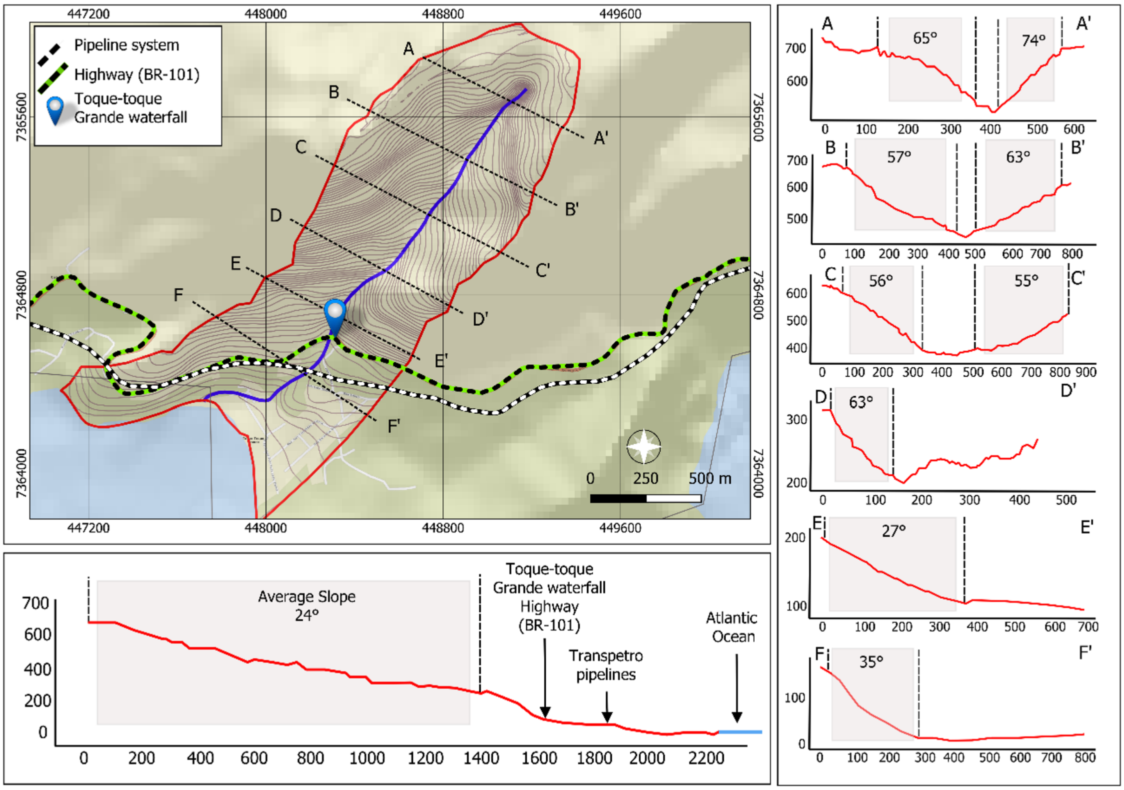


Fig. 8 Topographic map of the study area and transversal and longitudinal profiles of the main drainage

A significant portion of debris flow processes forms along channels, by the collapse of natural dams or from previous shallow landslides and/or rockfall events.

Channel Slope at the headwaters region is around 24°, decreasing to 17° in the middle course, and further softening after the Toque-Toque Grande waterfall to slopes of 7° in the lower part (Fig. 9).

The valleys are highly incised in a "V" shape in the upper sections and middle course of the drainage headwaters. In the lower portion, following the softening of slopes after the Toque-Toque Grande waterfall, the valleys still retain a degree of incision, albeit significantly reduced.

This characteristic pattern, resembling a ramp, has all the conditions for the development of debris flows, enhancing destabilization by imparting high kinetic energy to the initial movements (Fig. 11).

The debris-flow event

The debris-flow event occurred on the night between February 18 and 19, 2023, in the –Toque-Toque Grande catchment. For a better understanding of the debris flow in the study area, a fieldwork was conducted to mapping the main triggering factors and to supporting the simulation of the event using RAMMS. The simulation helped to determine important parameters such as flow height, velocity along its trajectory, runout distance, and magnitude. Figure 12A and B show the simulation results, where the maximum height reached up to 3 m along the main channel, at its middle section and near the pipeline, covering 2.1 km, reaching up to the shoreline.

Figure 12A shows the scars of the landslides upstream of the catchment, which were responsible for triggering the debris flow and were used for modeling. These landslides represent an initial volume of 5,083.7 m^3. Although this volume is not significant compared to other events in the Serra do Mar that initiated debris flows, the material deposited in the channel contributed to the increase in volume and the development of the debris flow. (Dias et al. 2022; Cabral et al. 2023b; Veloso et al. 2023a).

The model calibration was performed using the coverage index (Ω) proposed by Schraml et al. (2015), based on the comparison of observed and modeled areas covered by RAMMS. As illustrated in Fig. 8, the area affected by the debris flow according to the simulation greatly coincides with the deposits field observations, as well as with those estimated using satellite images and aerial photographs, with Ω values of 80%.

The debris flow had several pulses, as evidenced by several breached dams along the main channel, consisting mainly of large rock-boulder (< 5 m) and large wood (LW). The pipelines that cross the river basin were not seriously compromised, due to a bridge built as a protective structure. However, after the event, the bridge needed renovations due to the significant impact (Fig. 13C).

The destruction of houses at the forefront of the Toque-Toque Grande neighborhood was caused by the large volume of medium to small-sized rock boulders, coarse sediments, and tree trunks. These elements, as observed in Figs. 11 and 13 acted as a barrier to larger-sized materials. As a result, mud and some of the less

Fig. 9 Comparison of the Toque-Toque Grande waterfall before and after the debris flow. **A** Frontal record of the waterfall taken on 04/05/2022, where it is possible to observe a large number of trees, wooden, and blocks fallen from the upper parts of the watershed. **B** Aerial record by drone on the date of 13/11/2023, showing the waterfall completely exposed due to the significant erosive power of the debris flow. To watch the video, please access the following. link: [https://www.youtube.com/watch?v=lwcrSpGc4iE]

voluminous material from the flow managed to surpass this barrier and reach the sea.

Estimation of the debris-flow hazard index

The estimation of the debris-flow hazard index for pipeline crossings is based on the hazard index for the study areas and is defined through the correlation between susceptibility and vulnerability assessments.

Susceptibility analysis

The definition of susceptibility took into consideration four main parameters that condition debris-flow initiation in the catchment: altimetric gradient (m), slope (°), basin length (km), and total area (km^2). These values were obtained through field surveys and morphometric analysis, where a classification was assigned to each parameter (Table 3).

The altimetric gradient value (H) was around 680 m, classified as order 3, while the slope of the main channel (D) averaged 27°, also classified as class 3. The length of the basin (WL) was 1.68, classified as order 1, and finally, the basin area (A) was 1.8 km^2, classified as class 4. The sum of all parameters was 11.

Vulnerability analysis

Vulnerability in this study was defined through parameters such as the distance traveled (runout) by the debris flow, establishing a relationship between velocity and the height of the flow in the pipeline crossing section. The magnitude of the event was related to the volume obtained through modeling (Fig. 12) and finally, the construction method of the pipelines in the channel crossing areas (Table 4).

With the debris flow had a peak velocity of around 10.7 m/s and a maximum flow height of 3 m. The estimated magnitude was approximately 6873.4 m^3, and the construction method of the pipelines in the channel crossing section is underground. The sum of all vulnerability parameters was 7.

Debris-flow hazard index

To obtain the debris-flow hazard index, the final values of susceptibility and vulnerability classification were combined through the hazard matrix, resulting in the hazard index for the Toque Toque Grande catchment (Fig. 14). The hazard index classification combined susceptibility and vulnerability values through the hazard matrix described in previous sections, resulting in individual

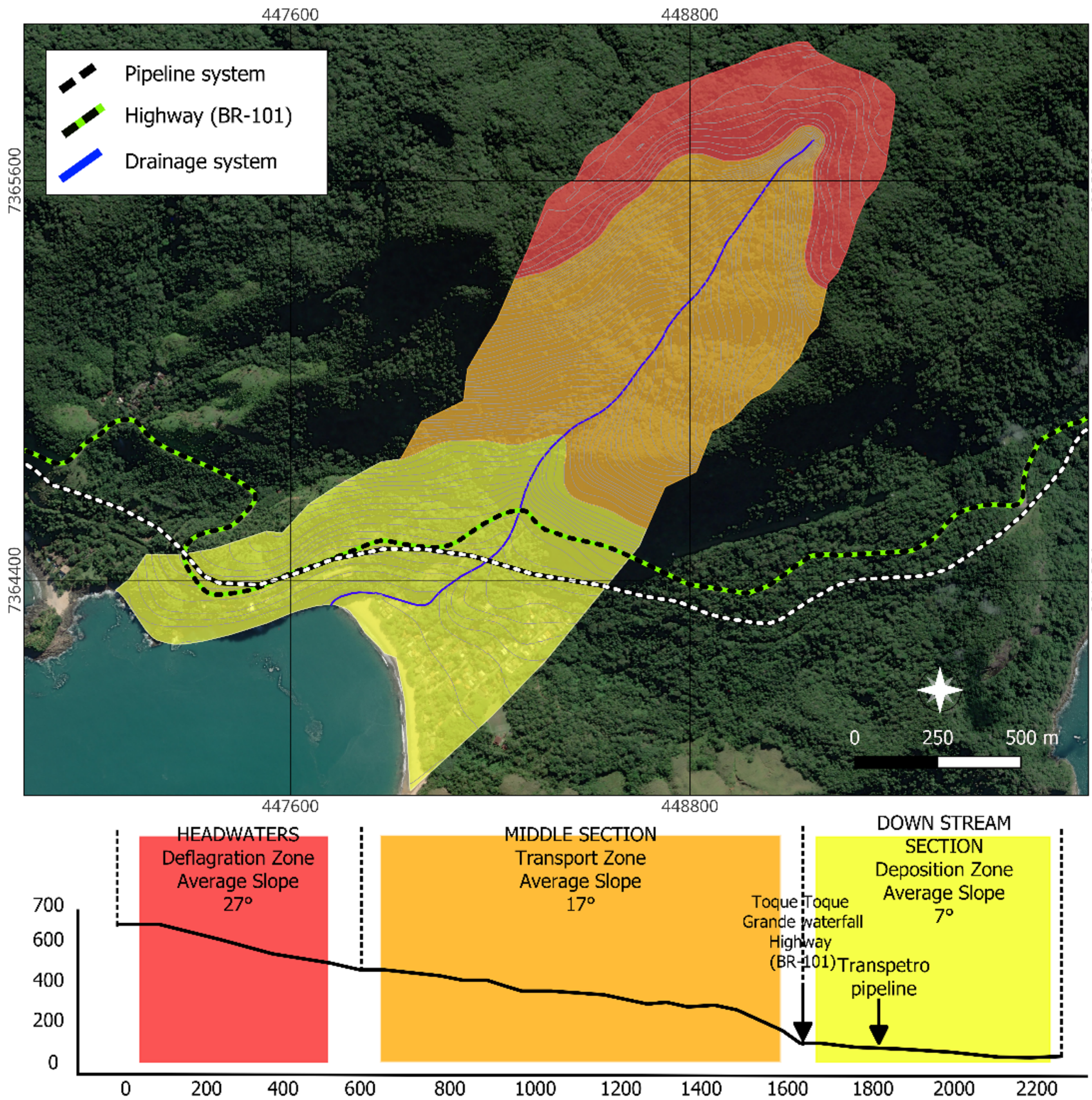


Fig. 10 Slope profile of the basin's main drainage

hazard indexes for each pipeline crossing section in the selected hydrographic basins for the research application.

For channel crossing sections classified as H-1, the adoption of specific contingency plans at the local scale for each hydrographic basin is recommended. In cases of sections classified as H-2, it is recommended to incorporate the hydrographic basins into a logic of non-structural actions for natural disaster response, including contingency plans and, preferably, real-time pluviometric and geotechnical monitoring.

In cases of sections classified as H-2, such as in Toque Toque Grande, structural interventions are required (e.g., stabilization structures, sediment retention dams, and sediment control), to reduce vulnerability, also including specific preventive plans based on real-time monitoring and alert systems, as well as plans specific to the basins.

Based on the combined results of susceptibility and vulnerability analysis, expressed through the hazard matrix, the hazard index attributed to the specific drainage crossing segment intercepted by the pipeline system in the Toque-Toque Grande watershed reveals a concerning scenario, classified as level 18 (H-2). This index indicates a significant and imminent danger of debris flow occurrence. However, thanks to the protective measures implemented on the pipelines, the risk of disaster occurrence and escalation is significantly reduced (Fig. 15).

Fig. 11 Documentation of erosion caused in the main drainage by the debris flow. **A** Record of metric blocks and deposits in the main drainage. **B** Documentation of imbrication of large woods and metric blocks deposited in the main drainage after the passage of the debris flow. **C** Aerial view of the section crossing the Petrobras pipelines where the construction managed to protect the infrastructures after the passage of the debris flow. To watch the video of the debris flow passing through this section, please access the following link: [https://www.youtube.com/watch?v=w2EuEz2mEeo]

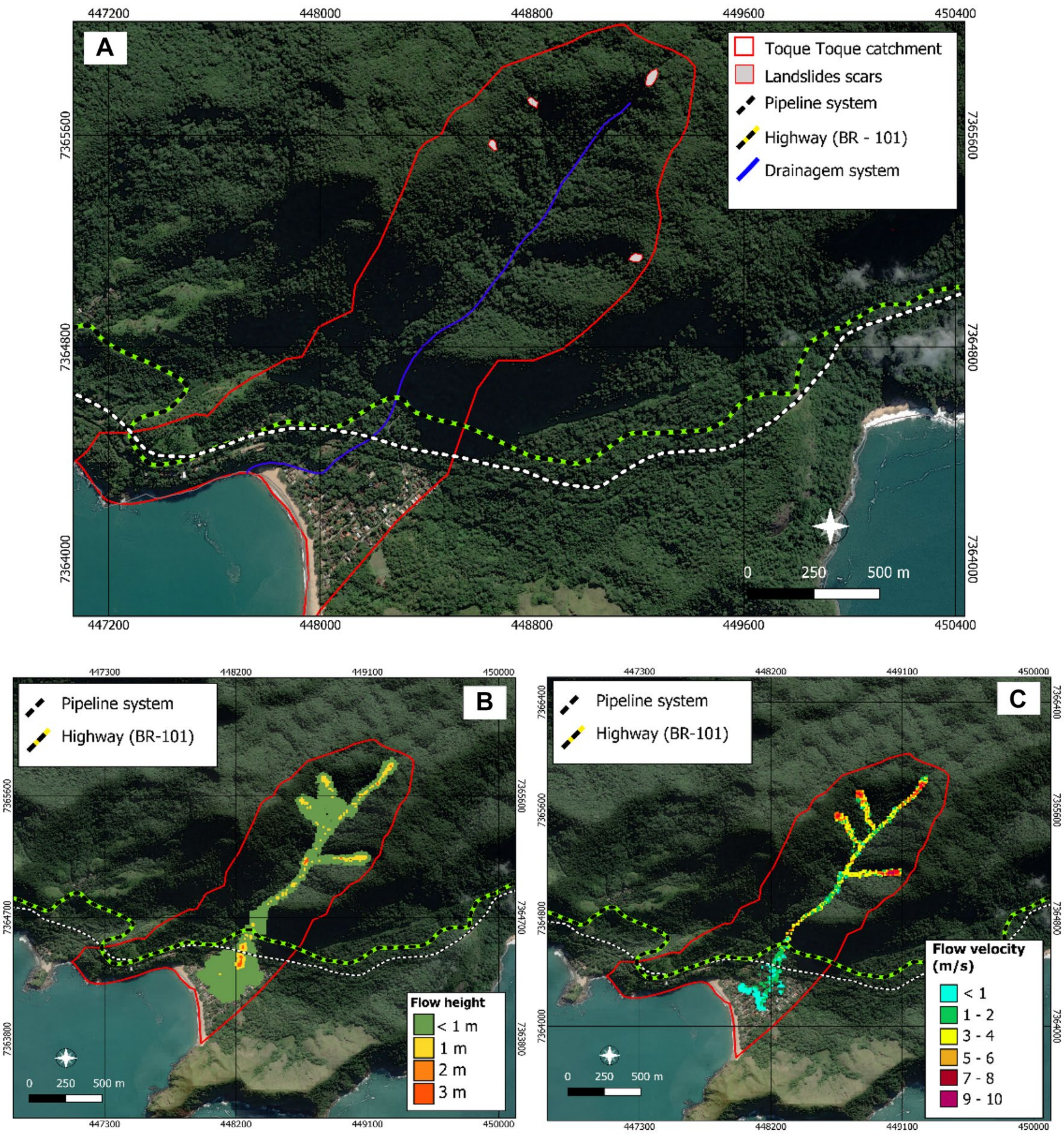


Fig. 12 **A** Mapping of landslide scars recorded upstream of the catchment using satellite images, used to estimate the initial volume. **B** Height of the modeled debris flow along its trajectory in the catchment. **C** Estimated velocity of the debris flow along its trajectory in the catchment

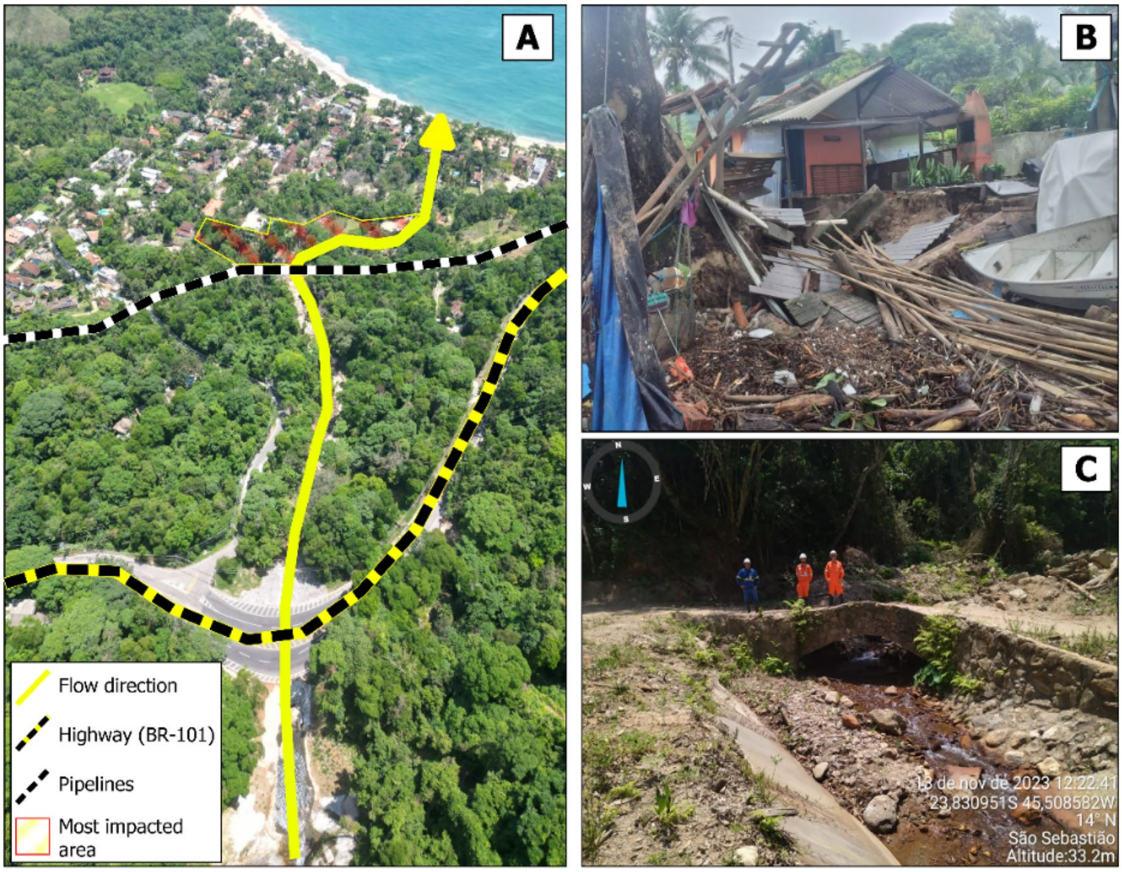


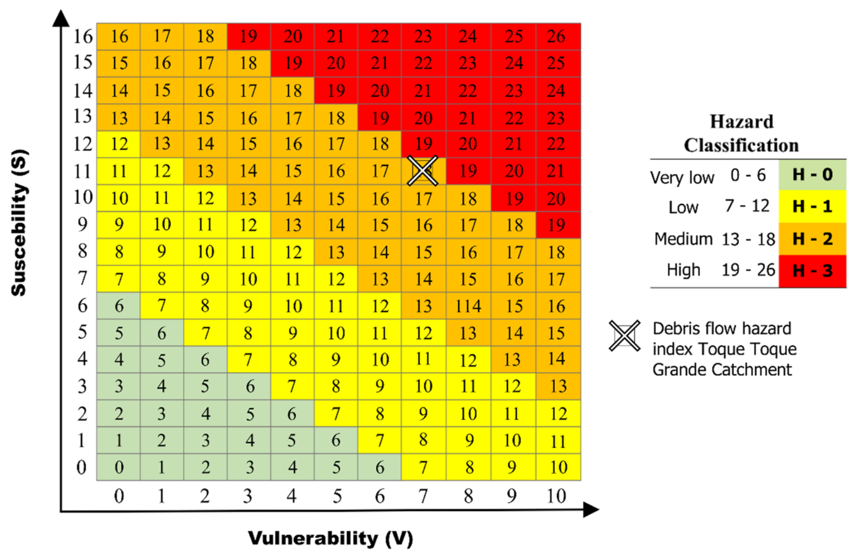
Fig. 13 Record of the path taken by the flow in the study area. **A** Path taken by the debris flow overlaid with the Highway (BR-101), pipeline system, and the most affected residential areas. **B** Frontal view of one of the residences affected by the impact of the flow. **C** Record of the protective structure responsible for maintaining the integrity of the pipeline at the crossing section with the main drainage. To view the video of the waterfall situation, access the link: [https://vimeo.com/user214436941]

Table 3 Classification of susceptibility in Toque Toque Grande watershed

Catchment	Altimétric gradient (H)	Class	Slope channel (D)	Class	Catchment lenght (WL)	Class	Catchment area (A)	Class	Total
Tq_Tq_ Grande	680	3	27	3	1.68	1	1.8	4	11

Table 4 Result vulnerability classification

Catchment Tq_Tq_Grande	Flow characteristics		Magnitude (m^3)	Constuctive method	Total
	Velocity (m/s)	Maximum height (m)			
	10.7	3.0	6873.4	Underground pipeline with protection work	
Class	3		4	0	7



Toque Toque Grande catchment	Susceptibility	Vulnerability	**HAZARD INDEX**	Classification
	11	7	18	**H-2**

Fig. 14 Debris-flow hazard index classification matrix in the study area

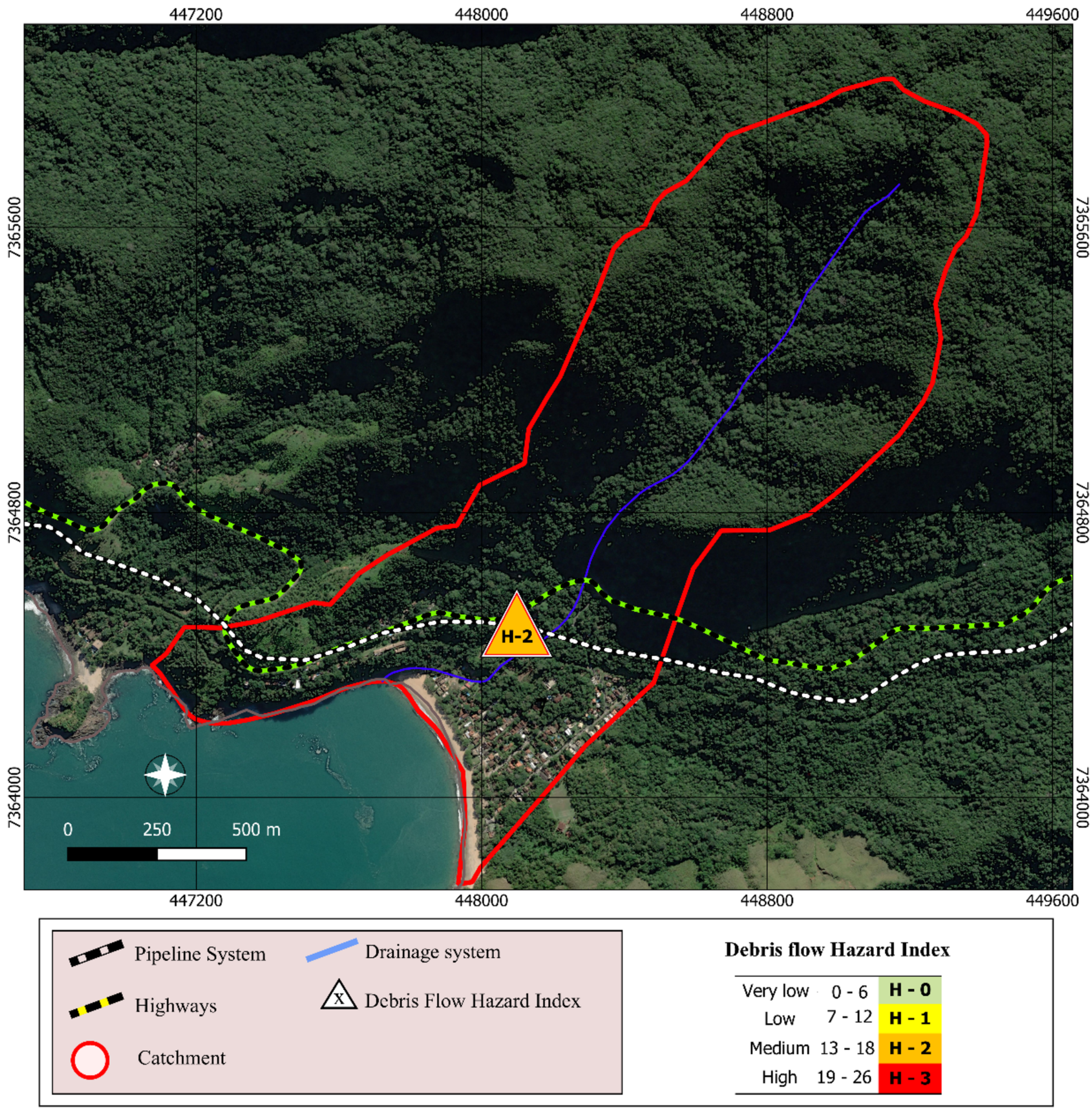


Fig. 15 Hazard index for debris flows on pipelines in the study area

Conclusions

This study aimed at assessing the initiation and behavior of a debris-flow event that occurred in São Sebastião – SP, in February 2023, in the context of an unprecedented and atypical precipitation event in Brazil. Additionally, a comprehensive assessment of the risks associated with the occurrence of debris flows in sections of drainage crossings traversed by pipelines was conducted, based on the application of the debris-flow hazard index in areas with strategic infrastructures and urban densifications at risk of impact, resulting in some significant conclusions that can guide risk strategies and protective measures.

Another important point was the observation of the magnitude of the event that occurred in February 2023, through the erosion caused in the main drainage, evidenced by the comparison of the Toque-Toque Grande Waterfall before and after the disaster, showing the necessity and urgency of structural protection measures. In addition, through the analysis of geomorphological constraints and channel conditions, the influence of these factors on the formation and development of debris flows was highlighted, as the understanding of the morphological and topographic characteristics of a catchment is fundamental for the evaluation and prevention of debris flows.

This analysis, combined with computational modeling of the debris-flow event, allowed the estimation of the flow height and velocity along its trajectory in the catchment, providing essential information to understanding the dynamics of the phenomenon. The identification of areas prone to debris flows and the implementation of mitigation measures, such as the protective structure installed over the pipeline in the Toque-Toque Grande catchment, which demonstrates the importance of structural preventive actions aimed at reducing the impacts of these events.

In summary, this study highlighted the complexity and importance of multidisciplinary approaches to understand, assess, and manage the risk of debris flows. The conclusions presented here are intended to significantly support strategies for prevention, emergency response, and protection of infrastructure in the face of these environmental and operational challenges.

Author contribution

Mr. Vinicius Queiroz Veloso worked on the development and writing of the manuscript, organized and collected fieldwork data. Dr. Fabio Augusto Gomes Vieira Gomes Reis organized the fieldwork campaign, contributed with the development and organization of the manuscript. Dr. Victor Cabral and Dr. Claudia Vanessa dos Santos Corrêa contributed to the fieldwork and writing of the manuscript. Mr. Thiago Castro Ribeiro, Agostinho Tadashi Ogura and Marcelo Fischer Gramani worked on reviewing and processing the data. Dra. Lucilia do Carmo Giordano and Mr. Artur A. Sá contributed to the writing and organization of the fieldwork and data collection. Dra. Joana Paula Sanchez and Caiubi Emanuel Souza Kuhn aided the collection of fieldwork data and data processing. Mrs. Pedro Victor Serra Mascarenhas and Wanderley Russo aided in the fieldworks, collection data, and writing the manuscript.

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Data availability

The datasets generated during our study are available from the corresponding author upon request.

Declarations

Competing interests The authors declare no competing interests.

References

Bernard M, Gregoretti C (2021) The use of rain gauge measurements and radar data for 413 the model based prediction of runoff generated debris flow occurrence in early 414 warning system. water resources research 57(3)

Cabral V, Reis F, Veloso V, Correa C, Kuhn C, Zarfl C (2023a) The consequences of debris flows in Brazil: a historical analysis based on recorded events in the last 100 years. Landslides 1–19. https://doi.org/10.1007/s10346-022-01984-7

Cabral V, Reis F, Veloso V, Ogura A, Zarfl C (2023b) A multi-step hazard assessment for debris-flow prone areas influenced by hydroclimatic events. Eng Geol 313:106961. https://doi.org/10.1016/j.enggeo.2022.106961

Cabral VC, Reis FAGV, Mendoza CM, Oliveira A (2022) Model-based assessment of shallow landslides susceptibility at a petrochemical site in Brazil. Rev Bras Geomorfol 23:1394–1419. https://doi.org/10.20502/rbg.v23i2.2084

Carranza EJM, Castro OT (2006) Predicting lahar-inundation zones: case study in West Mount Pinatubo, Philippines. Natural Hazards 37:331–372

Carvalho LMV, Jones C, Liebmann B (2022) Extreme precipitation events in southeastern South America and large-scale convective patterns in the South Atlantic convergence zone. J Clim 15(17):2377–2394. https://doi.org/10.1175/1520-0442

Corrêa CVS, Vieira Reis FAG, Giordano LC, Cabral VC, Gramani MF, Gabelini BM, Duz BG, Veloso VQ (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 - UFRJ 44:1–14. https://doi.org/10.11137/1982-3908_2021_44_43313

Costa WMD (2023) Os Temporais e a Catástrofe em São Sebastião-SP no Carnaval de 2023. Revue franco-brésilienne de géographie/Revista franco-brasilera de geografia (58)

Dias VC, Vieira BC, Gramani MF (2016) Parâmetros morfológicose morfométricos como indicadores da magnitude das corridas de detritos na Serra do Mar Paulista. Confins 29. https://doi.org/10.4000/confins.11444

Dias VC, McDougall S, Vieira BC (2022) Geomorphic analyses of two recent debris flows in Brazil. J S Am Earth Sci 113:103675

dos Santos ÁR (2004) A grande barreira da Serra do Mar: da trilha dos Tupiniquins à Rodovia dos Imigrantes. o Nome da Rosa

Eybergen FA, Imeson AC (1989) Geomorphological processes and climatic change. Catena 16(4–5):307–319

Facuri GG, de Lima Picanço J (2021) Evaluations and proposals for the debris flow hazard mapping method of the GIDES Project. Landslides 18(1):339–352

Frank F, McArdell BW, Oggier N, Baer P, Christen M, Vieli A (2017) Debris-flow modeling at Meretschibach and Bondasca Catchments, Switzerland: sensitivity testing of field-data-based entrainment model. Nat Hazards Earth Syst Sci 17(5):801–815. https://doi.org/10.5194/nhess-17-801-2017

Giordano LC, Marques ML, Reis FAGV, Corrêa CVS, Riedel PS (2023) The suitability of different vegetation indices to analyses area with landslide propensity using Sentinel -2 Image. Boletim De Ciências Geodésicas 29:2023008. https://doi.org/10.1590/s1982-21702023000300008

Goncalves J (2015) Caracterização e variabilidade de situações sinóticas associadas a episódios de chuva intensa e chuva persistente durante a estação chuvosa na Região Sudeste do Brasil (Doctoral dissertation, Dissertação (Mestrado)—Instituto Nacional de Pesquisas Espaciais (INPE))

Gramani MF (2001) Caracterização geológica-geotécnica das corridas de detritos ("Debris Flows") no Brasil e comparação com alguns casos internacionais. Escola Politécnica da Universidade de São Paulo (EP-USP)-Departamento de Engenharia de Estruturas e Geotécnica (PEF). São Paulo

Guo X, Cheng J, Yin C, Li Q, Chen R, Fang J (2023) The extraordinary Zhengzhou flood of 7/20, 2021: how extreme weather and human response compounding to the disaster. Cities 1(134):104168

Graf C, McArdell B (2008) Simulation of debris flow runout before and after construction of mitigation measures: an example from the Swiss Alps. Proceedings of the International Conference on DEBRIS FLOWS: Disasters, Risk, Forecast, Protection. Pyatigorsk, Russia, 22–29:233–236

Graf C, McArdell BW (2011) Debris-flow monitoring and debris-flow runout modelling before and after construction of mitigation measures: an example from an instable zone in the Southern Swiss Alps. In: Lambiel C.; Reynard E.; Scapozza, C. (eds) La géomorphologie alpine: entre patrimoine et contrainte. Actes du colloque de la Société Suisse de Géomorphologie, 3–5 septembre 2009, Olivone. Géovisions no 36. Lausanne, Université de Lausanne Institut de Géographie 245–258

Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. Landslides 11(2):167–194. https://doi.org/10.1007/s10346-013-0436-y
IPCC (2022) IPCC sixth assessment report: impacts, adaptation and vulnerability
IPT (1981) Mapa Geomorfológico do Estado de São Paulo. Escala 1:500.000. São Paulo. 2v. (IPT monografias, 6 Publicação, 1184)
IPT – Instituto de Pesquisas Tecnológicas (1987). Estudos das instabilizações de encosta da Serra do Mar na região de Cubatão objetivando a caracterização do fenômeno "corrida de lama" e da prevenção dos seus efeitos. Relatório 26.258. São Paulo: IPT, v. 1
Jones C, Carvalho LMV (2002) Active and break phases in the South American Monsoon System. J Clim 15:905–914
Kanji MA, Cruz PT, Massad F (2007) Debris flow affecting the Cubatão oil refinery. Brazil Landslides 5(1):71–82. https://doi.org/10.1007/s10346-007-0110-3
Lopez MDCS, Pinaya JLD, Pereira Filho AJ, Vemado F, Reis FAGV (2023) Analysis of extreme precipitation events in the mountainous region of Rio de Janeiro, Brazil. Climate 11:73–15. https://doi.org/10.3390/cli11030073
Manzolli TF, Cunha MA, Boggiani PC, Pizzato E, Paula MSD (2018) Corrida de detritos na Bacia hidrográfica do Rio Paúba-São Sebastião (SP). In Anais do Congresso Brasileiro de Geologia de Engenharia e Ambiental
Marengo JA, Cunha AP, Seluchi ME, Camarinha PI, Dolif G, Sperling VB, Alcântara EH, Ramos AM, Andrade MM, Stabile RA, Mantovani J (2024) Heavy rains and hydrogeological disasters on February 18th–19th, 2023, in the city of São Sebastião, São Paulo, Brazil: from meteorological causes to early warnings. Natural Hazards, pp.1–28
Massad F (2002) 'Corridas de massas geradas por escorregamentos de terra: relação entre a área deslizada e a intensidade de chuva'. In: XII Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica. São 7 Paulo, São Paulo
Massad F, Cruz PT, Kanji MA (2009) "Debris flows" em Cubatão-SP: danos em instalação industrial e em barragens-gabião. COBRAE'2009: Anais
Neto D, de Marins C, Correia CT, Tassinari CCG, Munhá JMU (2009) Os anfibolitos do complexo costeiro na região de São Sebastião. SP Geologia USP Série Científica 9(3):71–87
Pereira Filho AJ, Vemado F, Vemado G, Gomes Vieira Reis FA, Giordano LC, Cerri RI, Santos CC, Sampaio Lopes ES, Gramani MF, Ogura AT, Zaine JE, Cerri LES, Augusto Filho O, D'Affonseca FM, Amaral CS (2018) A step towards integrating CMORPH precipitation estimation with rain gauge measurements. Adv Meteorol 2018:1–24. https://doi.org/10.1155/2018/2095304
Rebetez M, Lugon R, Baeriswyl PA (1997) Climatic change and debris flows in high mountain regions: the case study of the Ritigraben torrent (Swiss Alps). Springer, Netherlands, pp 139–157
Rickenmann D, Zimmermann M (1993) The 1987 debris flows in Switzerland: documentation and analysis. Geomorphology 8(2–3):175–189. https://doi.org/10.1016/0169-555X(93)90036-2
Sant'Anna Neto JL (2001) História da climatologia no Brasil: gênese e paradigmas do clima como fenômeno geográfico. Tese (Livre Docência em Geografia) – Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente, SP. 2001
Scheidl C, Rickenmann D (2010) Empirical prediction of debrisflow mobility and deposition on fans. Earth Surf Proc Land 35:157–173. https://doi.org/10.1002/esp.1897
Schraml K, Thomschitz B, McArdell BW, Graf C, Kaitna R (2015) Modeling debris-flow runout patterns on two Alpine fans with different dynamic simulation models. Nat Hazards Earth Syst Sci 15(7):1483–1492. https://doi.org/10.5194/nhess-15-1483-2015
Scott KM (1971) Origin and sedimentology of 1969 debris flows near Glendora, California. Geol Surv Prof Pap 750:242–247
Takahashi T (1991) Debris Flow. IAHR, Monograph. Balkema, Rotterdam. p. 168
Takahashi T (2006) Debris flows: mechanics, prediction and countermeasures. Taylor and Francis, Balkema, Leiden
Veloso VQ, Reis FAVG, Cabral V, Zaine JE, dos Santos Corrêa CV, Gramani MF, Kuhn CE (2023a) Hazard assessment of debris-flow-prone watersheds in Cubatão, São Paulo State. Brazil Natural Hazards 116(3):3119–3138
Veloso VQ, Reis FAGV, Cabral VC, Giordano LC, Correa CVS, Kuhn CES (2023b) Challenges and perspectives in applying the environmental sensitivity index to pipelines: a review on the prevention and management of oil spills disasters. Environ Monit Assess 195:1449. https://doi.org/10.1007/s10661-023-12034-7
Varnes DJ (1978) Slope movement types and processes. Special report 176:11–33
Westra S, Fowler H, Evans J, Alexander L, Berg P, Johnson F, Kendon E, Lenderink G, Roberts N (2014) Future changes to the intensity and frequency of short-duration extreme rainfall. Rev Geophys 52:522–555. https://doi.org/10.1002/2014RG000464

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