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Methodological proposal for integrating debris flow hazard index with environmental sensitivity index in pipelines

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UNIVERSIDADE ESTADUAL PAULISTA
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Tese de Doutorado apresentada ao Instituto de Geociências e Ciências Exatas do Câmpus de Rio Claro, da Universidade Estadual Paulista “Júlio de Mesquita Filho”, como parte dos requisitos para obtenção do título de Doutor em Geociências e Meio Ambiente

Orientador: Prof. Dr. Fabio Augusto Gomes Vieira Reis
Coorientador: Prof. Dr. Artur Agostinho Abreu de Sá

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Resumo

Este trabalho aborda o desenvolvimento de metodologia complementar na gestão de desastres naturais incorporadas ao Índice de Sensibilidade Ambiental ao Derramamento de Óleo (ISL) ou Carta SAO para trechos de travessia de drenagens transpassados por dutovias. Embora muitas abordagens de mapeamento se concentrem em áreas costeiras e marinhas, o estudo destaca a necessidade de aprimorar as metodologias aplicadas a trechos continentais que apresentam alto potencial para ocorrência de desastres naturais associados a eventos geodinâmicos. O estudo inicia com uma revisão bibliográfica e uma análise histórica, identificando lacunas metodológicas no uso do Índice de Sensibilidade Ambiental e da Carta SAO no Brasil e no mundo. A partir disso, sugere abordagens para o avanço no desenvolvimento de mapeamentos de perigo ao derramamento de óleo em áreas continentais, focando na gestão de riscos e na prevenção de desastres tecnológicos desencadeados por desastres naturais (Natechs). São apresentados procedimentos metodológicos para contribuir nas estratégias de prevenção e resposta em áreas sensíveis ao derramamento de óleo em dutovias continentais, por meio da criação de um índice de perigo para a ocorrência de fluxos de detritos em trechos de travessia de drenagem nos municípios de Cubatão e São Sebastião (SP). Esse índice foi baseado na relação entre suscetibilidade e vulnerabilidade e se mostrou eficaz para hierarquizar áreas de perigo iminente, considerando os potenciais impactos ambientais e vazamentos de óleo. A metodologia foi validada por um evento de fluxo de detritos ocorrido entre os dias 18 e 19 de fevereiro de 2023 na bacia hidrográfica de Toque Toque Grande, em São Sebastião, permitindo a calibração dos modelos e o ajuste dos valores do índice. Adicionalmente, o trabalho propõe um sistema de monitoramento pluviométrico em tempo real, baseado em limiares de precipitação crítica e coleta de dados em tempo real, para complementar o índice de perigo a fluxos de detritos nas áreas de dutovias selecionadas. O trabalho indica um plano de gestão de risco dividido em duas partes: (i) mapeamentos estáticos e (ii) monitoramento dinâmico. Os mapeamentos estáticos referem-se à representação cartográfica das áreas de estudo, considerando a hierarquização do índice de perigo a fluxos de detritos. O monitoramento dinâmico, diz respeito ao sistema de monitoramento pluviométrico e em tempo real, baseado nos limiares de precipitação crítica, sistematizado em níveis operacionais que definem o grau de risco das chuvas responsáveis por deflagrar eventos de deslizamentos e fluxos de detritos, que possam impactar as dutovias nas áreas mapeadas.

Palavras-chave: Environmental Sensitivity Index, Real-time Monitoring Disasters, Debris flows, Hazard Management, Oil Spill, Disaster Reduction

Abstract

This work addresses the development of a complementary methodology in natural disaster management, incorporated into the Environmental Sensitivity Index (ESI) or ESI Maps, for segments of drainage crossings intersected by pipelines. Although many mapping approaches focus on coastal and marine areas, this study emphasizes the need to improve methodologies applied to continental segments, which have a high potential for natural disasters associated with geodynamic events. The study begins with a literature review and historical analysis, identifying methodological gaps in the use of the Environmental Sensitivity Index and ESI Maps in Brazil and globally. Based on this, it suggests approaches for advancing the development of oil spill hazard mapping in continental areas, focusing on risk management and the prevention of technological disasters triggered by natural hazards (Natechs). Methodological procedures are presented to contribute to prevention and response strategies in areas sensitive to oil spills in continental pipelines, through the creation of a hazard index for the occurrence of debris flows in drainage crossing segments in the municipalities of Cubatão and São Sebastião (SP). This index was based on the relationship between susceptibility and vulnerability and proved effective in prioritizing areas of imminent danger, considering potential environmental impacts and oil spills. The methodology was validated by a debris flow event that occurred between February 18 and 19, 2023, in the Toque Toque Grande watershed in São Sebastião, allowing for the calibration of models and adjustment of the index values. Additionally, the study proposes a real-time rainfall monitoring system, based on critical precipitation thresholds and real-time data collection, to complement the hazard index for debris flows in the selected pipeline areas. The study outlines a risk management plan divided into two parts: (i) static mapping and (ii) dynamic monitoring. Static mapping refers to the cartographic representation of the study areas, considering the prioritization of the debris flow hazard index. Dynamic monitoring involves the real-time rainfall monitoring system based on critical precipitation thresholds, systematized into operational levels that define the risk degree of rainfall events capable of triggering landslides and debris flows that may impact the pipelines in the mapped areas.

Key-words: Environmental Sensitivity Index (ESI), Real-time Monitoring Mass Movements, Debris flows, Hazard Management, Oil Spill, Disaster Reduction

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1 Introduction

In recent decades, in Brazil, the oil industry has experienced rapid expansion, driven by new exploration fronts, newly discovered fields, and substantial investments across its industrial chain. Within this context, significant advancements have been made in pipeline infrastructure for the transportation of oil and its derivatives. However, despite the high technological level of these endeavors, the management of risks for oil spill accidents caused by mass movements still lacks significant improvements.

Prevention, remediation, and assessment of these impacts can be conducted through systematic mapping instruments. One such instrument is called Environmental Sensitivity Maps for Oil Spills (ESM), which finds its greatest application and methodological advancements in coastal and marine areas. (Gunlach, E. and Hayes, M., 1978; Michel et al., 1978 Gunlach et al. 2001; Araujo et al., 2002 Araujo et al., 2006; Romero, 2009; Barbosa, 2010; Martins 2012, D’Fonseca et al. 2023).

Environmental Sensitivity Maps for Oil Spills (Carta SAO) constitute a fundamental source of primary information for planning contingency plans and response actions to oil spills. These maps aim to identify priority preservation areas, allowing for the allocation of available resources and the more efficient mobilization of protection and cleanup teams (Brazil, 2002; Araujo et al., 2002; Oliveira et al., 2003; Mendes et al., 2005; Barbosa, 2010; Martins et al., 2013; Costa, 2013; Martins, 2012).

According to Barbosa et al. (2010), the Carta SAO can be defined as a cartographic document legally required in contingency planning, in the overall assessment of damages, and in the implementation of response actions for incidents of oil and derivatives pollution. It is evident that the ESMs encompass a broad multidisciplinarity in their development, with the most important characteristic being the determination of the Coastal Sensitivity Index (CSI). This index refers to the characteristics of the physical environment and active processes.

The most used methodology for developing an Carta SAO, up to the present, is based on the reference documents by Gundlach and Heyes (1978), Michel et al. (1978), NOAA (1995), and Michel and Dahlin (1993). This methodology consists of three main components: (1) Coastal Sensitivity Index (CSI), where areas are classified from 1 (lowest sensitivity index) to 10 (highest sensitivity index), (2) biologically sensitive and vulnerable resources to oil, and (3) human use of resources with commercial, recreational, or subsistence value (Jensen et al., 1998). In Brazil, significant advancements have been made in methodologies for mapping oil-induced environmental sensitivity, referring to the NOAA guide (Araújo et al., 2006), Petrobras manual (Araújo et al., 2002), and Ministry of Environment specifications guide (MMA, 2002; MMA, 2004; Araújo et al., 2006), and by works of (Araujo et al., 2007; Bellotto, 2008; Cantagallo et al., 2008; GherardI et al., 2008; Lima et al., 2008; Noernberg et al., 2008; Rocha Oliveira et al., 2008; Silva et al., 2008). However, despite the significant contribution and progress resulting from these studies, they have mainly focused on coastal and marine areas, highlighting the importance of advancing this specific mapping type to continental areas. The bias towards marine and coastal environments in the early studies of environmental sensitivity to oil spills is now evident with the consolidation of methodologies oriented towards these settings.

There is a growing volume of studies proposing the use of Oil Environmental Sensitivity for environments beyond coastal and marine areas. In Brazil, studies for continental areas have been developed and presented such as the Environmental Risk Mapping (MARA), developed through cooperation between the Environmental Company of the State of São Paulo (CETESB) and Petrobras, as outlined by Mendes et al. (2005). Studies in the Amazon region were conducted by Araujo et al. (2006) and Ferreira and Beaumond (2008), in the Itajaí Valley, in the state of Santa Catarina. Characterization of the physical environment as a subsidy for Cartas SAO was carried out by de Paula (2007). Additionally, the application of ESMs in the road transport environment on the Tamoios Highway (SP-099), in the state of São Paulo, was conducted by Martins (2012).

In other parts of the world, reference works have been developed by NOAA, including lacustrine, riverine, and marsh environments (NOAA, 1995; Petersen et al., 2002). Subsequently, with NOAA's inclusion of inland environments, other studies began to emerge proposing similar methods: Hayes et al. (2005) for the Great Lakes of Canada, Hayes et al. (1997) for the southwestern region of the United States, Zengel et al. (2001a) for the Caribbean, and Zengel et al. (2001b) for the southern state of Florida (USA).

Thus, it has been observed that the majority of oil spill accidents occur in terrestrial environments, mainly linked to pipeline transportation (Costa, 2013), with pipeline rupture and leakage being the main causes. It is noteworthy that, according to the author, the number of accidents occurring in terrestrial environments is significantly higher than the number of oceanic accidents. The distinction lies in the fact that, in oceanic environments, the volumes of leakage are much larger. Consequently, a lack of more comprehensive studies within these methodologies concerning surface dynamics phenomena directly associated with pipeline ruptures has been identified.

The pipeline system along the coast of the State of São Paulo presents a wide range of environmental factors that can impact the operational aspects of its activities. Among these factors, gravitational mass movements, such as debris flows, stand out due to their extent, destructive potential, and frequent recurrence in these areas.

The dynamics of gravitational mass movements in Brazil have resulted in various economic, social, and environmental issues and losses. In mountainous regions such as the Serra do Mar in the southern and southeastern coast of Brazil, where occurrences of these natural disasters are frequent due to heavy rains, gravitational mass movement processes can manifest in various forms (Augusto Filho, 1992; Cerri et al., 2002; Gramani, 2001; Cruz et al., 2001).

The coast of São Paulo presents situations of potential risk, especially when examining the various patterns of land use and occupation found on slopes and adjacent alluvial plains located at the foot of the mountain range, as well as along various streams originating in the mountains with high flow energy and erosive potential. In these areas, the occurrence of mass movements such as debris flows is primarily triggered by extreme rainfall events and geomorphological, geotechnical, and geological factors.

The occurrences of these mass movements are widely influenced by extreme precipitation and factors related to geomorphology, geotechnical conditions, and geology (Petri and Suguio, 1971; Ogura et al., 2000; Znamensky et al., 2000; Massad, 2002; Cabral et al., 2023b).

Numerous studies address methodologies for the characterization, definition, and management of geological risks related to gravitational mass movements in urban and coastal areas in Brazil (Cerri & Carvalho, 1990; Cerri et al., 1990a, 1990b; Ogura & Augusto Filho, 1991; Cerri, 1992; Cerri, 1993; Zuquette et al., 1995; Augusto Filho, Alheiros, 1997; Augusto Filho, 2006; Gramani, 2000; Ogura and Santoro, 2002).

Works related to risk assessment and mapping are still in early stages. According to UN-ISDR (2004), the concept of environmental risks encompasses a wide range of physical phenomena within the earth system, including geophysical, meteorological, hydrological, geological, technological, biological, and socio-political factors, either individually or in complex relationships. While most risks are avoidable, disasters are not, making it essential to study and investigate past risks, monitor the current situation, and understand and predict future risks to minimize the impact of disasters (Tominaga et al., 2009).

According to Tominaga et al. (2009), risk refers to the potential for a harmful natural process or phenomenon to occur at a specific location and within a certain period of time. Thus, risk mapping represents the spatial and temporal probability of a process or phenomenon with the potential to cause damage to occur (Varnes, 1984; Einstein, 1988; UN-ISDR, 2004; Tominaga, 2007).

Normally, two types of approaches are used for risk analysis and mapping: qualitative and quantitative. Qualitative methods are primarily based on field technician analyses, utilizing observations and aerial photographs, geomorphological analysis, and correlation of thematic maps. On the other hand, quantitative methods rely on statistical analyses through the comparison and combination of the spatial distribution of phenomena with the parameters involved in the processes (Tominaga et al., 2009).

The research area encompasses the Petrobras pipeline system along the coast of São Paulo, a section that comprises an important logistical axis of Brazil in the municipalities of Cubatão and São Sebastião. These areas are subject to persistent problems related to surface dynamics processes, especially landslides, runoff, and debris flows. Therefore, the execution of this research was justified by the following questions: (i) Is it possible to develop a methodology for mapping the danger of debris flow occurrence that can be integrated with environmental sensitivity indices to enhance action and contingency plans? (ii) Is it possible to develop a real-time rainfall monitoring system capable of assisting disaster prevention measures?

Thus, to answer these questions, this thesis aimed to: (i) present an overview of the challenges and perspectives of the environmental sensitivity index to oil spills in Brazil and worldwide, pointing out some pathways and challenges to be followed for mitigation and prevention; (ii) develop a hazard mapping methodology for debris flow applied to pipelines that could be integrated with the oil sensitivity index; (iii) evaluate the methodology in the studied areas and verify its replicability; and (iv) develop a rainfall monitoring system for gravitational mass movements, based on the association of critical precipitation thresholds and the real-time data collection and visualization.

The results obtained made it evident the complexity and urgency in addressing the challenges related to tackling climate change, environmental sensitivity, and natural disaster management, especially in sections traversed by pipelines. The proposed integrated approach provides a promising framework for addressing the challenges related to natural disaster management and environmental sensitivity in critical areas, such as those crossed by pipelines. By combining methodologies for mapping debris flow hazards with environmental sensitivity indices and real-time rainfall monitoring systems, we can significantly strengthen action and contingency plans, empowering authorities to take more effective preventive measures. The urgency of this approach is underscored by the complexity of the challenges faced and the strategic importance of the areas in question, emphasizing the ongoing need for research and the implementation of innovative solutions to ensure the safety and sustainability of these critical regions.

2 Thesis Objectives and Structure

The main objective of the research is to develop a methodological proposal for integrating hazard mapping of pipeline reach by debris flows with the Environmental Sensitivity Index for oil spills in a continental section of the São Paulo coast and Serra do Mar.

The specific objectives of this research project are:

(i) Identify the main methodological gaps in the Environmental Sensitivity Index by conducting a literature review and database survey regarding the actual situation of oil spills in Brazil and worldwide;

(ii) Develop and validate a methodology for a debris flow hazard index in pipelines that can be incorporated into drainage crossing sections for pipelines;

(iii) Develop a rainfall monitoring system based on data collected from automatic rain gauges correlated with critical precipitation indices as a management tool for these areas;

The thesis is structured so that each chapter represents a complete version of a scientific article addressing the schedule and research stages, transitioning from the global-scale analysis of oil spill events to methodological development for the Brazilian context.

In Chapter I, a review of major oil spills in Brazil and worldwide is conducted, highlighting key existing works considered epistemological landmarks. Some observations are made regarding the main methodological gaps in terms of environmental sensitivity mapping for continental and terrestrial sections. Furthermore, certain pathways are suggested to better assess these areas, considering pipelines and their susceptibility to debris flow impacts.

Chapter II presents a methodological proposal for creating a debris flow hazard index for pipelines. This involves relating susceptibility mapping to vulnerability assessment, leading to key hazard zoning results and defining pipeline crossing sections over drainage areas with higher risk of impact and subsequent oil leakage.

Chapter III validates the methodology of the debris flow hazard index in pipelines through its application to a debris flow event that occurred between the 18th and 19th of 2023 in São Sebastião – SP.

Chapter IV presents a proposal for a real-time rainfall monitoring system based on the use of critical precipitation thresholds for the study areas, validated during an intense rainfall event that resulted in the disaster in São Sebastião in February 2023, and a rainy event that did not result in occurrences between February 23 and 26, 2024.

Finally, the concluding section of the thesis summarizes the obtained results and discusses potential solutions and directions for future research.

Chapter 1: Challenges and perspectives in applying the environmental sensitivity index to pipelines: a review on the prevention and management of oil spills disasters

Vinicius Queiroz Veloso, Fabio Augusto Gomes Vieira Reis, Victor Carvalho Cabral, Lucilia do Carmo Giordano, Claudia Vanessa Corrêa dos Santos, Caiubi Emanuel Souza Kuhn

Abstract

The oil spill environmental sensitivity index is a key tool for preventing and dealing with environmental disasters caused by oil spills. This study aims to review the available literature on the subject and highlight the importance of methodological advances to improve how the index is applied in continental areas, especially in regions crossed by pipelines. Most current mapping techniques focus on coastal areas and fail to consider the stretches of land that are vulnerable to geodynamic natural disasters. In this context, the need to implement environmental sensitivity indices specific for pipelines has become urgent. This study also presents an overview of the main accidents around the world and a detailed analysis of the history of Brazilian disasters related to oil spills along continental stretches, with a focus on pipelines and natural disasters. In addition, this work highlights the importance of carrying out new research in mountainous areas of Brazil and is aimed at preventing Natechs (natural hazard triggering technological disasters) and improving contingency plans. As a result, several pathways have been identified, which involves the necessity of resolving gaps in terrestrial environmental sensitivity mapping methodologies, particularly as applied to pipelines. Furthermore, solutions must be capable of integrating terrestrial, fluvial, coastal and maritime environmental sensitivity mapping techniques. Moreover, the need to implement dynamic risk monitoring systems in real time is critical to help manage such a complex problem.

Keywords: Oil spill, Pipelines, Natechs, Debris flow, Environmental sensitivity index, Natural disaster.

1 Introduction

Evidence suggests that human activity has contributed to climate change and, as a result, the incidence of what have traditionally been defined as environmental and natural disasters, including floods, hurricanes, tornadoes, earthquakes and tsunamis, have increased. (Alcántara-Ayala 2002; Birkmann et al. 2013; Banhozer et al. 2014; Hallegate 2016; Lowe et al. 2019; Cabral 2023b).

Although some authors classify environmental and natural disasters in the same way, in this work, we chose to differentiate them. According to the UN-ISDR (2009), the term disaster refers to the serious disruption in the functioning of a community or society, resulting widespread human, material, economic or environmental damages, and when these losses that exceed the capacity of the affected community or society to respond using its own resources. That is, a disaster is an aspect of risk and arises from the combination of hazards, vulnerable conditions and an insufficient capacity or measures to reduce the potential negative risk consequences (Hader et al 2021; Kuhn et al 2022).

Environmental disasters are catastrophic events that result from human activity and have a devastating impact on different aspects of the environment, including ecosystems and biodiversity, wildlife and agriculture, and air and water quality. These include human-induced disasters such as oil spills, chemical explosions and the release of nuclear radiation, where the influence of human activity is clear and direct (Pachauri and Mayer 2015; Hader et al. 2021).

Environmental disasters are not random and do not happen by chance. They are the convergence of hazards and vulnerable conditions. Disasters not only reveal social, economic, political and environmental problems but unfortunately contribute to exacerbating them. Such events represent serious challenges for development, as they erode gains in terms of political, social and educational progress, as well as progress in infrastructure and technological development. (Norris et al. 2002; Hader et al. 2021; Kuhn et al. 2022).

Natural disasters can be defined as natural processes or phenomena that occur in the biosphere that constitute a harmful event. Natural hazards can be classified by their origin, namely, geological, hydrometeorological or biological (Kuhn et al. 2022). Hazardous events can vary in magnitude or intensity, frequency, duration, area of extent, speed of onset, spatial dispersion and temporal spacing. (UN-ISDR 2009).

Thus, we can say that there is a causal relationship between environmental disasters and natural disasters, justified by the expansion of human activities that increase infrastructure and the frequency of environmental disasters. Oil spills are usually consequences of leaks in the ocean or on continental landforms, and they are the result of accidents onboard oil tankers, incidents with drilling platforms, and ruptured pipelines (Cabral et al. 2021; Cabral et al. 2022; Cabral et al. 2023b; Veloso et al. 2023). Regardless of the environment (continental or maritime), the effects can be devastating in the environment, affecting the entire ecosystem (Rodrigues et al. 2023). An issue that compounds the challenges of dealing with oil leaks is how difficult they are clean and the length of time over which they persist (D’affonseca et al. 2023).

In the 1970s, after major environmental accidents involving oil tankers such as Jakob Maersk (1975) in Portugal and Urquoia on the Spanish coast (1976), a group of scientists began to develop a methodology to map the areas most sensitive to oil spills and to create contingency protection plans for US coastal areas (Gundlach and Hayes 1978; Michel et al. 1978).

This methodology was called the oil spill environmental sensitivity index (ESI), and its function was fundamentally preventative in nature, and to evaluate and remediate the impacts of oil spills. This methodology was originally based on ranking coastal environments on a scale of 1 to 10 in terms of potential vulnerability to oil spill damage and was called the Environmental Vulnerability Index (Gundlach and Hayes 1978; D’affonseca et al. 2023).

Over the following decades, this methodology was improved and standardized, and ultimately became a reference widely used throughout the world, establishing itself, among others, as the Environmental Sensitivity Index (ESI) (Michel et al. 1978; Gundlach and Heyes 1978; Walker et al. 1978; Michel and Dalin 1993; Halls et al. 1997; Petersen et al. 2002; Wheaters et al. 2009, de Aquino et al. 2013; Petersen et al. 2019; D’affonseca et al. 2023; Rodrigues et al. 2023).

Brazil, a country with a coastline that is approximately 7,491 kilometers in length, has a large crude oil extraction and transport network and a sad history of environmental accidents and this methodology was also successfully applied where it was called the Environmental Sensitivity Charts for Oil Spills (Carta SAO), (Awazu and Poffo 1986; Maldonado et al. 1987; MMA 2002; Araujo et al. 2002; MMA 2004; Araujo et al. 2006; Cerri et al., 2022; D’affonseca et al. 2023).

The ESI is an essential component and primary source of information for contingency planning and damage assessment in oil spill cases (D’affonseca et al. 2023). This index serves as a fundamental tool for guiding actions in response to oil spills. By identifying environments with preservation priority, it enables the allocation of available resources and more efficient mobilization of protection and cleaning teams (MMA 2002; MMA 2004).

The consolidation of the Environmental Sensitivity Index (ESI) was a significant advancement in combating oil spill events. It was based on the standardization efforts conducted by NOAA and served as a basis for environmental agencies and institutions around the world (Martins et al. 2012; D’affonseca et al. 2023).

Given the reality in Brazil and the emergence of Pre-Salt, which led to the discovery of new oil exploration fields in recent decades and was responsible for the implementation and expansion of an entire production, transport and storage network (particularly in terrestrial environments), it is essential to focus efforts on developing and implementing methodologies to incorporate these areas into the Environmental Sensitivity Indices.

Within this context, there has been great progress specifically in the infrastructure of pipelines for transporting oil and its derivatives, which today represent 21% of the Brazilian logistics model (Chiossi, 2015), but despite the high technological level of these projects, the management of oil leakages caused by gravitational mass movements still needs substantial improvements (Corrêa et al. 2017; Corrêa et al. 2021).

According to records from EM-DAT (2009), there were 150 natural disasters in Brazil, from 1900-2006. Of the total that occurred, 84% occurred from the 1970s. A total of 8,183 fatalities were attributed to these, as was a loss of approximately 10 billion dollars (Kuhn et al., 2022).

The dynamics of gravitational mass movements in Brazil have resulted in various economic, social and environmental problems and losses. In mountainous regions, such as Serra do Mar on the south and southeast coast of Brazil, where these natural disasters are recurrent due to high rainfall, gravitational mass movement processes can manifest in several ways. (Augusto Filho 1992; Cerri 1992; Gramani 2001; Cruz et al. 2003; Corrêa et al. 2017; Corrêa et al. 2021; Hader et al. 2021; Cabral et al. 2021; Cabral et al. 2023a; Cabral et al. 2023b; Veloso et al. 2023).

Much of the Brazilian pipeline infrastructure is present along the Brazilian Serra do Mar (Figure 1), which covers a region that extends for 1500 km along the south and southeast coast (Vieira and Gramani, 2015; Corrêa et al. 2021) and has the highest population density in the country with an average of 100 inhabitants per km² (IBGE 2012). This means that most natural disasters of geodynamic origin (with emphasis on debris flows) are concentrated in this region (Kuhn et al., 2022; Veloso et al. 2023).

Debris flows are defined as one of the most destructive processes both worldwide and in Brazil (Kahn 2005; Álvala et al. 2019). They are phenomena initiated by intense precipitation events and behave like density flows, transporting large amounts of material along the drainages in stretches characterized by steep slopes and high elevation gradients, which results in powerful impacts and wide zones of destruction (Pereira Filho et al. 2018; Cabral et al. 2021; Cabral et al. 2023a; Cabral et al. 2023b; Lopez et al. 2023 Veloso et al. 2023).

According to Gartner and Jakob (2019), pipelines that cross mountainous terrain, drainage crossings and channels along valley floors can be susceptible to various geodynamic impacts, including debris flows. In Canada, for example, 22% of the faults and leakage problems are related to geodynamic hazards (Porter et al. 2016).

Figure 1 - Representation of Serra do Mar and the Brazilian pipeline network

There are several records of ruptures caused by debris flows; for example, in British Columbia, a gas pipeline rupture caused by the impact of a debris flow resulted in environmental damage to an untouched stretch of coast (Jakob et al. 2004; Boultbee et al. 2006;

Porter et al. 2016). There was also an event registered in Montecito, California that caused a pipeline to explode, which impacted several houses (Kean et al. 2019). In Brazil in 2017 in the municipality of Guaratuba, Parana, a debris flow reached a Petrobras pipeline network at a drainage crossing and a small bridge, though there was no record of a large leak or victims. (Cabral et al. 2021).

Similarly, many other cases can be cited throughout the world; thus, considering the social, environmental and economic context of Brazil, this highlights the need for methodological advances and the mapping of pipeline crossing sections subject to debris flows to avoid environmental catastrophes caused by natural disasters.

This work aims to carry out a review on the main environmental accidents, methodological advances and current situation of the Environmental Sensitivity Index through a systematic bibliographical review.

2 The global applications of the environmental sensitivity index

The occurrence of major environmental disasters related to oil spills worldwide were the main motivators, prompting numerous researchers to develop methodologies aimed at mitigating and reducing the impact of these accidents. According to ITOPF (2022), the largest oil spill-related disasters in the world were concentrated on the west and northwest coasts of Europe and northwest Africa, with occurrences also across the globe, as shown in Fig 1.

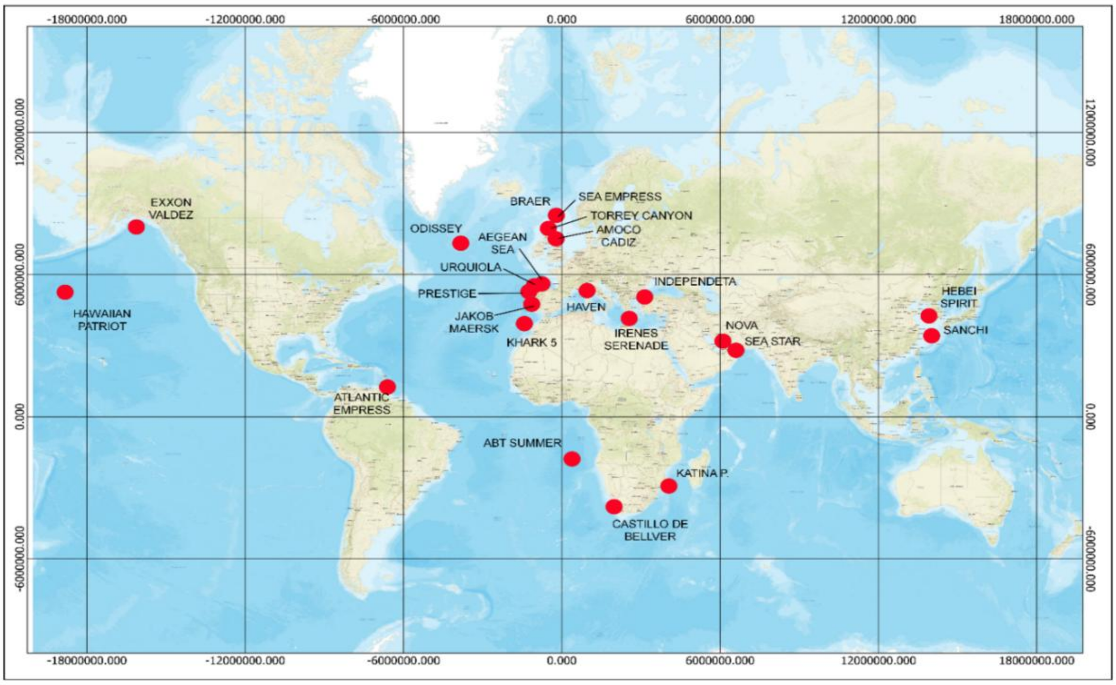

Figure 2 -Location of the 20 largest oil spills throughout the world. (ITOPF, 2022)

The first studies were developed by Michel et al. (1978) and Gunlach and Hayes (1978), based on the analysis of three large oil spills (the Metula oil tanker spill in 1974 in Chile, Urquoia in 1976 in Spain and Jakob Maersk in Portugal in 1975 (Michel et al. 1978)) where the oil spill vulnerability index was presented with a ranking of coastal environments on a scale of 1 to 10 in terms of potential vulnerability to oil spill damage (D’affonseca et al. 2023). (Fig 2)

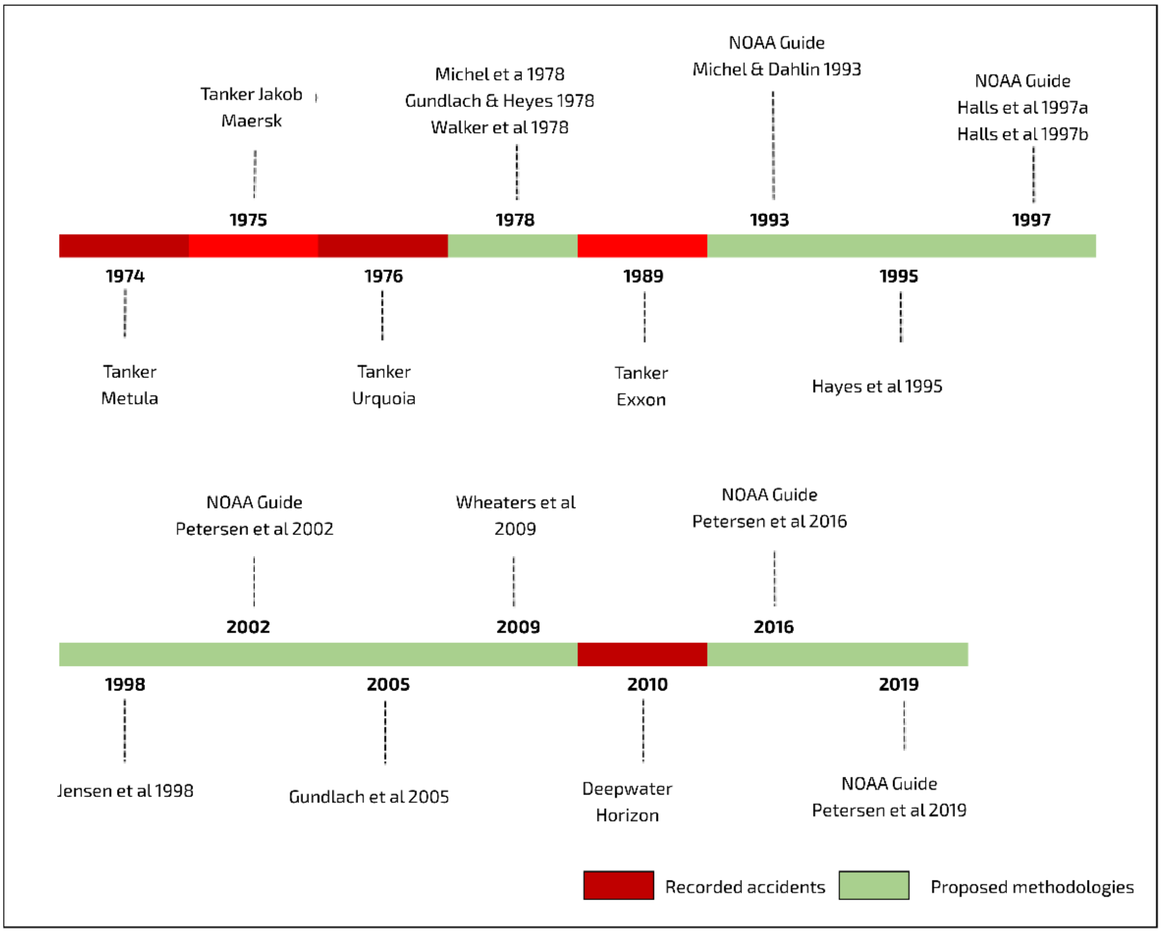

Figure 3 - Timeline of the main accidents throughout the world and methodological milestones that advanced the Environmental Sensitivity Index (ESI)

The methodology proposed by Michel et al. (1978) is based on the pattern of occurrence and the duration of the oil in different coastal environments, although biological susceptibility and ease of manual cleaning are also considered (Martins et al. 2013). Therefore, Gunlach and Hayes (1978) based their classification on shoreline interaction with physical processes that control oil deposition, persistence or duration of oil in the environment, and the extent of biological damage. The combination of these two complementary methodological proposals formed the basis of NOAA manuals.

In 1989, the accident with the Exxon Valdez oil tanker along the coast of Alaska, which spilled 11 million gallons of oil, contaminating more than 2000 km from the coast, motivated an improvement to the methodological approach of mapping the environmental sensitivity of a region to oil spills. With the intention of establishing a mapping and documentation standard for the US, NOAA developed a guide for producing such mappings (Michel and Dahlin 1993).

This guide marked a milestone and continues to be constantly updated and serves as a reference for the preparation of all oil spill sensitivity manuals worldwide (Halls et al. 1997; Peterson et al. 2002; Peterson et al. 2016; D'affonseca et al. 2023).

The ESI is composed of three main components: (i) a coastline ranking system (ISA) on a scale of 1 to 10, where the higher the index, the greater the sensitivity; (ii) biologically sensitive oil resources; and (iii) human use of resources of commercial, recreational or subsistence value (Jensen et al. 1998; D'affonseca et al. 2023).

In fact, most works are consolidated and concentrated in marine and coastal areas, highlighting the need to develop methodologies for continental environments. To fill this gap, NOAA included sensitivity to oil spills in lake, river and swamp environments in the update of its indices (NOAA 1995; Petersen et al. 2002).

With this update by NOAA and the inclusion of aquatic environments, several studies emerged to contribute methodologies for terrestrial regions, such as the proposal by Hayes et al. (1995) for the Canadian Great Lakes, Hayes et al. (1997) for the southwestern USA, Zengel et al. (2001a) for the Caribbean, Zengel et al. (2001b) for southern Florida (USA), and Araujo et al. (2006) for the Amazon region.

Among these methodologies, we highlight the proposal by Heyes et al. (1997), which applied to small lakes and streams in the southeast of the USA and is called the Range Sensitivity Index (RSI). This index is based on the navigability of rivers, current pattern, size of the river, presence of oil accumulation points and the presence of flow and bifurcations in the channels.

Another interesting methodology is the proposal for watersheds, called the watershed sensitivity index (WVI) (Jensen et al. 1998; Weather et al. 2009; D'affonseca et al. 2023). This index is very similar to the RSI, and its main function is to identify the sector of the continental hydrographic basins in which the most sensitive rivers and streams are located, and even ranks the basins with the highest priority for mapping and planning sensitive areas.

Still in terrestrial environments, proposals were made for mapping leaks in pipelines, a topic addressed in this work. Gundlach (2005) highlights the importance of paying special attention to continental areas crossed by pipelines, and, to maintain alignment with the NOAA method, applies with a classification of 1 to 10 and use of the same symbols.

The Table 1 shows the main works developed in the world on the oil sensitivity index, togeter with the authors and the proposed methodologies.

Table 1 - Main works on the Environmental Sensitivity Index (ESI)

Year	Title	Authors	Application Environment	Methodologies
1978	Application of an oil spill vulnerability index to the shoreline of lower Cook Inlet, Alaska	Michel et al. (1978)	Coastal	Coastal environments rated on a scale of 1 to 10, considering biological susceptibility and ease of manual cleaning/removal of oil
1978	Vulnerability of coastal environments to oil spill impacts.	Gunlach and Heyes (1978)	Coastal	Coastal environments rated on a scale of 1 to 10
1978	Effects of crude and diesel oil spills on plant communities at Prudhoe Bay, Alaska, and the derivation of oil spill sensitivity oil spills	Walker et al. (1978)	Coastal	Oil sensitivity rating for terrestrial environments and is based on experiments with crude oil and diesel oil
1993	Environmental Sensitivity Index Guidelines. National Oceanic and Atmospheric Administration	(Michel and Dahlin, 1993)	Coastal/ marine	First methodological guide to produce SAO Charts, establishing cartographic standardization and the 1 to 10 scale - initially developed for coastal and maritime environments
1995	Identifying and mapping sensitive resources for inland area planning	(Hayes et al. 1995)	Continental	Development of methodologies for estuarine, lake and large river environments. Rated from 1 to 10 from lowest to highest environmental sensitivity
1997	The reach sensitivity index (RSI) for mapping river and streams	Hayes et al. (1997)	Continental	Development of the River Reach Sensitivity Index (RSI), focusing on the classification of rivers considering their sensitivity and vulnerability and the degree of difficulty for oil recovery and containment
1997	Environmental Sensitivity Index Guidelines. National Oceanic and Atmospheric Administration V.2	Guia NOAA (Halls et al., 1997)	Coastal/ Continental	Inclusion of river environments in oil spill environmental sensitivity mapping

1998	A system Approach to environmental sensitivity index (ESI) mapping for Oil spill contingency planning and response	Jensen et al. (1998)	Continental	Development of the Watershed Vulnerability Index (WSI)
2002	Approach to Environmental Sensitivity Index	Guia NOAA (Peterson et al., 2002)	Coastal/marine/ continental	New standard of the methodologies proposed in the last decade: incorporation of the river reach sensitivity index (RSI) and the watershed vulnerability index (WSI), adapted for pipelines
2005	Pipeline and coastal environmental sensitivity mapping for the BTC pipeline system in Turkey	Gundlach et al. (2005)	Continental	Use of the RSI classification system in the context of mapping river systems based on the morphology of streams, riparian forest and forest/stream system interaction
2009	Reach sensitivity index mapping of the Amite River watershed in the Lake Pontchartrain Basin: A tool for restoration	Weathers et al. (2009)	Continental	Application of the River Reach Sensitivity Index (RSI) method, incorporating river geomorphology concepts
2016	Environmental Sensitivity Index Guidelines. National Oceanic and Atmospheric Administration	Petersen et al. (2016)	Coastal/marine/ continental	Maintenance of the methodology and update of the list of species
2019	Environmental Sensitivity Index Guidelines. National Oceanic and Atmospheric Administration	Petersen et al. (2019)	Coastal/marine/ continental	Maintenance of the methodology and update of the list of species

3 The environmental sensitivity index in Brazil

In Brazil, disasters related to oil spills have always been a serious problem. The initial records of mapping the environmental sensitivity to oil spills in Brazil were primarily focused on coastal areas. This was due to the high recurrence of accidents related to oil spills in these locations, which follows the global trend of presenting response plans to major environmental accidents.

The first oil spill recorded in Brazil occurred in 1974 in São Sebastião-SP and involved the dumping 6,000 tons of oil along the coastline by the oil tanker Takimiya Maru. Additionally, in 1975 the oil tanker Tarik Ibn Zyad dumped approximately 6,000 tons of oil in the Bay of Guanabara, Rio de Janeiro.

Accidents with pipelines have also had a severe impact and always represented a serious problem for the management of environmental disasters in Brazil. In 1988, the São Sebastião-Cubatão oil pipeline ruptured, dumping 1,000 tons of oil along the continental stretch, and in 1989, a breakdown in the same location was responsible for spilling 350 tons of oil.

The accidents mentioned above can be considered the main reasons that new methodologies emerged, which were based on international methodologies (Fig 4).

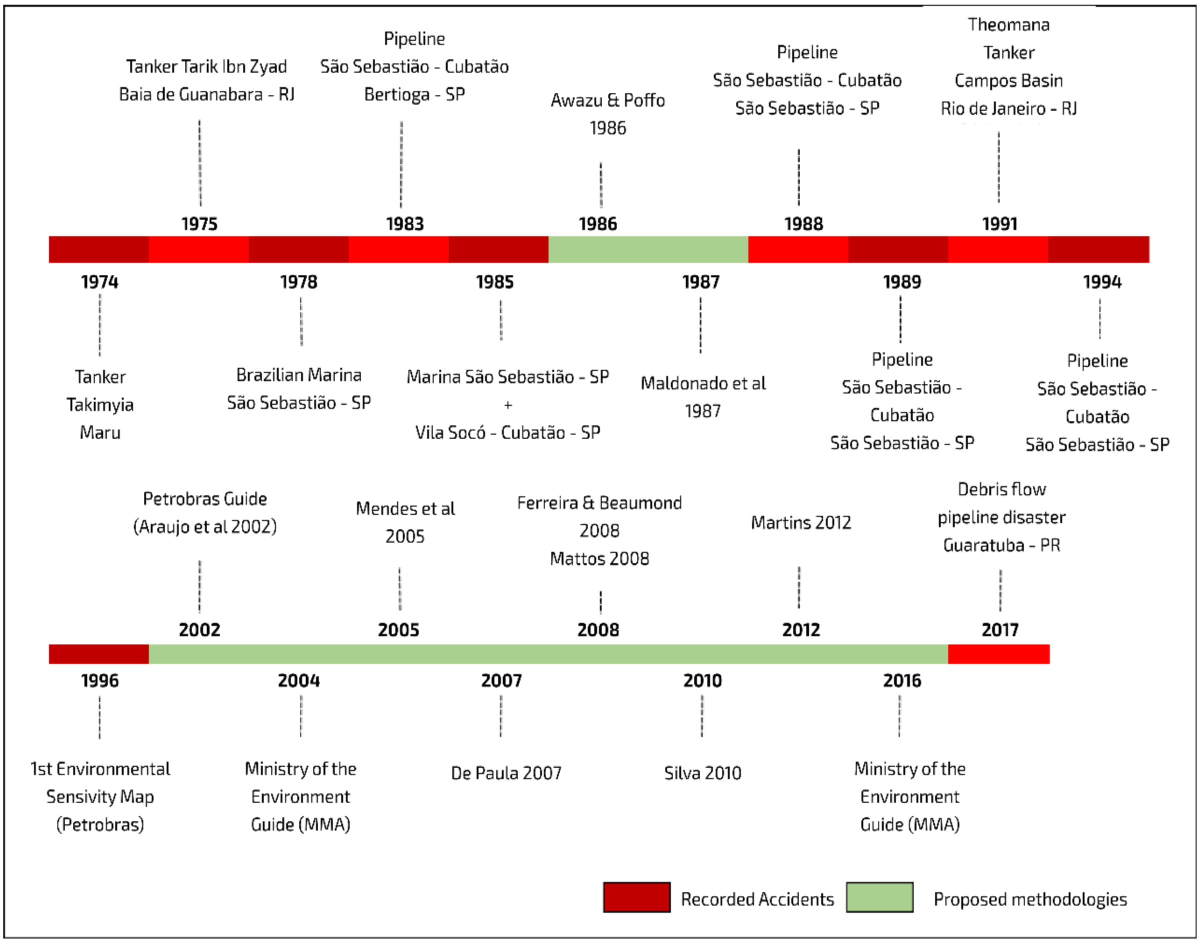

Figure 4 - Timeline of the central accidents and methodological milestones that advanced the Environmental Sensitivity Index (ESI) in Brazil.

As shown in Figure 4, one of the pioneering works in Brazil is that of Awazu and Poffo (1986), who proposed a method for defining the main areas to be protected in the event of the spilling of oil and oil derivatives along the North Coast of the State of São Paulo. Then, Maldonado et al. (1987) improved the methodology through a proposal to map coastal environments in the municipality of Ubatuba, São Paulo that were vulnerable to oil spills.

In 1993, Petrobras released the first oil susceptibility manual produced in Brazil, and it was only in 1996 that they began to be called Cartas SAO (Oil Environmental Sensitivity

Letters) and began to follow the standards proposed by NOAA (Araujo et al. 2006). This manual was used as support for another important document that has become an important methodological reference in oil sensitivity mapping, called “Specifications and technical standards for the preparation of oil spill sensitivity charts” prepared by the Ministry of the Environment and strongly influenced by NOAA manuals. (Araujo et al. 2006; MMA 2002; 2004).

According to the Ministry of the Environment (2004), the technical specifications of the Cartas SAO include three main types of information: (i) sensitivity to ecosystems (coastal and marine) according to the geomorphological characteristics of habitats and natural persistence of oil and its removal, classifying the environments from 1 to 10, where the higher the index, the greater the sensitivity; (ii) biological resources, with information at the species level for plants and animals sensitive to oil organized by remediation response; and (iii) socioeconomic resources and activities, which may be impaired by oil spills or by remediation responses.

There are also three agreed-upon cartographic scale levels: (i) strategic scale; (ii) tactical scale and (iii) detailed operational scale. These levels are standardized and defined by the Cartographic Plan for mapping Environmental Sensitivity to Oil (MMA, 2004).

In fact, as seen in Table 2, as well as on the world stage, there is a large concentration of mapping methodologies for the oil spill sensitivity index within marine and coastal regions in Brazil, which demonstrates the urgency that methodological advances are needed for continental areas.

Adaptation proposals that have sought to adapt environmental sensitivity indices to continental environments are very promising, such the road model proposed by Mattos (2008) and Martins et al. (2013), while Silva (2010) presented a methodology for mapping environmental vulnerability while transporting hazardous products via railways.

Regarding methodologies for pipelines, Mendes et al. (2005) proposed a method entitled Mapping of Environmental Risk (MARA), which preserved the 1 to 10 indices from the NOAA methodology, and these are measured by attributing weights to the different environmental parameters based on biodiversity, environmental restoration and habitat sensitivity.

In this context, the methodological advances related to the development of the Environmental Sensitivity Index occurred mainly for the maritime and coastal stretches. Table 2, below, shows the main works developed in Brazil for the oil sensitivity index, together with the authors and the proposed methodologies.

Table 2 - Typologies of accidents related to mass movement on pipelines in the USA, Canada and Europe

Year	Title	Authors	Application Environment	Methodology
1986	Mapping of areas to be protected in the event of oil spill and derivates on the North Coast of São Paulo	Awazu e Poffo (1986)	Coastal	Pioneering work proposing stretches of greater vulnerability to oil spills on the North Coast of São Paulo
1987	Vulnerability of coastal environments in the municipality of Ubatuba to the impact of na oil spill (North Coast of the State of São Paulo)	Maldonado et al. (1987)	Coastal	Second approach proposed in Brazil
1996	Specifications and technical standards for the elaboration of environmental sensitivity oil spill index	Petrobras (1996)	Coastal/ marine	First oil sensitivity mapping produced in Brazil by Petrobras
2002	Basic guide for preparing maps of environmental sensivity to oil spills in the Petrobras system: coastal and estuarine environments	Araujo et al. (2002)	Coastal/ continental	First guide to occurrence of oil spills in Brazil
2004	Specifications and technical standards for the preparation of environmental sensitivity oil spill index	Guia MMA (2004)	Coastal/ marine	(1) Strategic charts - regional, basin/maritime in scope with a scale of 1:500,000 (2) Tactical charts - encompassing the entire coastline of the basin, with an intermediate scale of 1:150,000 (3) Operational charts - detail with a range of high risk/sensitivity sites to oil spill with scale between 1:50,000 and 1:10,000
2005	Elaboration of methodologies for analysis of environmental risks	Mendes (2005)	Continental	Methodology for pipelines, which adapts the NOAA scale from 1 to 10, mapping road networks, conservation units, land use, fauna and sensitivity classification, defining environments to be primarily protected
2007	Characterization of the physical environment as a subsidy for the elaboration of environmental sensitivity index: application test in pipeline in Serra do Mar - SP	Paula (2007)	Continental	Methodological proposal for mapping and characterizing the physical environment, considering the geological and geomorphological aspects, correlating the presence of pipelines and the environmental impact of eventual accidents in the displacement of the contaminant
2008	Mapping of environmental sensitivity to oil spills in the watercourses of the Canhanduba river basin, Itajaí, SC	Beaumond and Ferreira (2008)	Continental	Methodology based on the Environmental Sensitivity Index (MMA, 2002) adapted for riverside regions
2008	Application of oil spill environmental sensitivity analyses to Brazilian road networks	Mattos (2008)	Continental	The methodology focuses on the characterization of areas impacted by highways that present a transport flow of hazardous products and highlights the biological, physical and socioeconomic attributes of the region, on digital maps. The classification is made as HIGH, MODERATE and LOW
2010	Mapping of environmental vulnerability for risk management in the rail transport of dangerous	Silva (2010)	Continental	Pioneer proposal for mapping classification of environmental vulnerability in the rail transport of hazardous products

	products – a methodological proposal			
2012	Environmental sensitivity index for oil spills on highways: proposal applied to Estrada dos Tamoios (SP-099)	Martins (2012)	Continental	Land Sensitivity Index (IST), based on the NOAA classification, and presents the following aspects as variables: (1) land slope; (2) the texture and depth of the mantle change; (3) water level depth and relative permeability.
2016	National emergency action plan for fauna impacted by oil	MMA (2016)	Coastal/ marine	Update of the Emergency Action Plan for the rescue of fauna

4 Analysis of accidents in pipelines induced by natural disasters around the world

Having clarified the objective of this work and having verified the need for methodological advances in applying the environmental sensitivity index to oil spills in continental areas, and focusing on natural disasters in pipelines, it is necessary to know the general scope of this problem within the primary global production centers. Therefore, a brief analysis of the data referring to Europe, USA, Canada and Brazil is presented below.

In Europe, Girgin and Krauffmann (2014), after extensive analysis of the European Gas Pipeline Incident Data Group (EGIG) database, show that landslides and floods represent the greatest threat to pipelines.

In the period from 1970 to 2010, 93 accidents were related to gravitational mass movement, representing a total of 7.5% of all accidents. Although the authors report some difficulty in detailing the information, Table 3 shows the distribution and typology of the gravitational mass movements that occurred. In the US, analysis was conducted by the Natural Research Council (NRC) and the Pipeline and Hazardous Materials Safety Administration (PHMSA) and consisted of data from 1982 to 2012. The authors verified 858 events (Table 3).

Geological hazards represent 37% of problems related to pipelines in the US, with landslides also being the most worrying element, with 46% of incidents having a geodynamic origin. These damages to pipelines characterized as typical failures by soil movement result in immense economic damage, with average costs estimated at 430,000 USD, which is more than double that for other causes such as corrosion and operational failure (Porter et al. 2004). Esford et al. (2004) estimates that 50% of accidents with pipelines in South America are caused by natural disasters, mainly landslides.

In Canada, a country with an immense network of pipelines, the database is not as detailed, but after analyzing data on pipelines incidents from 2008 to 2022 provided by the

Canadian government, it was also possible to establish an overview of the situation of the causes of accidents in Table 3.

Table 3 - Typologies of accidents related to mass movement on pipelines in the USA, Canada and Europe

USA		
Type	**Number of incidents**	**%**
Earthquake	63	9.4
landslide	312	46.4
Mudslide	33	4.9
Rockslide	6	0.8
Rock fall	8	1.2
Subsidence	163	24.2
Frost heave	41	6.1
Erosion	8	1.2
Other geological	1	0.1
Unknown	38	5.6
CANADA		
Type	**Number of incidents**	**%**
Corrosion and cracking	153	14.1
Defect and deterioration	142	13.1
Equipment failure	265	24.5
External interference	228	21.1
Incorrect operation	141	13
Natural disasters	96	8.9
Others	58	5.4
EUROPE		
Type	**Number of incidents**	**%**
Landslide	53	57.0
Flood	16	17.2
River	5	5.4
Mining	4	4.3
Dike break	1	1.1
Erosion	0	0.0
Other	2	2.2
Unknown	12	12.9

Of a total of 1083 accidents, 8.9% are related to natural disasters; however, due to the lack of detail in the database, it was not possible to establish which were related to soil movements.

Nevertheless, some accidents were worthy of note due to their relationship with natural disasters. Furthermore, accidents of sufficient magnitude and impact were also worthy of note, such as the one that occurred in Serra do Mar within in 2017 in the in Brazilian municipality of Guaratuba in the state of Paraná, when a flow of debris with an approximate volume of 120,195 m³ impacted a pipeline; fortunately, no oil leak occurred (Cabral et al. 2021).

An event that occurred in Hendek, Turkey, in 2019, involved a landslide impacting a gas pipeline, resulting in a huge explosion. An additional accident was recorded in Peru in 2016, where landslides resulted in ruptures in the Petroperu oil pipeline network, spilling 3,000 barrels of oil into the Amazon Jungle and polluting two tributaries of the Amazon River, resulting in inestimable environmental damage and financial losses.

Therefore, natural disasters, especially those of geodynamic origin, are the most worrying and deserve attention. According to Nyman et al. (2008), the frequency of pipeline rupture in relation to soil movements is 0.08 per 1000 km per year, of which 52% are caused by landslides.

5 Analysis of onshore oil spills in Brazil

Brazil, unlike the other locations analyzed, does not have a detailed public database regarding accidents and their causes, whether in the marine, coastal or continental environment. Therefore, this work opted to a search the database of environmental accidents at the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), linked to the Ministry of the Environment.

We had access to a database that contains all accidents related to oil spills that occurred in the period from 2006 to 2021. Therefore, an analysis was carried out to have a closer view of reality in relation to oil spill accidents. and the relevance of the importance of advancing in ISL methodologies for continental areas.

Brazil has an extensive network of pipelines, covering a large portion of the national territory. The total length of these pipelines, including both gas and oil pipelines, is 45 thousand kilometers (ANP 2021). These pipelines pass through diverse geomorphological divisions and different types of terrain. Among these divisions, the Serra do Mar poses major challenges in terms of the recurrence of natural disasters related to geodynamics.

Within the period analyzed, 9,067 accidents related to oil spills were recorded, with most occurring along the Southeast and South regions (Fig. 5).

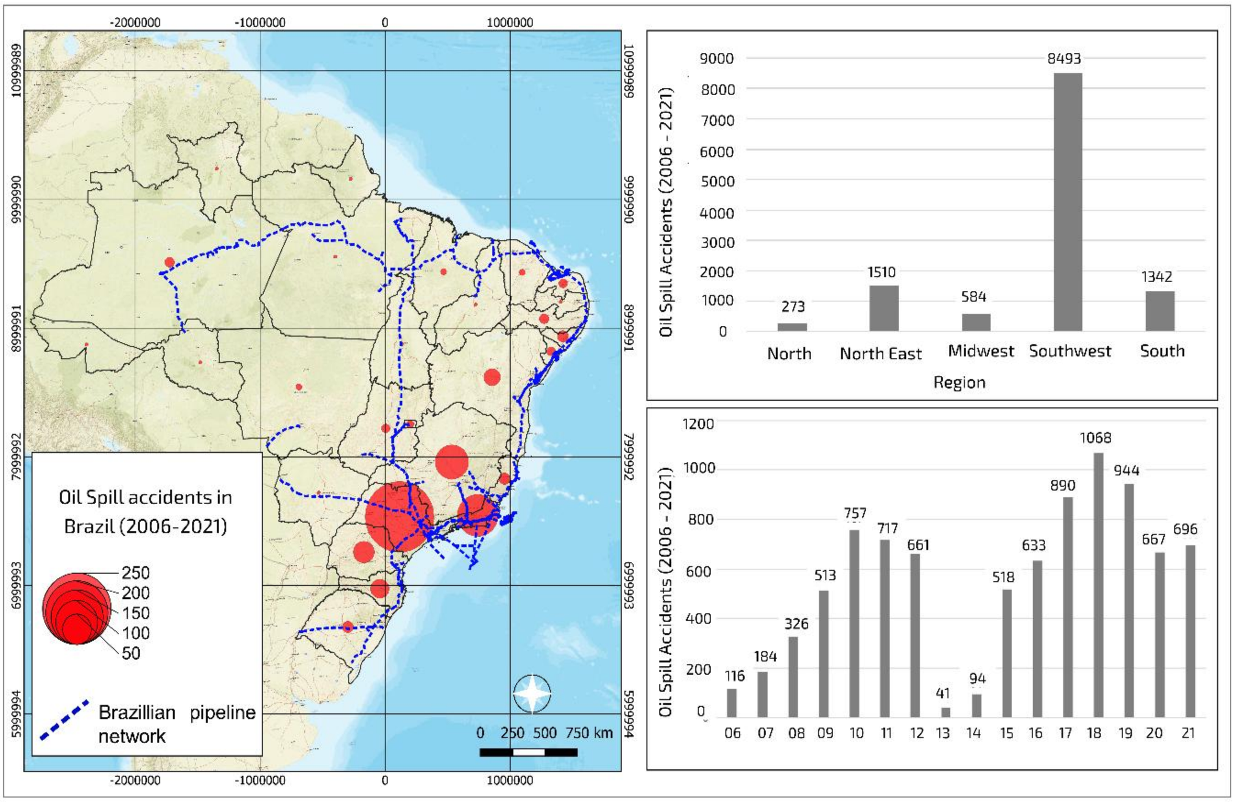

Figure 5 - Distribution of oil spill events in Brazil (2006-2021) (IBAMA)

Of the total number of occurrences recorded, according to the database, there were 5166 (54%) that occurred on land and 2953 (31%) that occurred within the marine environment, demonstrating that most accidents are concentrated in continental areas. (Table 4).

In the marine environment, most accidents are directly related to the operation of oil exploration platforms (1765, 18.56%), followed by problems with vessels (769, 8.09%) and terminals/ports and anchorages (419, 4.41%).

Regarding accidents occurring on land, the linear modes of transport with notable accident rates are roads with 3071 (32.23%) incidents, railways with 875 (9.2%) incidents, and pipelines with 503 accidents, which represents 5.29% of the total.

Therefore, as highlighted, the greatest concentration of accidents is along the south/southeast axis of Brazil, mostly in a continental environment, due in large part to the industrial and economic concentration of the country, together with the proximity of the main oil exploration fields in the pre-salt layer.

Table 4 - Origin of the primary oil spill occurrences in Brazil (2006-2021) (IBAMA)

Accident origin	Occurrences	(%)	Environment	Occurrences	(%)
Dam	114	1.20	Onshore	5166	54%
Pipeline	503	5.29			
Railroad	875	9.20			
Industry	506	5.32			
Fuel station	75	0.79			
Refinery	22	0.23			
Highway	3071	32.29			
Vessel	769	8.09	Offshore	2953	31%
Platform	1765	18.56			
Harbor/Anchorage	419	4.41			
Others	1392	14.64			

This section deserves a special analysis focused on the pipelines that are mostly concentrated in the geomorphological compartmentalization of Serra do Mar and are subject, as previously mentioned, to the occurrence of natural geodynamic disasters, mainly debris flows.

5.1 Pipelines in Serra do Mar and Debris Flows

The geographical region defined as Serra do Mar, which extends along the southeastern coast of Brazil from the north of the State of Rio de Janeiro to the State of Santa Catarina, exhibits unique and well-differentiated physiographic characteristics, which are maintained, with only very few and small local variations, along its entire length. Additionally, the Serra do Mar Mountain range constitutes a physiographic expression entirely developed in Brazilian territory. (Santos 2004).

In addition to housing, there is the important logistical infrastructure for the country's economy (ports, highways, railways, oil pipelines, and refineries). Due to this importance, more studies of debris flows, and hazard zoning methodologies are needed in Brazil, as highlighted by recent studies (Kobiyama et al. 2015; Cabral et al. 2023a, Veloso et al. 2023).

It is a geomorphological compartmentalization that extends along the west coast of Brazil with elevation differences of approximately 800 meters. The rocks are of Precambrian age and belong to the Atlantic shield, consisting predominantly of ophthalmic migmatites, schists, phyllites, quartzites, cataclastic rocks, mylonites and granites that all show schistosity dipping toward the slope (Tatizana et al. 1987).

The soils show great variation along the slopes, being practically nonexistent in the high slope areas. The soil profile in regions that are not as steep consists of a yellowish-brown, clay-silty, malleable colluvium the upper portion with low permeability. Its thickness usually ranges from 1 to 2 meters, but rarely exceed 2 meters. The landslide surface generally coincides with the separation between the colluvial soil and the underlying residual soil. Talus bodies developed at the foot of the slopes, forming convex features. (Wolle 1988; Tatizana et al. 1987).

Additionally, the average of 3,000 mm per year of rainfall increases slope instability, which is another example of how most natural disasters in Brazil are related to gravitational mass movements, mainly debris flows.

A debris flow is an extremely rapid, flow-like mass movement that travels along a steep, established channel and involves a saturated, unsorted mixture of granular soils, organics, and other debris (Hungr et al., 2001). The damage caused by debris-flows include the loss of human life, destruction of facilities, and damage to roads, pipelines, and vehicles (Jakob and Hungr 2005). Until now, only post-event repairs and protective infrastructure improvements have generally been executed after debris-flow occurrences. (Takahashi 1991; Rickenmann & Zimmermann 1993; Hungr et al. 2014; Bernard and Gregoretti, 2021; Veloso et al. 2023a).

In this context, research related to the occurrence and prevention of debris flows is minimal when compared to the extent of the impacts caused by the phenomena. There is a need for further studies that consider susceptibility and hazards, especially in environmentally and socioeconomically vulnerable areas, such as along sections of pipeline. (Veloso et al. 2023).

Much of the Brazilian pipeline infrastructure is present in Serra do Mar (Figure 6a), and after analyzing data on oil spill accidents from 2006 to 2022, 502 pipeline accidents were recorded, and these accidents occurred within 140 Brazilian municipalities. (IBAMA 2022).

Of the 140 municipalities affected by accidents, 60 (41%) are in Serra do Mar and are concentrated in three main zones (Figure 6). The first zone concerns the state of Rio de Janeiro, followed by the industrial center of Cubatão and part of the north coast of São Paulo and the axis of the states of Paraná and Santa Catarina where the accidents were concentrated between the municipalities of Joinville, Garuva, Guaratuba and Florianópolis.

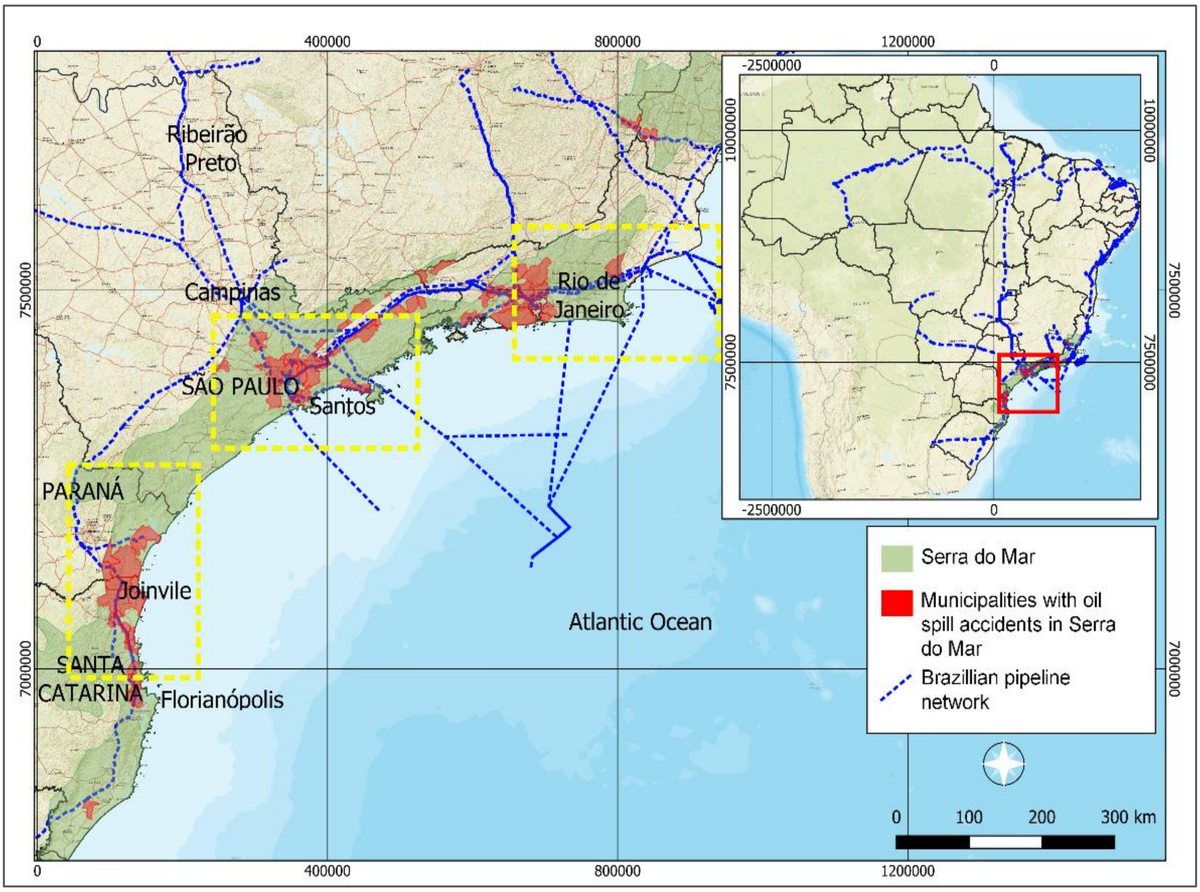

Figure 6 - Pipeline network present in Serra do Mar and the main stretches of registered accidents (2006-2022)

However, as previously mentioned, the accident database does not provide details on the cause of these oil spills, and work aimed at the safety of pipelines susceptible to the impact of debris flows is still developing.

Thus, we defined these three centers as the units of analysis for studying geodynamic events related to the debris flows. We then and correlated them with the records of the debris flows that occurred in the states of Rio de Janeiro, São Paulo, Paraná and Santa Catarina, which comprise the Serra do Mar region. (Figure 7).

Four states (SP, RJ, PR and SC) contributed 35 debris flow records, and these are among the largest disasters in the history of Brazil (Table 5). The state of São Paulo has 40% (14) of all registered events, followed by the state of Rio de Janeiro with 43% (15) and Santa Catarina and Paraná with 17% (6).

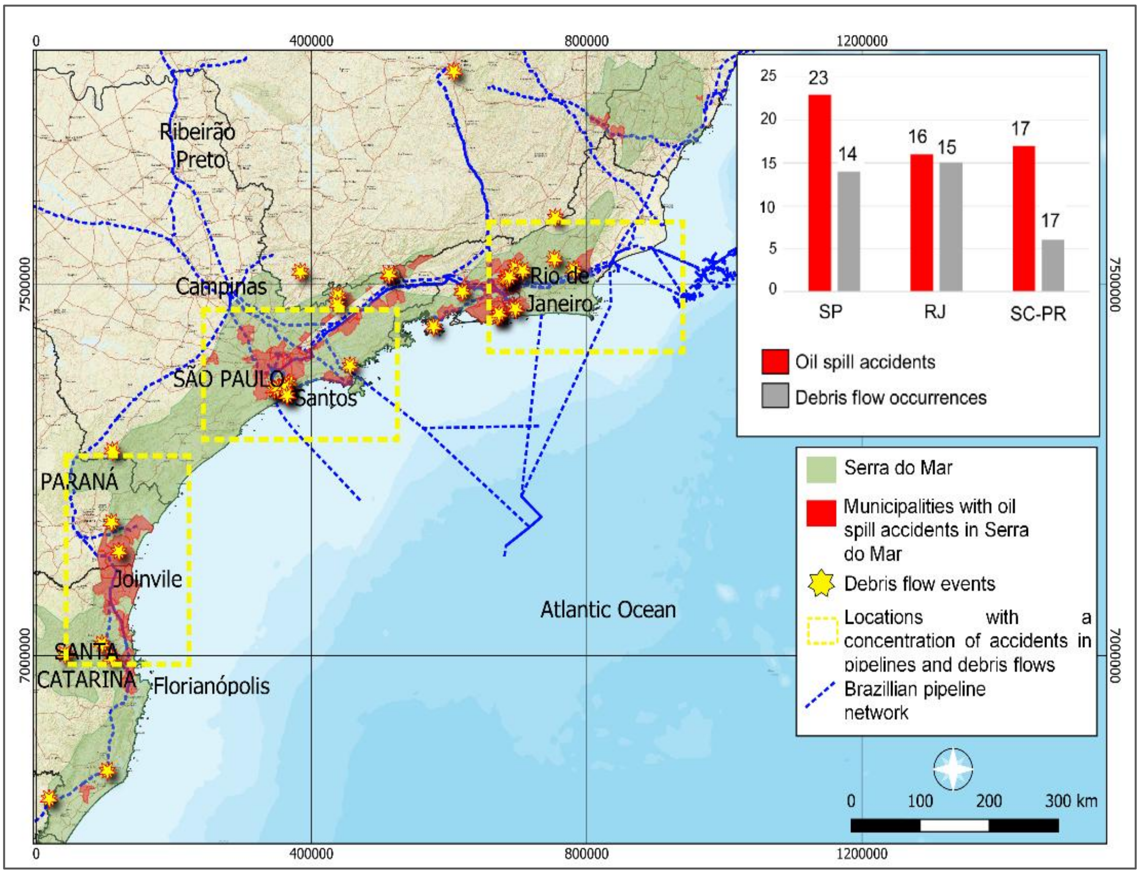

Figure 7 - Distribution of accidents related to pipelines in Brazil and their relationship with the occurrence of oil spills and debris flows.

By analyzing the geographic distribution of oil spill events and the location of disasters caused by debris flows, we can recognize the importance and relevance of addressing debris flow management in relation to pipeline safety. This highlights the need for developing oil spill sensitivity indices for continental areas.

Table 5 - A map of recorded debris flows in the three main states that comprise the Serra do Mar (Cabral et al. 2023a)

Date	Mountain range	Location	State	Economic Losses (USD)
1928	Serra do Mar	Santos	São Paulo	24,112,000
1956	Serra do Mar	Santos		N/A
1967	Serra do Mar	Caraguatatuba		63,449,964
1971	Serra do Mar	Cubatão		N/A
1975	Serra do Mar	Cubatão		N/A
1976	Serra do Mar	Cubatão		N/A
1985	Serra do Mar	Cubatão		N/A
1988	Serra do Mar	Cubatão		N/A
1994	Serra do Mar	Cubatão		73,332,253

1996	Serra do Mar	Ubatuba		N/A
1996	Serra do Mar	Cubatão		N/A
1999	Serra do Mar	Cubatão		N/A
2013	Serra do Mar	Cubatão		N/A
2014	Serra do Mar	Itaóca		5,578,975
1966	Serra do Mar	Rio de Janeiro	Rio de Janeiro	75,547,344
1966	Serra do Mar	Petrópolis		
1966	Serra do Mar	Petrópolis		N/A
1967	Serra do Mar	Rio de Janeiro		N/A
1967	Serra do Mar	Serra das Araras		N/A
1988	Serra do Mar	Petrópolis		N/A
1988	Serra do Mar	Rio de Janeiro		935,000,000
1996	Serra do Mar	Rio de Janeiro		N/A
2001	Serra do Mar	Petrópolis		190,757,690
2010	Serra do Mar	Niterói		146,587,277
2010	Serra do Mar	Angra dos Reis		180,668,819
2011	Serra do Mar	Petropolis		1,932,584,390
2011	Serra do Mar	Teresópolis		
2011	Serra do Mar	Nova Friburgo		
2013	Serra do Mar	Petrópolis		56,111,211
1990	Serra do Mar	Blumenau	Santa Catarina/Paraná	N/A
1995	Serra Geral	Timbé do Sul		71,311,286
2008	Serra do Mar	Blumenau		946,442,920
2011	Serra do Mar	Antonina/Morretes		76,095,510
2017	Serra do Mar	Guaratuba		N/A
2020	Serra do Mar	Presidente Getúlio		9,155,290

5.1.1 São Paulo State

The state of São Paulo is characterized by having the most recorded pipeline accidents associated with oil spills (49%), accounting for 247 accidents in the period from 2006 to 2022. This fact, added with the high recurrence rate of debris flows in the Serra do Mar where much of the pipeline infrastructure is present (mainly in the municipality of Cubatão) makes this stretch highly susceptible to environmental disasters on a regional scale.

The largest debris flow event recorded in the state of São Paulo is one of the most significant disasters in the history of Brazil, if not the world; it occurred in March 1967 in the municipality of Caraguatatuba (Figure 8A, B and C). A total of 760 extensive landslides in three hydrographic basins (Pau D’Alho, Rio Santo Antônio and Camburu), which were then channeled into the main drainages and resulted in debris flow processes descending from the slopes toward the city an estimated volume exceeding 7,600,000 m³. (Cruz 1975; Fulfaro et al. 1976; Gramani 2001; Massad et al. 2002).

Precipitation reached 585 mm within 48 hours at the rainfall stations in Caraguatatuba, 260 mm on the first day and 325 mm on the following day. In the end, this disaster left 436 dead and thousands more homeless, 400 houses were destroyed, and the estimated losses were $63,449,964 USD when adjusted for inflation (Massad et al. 2002; Kanji et al. 2003, Cabral et al. 2022).

To ensure safety and prevent environmental risks, it is essential that the Caraguatatuba area receive special attention. This is because the municipality is one of the main outlets for pre-salt gas, which makes constant mapping and monitoring crucial to prevent accidents and ensure the protection of the environment.

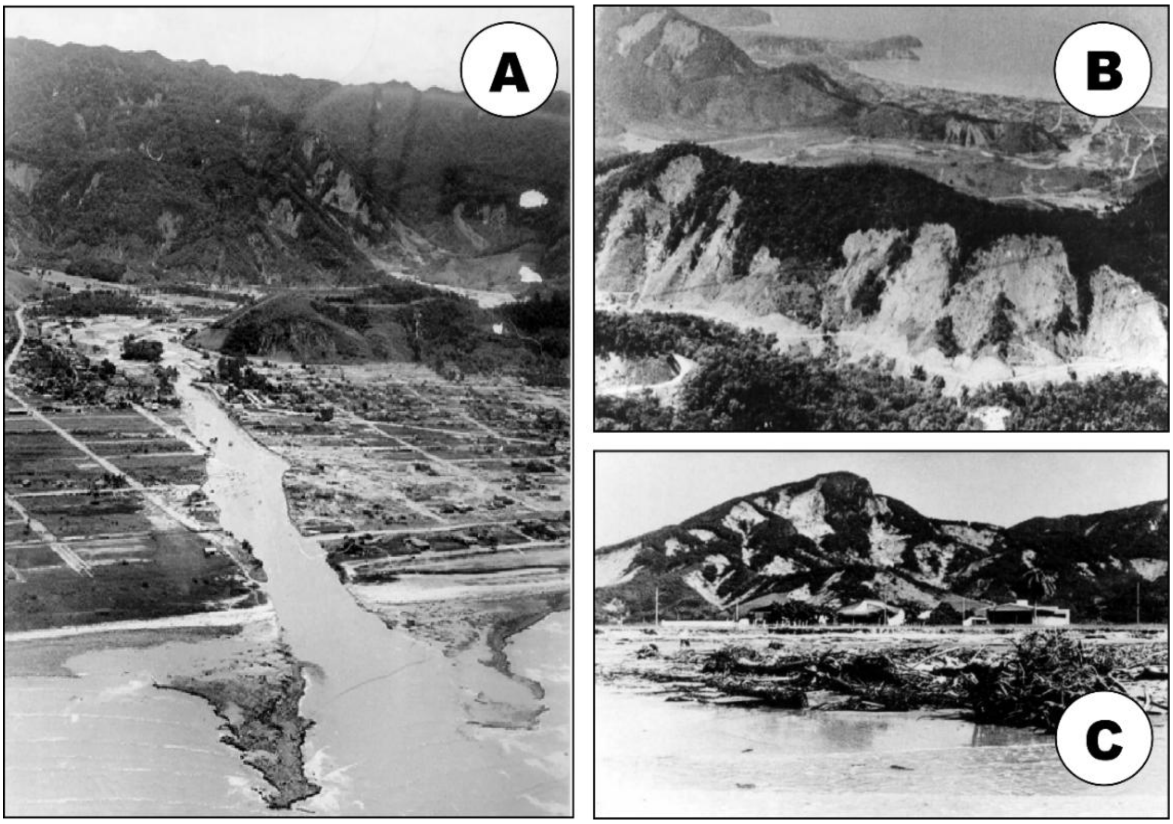

Figure 8 - Images of the disaster in Caraguatatuba in 1967. 8-A) The Serra do Mar after widespread landslides. 8-B) The coastal strip of Caraguatatuba destroyed by debris flows and the Serra do Mar is in the background where several widespread landslides occurred. 8-C) Destruction caused by the debris flows in the municipality of Caraguatatuba. (Source: Municipality of Caraguatatuba Archive)

In January of 1985, in the municipality of Cubatão, 380 mm of rain fell within 48 hours with a peak intensity of 84 mm per hour (Figures 9 A and 9 B). During this event, approximately 1600 landslides occurred, which reached the main channels of the drainage network and generated highly destructive debris flows with an approximate volume of 1,000,000 m^3. The industrial sector suffered severe damage, including ammonia that leaked into the Mogi River basin due to the rupture of a pipeline belonging to the Copebrás company (Vieira and Gramani 2015; Cabral et al. 2023a).

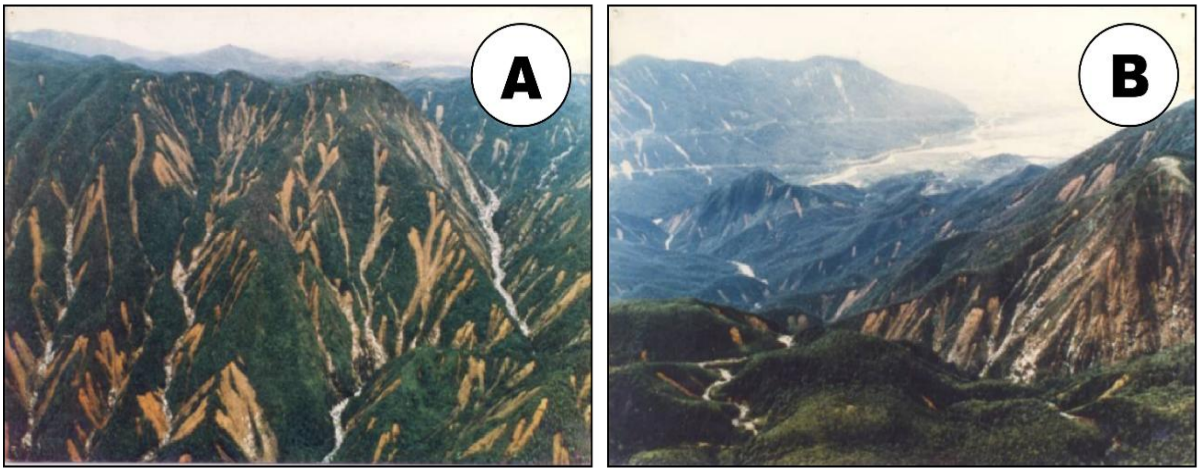

Figure 9 - Images of the disaster in Cubatão 1985. A) The Serra do Mar in Cubatão with widespread landslides and the main drainages filled with rock. B) Another stretch of Serra do Mar in Cubatão with widespread landslides. (Source: Kanji et al., 2017)

Another recorded and very well-documented debris flow event, which is noteworthy for its magnitude and impact, occurred in the municipality of Cubatão in February 1994 (Figure 10 A, B and C). A debris flow was triggered that reached the Presidente Bernardes Refinery (RPBC). This flow developed along the Pedras stream, and the main catalyst was precipitation on the order of 140 mm that fell over 3 hours with a peak intensity of 60 mm in 1 hour, followed by 105 mm over 2 hours.

With an approximate volume of 300,000 m^3 and a speed of 10 m/s, the debris flows caused destruction and damaged several of the refinery facilities; as a result of which operations were stopped for approximately 3 weeks, totaling a loss of $ 73,332,253 USD when adjusted for inflation (Massad et al. 2002; Massad et al. 2009; Kanji et al. 2007).

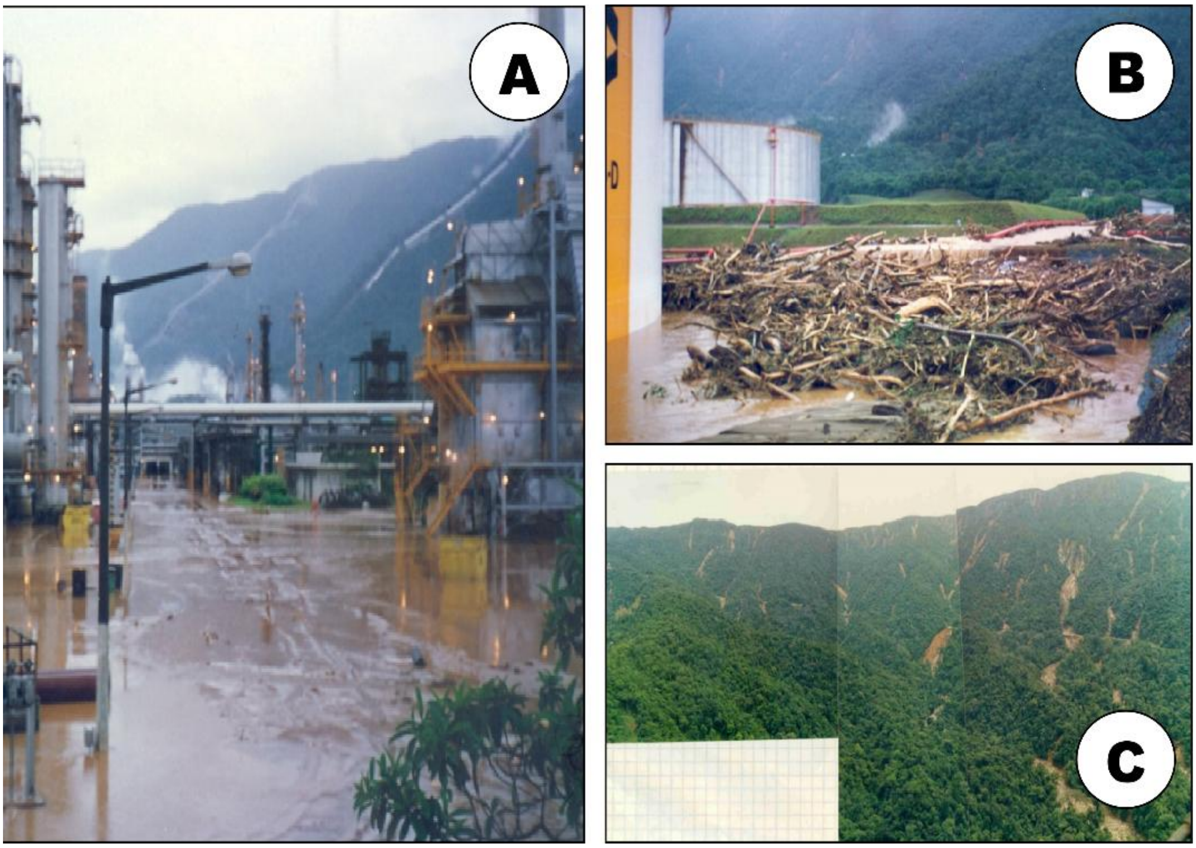

Figure 10 - Images of the disaster in Cubatão in 1994. A) The Presidente Bernardes refinery (RPBC) flooded by mud from the debris flow process. B) Photo of plant debris that impacted the refinery infrastructure. C) Serra do Mar in Cubatão with widespread landslides. (Source: Massad et al. 2009).

5.1.2 Paraná and Santa Catarina States

In the areas that comprise the states of Paraná and Santa Catarina, there are countless cases of accidents in pipelines associated with gravitational mass movements and debris flows, especially when analyzing the data, it is possible to notice recurrence at some points.

Regarding magnitude, the event that occurred in Timbé do Sul, Santa Catarina, in December 1995 (Figures 11A, B and C) stands out for its magnitude and destruction, where 29 people lost their lives, hundreds were left homeless and substantial material damage was recorded (Pellerin et 1997; Massad 2002).

This event impacted an area of 32 km^2, with an estimated precipitation between 300 and 500 mm over a period of 4 to 5 hours and 176 mm of rain over 24 hours. The volume of sediments associated with this debris flow was calculated by (Massad 2002) to be of approximately 4,000,000 m^3. When we consider the volume of water and the tree trunks, blocks of rock, soil and debris, the values may have reached the order of 8 to 10 million m^3. The total estimated losses were $71,311,286 USD at today’s value (Cabral et al. 2023a).

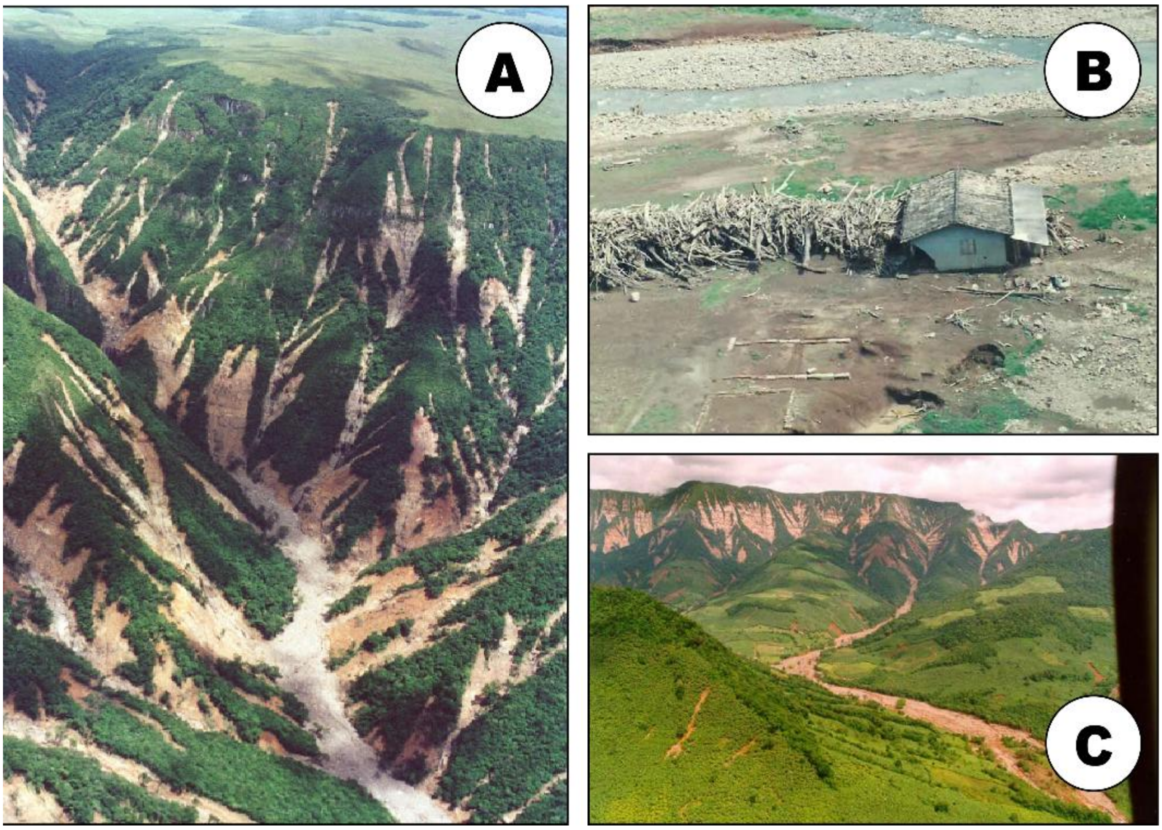

Figure 11 - Images of the disaster in Timbé do Sul in 1995.A) Serra do Mar in the background in Timbé do Sul 1995 with widespread landslides, B) Image of a house impacted by plant debris. C) Aerial view of Serra do mar with widespread landslides and main drainages eroded by debris flow

Additionally, an event occurred in the municipality of Guaratuba, Paraná, in February 2017 in the Pedra Branca watershed (Figure 12A, B, C and D), that triggered a debris flow with an estimated magnitude of 120,195 m^3, a peak flow of 2146.7 m^3 and an approximate speed of 26.5 m/s. The debris flow was caused by 188 mm of rain that fell over 3 hours, with a maximum intensity of 128 mm/h and an estimated return period of 15 to 20 years. When combined with the intense accumulation of debris in the channel (37,000 m^3), this indicates that new high-magnitude debris flows in the watershed and in the region may occur in the next two decades. (Cabral et al. 2021, Cabral et al. 2023a).

This event was initiated by several shallow landslides at the headwaters of the watershed, affecting a small village upstream and directly impacting the network of oil pipelines that cross the basin. Fortunately, no fatalities were recorded, and oil leaks could be prevented in time.

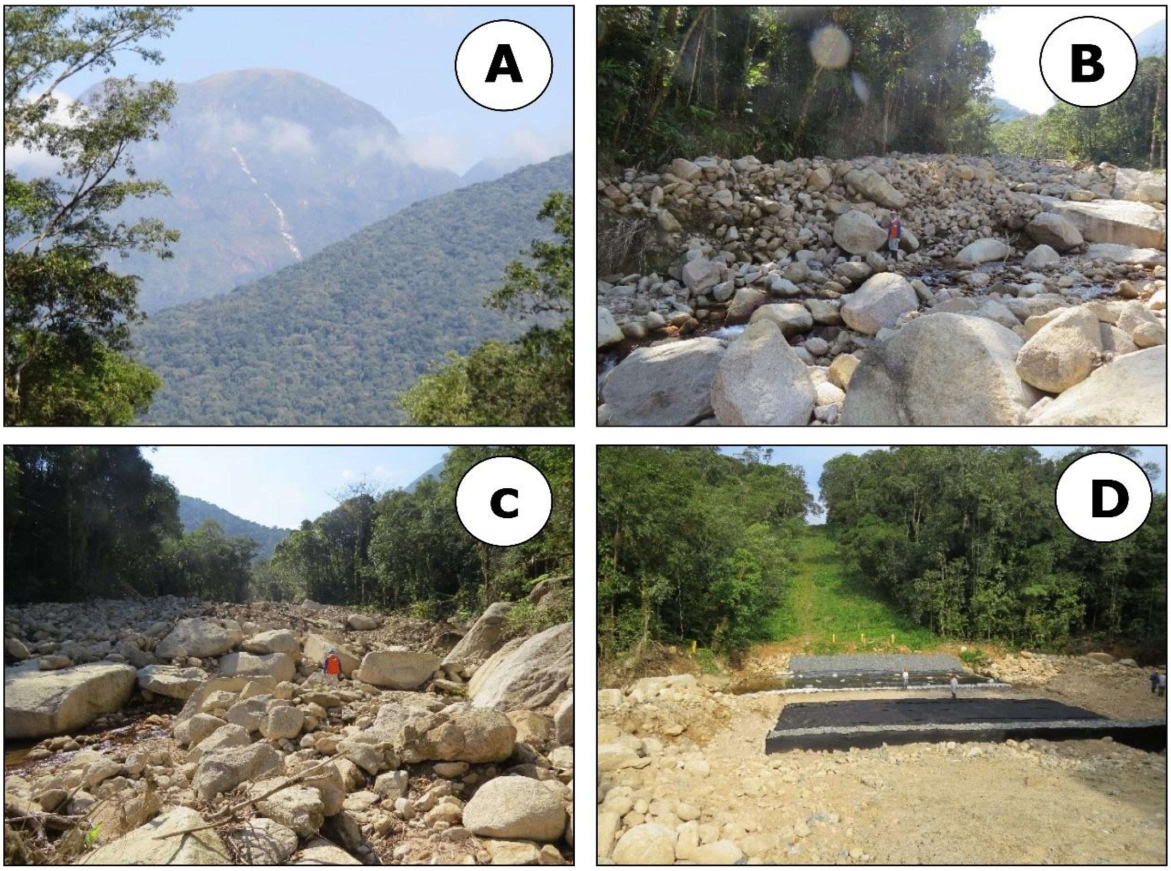

Figure 12 - Images of the disaster in Guaratuba/PR 2017.A) The Serra do mar in the background with evidence of the passage of the debris flow. B) The main drainage where it is possible to verify the erosive effect of the debris flow, the volume of transported material and destruction. C) Image of the main drainage where it is possible to notice the destruction caused by the passage of the debris flow and the large amount of mobilized rock blocks. D) The section where the pipeline network was affected under reconstruction after being impacted by the flow of debris. (Source: Victor Carvalho Cabral/Vinicius Q. Veloso)

6 Discussion

Throughout the course this study, it was possible to broaden our understanding regarding the environmental sensitivity index when applied to oil spills, both in Brazil and worldwide. The need for methodological improvements was identified, in particular the implementation of an environmental sensitivity index specific for terrestrial environments, with a focus on pipelines. Furthermore, there is a need to implement dynamic environmental monitoring systems.

The pipelines stretch hundreds of kilometers and, in most cases, are located in areas of environmental vulnerability. In Brazil, in particular, they are subject to the impact of natural disasters of geodynamic origin, which can cause rupture and eventual oil leakage. In view of this scenario, the need for integrated and actionable river and land environmental sensitivity maps, which are still in an early stage of development, is reinforced. This is because many accidents evolve from terrestrial environments and then impact riverine and coastal environments, as in the case of rupture of terrestrial pipelines. (Dias-Brito et al 2014).

The available data on oil spills associated with pipeline accidents of geodynamic origin (which are mainly debris flows in Brazil and elsewhere in the world) suggest that there is high degree of relevance regarding the importance of preparing specific mapping and contingency plans, such as the implementation of environmental sensitivity indices for pipelines. (Sweeney et al. 2005).

Thus, the current mapping techniques mostly take into account the coastal areas (Figure 13), while disregarding the stretches crossed by pipelines responsible for transporting a large volume of oil, which can be affected by accidents of geodynamic origin.

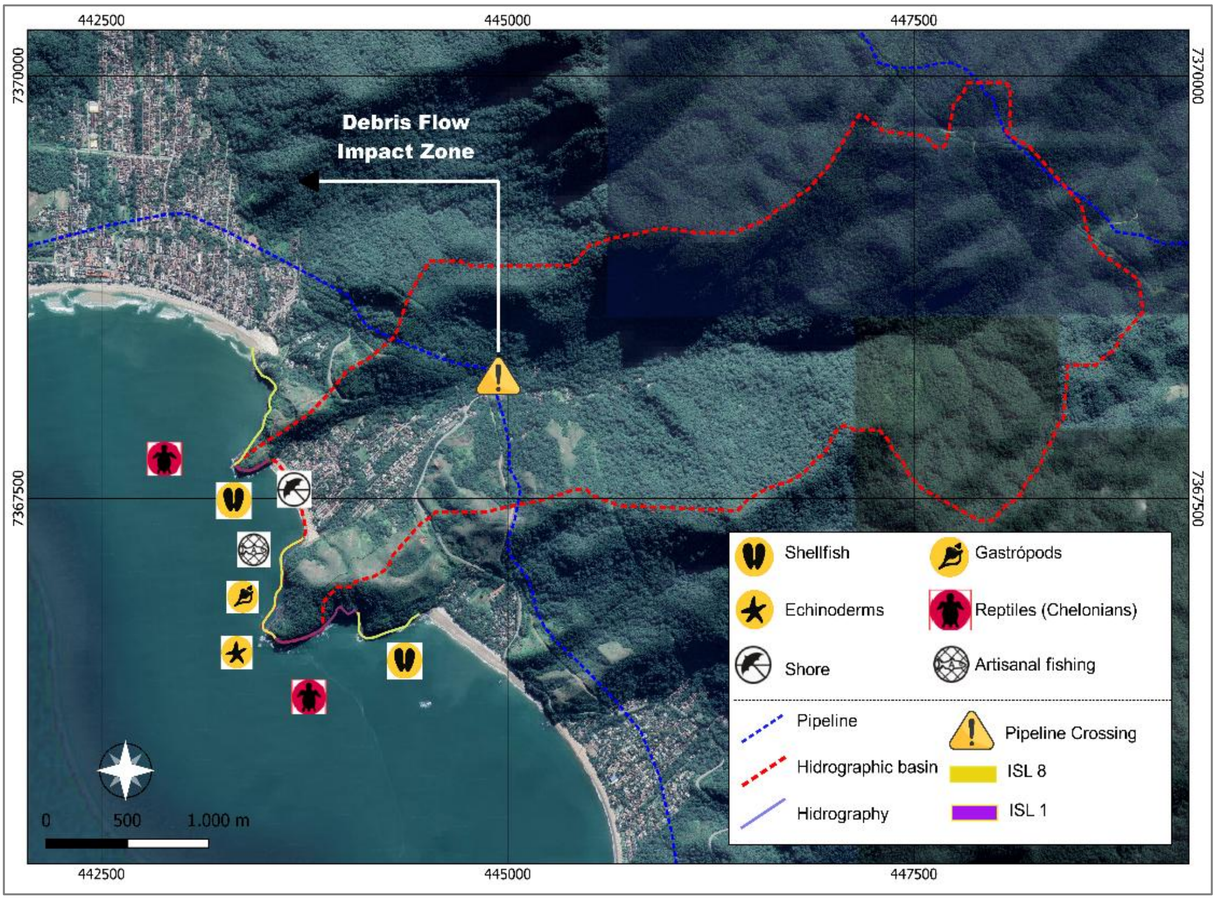

Figure 13 - Example of environmental sensitivity index mapping for oil spills on the coast of São Paulo-SP, where it is possible to notice the concentration of information on the coastline. Note the insertion of an icon for hazard mapping the occurrence of debris flows in stretches of pipelines crossed by rivers.

According to Oliveira et al. (2013), the task of classifying environmental sensitivity in terrestrial environments is much more complex than in coastal areas because in coastal areas sufficient classification requires only an emphasis on the geomorphology of the narrow tidal zone, which is represented cartographically by the coastline and is restricted to beaches, rocky shores, artificial structures and mangrove areas. Regarding terrestrial areas, it becomes necessary to identify spatial units of sensitivity, where a large variety of combinations of terrain, relief, soil nature, rock types and surface occupation patterns must be considered.

One of the first works carried out to establish environmental sensitivity indices for pipelines was developed by Walker et al. (1978), followed by Gundlach et al. (2005) and Mendes et al. (2005), who developed methodologies for environmental risk mapping of pipeline sections. They based their work on the methodology standardized by NOAA, using a scale from 1 to 10 and the same symbology pattern. However, there are still many gaps to be filled regarding the methodology for mapping environmental sensitivity to oil in terrestrial environments.

Terrestrial environmental sensitivity indices, for instance, do not take into account the assessment of hydrographic basins, where there is the potential for impacts from debris flows on pipeline sections crossing drainage areas. Another important point is to incorporate susceptibility assessment methodologies and numerical modeling to predict the occurrence of these phenomena in pipeline route mapping.

Currently, sensitivity to oil mappings relies on cartographic representation using icons to refer to socioeconomic and biotic aspects and coastlines to establish the oil sensitivity index (OSI) with values ranging from 1 to 10 (Figure 13). However, it has been recognized that there is a need for advancements in this methodology.

One proposed improvement is the integration of these three areas by generating 2D and 3D maps. Additionally, real-time monitoring of dynamic data related to logistics, production, and oil extraction could be implemented, as illustrated in Figure 15. This integrated approach would allow for a more comprehensive and efficient analysis of oil sensitivity, providing valuable information for decision-making.

The purpose of these maps is to provide preliminary information for quick decision-making regarding evacuations, implementation of works, and prevention of secondary disasters caused by debris flows. An operational real-time monitoring framework is essential for the functioning of this contingency plan.

Dynamic environmental monitoring is essential to ensure safety and protect the environment. One of the main methods used involves geographic information systems. It is important to note that the mapping database provided by the Environmental Sensitivity Index (ESI) is immense and valuable. Therefore, it is critical to integrate these data into a dynamic risk monitoring platform.

This platform will allow the static classification values of the ESI to be complemented with environmental data in real time, capable of detecting the occurrence of debris flows that could impact pipelines. Precipitation data, for example, can be used to identify possible landslides and other natural phenomena that could affect the integrity of the monitored area. By integrating these data, it is possible to provide more accurate and up-to-date information on the environmental situation, allowing for better decision-making and risk management. (Figure 14).

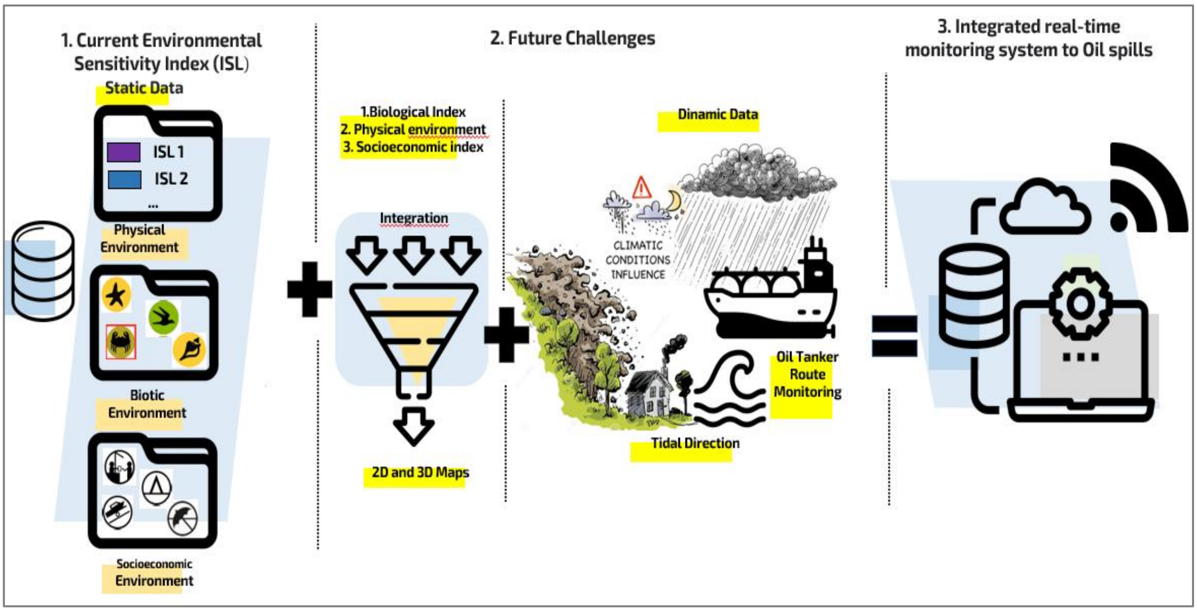

Figure 14 - Data integration scheme for implementing a dynamic environmental monitoring system

The use of environmental monitoring platforms can allow managers to act quickly and effectively in risk situations. With these platforms, it is possible to make more precise decisions regarding the displacement of teams for cleaning environments, containment of oil, evacuation of populations and prevention of secondary disasters. In addition, these platforms allow constant monitoring of vulnerable areas, triggering real-time alerts in case of imminent risks of environmental accidents. With the implementation of these platforms, managers can take proactive measures to protect the environment and the population, minimizing damage caused by accidents and allowing for faster and more effective action in an emergency.

It is noteworthy that the successful implementation of this platform depends on the availability of technologies capable of collecting and processing environmental data in real time. Therefore, it is essential to invest in the research and development of technologies capable of meeting this demand and enabling the creation of a dynamic and efficient environmental monitoring system.

7 Conclusions

Throughout this study, it was possible to perceive the need for methodological improvements and the implementation of environmental sensitivity indices for terrestrial environments, especially for pipelines, which are responsible for transporting large volumes of oil through environmentally vulnerable areas. It is essential to integrate these indices with fluvial and coastal environmental sensitivity maps for the elaboration of specific mapping and contingency plans, aiming to minimize the environmental impacts in the case of accidents of geodynamic origin. In this way, it becomes possible to develop effective strategies for preventing and responding to possible disasters, ensuring the protection of the environment and the safety of the population.

Although there are methodologies for mapping the environmental risk for pipeline sections, there are many gaps to be filled in relation to mapping the environmental sensitivity to oil in terrestrial environments, mainly for pipelines.

Additionally, the implementation of dynamic environmental monitoring systems is essential to ensure safety and to protect the environment. It is important to highlight that the database provided by the Environmental Sensitivity Index mappings is immense and valuable, and integrating them into a dynamic risk monitoring platform can provide more accurate and up-to-date information on the environmental situation, allowing for better decision-making and risk management. The use of environmental monitoring platforms can allow managers to act quickly and effectively in risk situations.

Chapter 2: Methodological proposal for applying a hazard index to debris flows in drainage crossing sections of pipelines in mountainous areas

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Abstract

Debris flows are the most destructive gravitational mass movements in Brazil and across the globe, resulting in severe social, economic, and environmental impacts. These events primarily occur in mountainous regions during extreme precipitation events, exhibiting extensive coverage and causing significant destruction. There is an urgent requirement to enhance research on the phenomenological aspects and establish methodologies for evaluating and mapping these phenomena, considering their growing frequency. The objective of this study was to create an approach that can be easily replicated in different regions. This approach focuses on evaluating the risks associated with hazards by analyzing the interplay between susceptibility and vulnerability. The goal is to develop a methodology that can offer valuable insights for decision-making in the context of pipeline risk management. To achieve this, we assessed eight hydrographic basins located in Cubatão and São Sebastião, both municipalities in the state of São Paulo, which have a known history of recurring debris flow incidents. The primary outcome produced was the execution of the debris flow hazard index. The findings emphasized the significance of morphometric, geomorphological and geological factors of the hydrographic basins, along with the crucial role of estimating the distance covered to establish contingency plans and make informed decisions regarding both structural and non-structural measures in areas with elevated levels of hazard. The research emphasized the need to understand and control the catastrophic consequences of debris flows, with a specific focus on risk assessment the referred. The creation of the debris flow risk index highlighted the significant impact of morphometric, geomorphological and geological factors, thus emphasizing the importance of estimating the distance traveled by debris to inform contingency plans. The conclusions underscored the importance of these parameters in making well-informed choices regarding structural and non-structural measures, thereby providing an asset for risk management, especially in regions susceptible to such destructive occurrences.

Keywords: Serra do Mar, Debris Flow Hazard, Pipelines, Hazard Assessment, Debris Flow Susceptibility, Debris Flow Vulnerability

1 Introduction

In recent decades, the Brazilian oil and gas industry has experienced rapid growth, driven by new exploration frontiers, the discovery of new fields, and significant investments across the entire production chain. In this context, considerable progress has been made, particularly in the infrastructure of oil pipelines designed for the transportation of petroleum and its derivatives.

However, despite the high technological level of these ventures, the management of oil leakage risks caused by mass movements still requires substantial improvements. To better assess, remediate, and improve response times to oil spills, methodologies have been developed and refined, such as the Environmental Sensitivity Index (ESI). The ESI has made significant advances and contributions in addressing oil spills along coastlines and in marine environments (Gundlach and Heyes 1978; Michel et al. 1978; Gundlach et al. 2005; Araujo et al. 2002; Araujo et al. 2006; Martins 2012, D’Fonseca et al. 2023, Veloso et al. 2023b).

The ESI constitutes a methodology that provides a fundamental source of primary information for the planning of contingency plans and response actions to oil spills. It aims to identify priority preservation environments, allowing the allocation of available resources and the more efficient mobilization of protection and cleanup teams (Brasil, 2002; Araujo et al., 2002; Oliveira et al. 2005; Mendes et al., 2005; Barbosa, 2010; Martins et al. 2013; Costa, 2013).

However, despite the significant contribution and progress resulting from these studies, they have predominantly focused on coastal zones and maritime sections. This highlights the importance of advancing this type of specific mapping for continental regions, however, according to Costa (2017), most oil spill incidents worldwide occur in terrestrial environments, primarily associated with oil pipeline transportation. In Brazil, this trend is confirmed with 54% of recorded oil spill incidents occurring in terrestrial environments, notably within the extensive pipeline network during the period from 2006 to 2021 (Veloso et al. 2023b).

The Brazilian pipeline network extends across a significant portion of the national territory, covering approximately 45000 kilometers, including both gas pipelines and oil pipelines. This network traverses diverse geomorphological features and types of terrain, with the Serra do Mar (SE Brazil) presenting the most significant challenges from the perspective of hazard and the recurrence of natural disasters related to geodynamics (Cabral et al. 2023b; Veloso et al. 2023a; Veloso et al. 2024).

The increase in the recurrence and magnitude of debris flow events on a global scale (Winter and Shearer 2014; Borga et al. 2014) is directly associated with the rise in the number of extreme rainfall events (Giorgi et al. 2011; Borga 2014; Westra et al. 2014; Cabral et al. 2023b). In Brazil, this increase is also evident from the high number of deaths related to debris flow occurrences in the last century, totaling 5,771 fatalities and 45 incidents. These incidents are primarily distributed in the southern and southeastern regions, concentrated mainly in the Serra do Mar (Cabral et al. 2023a).

In this context, the pipeline network in the Serra do Mar presents a wide range of physical environment factors that can compromise the operationalization of its activities and lead to serious environmental accidents. Among these factors, the impacts arising from gravitational mass movements, such as debris flows, stand out.

Therefore, there was a recognized lack of detailed and easily applicable and replicable studies and methodologies that incorporate the assessment of debris flow hazards into the impact and oil spill scenarios in pipeline crossings in the Serra do Mar.

Debris flows are sudden and impactful gravitational mass movements, with high recurrence in the Serra do Mar. These processes typically originate from one or more landslide events on steep slopes, entrenched valleys, and high-velocity drainage channels. They exhibit distinctive sedimentological characteristics and variable dynamics along drainage channels. During their development, volumetric changes are common due to the incorporation and/or deposition of materials in the liquid phase, reaching speeds of up to 28 m/s^{-1} (Massad et al. 1997; Gramani 2001; Kanji et al. 1997; Cabral et al. 2023b; Veloso et al. 2023a; dos Santos Correa et al. 2024).

For their occurrence, a set of conditions related to topography, available materials, and extreme rainfall is necessary. The locations that exhibit these three main conditions to a greater extent are the most prone to debris flow events (Kanji et al. 1997).

In this context, a methodology was devised to evaluate the frequency of debris flows in pipelines, based on the correlation between susceptibility and vulnerability. Susceptibility pertains to the probability of debris flow incidents in hydrographic basins and is assessed by conducting morphometric and geomorphological analyses of the basins, considering factors such as: (a) slope conditions, (b) drainage conditions, and (c) basin conditions. Vulnerability is characterized by the influence of debris flow on pipeline crossing sections along significant rivers. It is assessed by employing numerical computational modeling and GIS environment, incorporating parameters like flow height (m) and velocity (m/s) (Buwal, 1997; Hurllimann et al., 2005; Cabral et al., 2023b), as well as magnitude (m³) and the construction arrangement of pipelines within the crossing sections.

2 Studied Areas

Two study areas were designated in the municipalities of Cubatão and São Sebastião for the purpose of this application. These areas are known for experiencing frequent problems related to geodynamics, specifically debris flows. The identified regions encompass large sections of pipelines situated in the foothills of the Serra do Mar, making them highly vulnerable to such geological phenomena.

The application area of this study corresponds to the section of the Serra do Mar in the state of São Paulo, and it is divided into two municipalities crossed by pipelines, Cubatão and São Sebastião (Figure 1). Its choice was primarily driven by the fact that the field of study presents a significant diversity of environmental conditioning factors, such as its geological and geomorphological aspects, hydrological elements, and geotechnical considerations

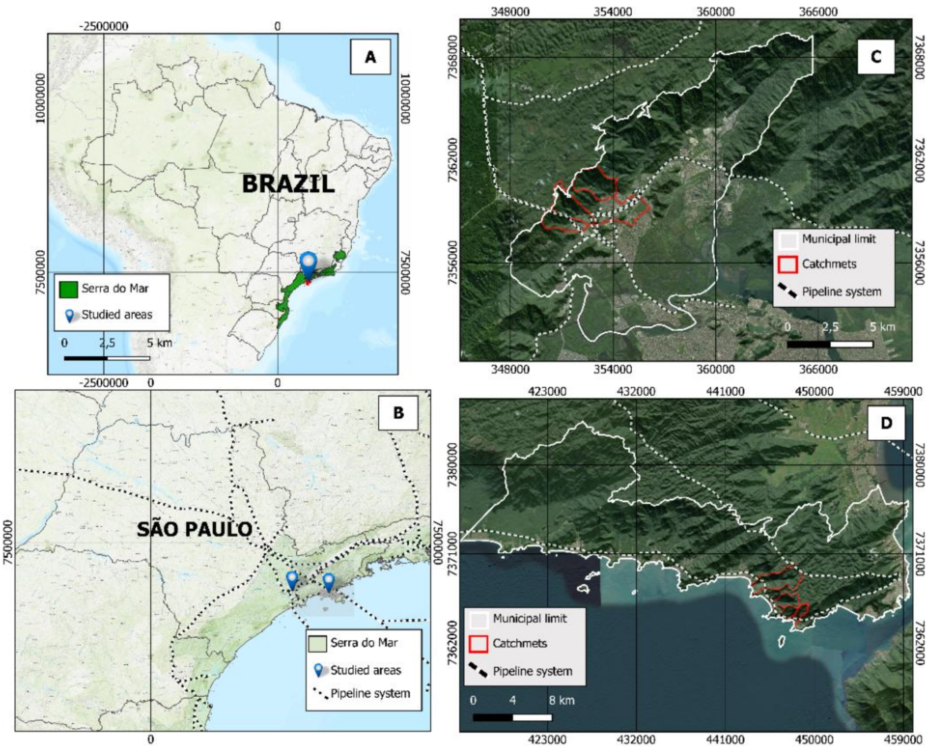


Figure 15 - Location of the studied areas.

. For research purposes, these factors constitute a substantial contribution to advancing our understanding of debris flows and their significance in the ESI. Secondly, this choice was influenced by the fact that the study areas constitute a significant petrochemical industrial complex with refineries and a pipeline system, substantial population density, and are situated within the Brazilian Atlantic Forest biome. This biome is characterized by high environmental vulnerability, especially in the event of potential oil spills resulting from pipeline ruptures.

2.1 Cubatão

The municipality of Cubatão, with approximately 130,000 inhabitants, is in the coastal geomorphological province, specifically in the festooned amphitheater subsystem (Hasui and Sadowsky, 1976).

This municipality hosts a nationally relevant industrial complex situated in the lowland stretch that extends along the valleys of the Mogi and Cubatão rivers. These industrial facilities, particularly those located at the foothills of the Serra do Mar, are at frequent risk of being affected by periodic natural hazards such as floods, landslides or debris flow.

In this sector, there is a noticeable presence of extensive slope failure on the mid-slope, which, in turn, separates the forms of active processes in the two distinct portions. The soil profile, when developed in less steep regions, consists in the upper portion of brown-yellow colluvium, clay-silt-sand, plastic, and low permeability, with an average thickness of 1 meter, rarely exceeding 2 meters. The sliding surface commonly coincides with the boundary between the colluvial soil and the underlying residual soil (Tatizana et al., 1987).

The geological context of the area is crossed by two major fault systems: the Cubatão Fault Zone and the Clastic Belt (Sadowsky, 1974). According to this author, the first extends along the southeast coast of the valleys of the Mogi, Cubatão, and Branco rivers, forming the southern boundary of a belt of ectinitic rocks present in the valleys of these rivers, alternating between thrust and normal transcurrent characteristics (Figure 16C).

The section comprises Precambrian rocks belonging to the Atlantic Shield, predominantly constituted by augen gneiss and stromatitic migmatites, schists, phyllites, quartzites, clastic rocks, mylonitic rocks, and granites, with a schistosity dipping toward the slope (Tatizana et al., 1987). This relief subsystem is characterized by third- and fourth-order drainage systems, developed in typical amphitheaters and well-defined interfluves, narrowing at the drainage outlets (IPT, 1986).

There is an extensive negative break in the mid-slope, throughout the amphitheater. This break separates two well-defined portions in terms of forms and dominant processes. In the upper portion, straight and steep escarpments (greater than 30º) predominate and are heavily affected by landslides and other mass movement processes such as debris flows. In the lower portion, convex-profiled slopes prevail, with moderate slopes (between 20º and 30º) that gradually soften toward the valleys, where downstream deposits are located (IPT, 1986). Talus bodies can be found at the base of the escarpments with features of convex slopes, exhibiting considerable thickness, reaching up to 60 m.

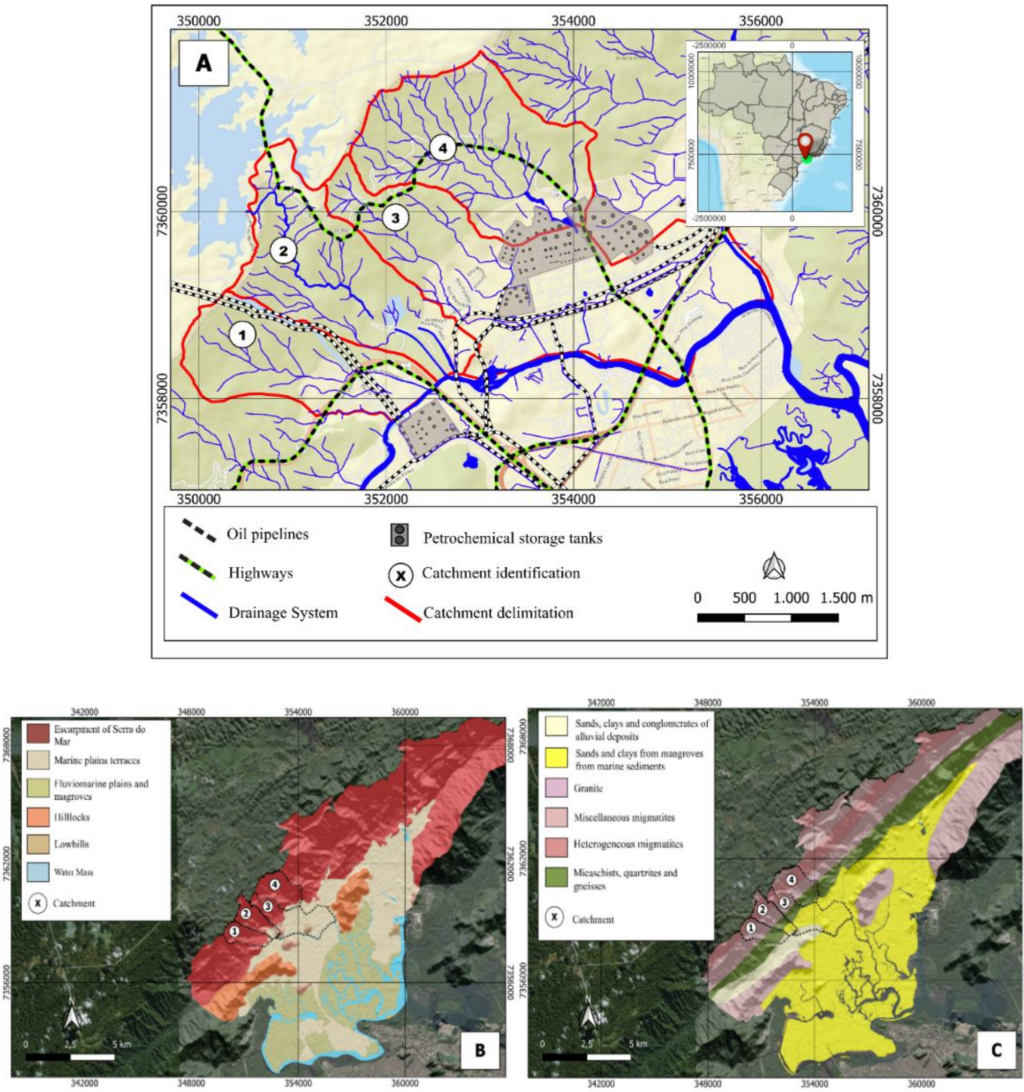
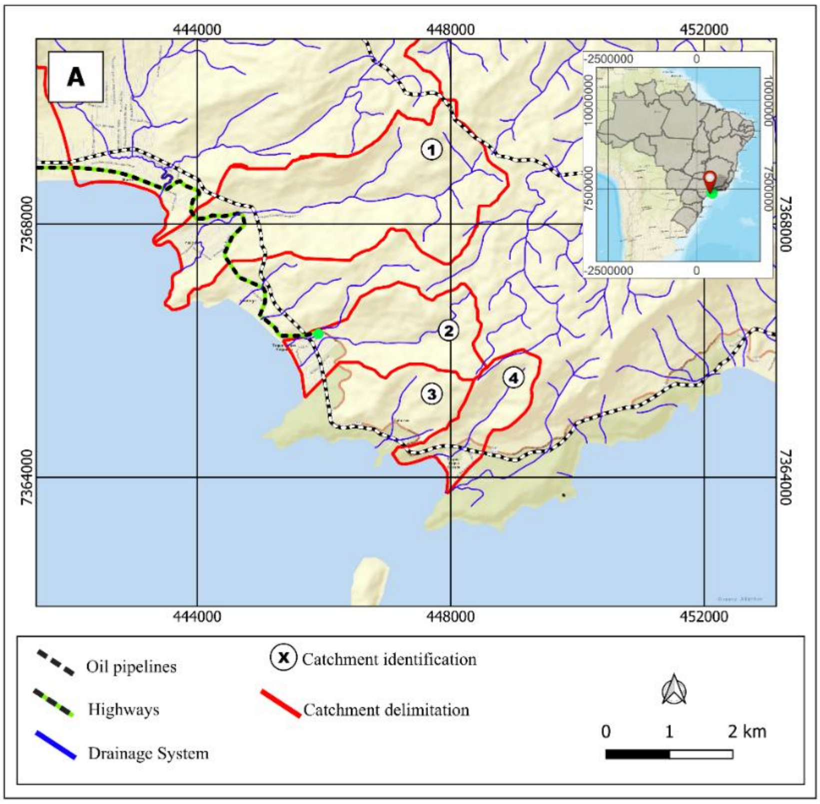


Figure 16 - A) Location of the river basins in the municipality of Cubatão and the surrounding infrastructure. B) Geomorphological context of Cubatão. C) Geological context of Cubatão.

Ten debris flow events were recorded in the eastern slopes of the Serra do Mar in Cubatão (Cabral et al., 2023b), with notable occurrences in the vicinity of the oil refinery in the years 1985, 1994 and 1996. The 1994 event resulted in the suspension of refinery operations for one week, causing USD$40 million in losses and damages (Massad 2002; Kanji et al. 2007; Massad 2009; Veloso et al. 2023a; Cabral et al. 2022a).

2.2 São Sebastião

São Sebastião is a coastal municipality with approximately 90,000 inhabitants, situated within the regional geological context of the Coastal Domain, part of the Ribeira Belt, in the Mantiqueira Province. According to Hasui (2012), the Mantiqueira Province extends along the coastal regions of the Southeast and South of Brazil, from the state of Bahia to Rio Grande do Sul, covering approximately 3000 km in length with a width that varies from 600 km in the north to 200 km in the south.nIn the local geological context (Figure 17A), the São Sebastião peninsula is characterized by the predominance of paraderived gneisses, described as relatively homogeneous rocks that follow the variations of the metasedimentary sequence (Dias Neto et al., 2009).



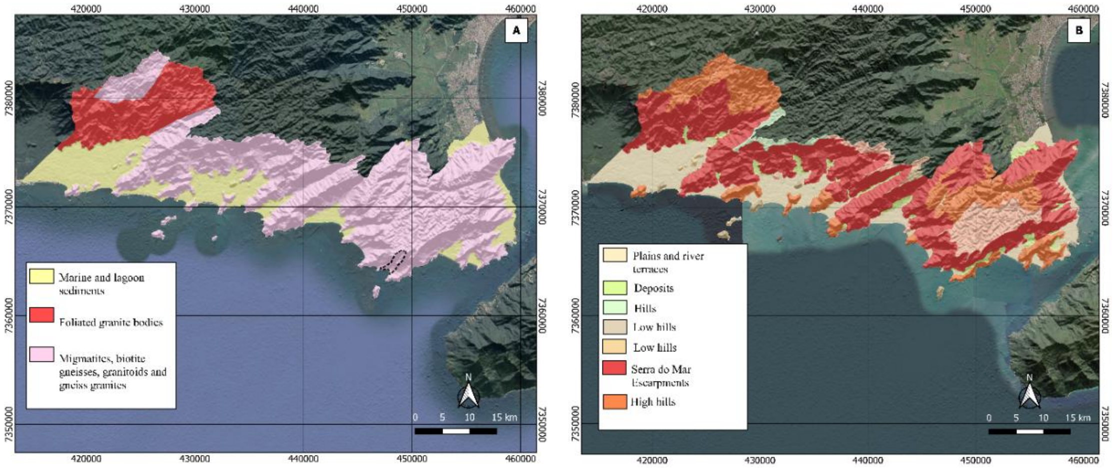


Figure 17 - Location of the river basins in the municipality of São Sebastião and the surrounding infrastructure. B) Geomorphological context of São Sebastião. C) Geological context of Sebastião.

According to the Geomorphological Map of the State of São Paulo (IPT, 1981), it is divided into two morphostructural units: (i) Coastal Province and (ii) Atlantic Plateau. The coastal plains are characterized as low, flat terrains near sea level with meandering drainage. The Atlantic Plateau presents the subzones of Festooned Scarps and Digitate Spurs, which are characterized by steep slopes (>30%), amplitudes greater than 100 meters, angular hilltops, straight-line slope profiles, entrenched valleys, and a high density of drainage.

The topography is influenced by the Serra do Mar, which exhibits various factors that can be considered determinants of severe mass movement processes. Among them, slopes emerge as the most important because steeper slopes lead to higher water runoff velocities, increasing erosive capacity (IPT, 1986).

3 Materials and Methods

In this chapter, we describe the materials used to assess the hazard of debris flows on pipelines in the selected areas. We present the methodological approaches and procedures used in the collection and analysis of data.

3.1 Risk scenario identification

The definition of risk scenarios in the selected watersheds is based on the infrastructure of the oil and gas sector at risk, with a focus on pipelines in drainage crossing sections, aiming to identify and estimate the impacts resulting from debris flows.

According to Gramani (2014), the development of a risk scenario involves mapping and measuring the impact of coarse materials with partial or destruction of structures, destruction of access roads (highways, bridges, pipelines, and crossings), and vulnerable housing. To achieve this, a profound understanding of the typology of the geodynamic processes in question is necessary, allowing the identification of destabilization features, geomorphological evidence, and, most importantly, establishing the probable reach and impact potential on objects at risk.

In addition, based on the study and survey of past debris flow occurrences in the study region, the use of critical analysis scenarios is proposed. This involves extreme rainfall scenarios to anticipate and assess potential risks.

3.2 Definition of susceptibility

Susceptibility refers to the likelihood of an eventual debris flow occurrence in watersheds and is directly dependent on triggering factors related to the geomorphology of the areas under assessment. Its determination considers the morphometric parameters of the watersheds, considering the primary triggering factors for debris flows in tropical mountainous areas related to slopes, drainage, and watersheds (Gramani 2001; Dias et al. 2016; Corrêa et al. 2021; Cabral et al. 2023b, Veloso et al. 2023a).

The highlighted parameters for evaluation include the altimetric gradient (m), channel slope (º), length of the watersheds (km), and watershed area (km²). Each of these parameters is classified on a scale from 0 to 4, and the sum of all can range from 0 to 16, where 0 represents a negligible probability of debris flow occurrence and 16 indicates the maximum possibility in the case of extreme and localized rainfall in the mapped watershed (Table 6).

Table 6 - Parameters used for evaluating susceptibility to debris flow occurrence

Susceptibility (16 points)	Parameter	Atributte	Interval	attribute weight
Geomorphological settings	Hillside	Altimetric gradient (H) (m)	>750	4
			500 -700	3
			200-500	2
			100 - 200	1
			< 100	0
	Drainage	Channel slope (D) (°)	>25	4
			15 - 25	3
			10 - 25	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) (km²)	< 5	4
			5 - 10	3
			10 - 15	2
			15 - 20	1
			> 20	0

3.3 Definition of vulnerability

The estimation of vulnerability was employed to determine whether debris flows can cause damage to drainage crossing sections of pipelines. This assessment was conducted through numerical computational modeling, where the reach radius of the debris flow was established, considering three crucial parameters: the height of the flow (meters) and the velocity (m/s) of the debris flow in the watershed areas where the main drainage intersects the pipelines. Additionally, field inspections were conducted to map the construction patterns of the pipelines at crossing sections.

Numerical modeling was performed using the RAMMS-DF software developed by the Swiss Federal Institute for Forest Snow and Landscape Research (WSL), which utilizes the Voellmy friction model for debris flows based on the Voellmy fluid flow law (Frank et al., 2017; Cabral et al., 2023b). This model assumes that debris flow is a continuous, depth-averaged model based on hydraulics and that flow resistance is divided into Coulomb dry friction (μ, dimensionless) and turbulent friction of viscous resistance (ξ, in m/s^2) (Christen et al., 2012; Frank et al., 2017; Cabral et al., 2023b).

Thus, the flow moves as a plug with the same average velocity (u, m/s) throughout the flow height (h, m). The frictional resistance (S, Pa) is given by Equation 1.

$$S = \mu N + \frac{\rho g u^2}{\xi} + (1 - \mu)N^0 - (1 - \mu)N^0 e^{-\frac{N}{N_0}} \tag{1}$$

$$N = phcos\ (\phi) \tag{2}$$

Where N is the normal stress on the bearing surface (Eq. 2), and N_0 is the yield stress of the flowing material, introduced to model ideal plastic materials (Hussin et al., 2012). In the equations, ρ represents bulk density (kg/m^3), g is the gravitational acceleration (m/s^2), and ϕ is the slope angle of the terrain (degrees). The input parameters of the model include a hydrograph or initiation volume as well as the resistance parameters μ and ξ (Cabral et al. 2023b).

3.2.1 Modeling and calibration

As the initial condition for modeling in RAMMS-DF, the operation is based on providing a digital elevation model (DEM), and values of μ and ξ were optimally combined based on deposition patterns described in the literature and observed in aerial photographs and fieldwork, as suggested by Aaron & McDougall (2019).

The simulation was based on the phenomenological initiation model according to slope failures at the drainage headwaters in the watersheds proposed by Takahashi (1981), Hungr (2004), and Takahashi (2006). For this, we assumed an initiation volume with a depth of 1 m (Tatizana et al., 1987; Cabral et al., 2023b), and that the slope failures occurred simultaneously due to the scarcity of available data.

The input values μ and ξ were optimally combined based on deposition patterns described in the literature and field deposit observations, as suggested by Aaron and McDougall (2019), Hürlimann et al. (2005), and Cabral et al. (2023b).

All simulations conducted in this study were performed using grids based on DEMs with a resolution of 5 m. To reduce the calculation time and numerical instabilities during the calculation process, we effectively employed a 10 m resolution grid for both case studies.

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 (Fig. 2) were systematically compared (Eqs. 3–5). Subsequently, a coverage index (Ω) is derived using Eq. (6), and the closer it is to 1, the more accurate the simulation results are:

$$\alpha = A\,x\,/\,A\ observed \quad (3)$$

$$\beta = A\,y\,/\,A\ observed \quad (4)$$

$$\gamma = A\,z\,/\,A\ observed \quad (5)$$

$$\Omega = \alpha - \beta - \gamma \quad (6)$$

Following this, the values of flow height (m) and velocity (m/s) were assessed and classified into four levels: Very Low (0), Low (1), Moderate (2), and High (3), based on Buwal's classification (1997). Finally, field inspections of the pipelines at crossing sections were conducted to verify the construction pattern of the pipelines. In this case, a classification from 0 to 3 was created, where 3 corresponds to exposed aerial pipes with the risk of impact, 2 corresponds to surface or subsurface pipes, 1 corresponds to buried pipes, and 0 to buried pipes with structural protection works.

Having done this, the values of flow height (meters) and velocity (m/s^{-1}) were assessed and classified into four levels: Very Low (0), Low (1), Moderate (2), and High (3), based on the classification by Buwal (1997) (Table 7).

Table 7 - Determination of vulnerability classes

Vulnerability (10 points)	Attribute	Inteval	Attribute weight
	Runoff	High	h > 1.0 m and v > 1.0 m/s
		Moderate	h < 1.0 m or v< 1.0 m/s
		Low	h < 0.4 m and v < 0.4 m/s
		Very Low	Non-affected areas
	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

3.4 Estimation of the Hazard Index

The concept of Hazard in this study is associated with the relationship between susceptibility and vulnerability (Eq. 7). To achieve this, a risk matrix was developed (Figure 4), where the two factors are correlated.

$$H = S+V \qquad (7)$$

Where Hazard is represented by *H*, susceptibility is denoted by *S*, and vulnerability by *V*.

In Figure 18, the x-axis represents the vulnerability classification (0 – 10), and the y-axis represents the susceptibility classes (0 – 16). The sum of these two factors yields the determined level of hazard for the pipeline networks in the watersheds.

When establishing susceptibility (S) and vulnerability (V) values, the hazard class (H) is then assigned on a scale ranging from 0 to 26, where values from 0 to 6 represent Very Low, 7 to 12 represent Low, 13 to 18 represent Medium, and 19 to 26 represent High.

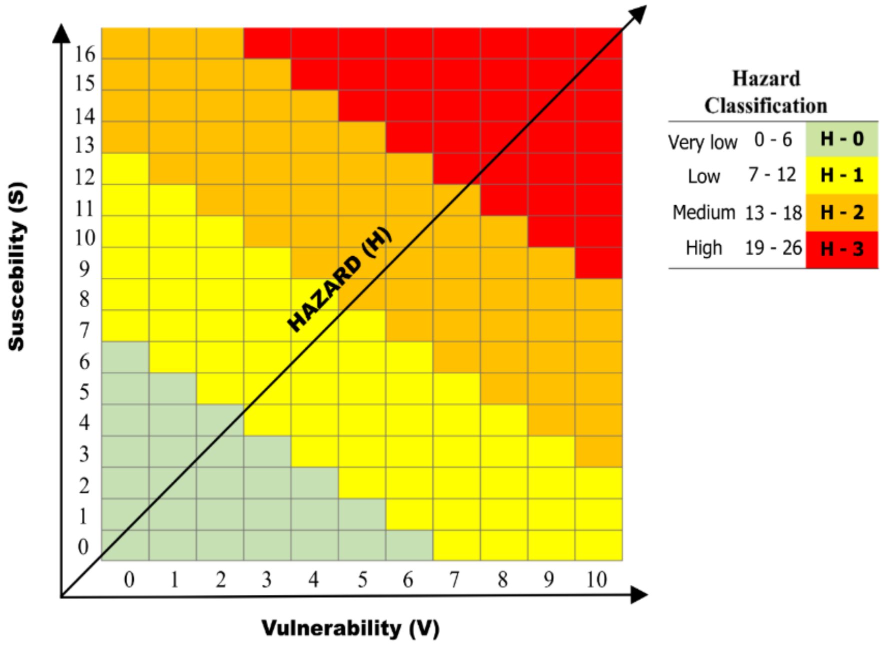


Figure 18 - Matrix of hazard classification for debris flow occurrence

4 Results and Discussions

4.1 Definition of Risk Scenarios

The purpose of defining the risk scenario in the studied watersheds was to identify drainage crossing sections intersected by pipelines prone to debris flow processes.

This involved understanding the influencing factors and estimating their impact and reach. To achieve this objective, it was crucial to define and map the at-risk infrastructure, especially pipelines, study historical events, and determine a critical precipitation threshold needed to initiate these processes based on critical thresholds proposed by Tatizana et al. (1987) and Kanji et al. (1997).

Thus, the following results are presented regarding the classification and definition of risk scenarios for the selected watersheds in the municipalities of Cubatão and São Sebastião.

4.1.1 History of Debris Flow Events in the Study Areas

First, debris flow events related data were compiled, referring to the historical debris flow occurrences in the study areas. This compilation also included factors such as watershed area ratio, elevation variation component, rainfall that triggered the event (mm/h), flow velocity, and volume. These data are presented in Table 8, based on references such as Massad (2002), Manzolli et al. (2018), Cabral et al. (2023b) and Veloso et al. (2024).

Despite the limited availability of data regarding the estimation of the magnitude of some events and the absence of more detailed historical records in the municipality of São Sebastião, this survey is crucial to comprehend the main triggers of these events from the perspective of geological-geotechnical, geomorphological and precipitation-related conditions.

Table 8 - Historical Survey of Debris Flow Occurrences in the Study Areas

	Location	Date	Area Basin (km²)	Precipitation	Velocity (m/s)	Volume (m³)
1	Cubatão, Grota Funda	1975	10,4	>140 mm/24h	8,4	$>10x10^6$
2	Cubatão, Rio Cachoeira	1976	4	40 mm/1h - 276mm / 24h	N/D*	$1x10^5$
3	Cubatão, Rio da Pedras	1985	2,64	84 mm/1 h - 265 mm/24h	N/D*	N/D*
4	Cubatão, Rio das Pedras	1988	3,4	25 mm/1 h - 135 mm/24h	N/D*	N/D*
5	Cubatão, Rio das Pedras	1994	2,64	60mm/1h - 214 mm/24 h	10	$3x10^5$
6	Cubatão, Rio das Pedras	1996	2,64	18 mm/1h	10	$1,6X10^4$
7	Cubatão, Estrada Anchieta	1999	N/D	128 mm/24h - 274mm/72h	N/D*	$3x10^5$
8	Cubatão, Rio Marcolino	2013	1,37	118/1h - 312mm/24 h	N/D*	N/D*
9	Cubatão, Ribeirão Cágado	2013	0,55	118/1h - 312mm/24 h	N/D*	N/D*
10	São Sebastião, Pauba	2014	8,26	44/1h - 211 mm/72 h	N/D*	N/D*

* Non data registered

Thus, based on the watershed data and the critical hourly precipitation indices estimated by Tatizana et al. (1987) and Kanji et al. (1997), a critical precipitation scenario for triggering debris flows was defined as a minimum of 120 mm over 72 h followed by hourly peaks of around 40 mm/h, as demonstrated below in Figure 19. It is important to note that the initiation of these events is much more complex, and there are various rainfall-related factors that can influence the occurrence of these phenomena. However, for this study, this pattern was chosen.

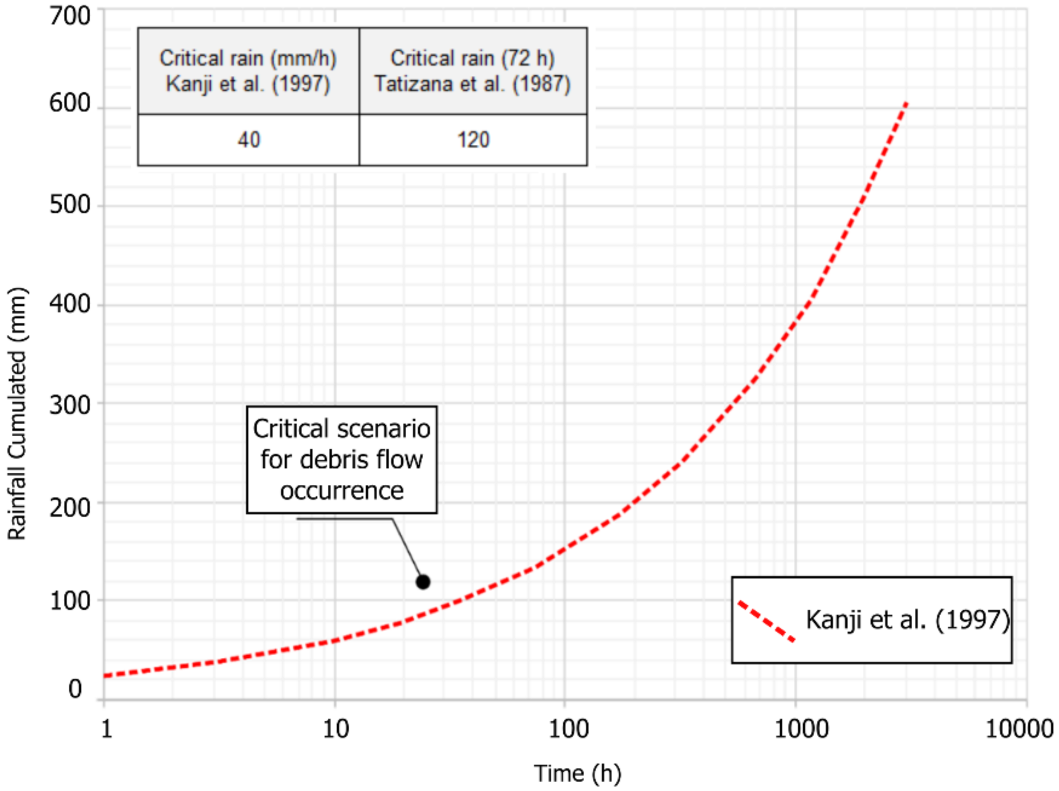


Figure 19 - Definition of Critical Precipitation Scenario for the Study Areas

4.1.1 Sections of drainage crossings at risk

Because of spatial analysis through geoprocessing and fieldwork, various risk situations were identified at drainage crossing points intercepted by pipelines in both study areas. Beyond the possibility of impact on the pipelines, the hazard of new impacts on the petroleum refinery in Cubatão, similar to those that occurred in 1994, was observed. Therefore, the hazard is directly related to the scale of the mass movement process and the position of the pipelines in relation to the path of the debris flow (Porter et al., 2004; Jakob, 2005; Gartner and Jakob, 2019), as depicted in Figures 20 and 21.

In the municipality of Cubatão, eight areas of pipeline impact risk were identified, including the section of the refinery located at the foot of the Serra do Mar in a zone of direct impact, as illustrated in Figure 20.

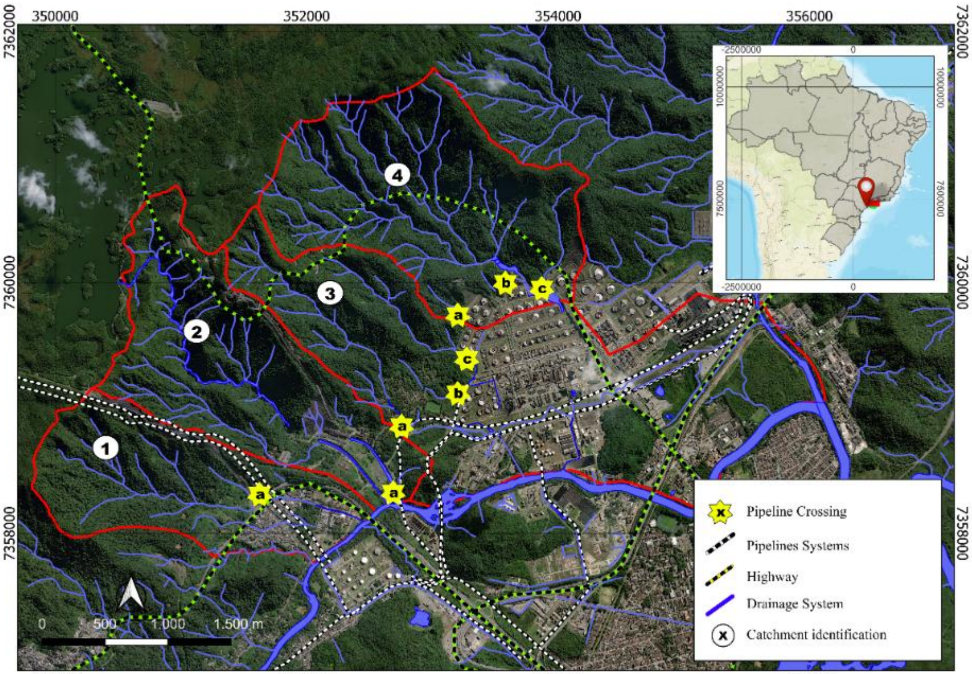


Figure 20 - Pipeline crossing mapped in the catchments of Cubatão

In the municipality of São Sebastião, four pipeline crossing points with a risk of impact were identified (Fig.21).

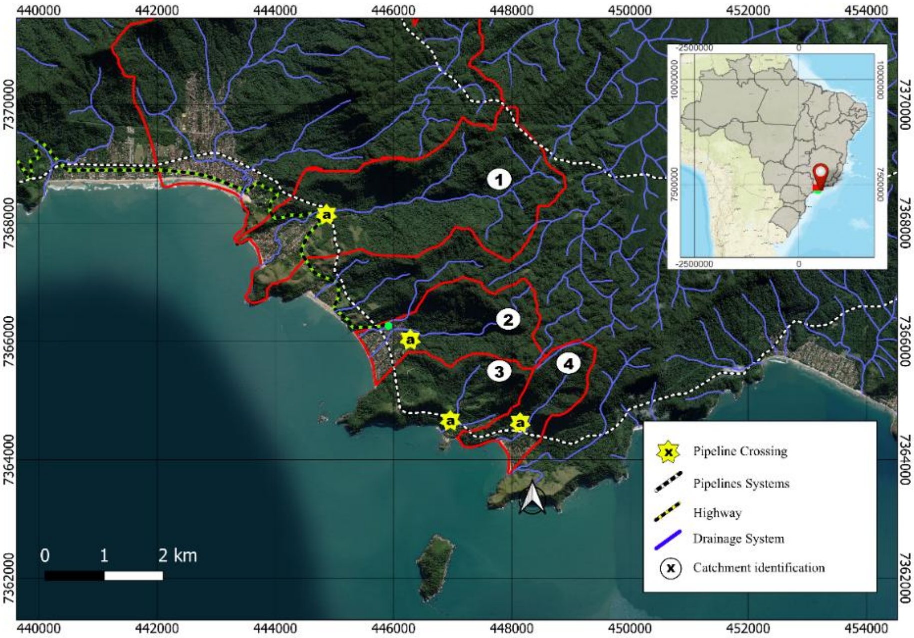


Figure 21 - Pipeline crossing mapped in the catchments of São Sebastião.

Figure 22 -Documentation of the situation of a watercourse crossing section intersected by pipelines and their respective construction patterns. A) Record of an aerial pipeline construction pattern. B) Example of a structure for the containment of potential flows in the pipeline zone. C) Crossing section segment marked with an underground pipeline. D) Section with signage indicating a submerged pipeline

With these points defined, the risk scenario was delineated in the study areas. The primary focus of this study was the hazard assessment of pipelines at drainage crossing sections. The main analyses of susceptibility, vulnerability, and hazard classification were predominantly performed in these areas. These sections, located in the final third of the deposition zone, pose the greatest risk of impact and the highest losses (Jakob, 2005; Veloso et al., 2023a).

4.2 Susceptibility Classification

After defining the risk scenarios and delineating the pipelines at risk in the study areas, the methodology for defining the susceptibility of watersheds to debris flow occurrence was applied. The methodology employed was based on the geomorphological assessment and classification of triggering factors for potential debris flows. The susceptibility values obtained for the eight watersheds in the two study areas are presented in Table 9.

Table 9 - Classification of susceptibility in the watersheds

	Altimétric gradient (H)	Class	Slope channel (D)	Class	Catchment lenght (WL)	Class	Catchment area (A)	Class	Total
Cubatão									
Catchment 1	751	4	25	4	1,64	1	2,12	4	13
Catchment 2	719	3	19	3	2,16	2	2,75	4	12
Catchment 3	707	3	19	3	2,12	2	5,30	3	11
Catchment 4	725	3	17	3	2,47	2	3,22	4	12
São Sebastião									
Catchment 1	570	3	10	2	3,25	3	8,26	3	11
Catchment 2	567	3	18	3	1,77	1	3,42	4	11
Catchment 3	570	3	18	3	1,78	1	1,62	4	11
Catchment 4	640	3	21	3	1,68	1	1,80	4	11

Upon analyzing the data, it is evident that the watersheds in the municipality of Cubatão have higher altimetric gradients ranging from 700 to 750 meters, steeper channel slopes between 17 and 25º, longer lengths, and total areas approximately ranging from 2 to 5 km². On the other hand, the watersheds in the municipality of São Sebastião exhibit smaller amplitudes between 570 and 640 m, gentler slopes ranging from 10 to 21º, shorter lengths compared to Cubatão, and areas varying approximately from 1.8 to 8 km².

4.2 Vulnerability Classification

For the definition of vulnerability in this work, the focus was on assessing the impact of debris flows on pipelines, particularly at the crossing sections, through computational modeling. The total distance traveled, height, and velocity of the debris flow were estimated to delimit the affected area caused by the phenomenon, thereby estimating the vulnerability of the structures.

To estimate these parameters for debris flows at the crossing sections, the chosen approach involved computational modeling using the RAMMS-DF software (Frank et al. 2017; Cabral et al. 2023b).

4.3.1 Modeling and calibration

Debris flow modeling was applied to estimate the area affected by debris flow in the eight watersheds of the two study areas. Because the only input data were the DEM and the values, no calibration of rheological parameters was required.

The modeling was developed on the basis of the establishment of mass movement initiation areas at the headwaters of the main drainages in the watersheds, following the phenomenological models defined by Takahashi (1981), Hungr (2014), and Takahashi (2006), with an apparent density of 2000 kg/m^3, as per previous approaches in studies of debris flows in highly incised rocky channels (Takahashi, 2006), and soil depths of ~1 m (Tatizana et al., 1987; Veloso et al., 2023a; Cabral et al., 2023b).

Simulation parameters values μ and ξ (m s -2) for volume (m^3), velocity (m s-1), impact force (kPa), maximum height (m), and reach area (m) simulated for the eight watersheds are presented in Table 10.

Table 10 - Simulation results performed with RAMMS 2D and vulnerability classification

Cubatão

Catchment	Crossing	Flow parameters		Magnitude volume (m^3)	Velocity (m/s)	Impact (kPa)	Maximum height (m)	Runoff (m)
		μ	ξ (m s^{-2})					
1	a	0.05	200	21491.8	13.67	373	2.97	1152
2	a	0.05	200	22453.7	13.67	348	3.82	600
3	a	0.05	200	18188.4	13.35	305	2.34	520
	b	0.05	200	18188.4	13.35	305		
	c	0.05	200	18188.4	13.35	305		
4	a	0.05	200	20538.0	10.60	224	2.33	420
	b	0.05	200	20538.0	10.60	224		
	c	0.05	200	20538.0	10.60	224		

São Sebastião

Catchment	Crossing	Flow parameters		Volume (m^3)	Velocity (m/s)	Impact (kPa)	Maximum height (m)	Runoff (m)
		μ	ξ (m s^{-2})					
1	a	0.03	200	33752.4	10.8	232	2.27	530
2	a	0.03	200	23279.1	10.4	215	3.21	760
3	a	0.05	200	4651.35	10.5	221	2.15	560
4	a	0.05	200	6873.4	10.7	229	2.30	690

In Figure 23, we present the outcomes of computational modeling in the municipalities of Cubatão and São Sebastião, showcasing the debris flow heights.

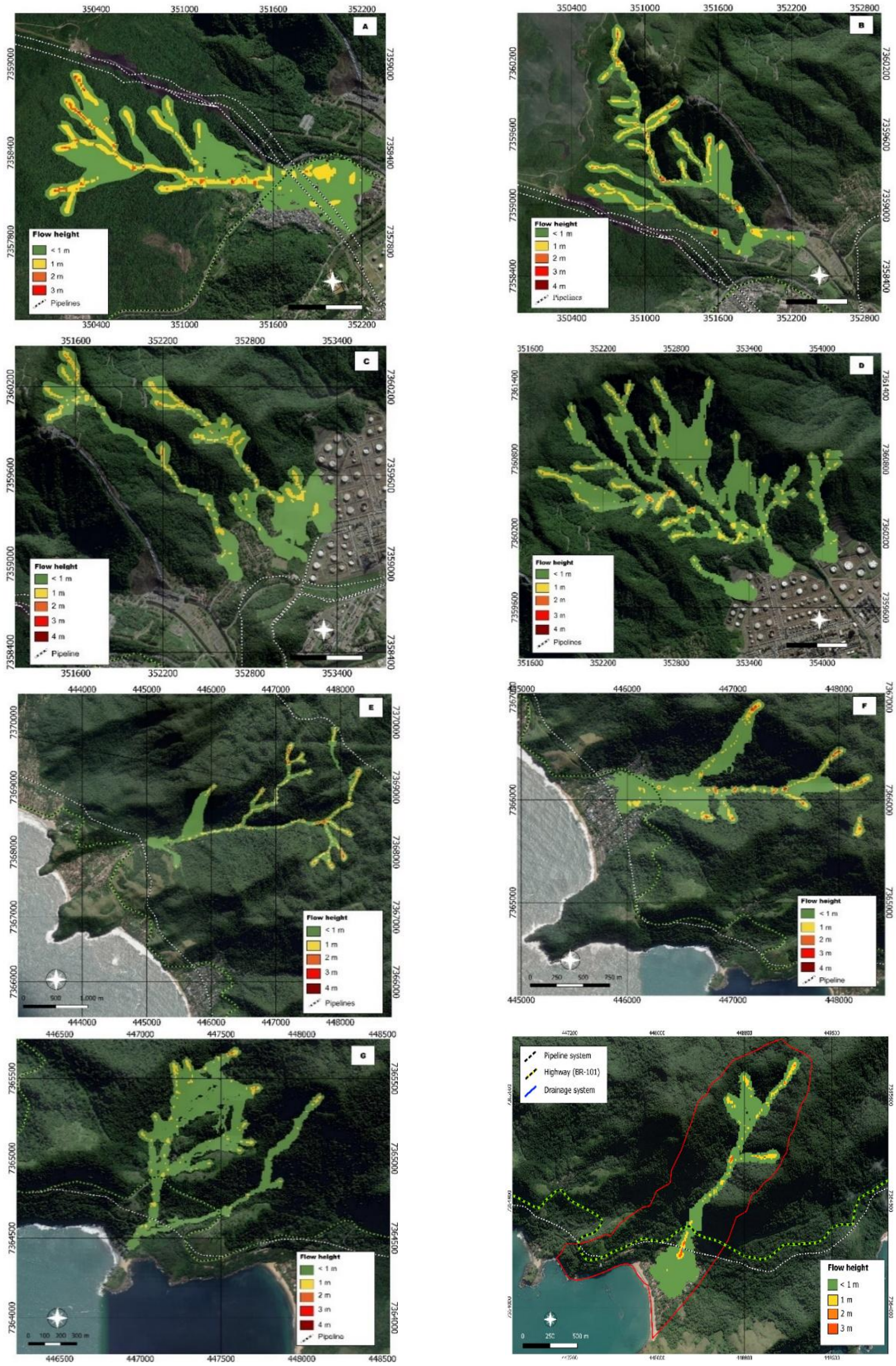


Figure 23 - RAMMS modeling results showing maximum flow height. A) Cubatão, catchment 1. B) Cubatão, catchment 2. C) Cubatão, catchment 3. D) Cubatão, catchment 4. E) São Sebastião, catchment 1. F) São Sebastião, catchment 2. G) São Sebastião, catchment 3. H) São Sebastião, catchment 4.

An important parameter in the analysis of debris flows is the height of these flows at crossing sections, in the municipality of Cubatão, the maximum recorded height was 3.82 meters in catchment 2, indicating a high risk in this area. Catchments 3 and 4 recorded flow heights of 2.34 meters and 2.33 meters, respectively, showing less intense but still significant flows. Of particular concern is catchment 1, which features an aerial pipeline crossing with a flow height of 2.97 meters, making this section one of the most concerning due to its potential impact on infrastructure. In the municipality of São Sebastião, the recorded heights were 2.27 meters in catchment 1, 3.21 meters in catchment 2, 2.15 meters in catchment 3, and 2.30 meters in catchment 4. From the perspective of impact on pipelines, the most concerning heights are those observed in catchments 3 and 4. Although these heights are lower compared to catchment 2, they still present significant risks to infrastructure integrity.

The calibration of the models was conducted using the coverage index (Ω) proposed by Schraml et al. (2015), based on the comparison of the observed and modeled areas traversed by RAMMS. This validation assessed the reliability of the simulations conducted. As depicted in Figure 24, the area affected by the modeling of debris flows reliably coincides with the deposits observed in the field in the municipalities of Cubatão and São Sebastião, as well as those estimated through satellite images, with Ω values above 50% accuracy.

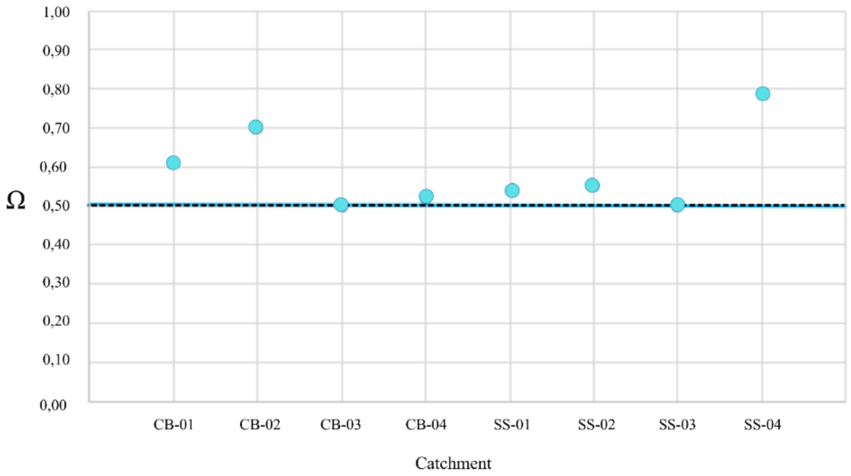


Figure 24 - Comparison of Calibrations using coverage index (**Ω**) from debris flow simulations for selected basins in the study areas.

4.3.2 Pipeline construction pattern

The information about the construction method of the pipelines along the study areas was also utilized to assign a vulnerability classification. Fieldwork was conducted to differentiate whether the pipelines are aerial, surface, underground, or if they have structural protection works.

Table 11 - Description of the construction pattern of the pipelines at the drainage crossing sections in the watersheds.

Cubatão	Crossings	Constructive standard	Class
Catchment 1	a	aerial	3
Catchment 2	a	underground	1
Catchment 3	a	underground	1
	b	underground	1
	c	underground	1
Catchment 4	a	underground	1
	b	underground	1
	c	underground	1
São Sebastião			
Catchment 1	a	underground	1
Catchment 2	a	underground	1
Catchment 3	a	underground with protection	1
Catchment 4	a	underground with protection	0

4.4 Debris flow hazard index at drainage crossing sections

The hazard index classification combined susceptibility and vulnerability values through the hazard matrix described in previous sections, resulting in individual hazard indices for each crossing section intersected by pipelines in the selected watersheds for the research application (Table 12 and Figure 25).

Table 12 - Estimation of debris flow hazard index in the selected watersheds

	Susceptibility	Vulnerability	**HAZARD INDEX**	Classification
Cubatão				
Catchment 1	13	10	23	**H-3**
Catchment 2	12	5	17	**H-2**
Catchment 3	11	5	16	**H-2**
		6	17	**H-2**
		7	18	**H-2**
Catchment 4	12	7	19	**H-3**
		8	20	**H-3**
		7	19	**H-3**
São Sebastião				
Catchment 1	11	5	16	**H-2**
Catchment 2	11	7	18	**H-2**
Catchment 3	11	8	19	**H-3**
Catchment 4	11	7	18	**H-2**

In scenarios with a hazard index between 0 and 6, the areas show no signs of impact on pipelines and are classified as VERY LOW. In sections with a hazard index between 7 and 12, the pipelines are classified as having a LOW risk of impact. In watersheds with an index between 13 and 18, the hazard index is considered MEDIUM. Finally, in watersheds classified from 19 to 26, the hazard index is HIGH, and they are the most concerning from a severity perspective. (Fig. 25)

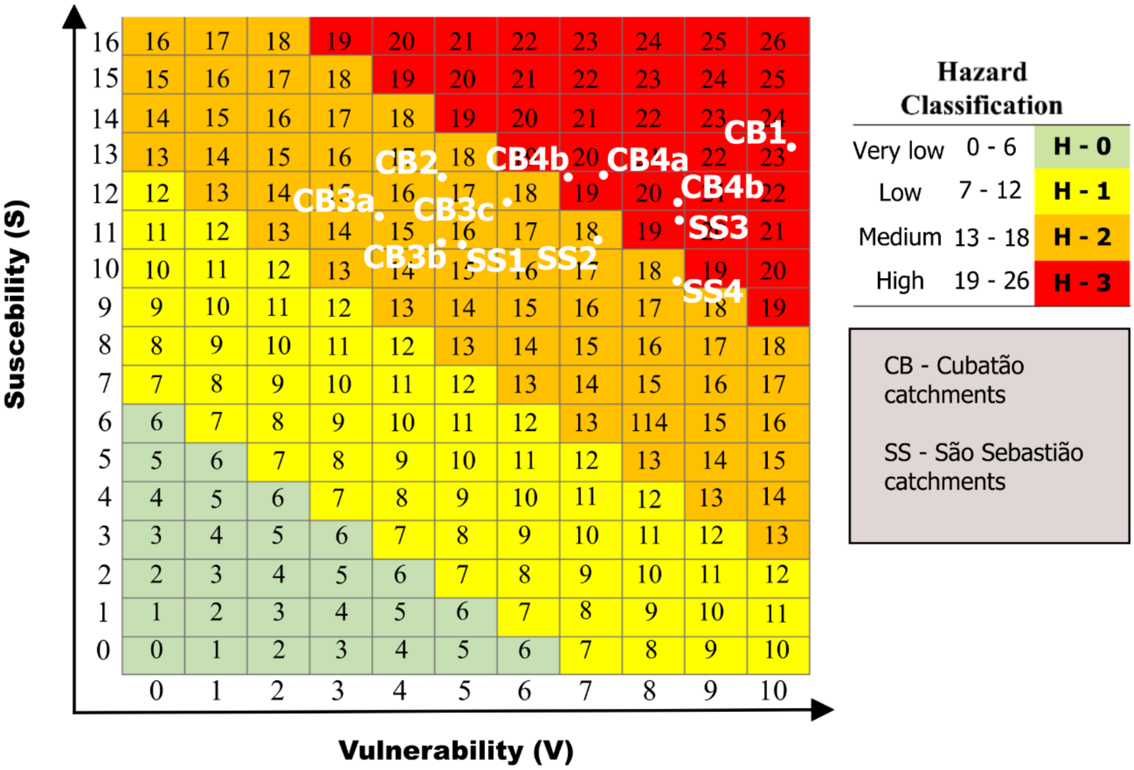


Figure 25 - Classification of the debris flow hazard index at crossing sections in the selected watersheds

For the municipality of Cubatão, catchments 2 and 3 had a MEDIUM hazard assessment (H-2) regarding the occurrence of debris flows at all crossing sections. However, catchments 1 and 4 were classified with a HIGH hazard assessment (H3) for the occurrence of debris flows, reinforcing a severe situation for these two locations.

Regarding watersheds 2 and 3, because of their shape and distance from the deposition area, they do not pose a significant hazard for impacts on nearby structures caused by debris flows. There are no historical records of significant events in these sections. However, a concern is that a large portion of the rocky material, originating from weathering and fractures, is contained in the upper third of the slope susceptible to being transported to the lower thirds through debris flows in the case of extreme and localized precipitation. Therefore, future fieldwork in these main drainages would be necessary to assess the amount of mobilizable material in the upper thirds of the watersheds.

It illustrates the imminent hazard to which the crossing sections are exposed, along with the infrastructure and population density in the direct path of impact, especially at the crossing sections of watersheds 1 and 4, which are classified as HIGH hazard and with a significant history of debris flow recurrence in recent decades. (

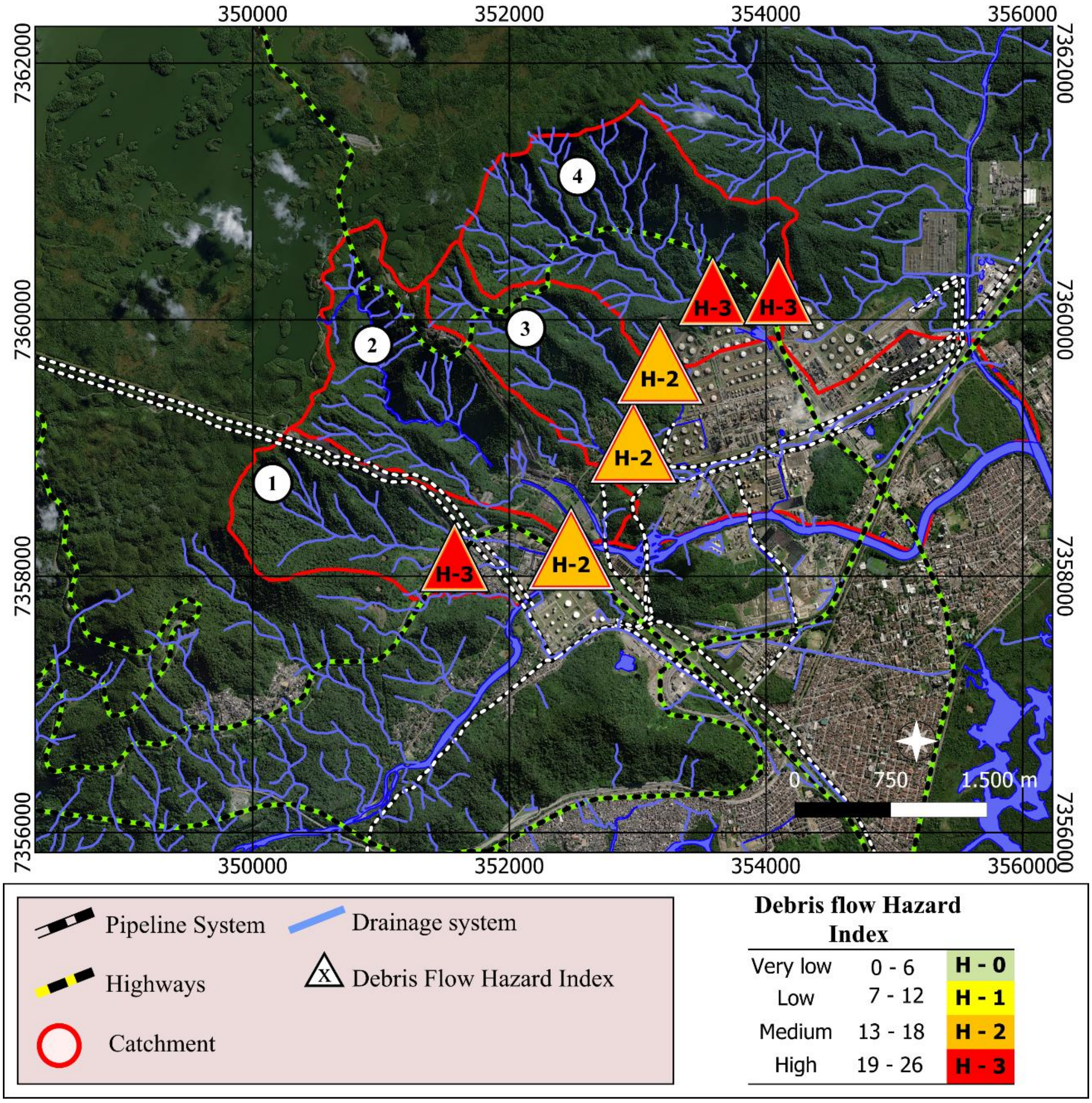


Figure 26 - Cartographic representation of the Debris Flow Hazard Index in the watersheds intersected by pipelines in the municipality of Cubatão.

Subsequently, Figure 27 represents the Debris Flow Hazard Index for São Sebastião. Unlike the previous study area, the scenario is not as severe but is critical in specific areas.

In the municipality of São Sebastião, Catchments 1, 2, and 3 were assessed with a MEDIUM hazard index (H2), while Catchment 3 was classified with a HIGH hazard index (H3). Notably, Catchment 4 received a MEDIUM hazard index (H2) due to the protective measures implemented for the pipelines; however, from the perspective of susceptibility and vulnerability, it is the most concerning in terms of safety

Although vulnerability scenarios suggest that debris flows could reach the pipelines in these sections, the shape and size of the watersheds would play a role in dissipating the flow along the drainage channel, reducing its speed and consequent impact force with the smoothing of the slope. Therefore, in the crossing sections, events would be predominantly restricted to flash floods, reducing the destructive potential of any eventual occurrences in these sections.

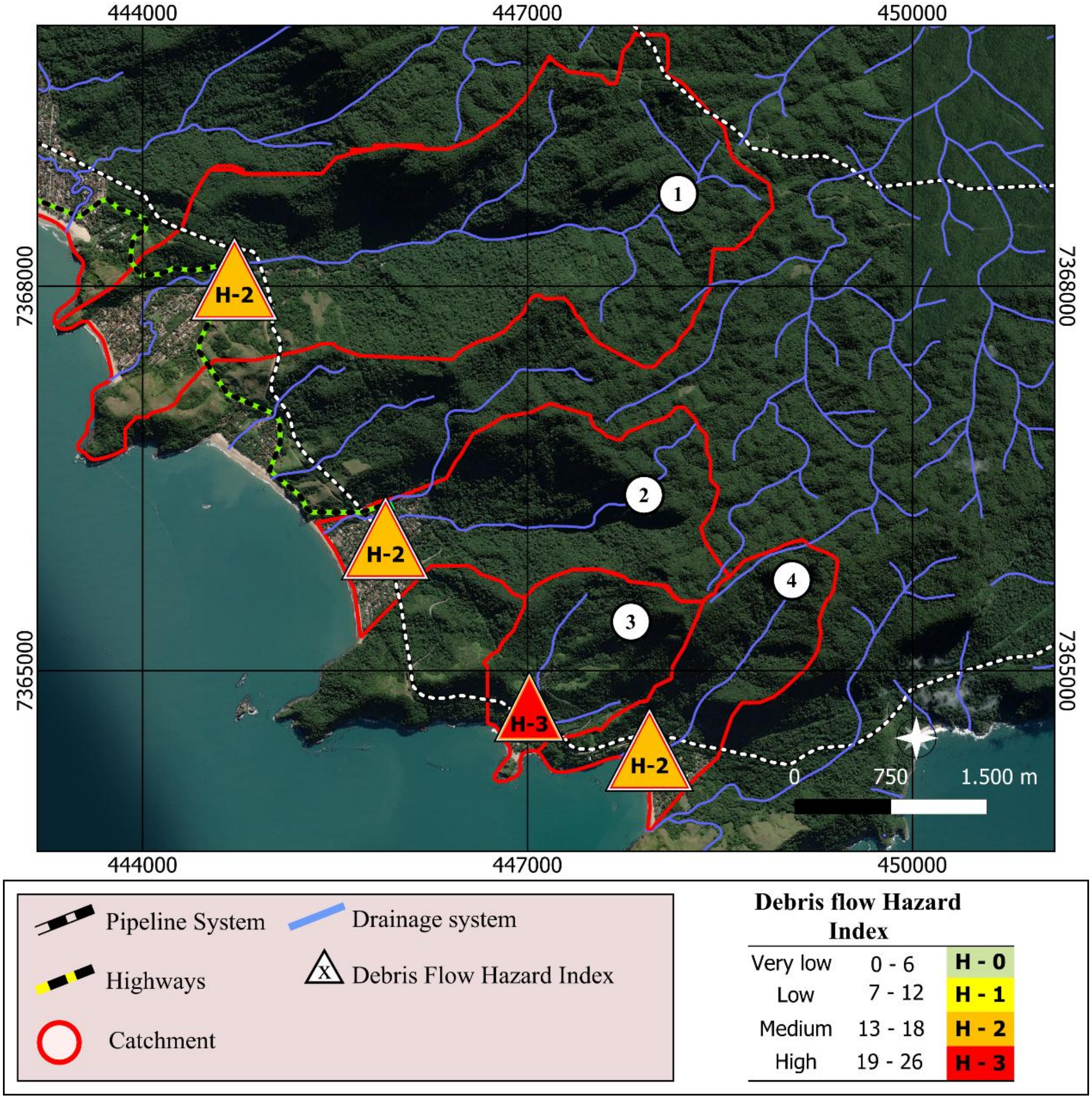


Figure 27 - Cartographic representation of the Debris Flow Hazard Index in the watersheds intersected by pipelines in the municipality of São Sebastião.

5 Conclusions

This study aimed to develop a debris flow hazard index for drainage crossing segments with a focus on pipelines, based on the relationship between susceptibility and vulnerability. The goal is to integrate this indicator into Environmental Sensitivity Indexes (ESIs), adding another layer to the assessment of susceptibility to oil spills. In other words, this approach considers the aspects of the physical environment, the geodynamics in continental areas and their dynamics in prioritizing the most vulnerable areas.

The application of this methodology to drainage crossing sections proved to be satisfactory in terms of assessment and characterization of these sections as specific risk areas susceptible to impacts of great magnitude that could lead to environmental disasters on a regional scale. Its effectiveness was confirmed by the occurrence of a debris flow in one of the critical basins mapped as H-3 during this study, in February 2023, where extensive destruction was recorded within the reach of the flow. However, the pipeline remained intact due to a containment structure recently built by Transpetro. Unfortunately, residences, vehicles, and the SP-055 highway were destroyed, but fortunately, there were no fatalities in this section.

Based on the adopted phenomenological model of the initiation, occurrence, and deposition of debris flows, it can be stated that from a geomorphological, geological and geotechnical perspective, the study areas are susceptible to the occurrence of these phenomena. It all depends on the incidence of exceptional rainfall events, which unfortunately have become more frequent, particularly in the Serra do Mar region.

It is important to consider a broad view of the hazard scenarios when assessing the impact on pipeline sections, considering the entire surroundings of the watersheds and not just the pipelines themselves. In this way, all eight watersheds in the two municipalities could be compared, and from the perspective of susceptibility, vulnerability and hazard, there is a concern in both cases. Due to the evidence presented in this research, it is highly advisable that areas classified with a LOW debris flow hazard index (H1) have specific contingency plans at the local scale for each watershed.

In cases classified as MEDIUM (H2), it would be ideal for hydrographic basins to be incorporated into a logic of non-structural actions to address natural disasters, encompassing contingency and monitoring plans, as well as real-time pluviometric and geotechnical alert systems. Specific operations during periods of more intense rainfall should also be considered.

For areas classified as HIGH (H3) hazards, these represent specific cases requiring structural interventions (e.g., stabilization works and sediment dams), complemented by preventive plans based on real-time monitoring and alert systems, as well as specific contingency plans for hydrographic basins.

As a note for further studies, it becomes evident that there is a need for a more in-depth investigation into specific extreme precipitation events and their correlation with the initiation of debris flows. This is essential for better delineating critical thresholds for both accumulated and hourly rainfall. In addition, the validation of these thresholds for implementation in a real-time monitoring system is crucial.

Chapter 3: 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

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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

1 Introduction

In recent decades, numerous studies have addressed and attempted to understand the dynamics of debris flows, their genesis, the main triggering factors and, particularly, the increase in their recurrence in various parts of the world (Varnes 1978; Takahashi 1991; Rickenmann & Zimmermann 1993; Hungr et al. 2014; Bernard and Gregoretti 2021; Veloso et al., 2023b).

Debris flows are highly destructive phenomena, characterized by high velocity and a long run out, typically associated with extreme rainfall events in mountainous areas, such as the Serra do Mar Mountain range in Brazil (Gramani 2001; Veloso et al, 2023b). They primarily occur in steep drainage courses that are abundant in in-channel rocky boulders and unconsolidated sediments, resulting highly dense flows (Varnes 1978; Takahashi 1991; Rickenmann 1990; Bovis & Jakob 1999; Iverson 2000; Gramani 2001; Kahn 2005; Milne et al. 2008; Hungr et al. 2014; Alvala et al. 2019).

The Serra do Mar region has one of the highest rainfall indices in Brazil (Gramani 2001). Periodically, exceptional and extreme rains occur in this area, such as those that hit the northern coast of the state of São Paulo in February 2023 (Marengo et al. 2024). However, it is premature to associate these rainfall patterns with the phenomenon of global warming.

Debris-flow recurrence interval is decreasing, as numerous studies and reports show, such as Eybergen & Imeson (1989); Rebetez et al. (1997); Westra et al. (2014); Pereira Filho, 2018; IPCC (2022); Giardino (2023); Cabral et al. (2023b); Giordano et al. (2023); Lopez et al. (2023), among others. These studies discuss and highlight the urgency regarding climate variability and the need for a better understanding of their influence on frequency and magnitude of landslides and debris flows

The heavy rains that struck the northern coast of São Paulo state between the 18th and 19th of 2023 in the São Sebastião region is a recent example. Their occurrence triggered numerous landslides along the entire coastline of northern São Paulo, resulting in 65 deaths in the Barra do Sahy neighborhood in São Sebastião (Marengo et al. 2024), over 1000 displaced individuals, and damages totaling USD $122,4 million, according to the municipal administration.

According to the official meteorological and natural disaster monitoring agencies, the National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) and the National

Institute of Meteorology (INMET), it was the largest rainfall event to occur in 24 hours in the history of Brazil since records began. According to Metsul, an organization that conducts meteorological monitoring, some areas recorded between 600 and 700 mm of rainfall in less than 24 hours, with accumulations of up to 400 mm in less than six hours, especially in the municipalities of Bertioga and São Sebastião. This event was compared by the agency to the catastrophic event that destroyed the city of Zhengzhou in 2021 (Guo X et al. 2021; Metsul, 2023).

Several areas along the coast of São Sebastião experienced landslides, collapses, floods, and the initiation of a debris flow in the Toque-Toque Grande watershed. This watershed characterized as an area prone to the initiation of such processes. The well-defined, deeply incised drainage line with steep slopes in the upper portions are highly favorable to erosion and landslides. The high gradient of the main drainage, coupled with the presence of steep ramps containing abundant woody and rocky material, facilitates the accumulation of sediments resulted from previous landslides and local remobilizations, which act as potential source areas fora debris-flow event. Adding to the situation is the high density of residential areas in the region, the presence of one of the main federal highways (BR-101) serving as a crucial regional logistics route and an oil pipeline crossing in the drainage course, within the impact zone of a potential debris-flow event.

In this context, this study characterizes the debris-flow event in the Toque-Toque Grande watershed, paying special attention to the drainage crossing section traversed by oil pipelines. For the hazard assessment, the Debris-flow Hazard Index was applied following Veloso et al. (2024a). The application of the debris flow hazard index in sections of crossings for pipelines highlighted the importance of an in-depth individual analysis for each area, necessitating the adoption of specific structural and non-structural measures for each sector depending on the classification. The increasing frequency and volume of extreme precipitation require risk management strategies adapted to each scenario and scale, moving towards prevention to reduce the impacts of disasters on infrastructure, civil society, and the environment. Additionally, risk scenarios were tested, based on geomorphological and meteorological analysis, as well as on the estimation of magnitude through numerical modeling.

2 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. 28B). 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 30º and altimetric gradients ranging between 850 and 950 m. This relief is responsible for blocking moisture coming from the Atlantic Ocean, which, when attempting to cross this topographic barrier, precipitate upon reaching higher elevations in the form of rain, characterizing orographic rains (IPT, 1987).The scarps of the Serra do Mar 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 observed on the edge of the Atlantic Plateau (IPT, 1987).

São Sebastião (Fig. 28C) is a coastal municipality with approximately 90 thousand inhabitants, situated in the regional geological context of the Coastal Domain, part of the Ribeira Belt, in the Mantiqueira Province.

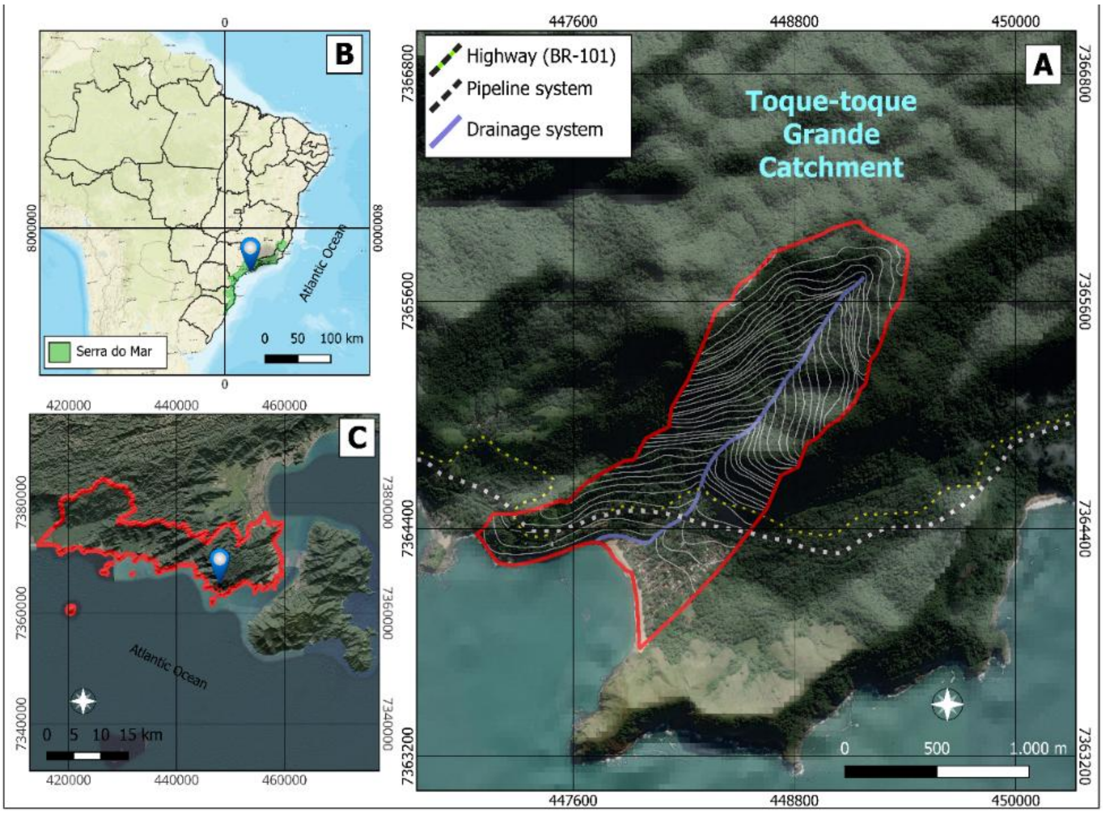


Figure 28 - Location of the study area. A) Location of the Toque-Toque Grande watershed, São Sebastião - SP. B) Location of the study area in the Brazilian territory. C) Location of the study area in the municipality of São Sebastião - SP.

In the local geological context (Fig. 29A), 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 drainage. The Atlantic Plateau presents the subzones of Festooned Scarps and Digitate Spurs, which are characterized by steep slopes (>30%), amplitudes exceeding 100 meters, angular hilltops, rectilinear slope profiles, entrenched valleys, and high drainage density, which are fundamental elements in slope instability processes (Fig. 29B).

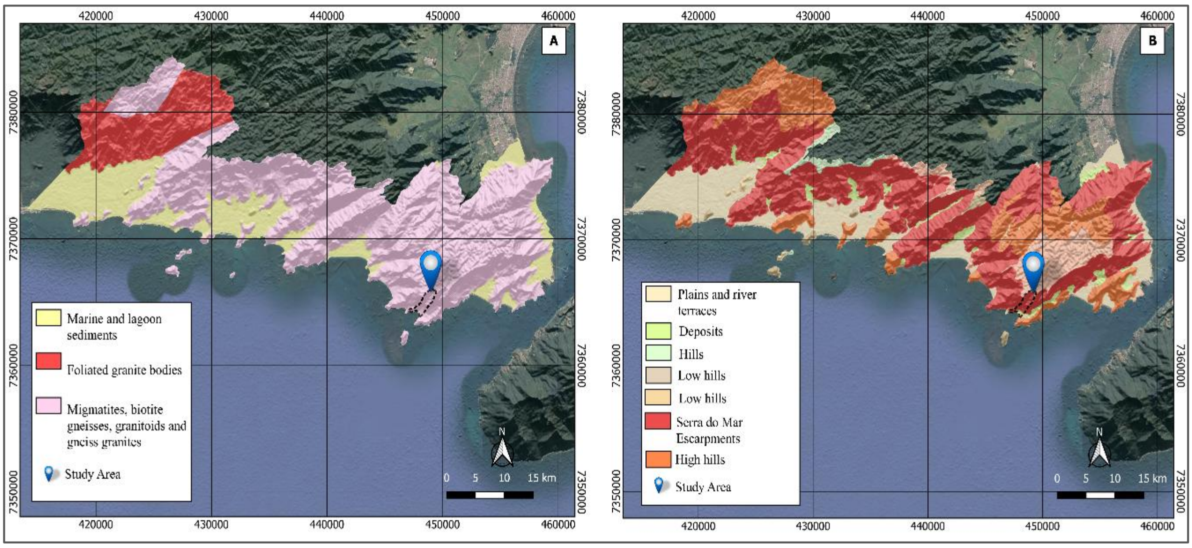


Figure 29 - A) Geological context of São Sebastião. B) Geomorphological context of São Sebastião

Therefore, the topography is influenced by the Serra do Mar, which presents several factors that can be considered determinants of severe mass movement processes. Among them, slopes emerge as the most important because steeper slopes lead to higher water runoff velocities, increasing erosive capacity (IPT, 1986).

3 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; (ii) assessment of the geomorphological conditions of the watershed affected by the debris flow, considering the main factors controlling their initiation; (iii) estimation of the hazard index for the occurrence of debris flows on highways.

3.1 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 done 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 30).

	Code	Automatic Rain gauges
1	355070414A	Boiçucanga
2	355070413A	Toque-Toque Pequeno
3	355070410A	Juquehy
4	355070411A	Juquehy 2
5	355070402A	Barra do Uma
6	355070418A	Praia Grande
7	352040004A	São Pedro
8	352040005A	Barra Velha
9	351050015A	Fazenda Serra mar
10	351050003A	Rio Claro
11	355070403A	Jaraguá
12	355070407A	Morro do Abrigo

Figure 30 - Rain gauges used for evaluating the extreme event in the study area.

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

3.2 Geomorphological analysis

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

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

The estimation of the Debris Flow Occurrence Hazard Index is based on the correlation of two factors: (i) susceptibility and (ii) vulnerability. The susceptibility value 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. 31).

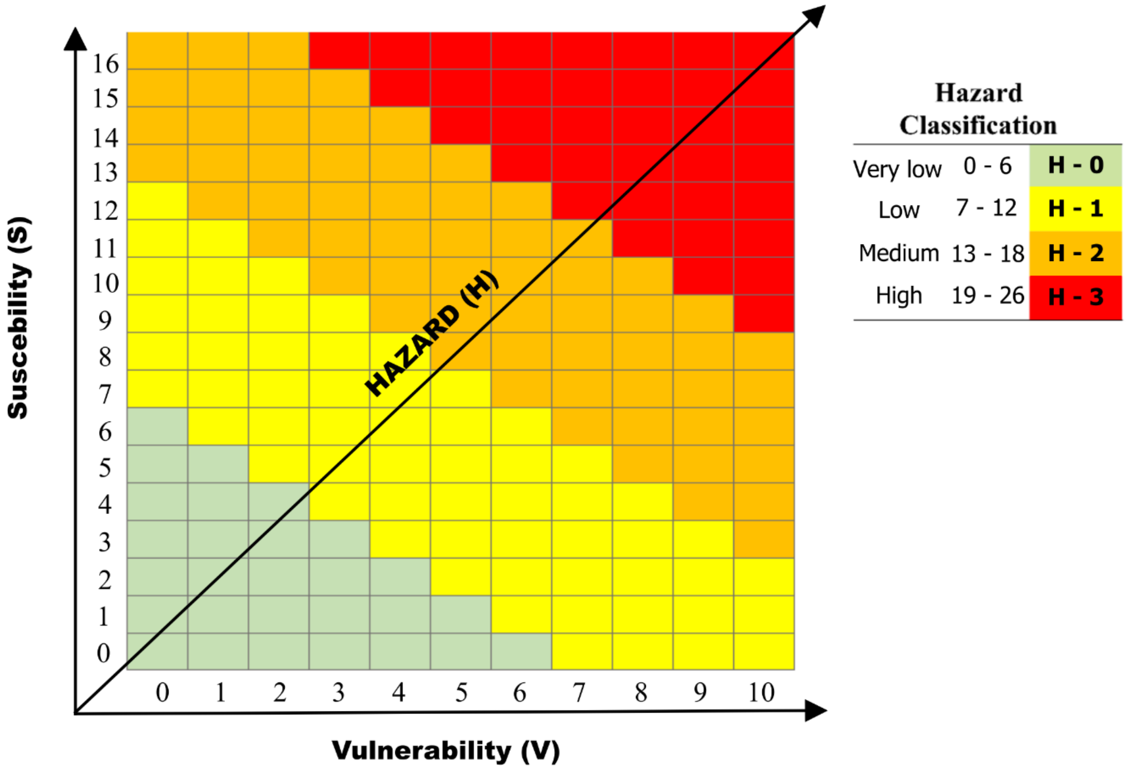


Figure 31 - Matrix of hazard classification for debris flow occurrence

Susceptibility refers to the likelihood of eventual debris flow occurrence in watersheds and is directly dependent on triggering factors related to the geomorphology of the areas under evaluation. Its determination considers 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; Veloso et al. 2024a)

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 case of extreme and localized rainfall in the mapped basin (Tab. 13).

Vulnerability, on the other hand, determines the damage that debris flows can cause to all mapped infrastructure in 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.

Table 13 - Parameters used for evaluating susceptibility to debris flow occurrence

Susceptibility (16 points)	Parameter	Atributte	Interval	attribute weight
Geomorphological settings	Hillside	altimetric gradient (H) (m)	>750	4
			500 -700	3
			200-500	2
			100 - 200	1
			< 100	0
	Drainage	channel slope (D) (°)	>25	4
			15 - 25	3
			10 - 25	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) (km²)	< 5	4
			5 - 10	3
			10 - 15	2
			15 - 20	1
			> 20	0

Its classification was based on numerical computational modeling, where the reach radius of the debris flow was established, 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 drainage course intercepts the pipelines; (ii) estimation of the magnitude of the process based on the volume of mobilized material (m^3); and (iii) the construction method of the pipes (Tab. 14).

The numerical modeling was conducted using the RAMMS-DF software 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; Veloso et al., 2024a).

Table 14 - Determination of vulnerability classes

Vulnerability (10 points)	Attribute	Inteval	Attribute weight
	Runoff	High	$h > 1.0$ m and $v > 1.0$ m/s
		Moderate	$h < 1.0$ m or $v < 1.0$ m/s
		Low	$h < 0.4$ m and $v < 0.4$ m/s
		Very Low	Non-affected areas
	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

4 Results

4.1 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 flows. This positioning tends to favor, especially during the summer, heavier rainfall. Additionally, the orographic factor of the Serra do Mar with its steep slopes along the coastline plays a 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; WM Costa, 2023).

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 initial peaks of hourly intensity in the study area were reached around 4:00 AM (UTC). on February 19th, with no significant accumulated precipitation prior to that time.

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 watershed, triggering landslides in the upper sections of the watershed feeding the drainage line, breaking natural barriers and initiating the first pulses of debris flows (Fig. 32A and 32B).

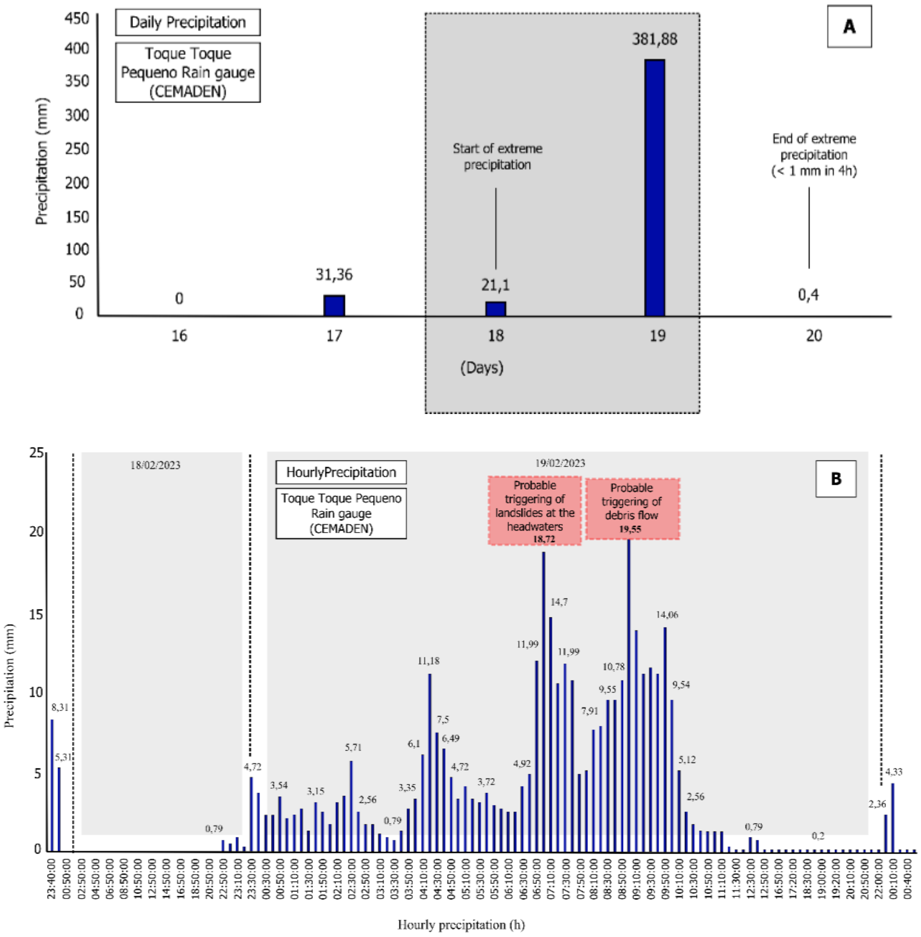


Figure 32 - A) Daily precipitation analyzed for February 18th and 19th, 2023, for the Toque-Toque Pequeno rain gauge (closest to the study area, located 2.8 km away). B) Precipitation recorded by the rain gauge between February 18th and 19th, indicating the onset of the main events responsible for triggering the debris flow.

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 Brazilian territory, especially in the Southeast, met with a cold front advancing from the southern region of the country over the Serra do Mar, resulting in this unprecedented rainfall event (Fig. 33).

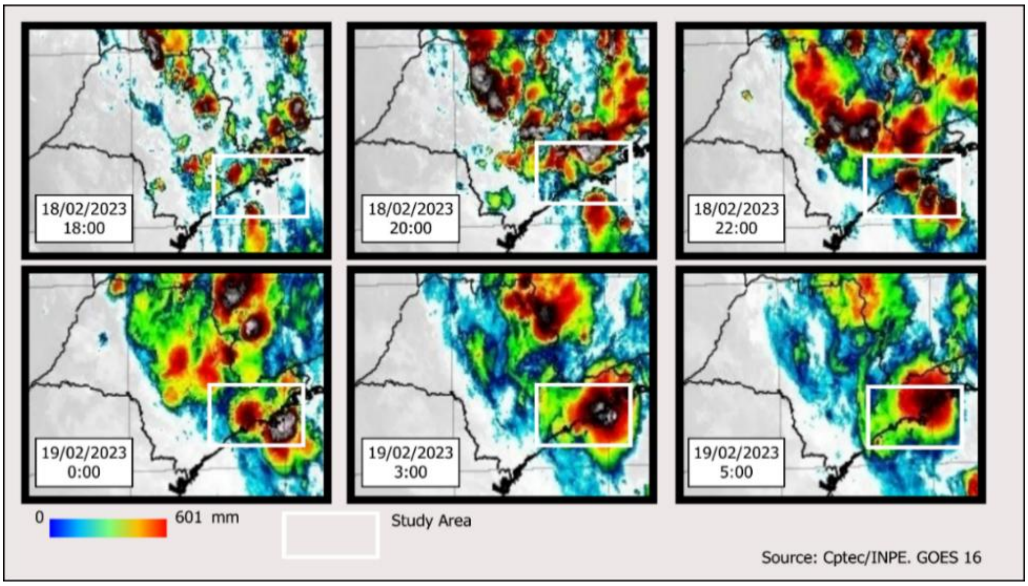


Figure 33 - Analysis of the phenomenon through GOES 16 satellite images.

An important relationship was developed by Jones and Liebmann (2002) regarding the influence of the South Atlantic Convergence Zone (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. This topographic feature is responsible for the seasonal maximum precipitation along the coast, decreasing 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 & Carvalho, 2002; Gonçalves, 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.

For this purpose, an interpolation of rainfall values during the event was performed using data from these rain gauges, where it is possible to notice the predominant role of the Serra do Mar in the concentration of rainfall. The extreme precipitations were confined to the ridge line of the mountain range, presenting impressive values of 601 mm/24 h in Barra do Sahy with hourly peaks of 106 mm and 591 mm/24 h with hourly peaks of 92.2 mm in Juquehy (Fig. 34).

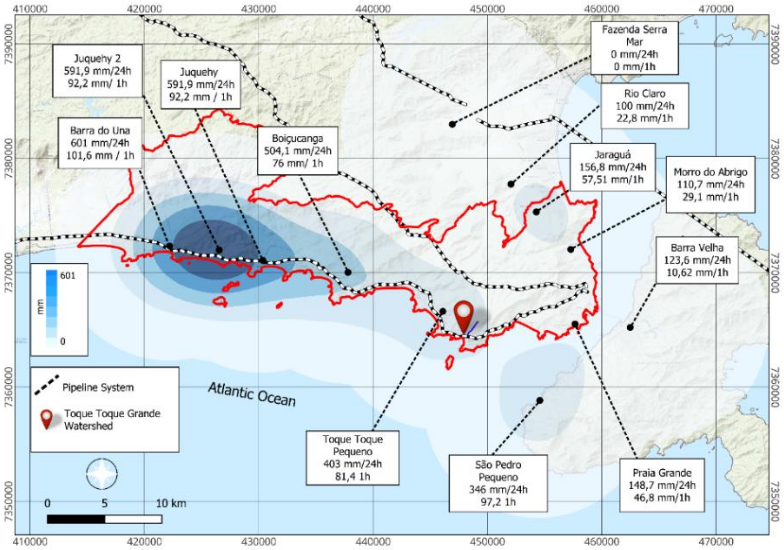


Figure 34 - Representation through interpolation of Cemaden's automatic rain gauges, highlighting the orographic factor in extreme precipitation in São Sebastião, SP.

4.2 Geomorphological analysis

At this stage, the analysis of the main geomorphological factors that trigger debris flows was performed (Fig. 35). The following are the results of slope aspects mapping, drainage courses and magnitude estimation.

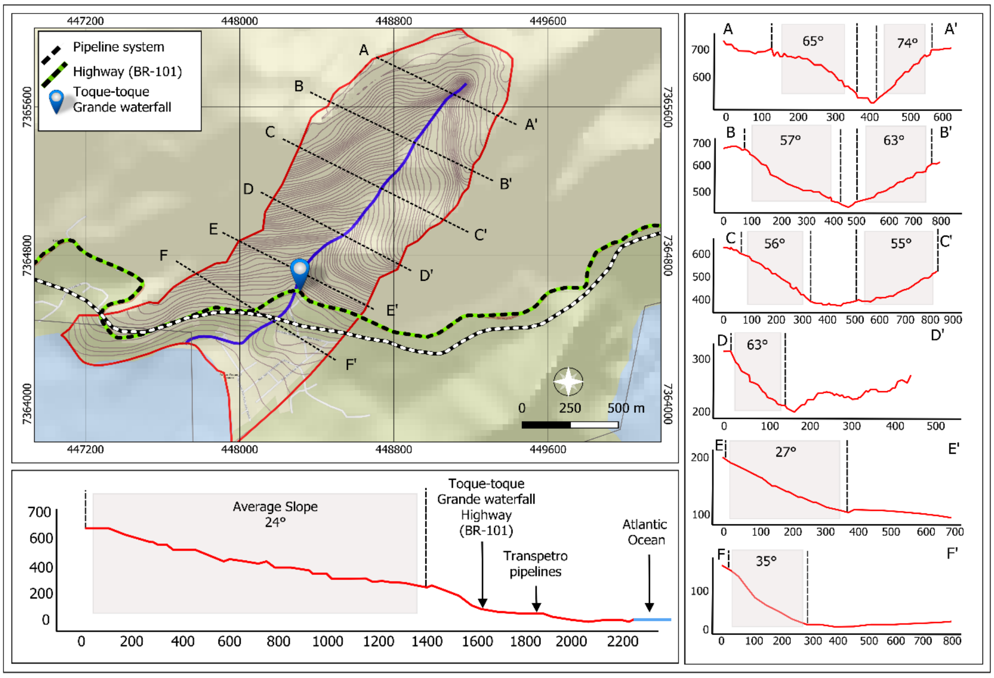


Figure 35 - Topographic map of the study area and transversal and longitudinal profiles of the main drainage

4.2.1 Slope conditions

Through fieldwork, it was possible to observe the extensive destruction caused by the debris flow Overall, the watershed covers an area of 1.8 km², with an elevation range of approximately 680 meters, a length of 1.5 km, and steep slopes ranging from approximately 24º to the section where a topographic break occurs, marked by the Toque-Toque Grande waterfall intersected by the BR-101 highway (Fig. 36A).

Due to its small size, high altimetric gradient, and steep slopes, rainfall tends to occur with higher average intensity per area in a more uniform manner in the catchment compared to larger basins, resulting in longer concentration times. Generally, smaller basins exhibit steeper slopes and are more susceptible to orogenic effects, making them more prone to triggering debris flows.

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 flow event, indicating the impact power and erosive competence of the flow (Figs. 36A and 36B).

Regarding the slope of the slopes analyzed through morphometric analysis (Fig. 35), characteristics and factors favorable to destabilization processes (shallow translational landslides, block falls, 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 parts of the basin. However, using 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.

There is a predominance of rectilinear slopes in the upper portions with slopes exceeding 30°, which are considered the most critical for landslides. The slopes in the initiation zone located at the headwaters exhibit strong geomorphological and structural conditioning factors, with valleys deeply incised in a "V" shape, featuring slopes ranging approximately from 74º to 63º at higher elevations, decreasing from 63º to 55º in the middle course, and reaching 35º in the deposition zone at the foot of the watershed (Fig. 36).

Figure 36 - 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]

This topographic profile pattern reinforces the hypothesis of the development of debris flow processes, bearing a striking resemblance to the watersheds studied in Cubatão, also located in the São Paulo state portion of Serra do Mar (Massad et al. 2002; Kanji et al. 2007; Massad et al. 2009; Veloso et al. 2023a, Cabral et al. 2023a). In these areas, the main drainage course, due to their steep slope and topographic discontinuities, 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.

4.2.2 Drainage conditions

The drainage courses influence the formation and development of a debris flow process through their geomorphological characteristics and associated sedimentary deposits. The material mobilized by a debris flow along a drainage does not solely originate from the slopes; a significant portion, especially coarser materials, is incorporated along the flow path, which in some events form the primary sediment source (Scott, 1971; Varnes, 1978; Takahashi, 2006; Hungr et al., 2014).

A significant portion of debris flow processes forms along drainage lines through the collapse of natural dams or from previous events. The geomorphological and topographic characteristics of watersheds are fundamental to the formation of these processes. Therefore, to assess drainage conditioning factors, aspects of slope, and valley incision patterns of the main drainage were considered.

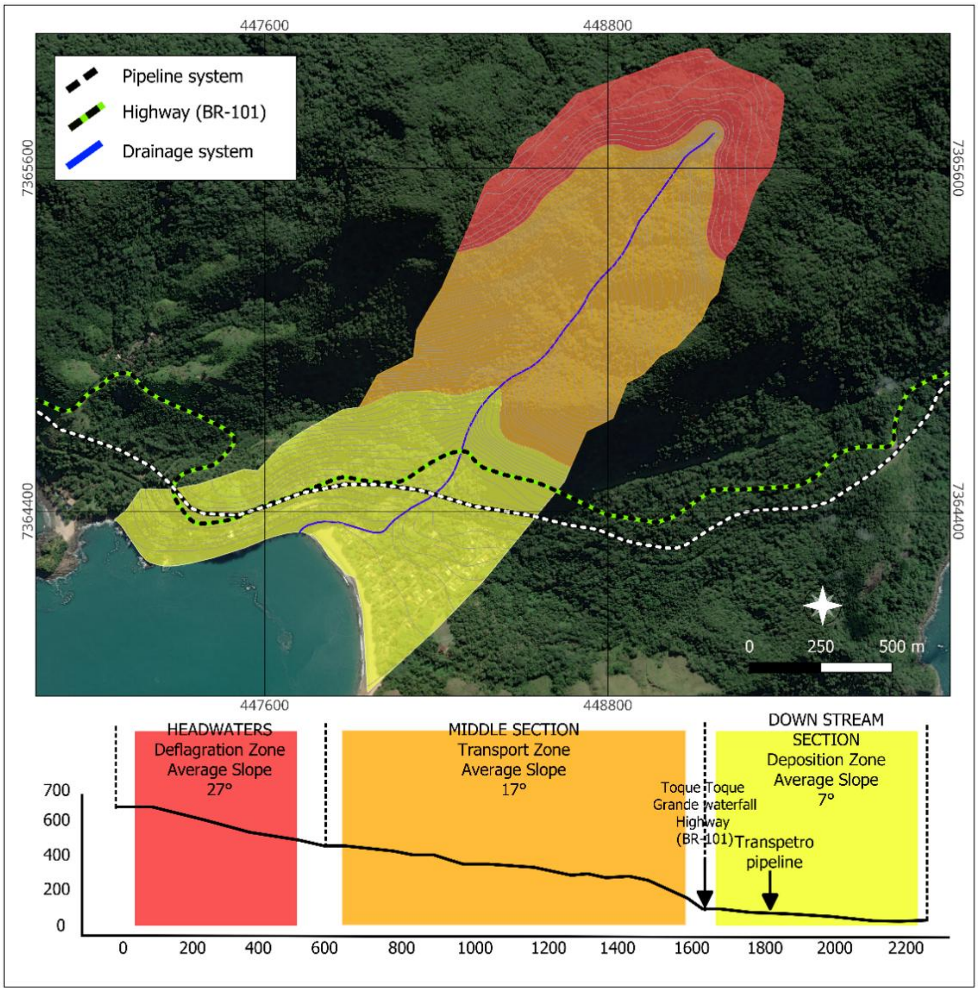


Figure 37 - Slope profile of the basin's main drainage

Channel Slope at the headwaters region are around 27º, decreasing to 17º in the middle course, and further softening after the Toque-Toque Grande waterfall to slopes of 7º in the lower part (Fig. 37).

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.

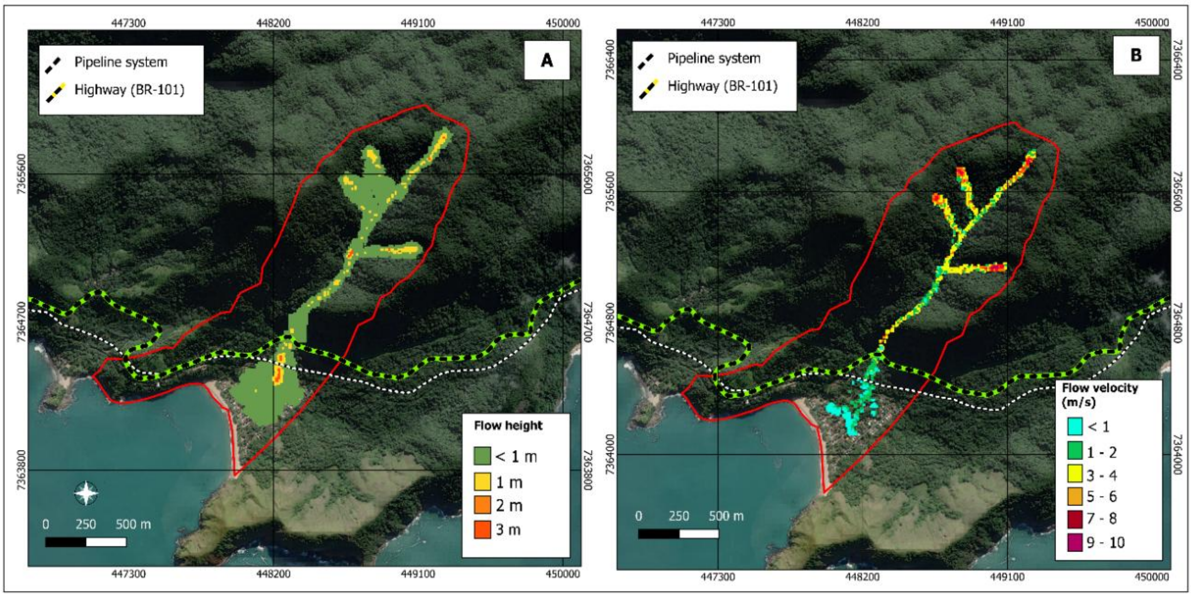
This characteristic pattern, resembling a ramp, possesses all the conditions for the development of a debris flow, enhancing destabilization by imparting high kinetic energy to the initial movements.

Figure 38 - 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]

4.2.3 Debris flow occurred in the study area

This was precisely what happened between February 18 and 19, 2023, in the municipality of São Sebastião - SP. On this day, the largest rainfall event in Brazil's history was recorded within a 24-hour period since the historical series began, claiming the lives of 65 people and displacing over 1000, with rainfall amounts exceeding 600 in 24 hours. These rains triggered a debris flow in the Toque-Toque Grande hydrographic basin, most likely initiated by landslides in the headwater region of the basin and possibly with contributions from materials deposited along the drainage.

To aid in understanding this debris flow process in the study area, a fieldwork was conducted to map the main triggering factors and simulate the event using RAMMS software. The simulation aimed to determine important parameters such as its height, velocity along the trajectory, reach radius, and magnitude. Figures 39A and 39B show the simulation results for the study area, where the maximum height reached 3 meters along the main drainage and at the drainage heads and pipeline section, covering a distance of 2.1 km, reaching up to the shoreline.



Catchment	Flow parameters		Volume (m³)	Velocity (m/s)	Impact (kPa)	Maximum height (m)	Runoff (m)
	μ	ξ (m s $^{-2}$)					
Tq_Tq_Grande	0.05	200	6873.4	10.7	229	2.30	690

Figure 39 - A) Height of the modeled flow along its trajectory in the basin. B) Estimated velocity of the modeled flow along its trajectory in the basin.

The debris flow began during the night from February 18th to February 19th, driven by intense rains that caused instability in the hydrographic basin. Evidence, such as deposits and indicates that several downstream dams in the hydrographic basin breached, releasing pulses containing a large amount of rock and vegetal material. Fortunately, the pipeline corridor was not compromised due to a recently constructed containment structure over the river by

Petroleum Transport S.A (Transpetro). However, following the event, the bridge required renovations due to significant impact (Fig. 40C).

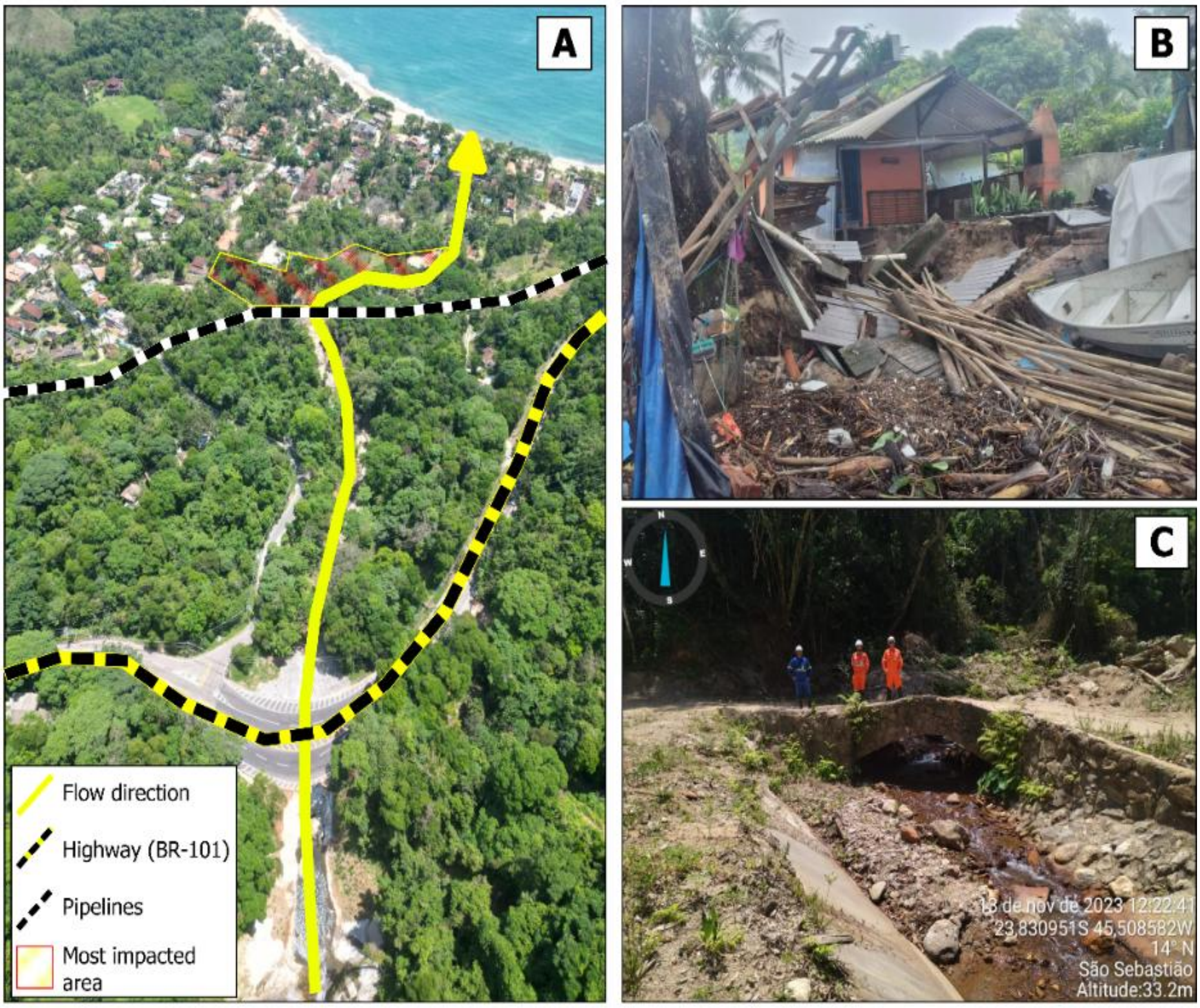


Figure 40 - Record of the path taken by the flow in the study area. A) Path taken by the debris flow overlaid with the Highway (BR-101), pipeline system, and the most affected residential areas. B) Frontal view of one of the residences affected by the impact of the flow. C) Record of the protective structure 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]

The destruction of houses at the forefront of the Toque-Toque Grande neighborhood was caused by the large volume of blocks, coarse material, and tree trunks. These elements, as observed in Figures 38, 41 and 42 acted as a barrier to large-sized materials. As a result, the mud and some of the less voluminous material from the flow managed to surpass this barrier and reach the sea.

Figure 41 - A) Record of the coastal zone with the deposition of the debris flow. B) Record of a residence destroyed by the impact of the debris flow. C) Record of a car completely destroyed, dragged along the drainage and deposited on the coastline.

Figure 42 - Record of the passage of the debris flow in the final third of the drainage, already at the shoreline. A) Deposition of large tree trunks dragged from the upper portions of the hydrographic basin. B) Record of the deposition of rocky material interlocked with trunks on the coastline. C) Record of the

erosive potential of the flow passage in the lower portions of the hydrographic basin. Source: Mariano Araújo Caccia Gouveia.

4.4 Estimation if debris flow hazard index in drainage crossing sections

The estimation of the debris flow hazard index for pipeline crossings is based on the proposal by Veloso et al. (2024), where the hazard index for the study areas is defined through the correlation between susceptibility and vulnerability assessments. The following is the classification presented:

4.4.1 Susceptibility definition

The definition of susceptibility took into consideration the utilization and classification of four main parameters conditioning the hydrographic basin directly involved in the initiation of debris flows: altimetric gradient (m), slope (º), length (km), and total area (km²). These values were obtained through field surveys and morphometric analysis, where a classification was assigned to each parameter (Tab 15).

Table 15 - 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

The altimetric gradient value (H) was around 680 m, classified as order 3, while the slope of the main channel (D) averaged 27º, 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 km², classified as class 4. The sum of all parameters was 11.

4.4.2 Vulnerability definition

Vulnerability in this study was defined through parameters such as the distance traveled 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 computational modeling (Fig. 12), and finally, the construction pattern of the pipelines in the drainage crossing areas (Tab. 16).

The vulnerability classification had runoff values with velocities around 10.7 m/s and a maximum debris flow height of 3 m. The estimated magnitude was approximately 6873.4 m³, and the construction pattern of the pipelines in the crossing section in the study area is underground. The sum of all vulnerability parameters was 7.

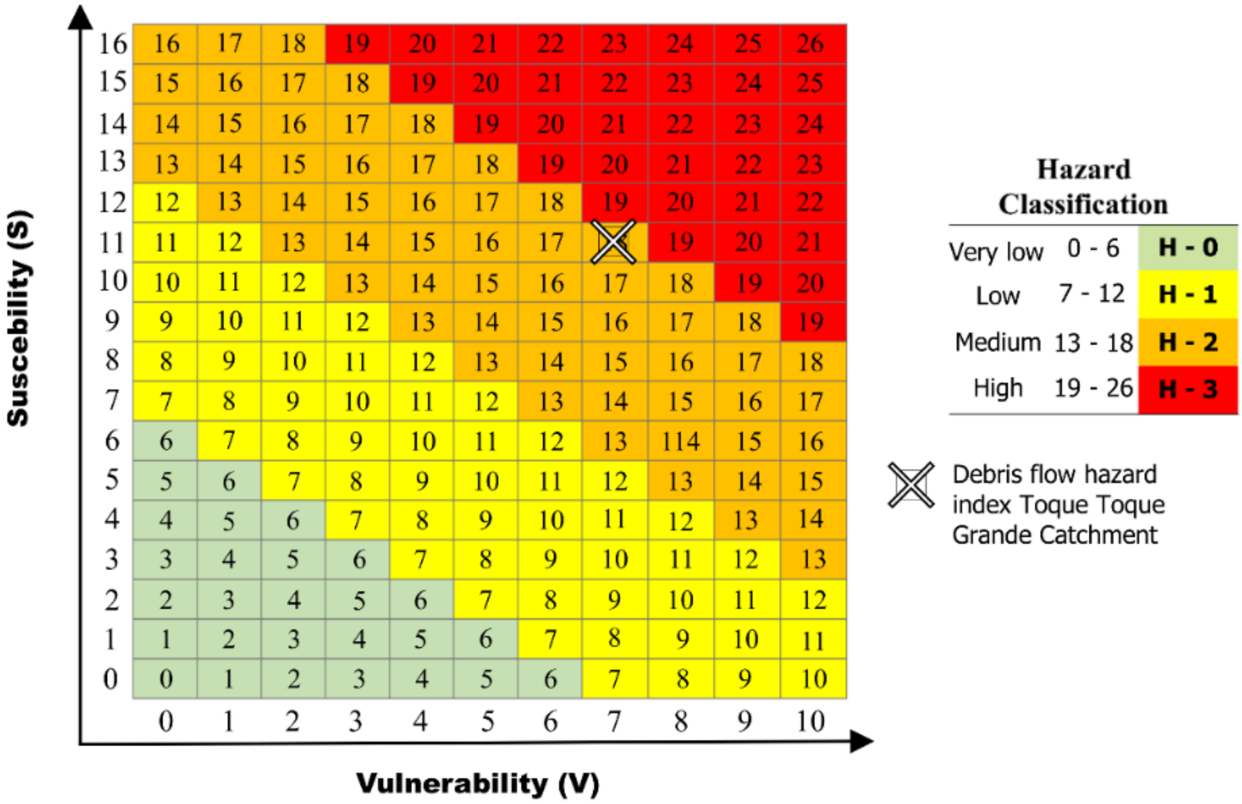
Table 16 - Results vulnerability classification

Catchment Tq_Tq_Grande	Runoff		Magnitude volume (m^3)	Constuctive method	Total
	Velocidade (m/s)	Maximum height (m)			
	10.7	3.0	6873.4	Underground Pipeline with protection work	
Class	3		4	0	7

4.4.3 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 watershed (Fig. 43).

The hazard index classification combined susceptibility and vulnerability values through the hazard matrix described in previous sections, resulting in individual hazard indexes for each pipeline crossing section in the selected hydrographic basins for the research application. For drainage 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.



16	16	17	18	19	20	21	22	23	24	25	26
15	15	16	17	18	19	20	21	22	23	24	25
14	14	15	16	17	18	19	20	21	22	23	24
13	13	14	15	16	17	18	19	20	21	22	23
12	12	13	14	15	16	17	18	19	20	21	22
11	11	12	13	14	15	16	17	☒	19	20	21
10	10	11	12	13	14	15	16	17	18	19	20
9	9	10	11	12	13	14	15	16	17	18	19
8	8	9	10	11	12	13	14	15	16	17	18
7	7	8	9	10	11	12	13	14	15	16	17
6	6	7	8	9	10	11	12	13	114	15	16
5	5	6	7	8	9	10	11	12	13	14	15
4	4	5	6	7	8	9	10	11	12	13	14
3	3	4	5	6	7	8	9	10	11	12	13
2	2	3	4	5	6	7	8	9	10	11	12
1	1	2	3	4	5	6	7	8	9	10	11
0	0	1	2	3	4	5	6	7	8	9	10
	0	1	2	3	4	5	6	7	8	9	10

Hazard Classification

Very low	0 - 6	**H - 0**
Low	7 - 12	**H - 1**
Medium	13 - 18	**H - 2**
High	19 - 26	**H - 3**

☒ Debris flow hazard index Toque Toque Grande Catchment

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

Figure 43 - Debris flow hazard index classification matrix in the study area

Based on the combined results of susceptibility and vulnerability analysis, expressed through the hazard matrix, the hazard index assigned to the Toque-Toque Grande hydrographic basin reveals a concerning panorama, classified as order 18 (H-2), indicating a significant and imminent danger of debris flow occurrence, however due to the protection measures implemented on the pipelines, the hazard of disaster occurring and escalating is reduced (Fig. 44).

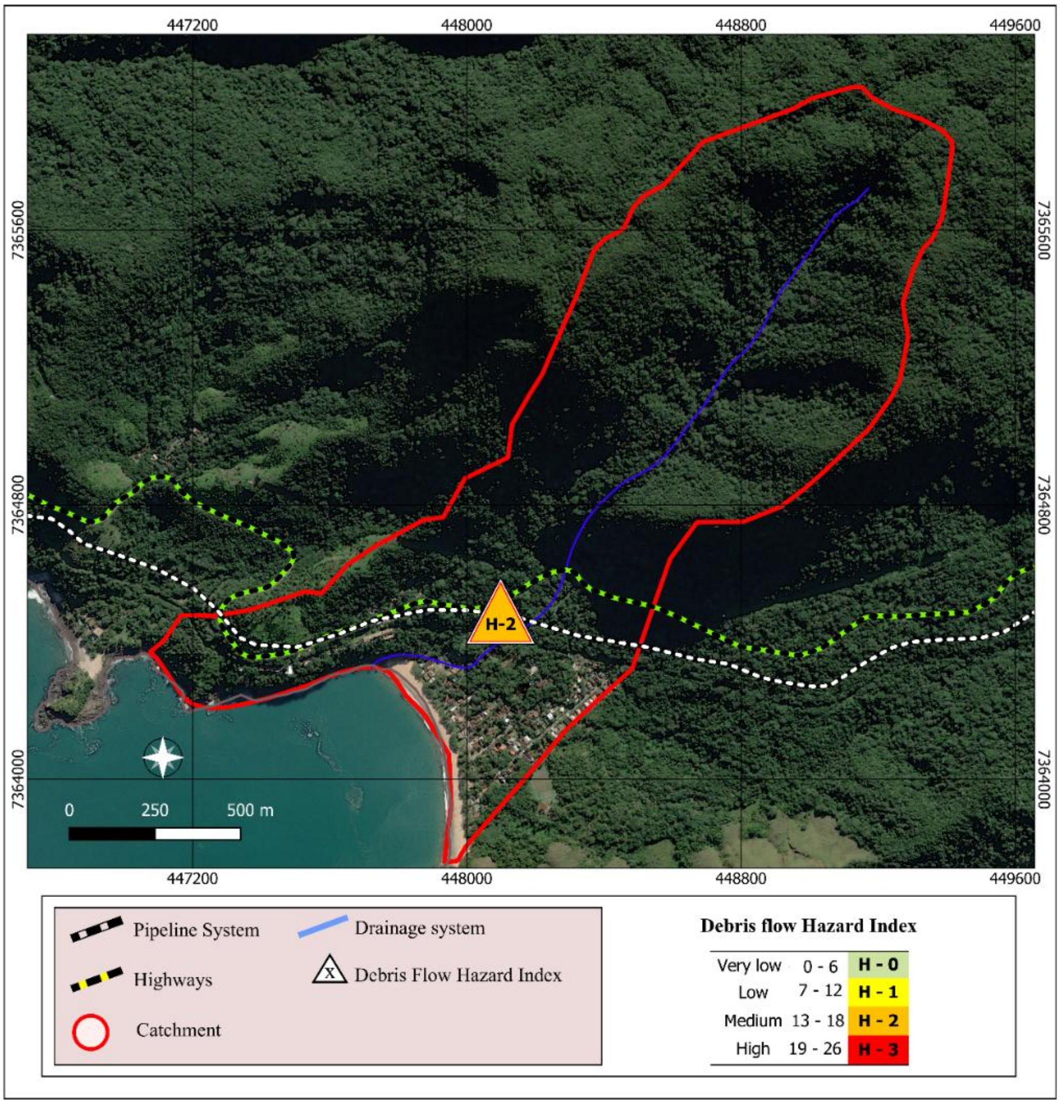


Figure 44 - Hazard index for debris flows on pipelines in the study area

This classification underscores the urgent need for the implementation of contingency plans and specific structural measures (e.g., stabilization structures, sediment retention dams, and sediment control) to mitigate the potential impacts resulting from high-magnitude debris flow events. Understanding and acting in response to this reality emerge as imperative for the safety and environmental preservation of the affected region.

5 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 drainage conditions, the influence of these factors on the formation and development of debris flows was highlighted, and understanding the morphological and topographic characteristics of the basins is fundamental for the evaluation and prevention of these events.

This analysis, combined with computational modeling of the debris flow, allowed visualization of the height and velocity of the flow along the trajectory in the watershed, providing essential information to understand the dynamics of the phenomenon.

The identification of areas prone to debris flows and the implementation of containment measures, such as the protective structure over the pipeline in the Toque-Toque Grande basin by Transpetro, demonstrate the importance of structural preventive actions aimed at reducing the impacts of these events.

In summary, this study aimed to highlight 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.

Chapter 4: Proposal for real-time rainfall monitoring of gravitational mass movements in Serra do Mar - SP – Brazil

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Abstract

Landslides represent a significant risk in Brazil and worldwide, especially in mountainous areas prone to extreme precipitation. Despite advances in risk reduction policies over the past decades, Brazil still faces challenges in adopting effective measures for natural disaster prevention. In the context of global climate variability and the increase in extreme events that affect thousands of people each year, there is an urgent need to implement risk reduction policies focused on prevention. This article presents a prototype of a real-time precipitation monitoring system based on critical rainfall thresholds for the early issuance of landslide alerts. The system was applied in the municipalities of Cubatão and São Sebastião, both located in the Serra do Mar Mountain range in the state of São Paulo, which have a long history of disasters related to mass gravitational movements during two rainy seasons (2022-2023) and (2023-2024), with particular emphasis on the disaster that occurred in São Sebastião. The disaster recorded in São Sebastião on February 19, 2023, registered the highest 24-hour precipitation in Brazil's history (>600 mm/24 h), resulting in 64 deaths and losses amounting to USD 122.4 million. This event highlighted the importance of implementing early monitoring systems focused on preventive actions. The system's functionality proved highly promising, demonstrating that it was possible to estimate scenarios for advancing operational levels as accumulated precipitation progressed, always correlated with weather forecasts. It is concluded that this system fits well within the logic of preventive monitoring, which is essential in the context of climate change and the increasing frequency of extreme events in various parts of the world.

Keywords: Landslides, Debris flows, Early warning system, Risk management, Real time monitoring

1 Introduction

Gravitational mass movements have been a major source of disruption in large urban centers, leading to loss of human lives, damages, and high recurrence. In this scenario, the need for the development of automated and integrated monitoring systems becomes prominent, allowing the detection of these phenomena in advance, so that preventive measures and civil defense plans can be more effective (Cerri, 1993; Guzetti et al., 2007; Bernard and Gregoretti 2021; Cabral et al., 2023a; Veloso et al., 2023a).

Precipitations play a significant role in triggering slope instability phenomena, through land preparation involving altering substrate parameters and increasing external stress. In this process, water infiltrates the soil altering its density, increasing weight, and reducing cohesion by eliminating capillarity and soil cementation, consequently increasing weight, resulting in increased acting forces and decreased cohesion. This decrease in cohesion can lead to significant saturation evolution, potentially causing landslides (Fukuoka 1980; Wolle 1989; Tatizana et al., 1987; Metodiev et al., 2018, Corrêa et al., 2021).

In the context of the Brazilian coastal range, Wolle (1989) found decreases in the cohesion coefficient values of some soils preserved in landslide scars, which would be sufficient to reduce the safety factor to values below 1.

The most promising methods for understanding these destabilization phenomena are based on rainfall correlations and meteorological forecasting, by defining limit equilibrium conditions for a given area (Onodera, 1974; Campbell, 1975; Guidicini and Iwasa, 1977; Okuda, 1980; Caine, 1980; Keefer et al., 1987; Tatizana et al., 1987; Marchi et al., 2002; Hurlimann et al., 2003; D'orsi, 2012; Imazumi et al., 2005; Gregoretti et al., 2016; Ávila et al., 2021). Through precipitation monitoring, it is possible to attempt to predict landslide formation in advance and evacuate the population effectively (Caine, 1980; Aleotti, 2004; Wieczorek and Glade, 2005).

In Brazil, one of the most robust civil defense systems associated with landslides is the national monitoring system developed and operated by the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN). This system is responsible for monitoring the entire national territory with over three thousand automatic rain gauges, nine weather radars, several geotechnical stations, and hydrological stations distributed across the country. However, what is observed is that at the local level, i.e., in municipalities, there is no preparedness to interpret and receive the alerts issued, as seen in the recent disasters that occurred in São Sebastião in February 2023.

Thus, this study aimed to develop a real-time precipitation monitoring system based on the collection of real-time data from automatic rain gauges correlated with the critical precipitation levels defined by Tatizana et al. (1987). The goal is to assist in preventive civil defense actions, primarily at the local level. This approach results in the provision of susceptibility indices and probabilities of destabilization events in the municipalities of Cubatão and São Sebastião, in the state of São Paulo, due to the significant history of landslides and debris flows recorded in the last decades (Cabral et al. 2023a; Veloso et al. 2024).

The innovation focuses on the potential to support preventive civil protection actions, emphasizing prevention, efficient data collection, and the detailed scale of rainfall monitoring. While traditional systems operate reactively, this work highlights the importance of disaster response time and local monitoring, noting that more robust systems like PPDC or CEMADEN lack this level of monitoring detail and benefit from lower development and implementation costs.

The system, along with the data obtained, was validated during two rainy seasons between 2023 and 2024 and demonstrated alignment with observed real-world conditions. Two extreme precipitation events were analyzed: the disaster that occurred in São Sebastião on February 19, 2023, and the rainfall event from January 23 to 26, 2024, which, despite showing significant precipitation peaks, did not result in disasters.

This model is expected to provide an advantage in supporting decision-making and can be easily integrated with other platforms, minimizing the effects of slope instability phenomena and the subsequent triggers of landslides. Furthermore, the continuation of this project should lead to a better understanding of geodynamic processes and the development of both structural and non-structural measures for impact mitigation.

Further studies must be conducted to ensure the utmost safety of the population and strategic infrastructure through the improvement of preventive plans.

2 Methodology

Precipitation is a crucial triggering factor for gravitational mass movements, and predicting or anticipating its occurrence is essential due to this issue. In this context, many studies around the world attempt to determine the amount of rainfall necessary to trigger these events, presenting both scientific and social challenges (Guzetti et al., 2007)

The methodology of this work was based on four steps: (i) adoption of the phenomenological model of the landslides; (ii) definition of the methodology of critical precipitation threshold to be used, which best suited the study areas; (iii) development of the real-time rainfall monitoring system; (iv) definition of the sites to be monitored based on the occurrence indices of disasters related to mass movement and the availability of automatic rain gauges. These steps are described in detail below.

2.1 Landslides monitoring

Landslides can be triggered by both prolonged precipitation accumulation and intense, short-duration rainfall events (Tatizana et al., 1987; Aleotti, 2004; Guzetti et al., 2007; Segoni et al., 2015; Hurlimann et al., 2019; Cabral et al., 2022; Veloso et al., 2024). These events typically involve rapid gravitational movements in specific areas of the terrain, driven by gravity, which create planar rupture surfaces associated with variations in soil and rock composition. These variations represent mechanical and hydrological discontinuities caused by geological, geomorphological, or pedological processes (Augusto Filho, 1992; Hungr et al., 2014; Veloso et al., 2023a).

Landslides are influenced by the prior saturation of the soil, which is affected by accumulated precipitation and intensified by short-duration, heavy rainfall events that serve as triggers for slope destabilization. In other words, the drier the soil, the more intense the rainfall required to trigger a landslide (Tatizana et al., 1987).

Thus, the most promising methods for preventive monitoring are linked to the correlation between rainfall and landslides, which is based on the identification of critical equilibrium conditions for a specific location. By monitoring rainfall, it becomes possible to predict landslides and evacuate populations in advance (Okuda, 1980; Guzzeti et al., 2007).

2.2 Rainfall thresholds

Natural disaster monitoring networks play a fundamental role in preventing tragedies worldwide, particularly when their purpose is to anticipate the initiation of gravitational mass movements, such as landslides (Campbell, 1975; Reichenbach et al., 1998; Corominas et al., 2005; Crosta and Frattini, 2003; Aleotti, 2004; Wieczorek and Glade, 2005; Guzzetti et al., 2020).

Empirical precipitation thresholds are established through studies of historical rainfall events that have resulted in landslides. These thresholds are typically represented by a lower limit line for critical precipitation conditions (Nikolopoulos et al., 2014; Marra et al., 2016). They have proven to be a valuable tool for predicting rainfall-induced landslides, particularly when integrated with real-time monitoring systems.

These systems represent a vital non-structural measure for mitigating the risks associated with these phenomena. According to Arattano and Marchi (2008), they can be classified into two main categories: (i) early warning systems and (ii) advance warning systems. Early warning systems focus on monitoring hydrometeorological phenomena, particularly intense and prolonged rainfall, with the goal of issuing timely alerts before events occur. These systems utilize a variety of sensors, including geophones, ultrasonic meters, video cameras, and trigger wires, among others.

On the other hand, advance warning systems, which are the focus of this work, rely on empirical correlations between precipitation and the initiation of events. Historical data are utilized to establish critical rainfall thresholds that may lead to slope instability (Endo, 1970; Campbell, 1975; Tatizana et al., 1987; Kanji et al., 2007).

The practical implementation of monitoring and alert systems based on critical precipitation thresholds is a reality in several regions worldwide. Successful applications have been reported in Italy (Berti et al., 2000; Marchi et al., 2002; Scotton et al., 2011; Coviello et al., 2015; Gregoretti et al., 2016), Switzerland (Hurlimann et al., 2003; McArdell et al., 2007; Bardoux et al., 2009), Austria (Hubl and Kaitha, 2010), Japan (Yin et al., 2011; Imazumi et al., 2005; Ikeda and Hara, 2003; Takeshi, 2011; Osaka et al., 2014), China (Zhang, 1993; Cui et al., 2005; Cui et al., 2018), and the USA (Coe et al., 2008; Kean et al., 2011). These cases exemplify how the integration of historical data with advanced technology can effectively safeguard areas vulnerable to gravitational mass movements.

In this context, the critical precipitation thresholds proposed by Tatizana et al. (1987) were selected for this study, as they continue to be utilized by the Preventive Civil Defense Plan of the State of São Paulo (PPDC). This research was conducted in the Serra do Mar region of Cubatão, using rainfall data from events that occurred over a 30-year period. In this section of the Serra do Mar, a series of envelopes are presented, which facilitate the visualization of safety thresholds for accumulated rainfall over a 4-day period. The landslide envelopes were categorized into four levels: induced landslides, scattered landslides, generalized landslides, and debris flows, based on Eq.8 and Fig. 45.

$$I(AC) = K \text{ x } Ac^{-0,933} \tag{8}$$

Where:

I represent the intensity sufficient to trigger landslides.

K is a parameter dependent on the geotechnical conditions of the slope and the intensity of landslides.

Ac accumulated rainfall over the previous 4 days.

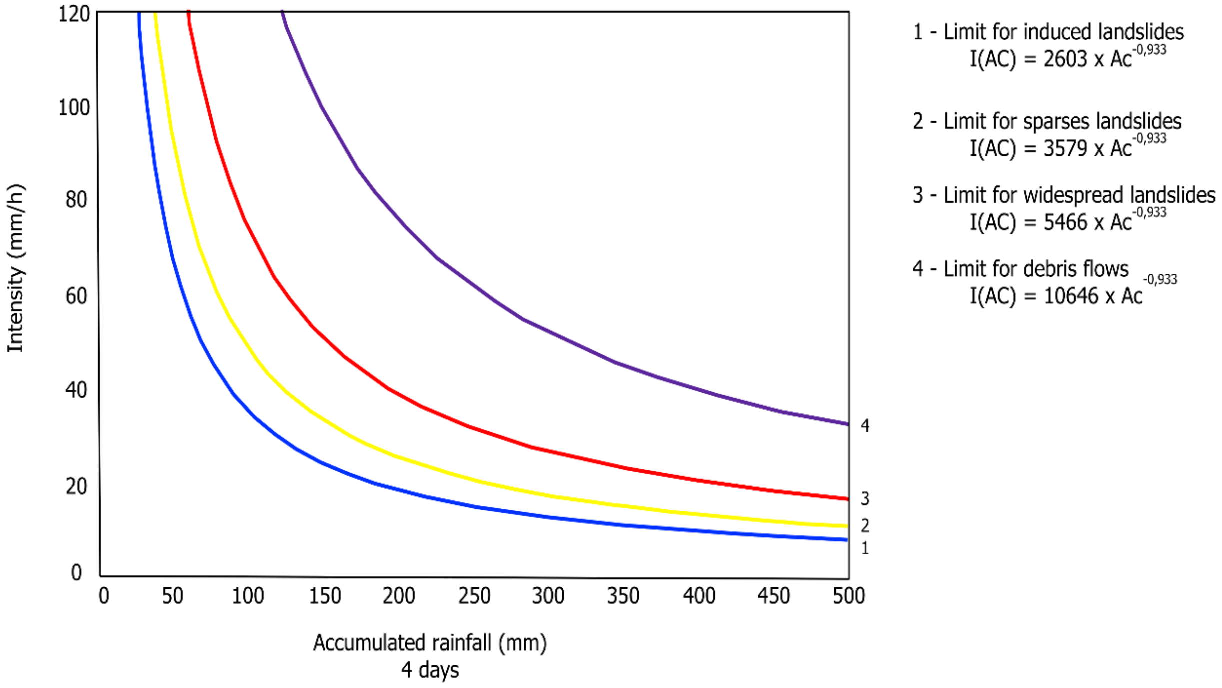


Figure 45 - Rainfall threshold (Tatizana et al. 1987).

In this work, Curve 1 for induced landslides is defined as the transition from normalcy to observation. Curve 2, which pertains to scattered landslides, represents the transition from observation to attention. Curve 3, associated with generalized landslides, indicates the transition from attention to alert, while Curve 4 for debris flows signifies the maximum alert level.

2.3 Proposed monitoring system

A landslide forecasting and monitoring system is based on two primary principles: the effective collection of observational data in real-time, which encompasses both field and remote data, and the integration of this data into real-time operational systems that rely on critical precipitation thresholds and weather forecasts (Okuda et al. 1976; Zhang, 1993; Suwa et al. 2000; Hurlimann et al. 2003; Itakura et al. 2005; Arattano and Marchi 2008).

The operation of the proposed monitoring system relies on sensors at one end. In this specific case, the automatic rain gauges from CEMADEN's observational network were utilized, integrated into a communication network that can function either point-to-point or through gateways. The data is transmitted to a cloud platform, where it undergoes validation and is subsequently stored in a database (Fig. 46).

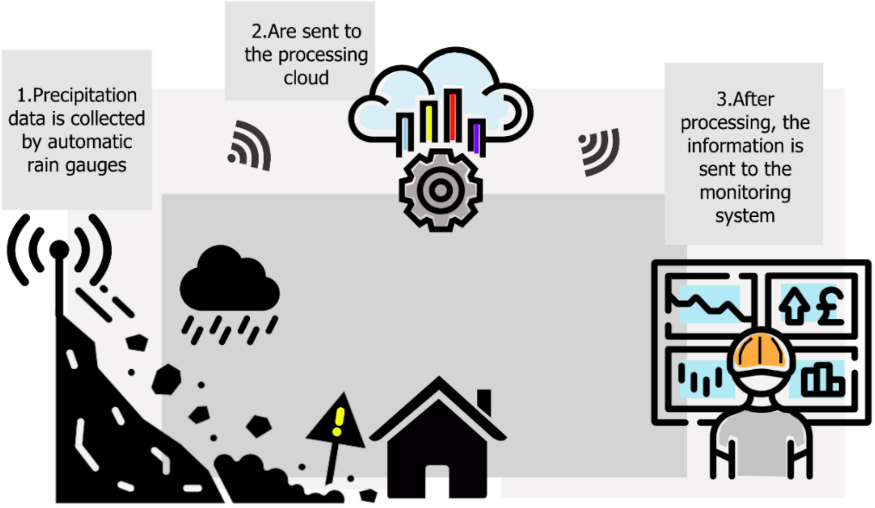


Figure 46 - Monitoring operating system

Thus, the pluviometric monitoring system for gravitational mass movements consists of two primary components: (i) the establishment of critical precipitation thresholds represented as envelopes, and (ii) their real-time comparison and monitoring, which facilitates the assessment of the evolution of risk scenarios (Fig. 47).

In this system, data is collected from CEMADEN’s rain gauges using data mining techniques and is subsequently inserted into database (https://mapainterativo.cemaden.gov.br)

Following this step, the functionality of the data display features is analyzed, and the data is presented on a visualization panel on a web page (Fig. 48).

The system collects and compares measurements obtained from automatic rain gauges. By cross-referencing this data with critical precipitation thresholds, it can determine "where" and "when" landslides are expected in the monitored areas. This level of detail and scale extremely important for effective decision-making and civil protection.

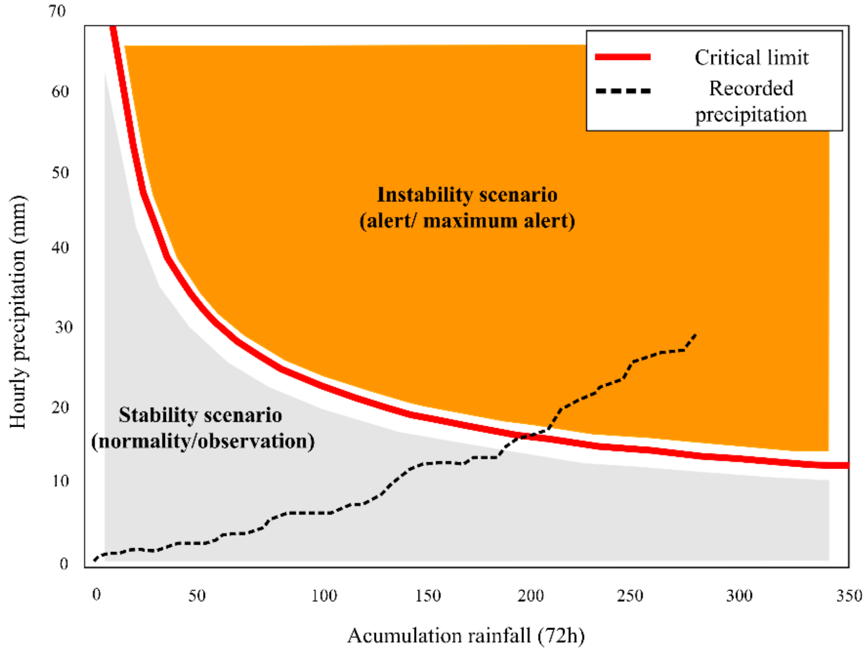


Figure 47 - Integrated system logic with critical precipitation thresholds.

Fig 48 displays the monitoring screen with precipitation values during any given event. It is possible to visualize rainfall values correlated with threshold lines (Observation, Attention, Alert, and Maximum Alert) according to the selected periods.

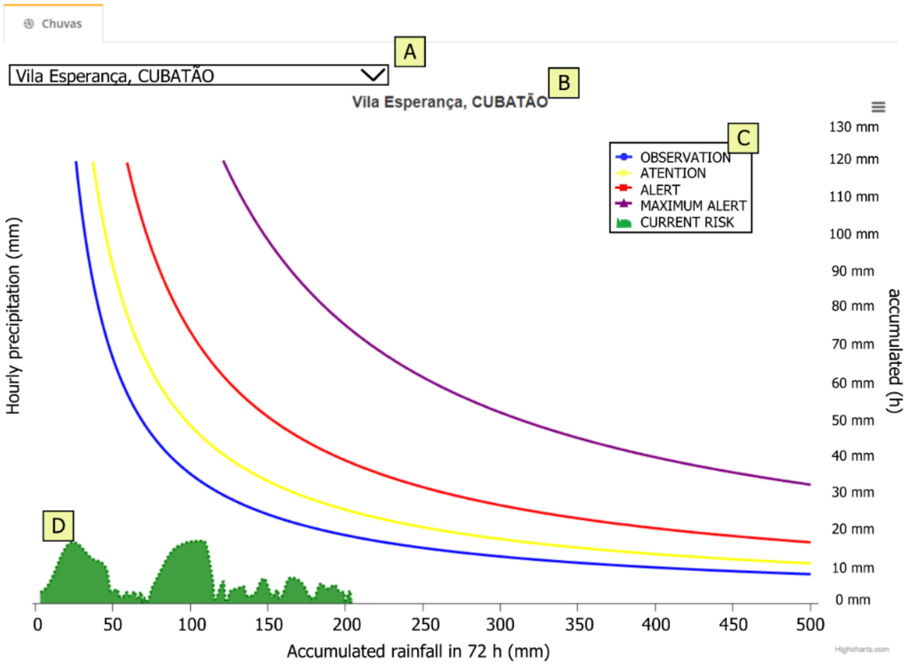


Figure 48 - Monitoring system interface. A) Rain Gauge Selection Button B) Rain Gauge Identification C) Legend with Levels of Operation of the Preventive Civil Defense Plan D) Representation of Real-time Precipitation and its Evolution.
http://104.236.210.226/new/desenv2/chuvas_todos_sp.php?device_code=2603491

Additionally, an auxiliary screen has been developed to visualize, represent, and sort all automatic rain gauges by the highest accumulated precipitation. The gauges can be grouped by accumulated precipitation time, ranging from highest to lowest (1 hour, 6 hours, 12 hours, 24 hours, 48 hours, 72 hours), to assist in identifying areas with the most critical accumulations (Fig. 49).

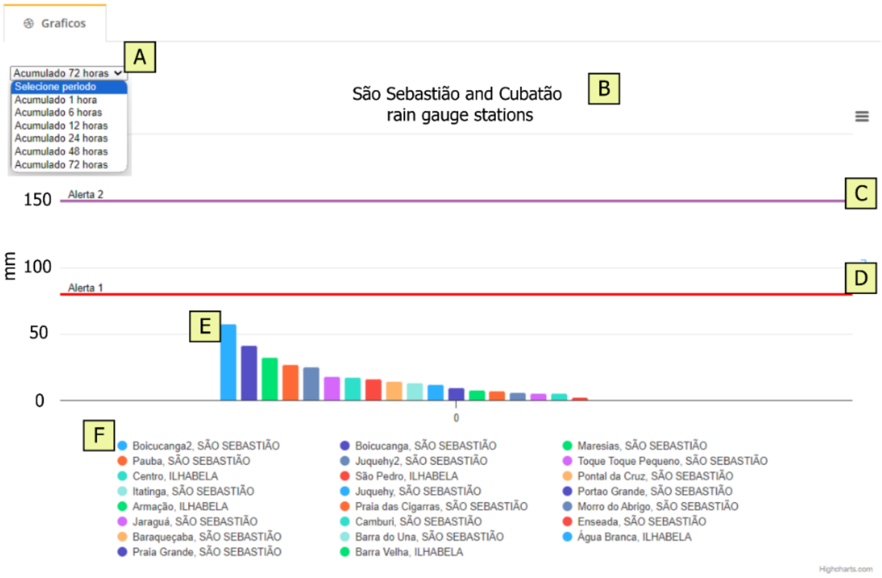


Figure 49 - Screen with all rain gauges grouped in descending order of accumulated precipitation. A) Accumulated Rainfall Viewing Period Selection Button B) Identification of Monitored Sites C) Critical Precipitation Threshold 2 (150 mm) D) Critical Precipitation Threshold 1 (80 mm) E) Representation of Precipitation by Rain Gauge F) Identification of Rain Gauges at Monitored Sites Grouped by Order of Highest Accumulation. https://dash.upsensor.com/new/desenv1/index_barra_sp.php?periodo=72

2.4 Definition of Monitored Sites

The sites selected for monitoring were initially determined based on the geodynamic events database of the São Paulo Institute of Technological Research (IPT), covering the period from 2000 to 2013. Following an analysis of the database, it was decided to conduct pilot monitoring in the municipalities of Cubatão and São Sebastião (Fig. 50), both situated in the Serra do Mar region of the state of São Paulo.

The two municipalities share similar characteristics concerning the influence of orogenic factors on precipitation, aligning with the established critical precipitation model. Additionally, they have a long history of landslide events.

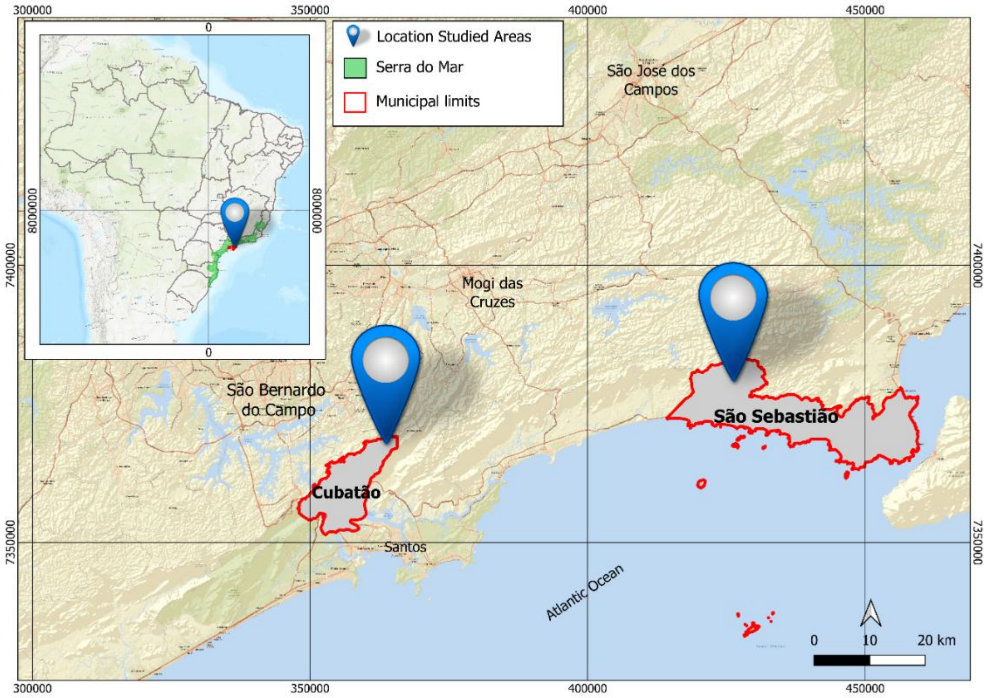


Figure 50 - Location of monitored sites

Through the geolocation of the services provided by IPT, as recorded in the database, a heat map was created to identify areas with a historically higher frequency of these events. Subsequently, this data was overlaid with the CEMADEN rain gauge network present in the regions. The coverage radii of the rain gauges were defined, and specific locations were selected for data collection and integration into the real-time monitoring system.

2.4.1 Description of monitoring sites

For the application of this methodology, two areas with significant land use and occupancy, as well as a notable history of natural disaster recurrence, were selected. The municipalities of Cubatão and São Sebastião were chosen due to their similar geomorphological and geological characteristics, particularly regarding the influence of orographic rains on the initiation of gravitational mass movements. The following section provides a description of these two areas.

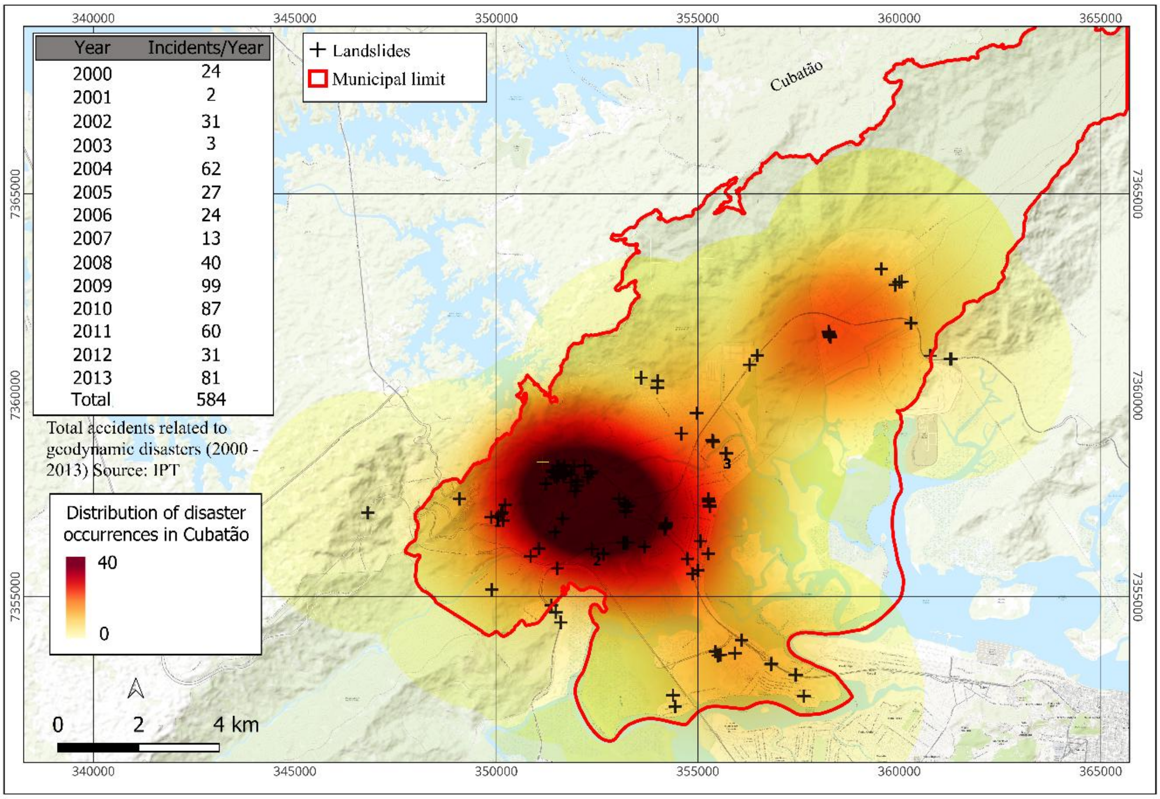
The municipality of Cubatão is in the metropolitan region of Baixada Santista in the state of São Paulo, with a population of approximately 130,000 inhabitants. It is situated on the slopes of the Serra do Mar. The Serra do Mar is a geomorphological feature that extends along the Brazilian coast, characterized by a retracted fault scarp with an elevation range of approximately 800 meters in the Cubatão region.

Its geology is associated with rocks of Precambrian age belonging to the Atlantic Shield, predominantly constituted by migmatites, schists, phyllites, quartzites, cataclastic rocks, mylonites, and granites, with schistosity dipping towards the slope.

The soils show significant variation along the slopes, being practically nonexistent in areas of high declivity, with average thickness of 1 meter rarely exceeding 2 meters, increasing in grain size with depth. The slip surfaces coincide with the separation surface between colluvial soil and overlying residual soil (Tatizana et al., 1987).

This, coupled with the presence of the Serra do Mar escarpment as a conditioning element of the climate through orographic rains, results in the region experiencing significant variations in rainfall with altitude variation. The most frequent and longest rains are associated with long durations (2 to 4 days) with high hourly precipitation intensities.

Thus, the historical record of disasters in the monitored site is concerning in terms of impact and recurrence (Fig. 51). Cubatão is one of the Brazilian municipalities with the highest number of registered occurrences of debris flows (more than 10) and with 584 landslide records just for the period from 2000 to 2013 (Cabral et al., 2022a; Veloso et al., 2023a).



Year	Incidents/Year
2000	24
2001	2
2002	31
2003	3
2004	62
2005	27
2006	24
2007	13
2008	40
2009	99
2010	87
2011	60
2012	31
2013	81
Total	584

Total accidents related to geodynamic disasters (2000 - 2013) Source: IPT

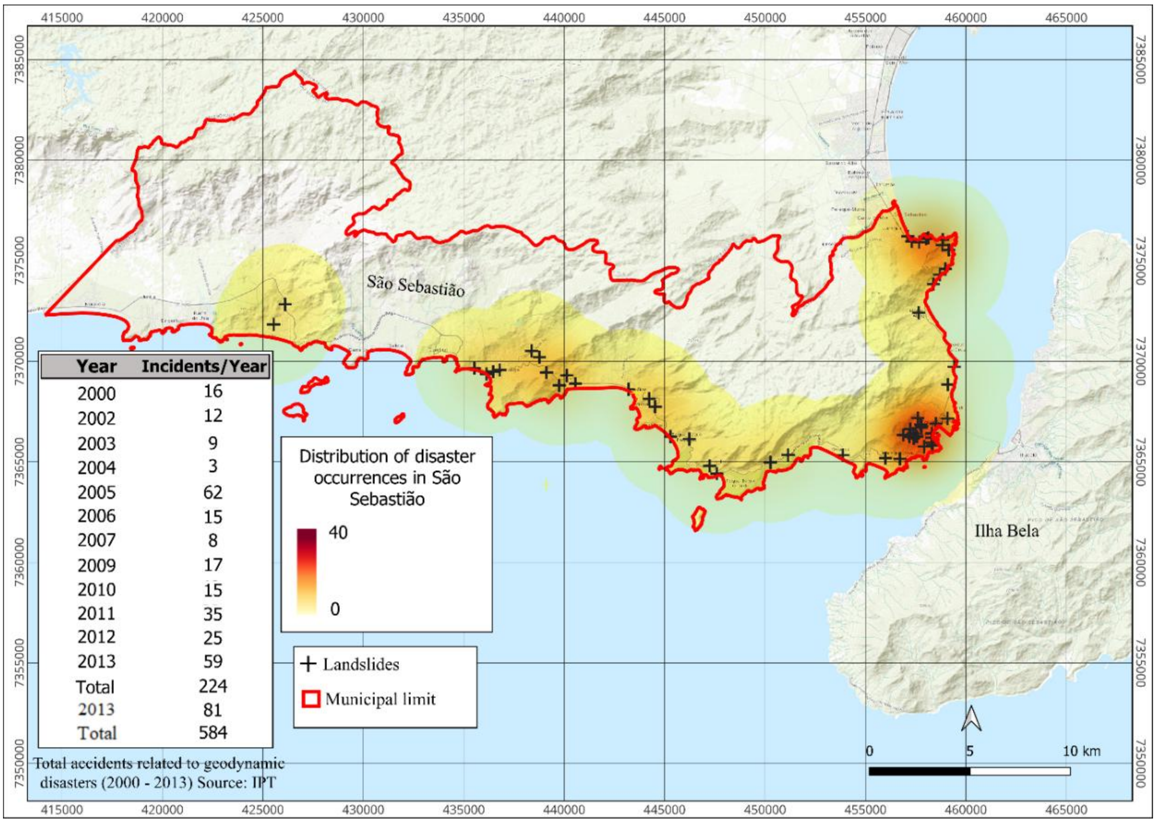
Figure 51 - Municipality of Cubatão with the distribution of events registered as geodynamic in origin (2000-2013). Source: IPT.

The municipality of São Sebastião is located on the northern coast of the State of São Paulo with approximately 90 thousand inhabitants, also situated in the Serra do Mar. Geologically, the area is characterized in the regional context of the Coastal Domain, integrating the Ribeira Belt, Mantiqueira Province, with rocks of relatively homogeneous composition predominating paraderived gneisses (Neto et al., 2009).

The soils in this stretch are also shallow, not exceeding 2 meters in thickness, practically non-existent at high altitudes, bearing a strong resemblance to the context of Cubatão. (Tatizana et al. 1987; Veloso et al. 2024).

The escarpment of the Serra do Mar also acts as a conditioning agent for precipitation through orography, causing precipitations with high duration and intensities above 400 mm/24h to become increasingly frequent, triggering more recurrent disasters (Marengo et al., 2024; Veloso et al., 2024).

This makes this site also used for the validation of the pluviometric monitoring system, since São Sebastião has some recent records of debris flows (Manzolli et al., 2018; Veloso et al., 2024) and a worrying recurrence of gravitational mass disasters totaling 224 in the period from 2000 to 2013 according to data from the IPT (Fig. 52).



Year	Incidents/Year
2000	16
2002	12
2003	9
2004	3
2005	62
2006	15
2007	8
2009	17
2010	15
2011	35
2012	25
2013	59
Total	224
2013	81
Total	584

Total accidents related to geodynamic disasters (2000 - 2013) Source: IPT

Figure 52 - Municipality of São Sebastião with the distribution of events registered as geodynamic in origin (2000-2013). Source: IPT.

3 Results

3.1. Monitoring assessment

As previously described, the monitoring system was implemented in the municipalities of Cubatão and São Sebastião, located in the state of São Paulo, due to their high incidence of landslides and extensive historical records. The evaluation was conducted over two rainy seasons in Brazil (October to March), during which two significant extreme events were highlighted and utilized for validation. The first event occurred between February 16 and 20, 2023, and the second between January 23 and 26, 2024.

To monitor the municipality of Cubatão, focusing on areas with the highest incidence of landslides, the CEMADEN rain gauges located at Cota – 200, Parque Jorge Fernando, and Vila Esperança were selected (Fig. 53).

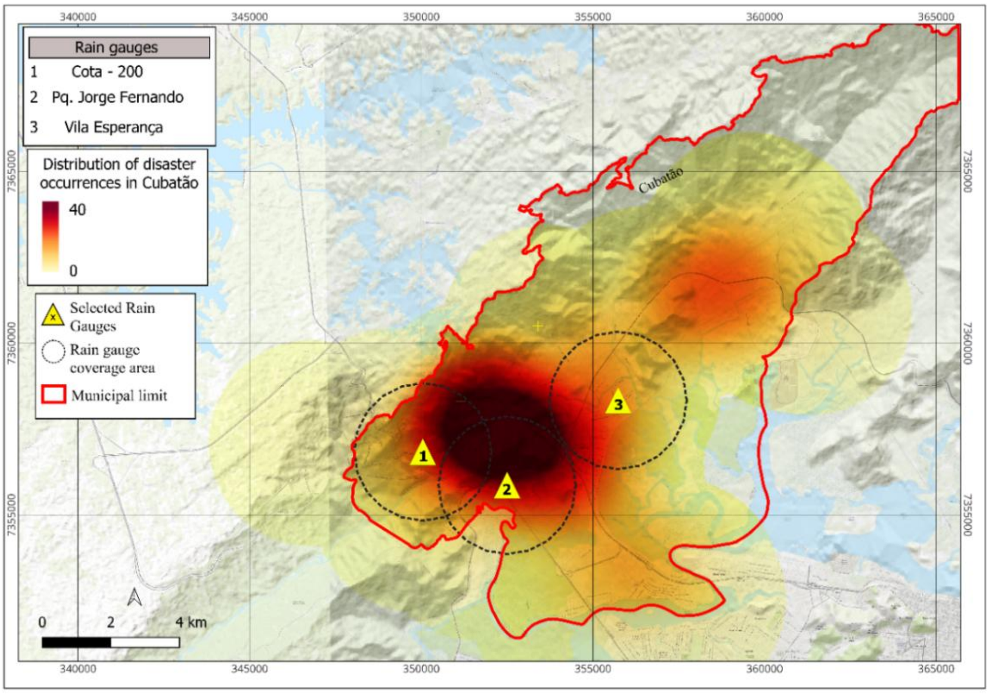


Figure 53 - Spatial distribution of events in the municipality of Cubatão and representation of automatic rain gauges selected for monitoring.

For the municipality of São Sebastião, nine rain gauges were selected along the coastline to enhance the visualization of precipitation data during the monitoring period from 2023 to 2024 (Fig. 54).

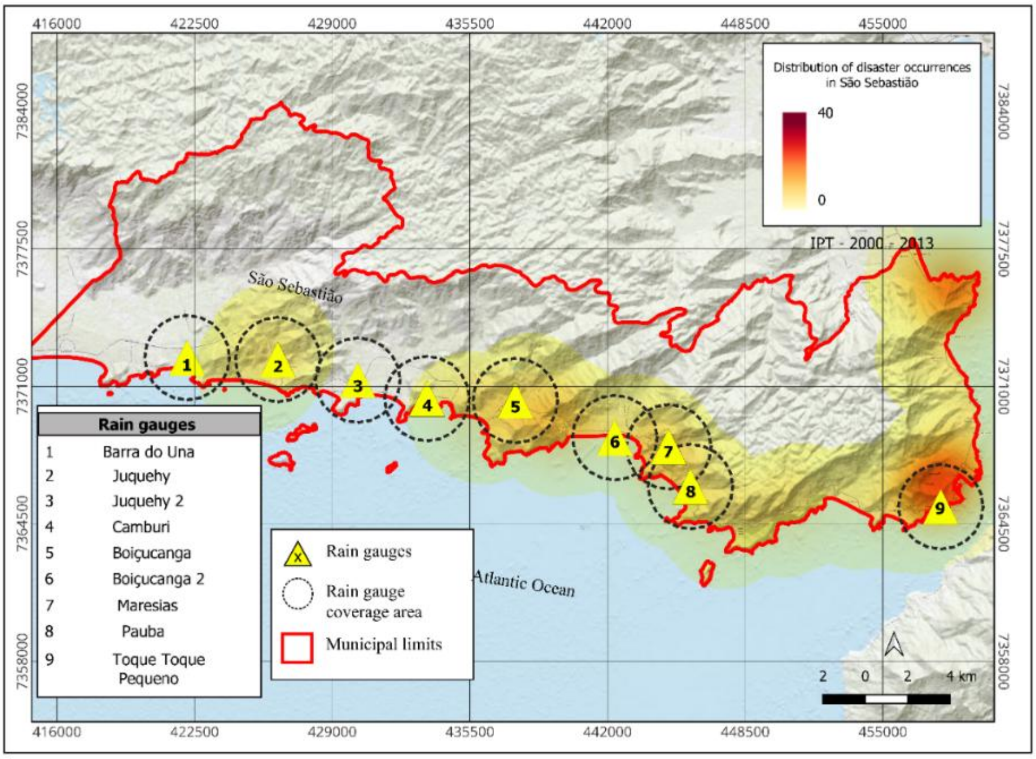


Figure 54 - Spatial distribution of events in the municipality of São Sebastião and representation of automatic rain gauges selected for monitoring.

3.1.1 Monitoring of the event during the 2022-2023 rainy season (16-20 FEB)

The rainfall monitoring conducted on the northern coast of São Paulo during the rainy season of 2022-2023 revealed a significant extreme weather event that occurred between February 16 and 20. The São Sebastião region recorded the highest 24-hour precipitation volume in Brazil's history, exceeding 600 millimeters in 24 hours. This resulted in catastrophic consequences, including 64 fatalities, road closures, and extensive material damage in the affected area.

The locations with the highest precipitation volumes were the Vila Sahy rain gauge (Barra do Una), which recorded peak rainfall intensities of 101.6 mm/h and a total of 213 mm in 24 hours; Juquehy 2, with peaks of 92.2 mm/h and a total of 200 mm; and Juquehy, with a peak of 78.3 mm/h and a total of 237 mm in 24 hours. These were followed by Boiçucanga, which recorded a peak of 76 mm/h and a total of 203.5 mm, and Toque Toque Pequeno, which experienced a peak of 81.4 mm/h and a total of 342.2 mm in 24 hours, resulting in a debris flow (Veloso et al., 2024).

Table 17 indicates that all these rain gauges entered Maximum Alert at 1:00 AM on February 19, 2023, due to the recording of extreme precipitation and weather forecasts predicting even higher rainfall volumes.

In contrast, the city of Cubatão did not experience severe precipitation during the same period, maintaining its operational levels at Observation. Only the rain gauge located in Vila Esperança recorded light rain, indicating a heterogeneous spatial distribution of the climatic event.

It is important to note that some rain gauges (Camburi, Boiçucanga 2, Maresias, and Pauba) became inoperative due to the exceptional intensity of the precipitation. Consequently, it was not possible to obtain accurate rainfall records from these locations, which may have resulted in an underestimation of the total impact of the event in certain areas.

Table 17 – Record of rain gauge operation levels in São Sebastião and Cubatão in 2023 during the event from February 16 to 2023

Rainy Season Monitoring 2022-2023 (16-20 FEB)

São Sebastião

	Rain gauges	Intensity (mm/h)	Accumulated rainfall (mm)	Operation level	Consequences
1	Barra do UNA	101,6	213	**MAXIMUM ALERT**	landslides, floods, road obstruction, deaths, displaced people
2	Juquehy 2	92,2	200	**MAXIMUM ALERT**	landslides, road obstruction, deaths, displaced people
3	Juquehy	78,3	237	**MAXIMUM ALERT**	landslides, road obstruction, deaths, displaced people
4	Camburi	no data	no data	no data	landslides, road obstruction, deaths, displaced people
5	Boiçucanga	76	203,5	**MAXIMUM ALERT**	landslides, road obstruction, deaths, displaced people
6	Boiçucanga 2	no data	no data	no data	no data
7	Maresias	no data	no data	no data	landslides, road obstruction, deaths, displaced people
8	Pauba	no data	no data	no data	Landslides, floods
9	Toque Toque Pequeno	81,4	324,2	**MAXIMUM ALERT**	Debris flows, road obstruction, pipeline impact
	Cubatão				
5	Cota 200	0	0	**OBSERVATION**	No events registred
6	Pq. Jorge Fernando	0	0	**OBSERVATION**	No events registred
7	Vila Esperança	31,2	1,7	**OBSERVATION**	No events registred

*No data – out of order

By analyzing the peak hourly intensity values and total precipitation, we can gain a clearer understanding of the magnitude and severity of this rainfall event. All operational rain gauges in São Sebastião reached Maximum Alert levels, significantly exceeding safety thresholds. Notably, the regions of Barra do Una and Toque Toque Pequeno were the most affected. In contrast, Cubatão did not experience significant increases in precipitation, remaining at the Observation level throughout the period.

Figure 55 presents the precipitation data from the São Sebastião and Cubatão rain gauges for February 19, 2023. This data, provided by the monitoring system, corresponds to the most critical period of precipitation when landslides were likely to have begun occurring.

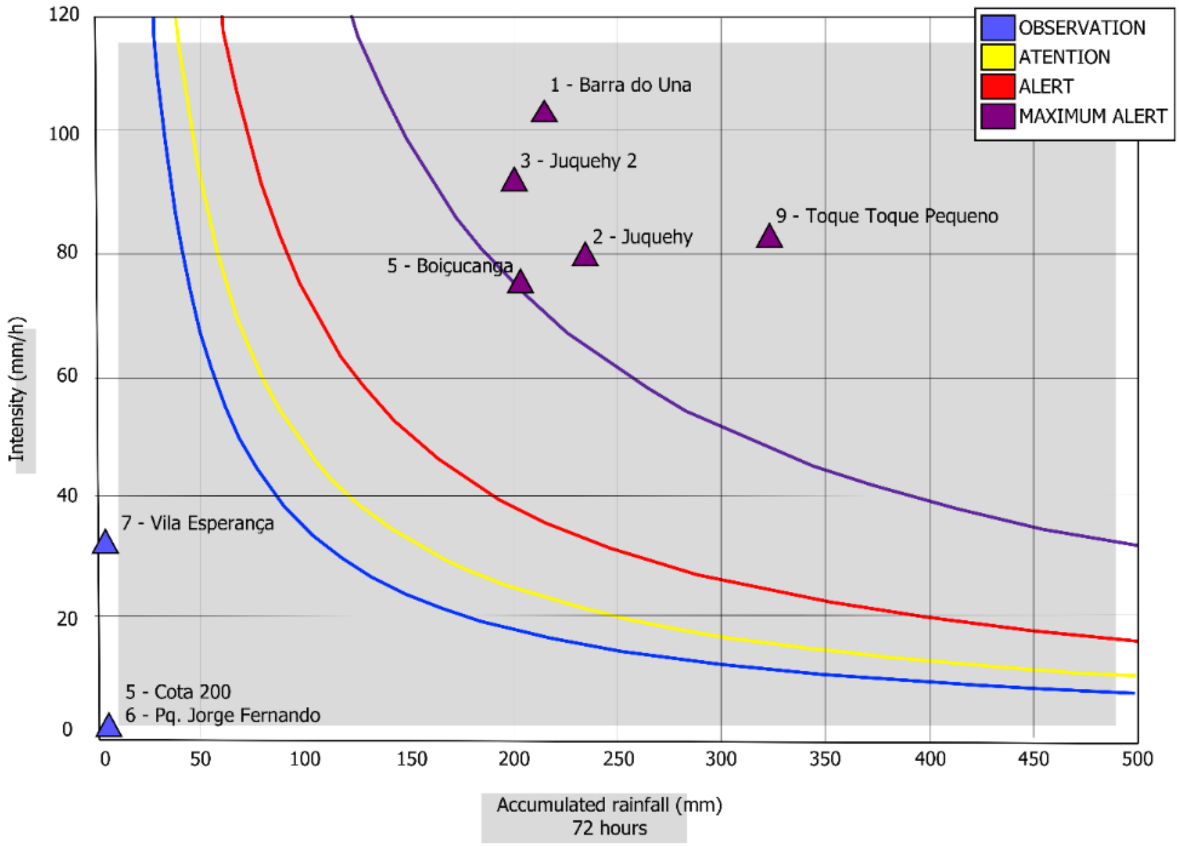


Figure 55 – Operating levels of the monitored rain gauges in 2023.

3.1.2 Monitoring of the event during the 2023-2024 rainy season (23-26 JAN)

In 2024, monitoring was conducted during the event that took place from January 23 to 26. As shown in Table 18, the Juquehy 2 and Maresias rain gauges experienced a change in their operating levels to Alert due to peak hourly intensities. However, shortly after the precipitation ceased, they returned to the Observation level.

Table 18 - Record of the operational levels of rain gauges in São Sebastião and Cubatão in 2024 during the event from January 23 to 26

Rainy Season Monitoring 2023-2024 (23-26 jan/24)					
São Sebastião					
	Rain gauges	Hourly intensity peak	Accumulated rainfall	Operation level	Consequences
1	Barra do UNA	20,85	3,38	**OBSERVATION**	no damage
2	Juquehy 2	37,12	132,9	**ATENTION**	no damage
3	Juquehy	31,84	139,9	**OBSERVATION**	no damage
4	Camburi	31,76	35,8	**OBSERVATION**	no damage
5	Boiçucanga	28,1	37,8	**OBSERVATION**	no damage
6	Boiçucanga 2	14,94	42,8	**OBSERVATION**	no damage
7	Maresias	38,09	166,9	**ATENTION**	floods
8	Pauba	55,7	37,9	**OBSERVATION**	no damage
9	Toque Toque Pequeno	60,9	30,6	**OBSERVATION**	no damage
Cubatão					
5	Cota 200	16,77	14,45	**OBSERVATION**	no damage
6	Pq. Jorge Fernando	5,69	11,44	**OBSERVATION**	no damage
7	Vila Esperança	26,16	25,75	**OBSERVATION**	no damage

The other rain gauges did not record any changes in operating levels, remaining predominantly at the Observation level (Fig. 56).

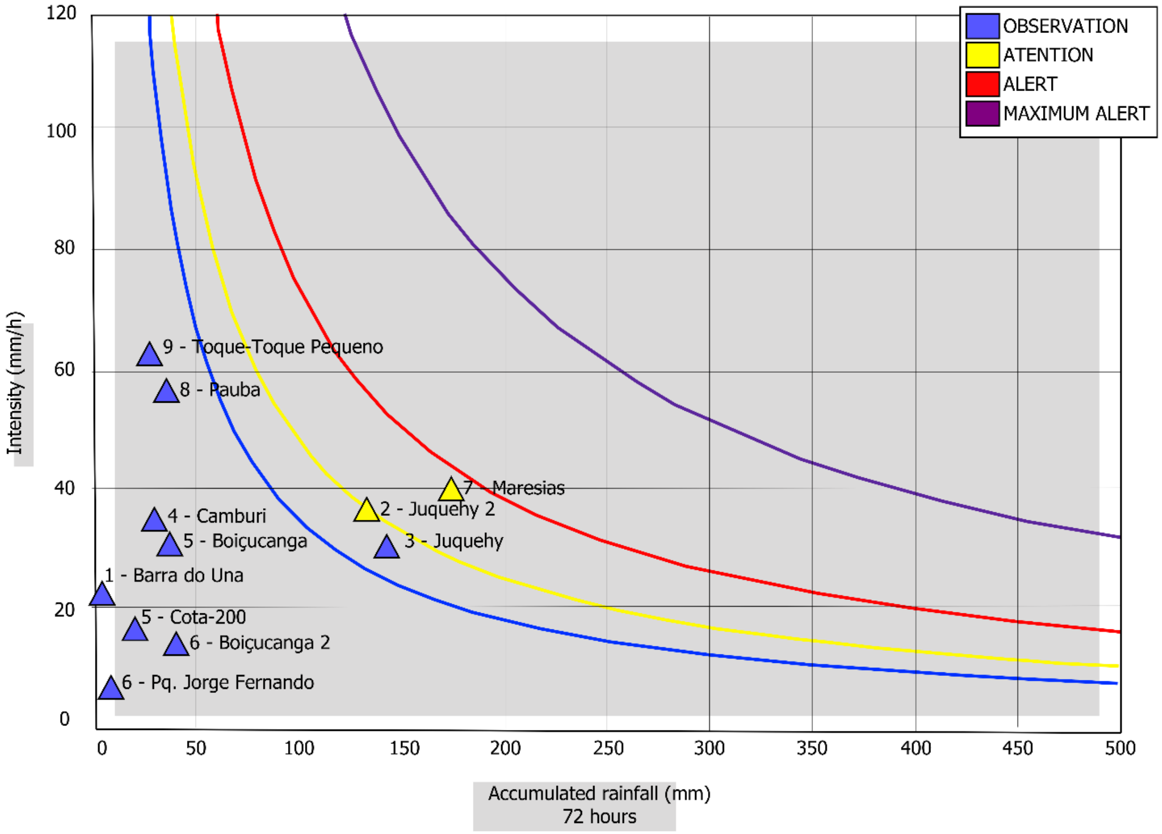


Figure 56 - Operating levels of the monitored rain gauges in 2024.

3.2 The disaster that occurred in 2023 in São Sebastião, São Paulo

The heavy rains that fell on the slopes of the Serra do Mar in the municipality of São Sebastião during the early hours of February 19, 2023, represented the largest 24-hour precipitation event ever recorded in Brazil's history.

According to Metsul Meteorology, this extreme precipitation event was triggered by a low-pressure system affecting the São Paulo coastline. Moisture from the ocean was forced to rise due to the topography of the Serra do Mar, where it collided with warmer continental air. This interaction resulted in orographic precipitation of unprecedented volume.

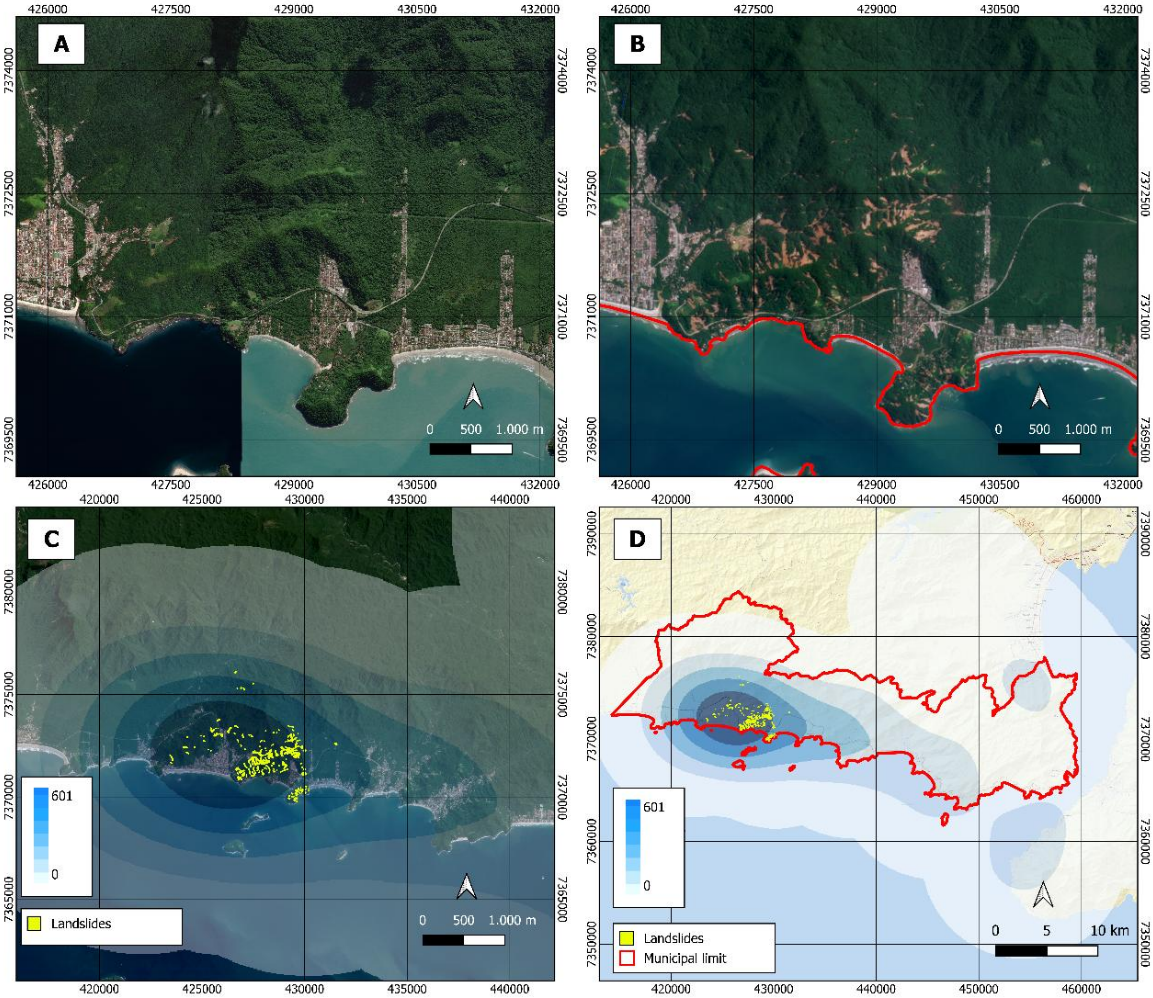


Figure 57 – Record of the São Sebastião 2023 disaster conditions. A) Satellite image of Vila do Sahy before the event. B) Satellite image of Vila do Sahy after the extreme precipitation, showing scars from widespread landslides. C) Correlation of the area with the highest precipitation with the highest incidence of widespread landslides. D) Spatial distribution of rainfall during the disaster, highlighting the highest concentration in Vila Sahy.

During the monitoring, it was observed that landslides occurred even in areas with dense vegetation, including sections of the untouched Atlantic Forest (Fig. 57). This phenomenon was attributed to the sudden nature of the rain event, which triggered landslides in São Sebastião, particularly in the Vila do Sahy area, where rain gauges recorded 101 mm of rainfall within just one hour. This volume characterizes a short-duration but high-intensity event, as indicated by the monitoring system (Fig. 58).

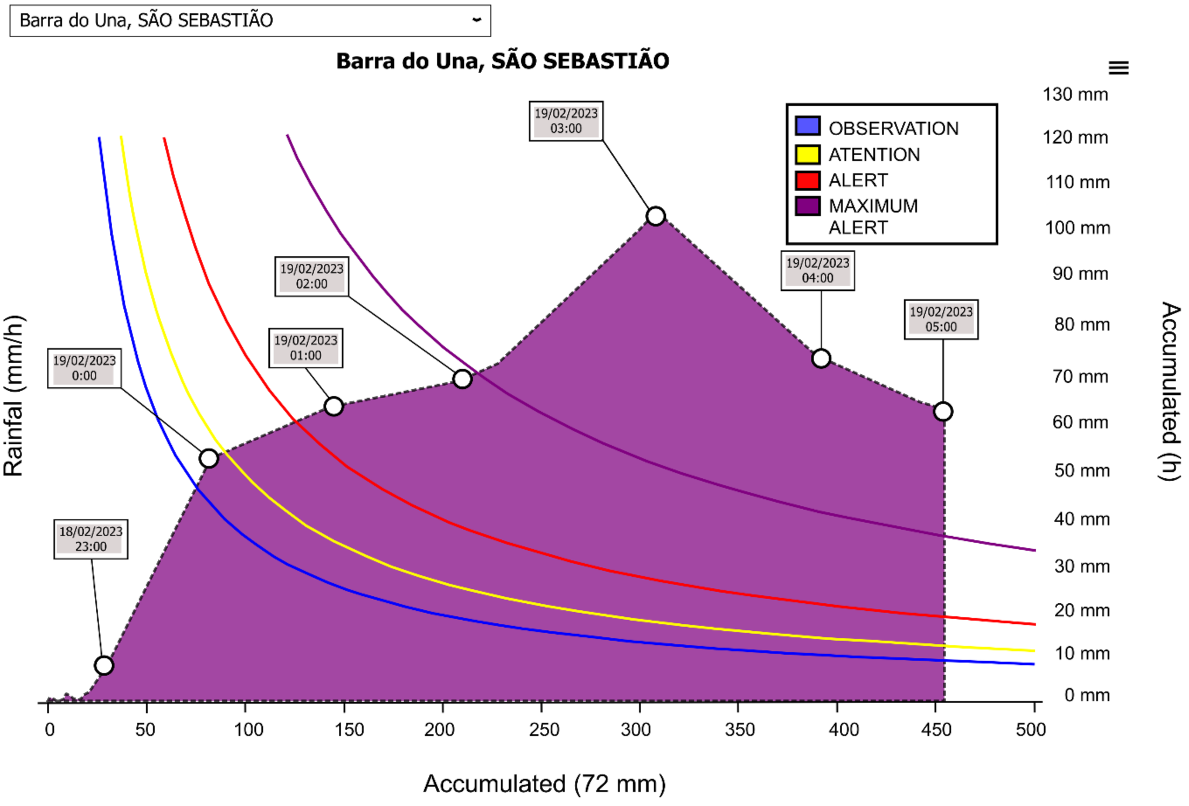


Figure 58 - Record of the Barra do Una rain gauge monitoring during the extreme precipitation event

In the early hours of February 19, a powerful convective cell developed over the municipality of São Sebastião, impacting an area of approximately 50 km² with significant intensity, where 648 mm of precipitation was recorded within 24 hours (Fig. 57 C and D). This extreme weather event triggered widespread landslides, resulting in 1070 scars identified through satellite imagery (Coelho et al. 2024), with an estimated volume of 973,000 m³ of soil, rock, and vegetation displaced from the slopes. The disaster led to 64 fatalities, 970 individuals being displaced, and 747 people left homeless. (Figs. 59 and 60).

Figure 59 - Record of the widespread landslides in São Sebastião. A) Landslide that affected homes in Vila Sahy. B) Record of homes impacted by landslides. C) Record of a broken slope blocking vehicle flow on the highway, isolating the area and complicating the rescue operations for injured and displaced victims.

Consequently, several areas were isolated, hindering access for rescue and relief teams. In addition to material damage, the event resulted in human casualties and the destruction of local infrastructure, including roads and homes, creating an emergency in the region. The situation was even more critical as the event occurred during the Carnival holiday, when the municipality, with a population of approximately 80,000 residents, typically receives around 1 million tourists (Fig. 60).

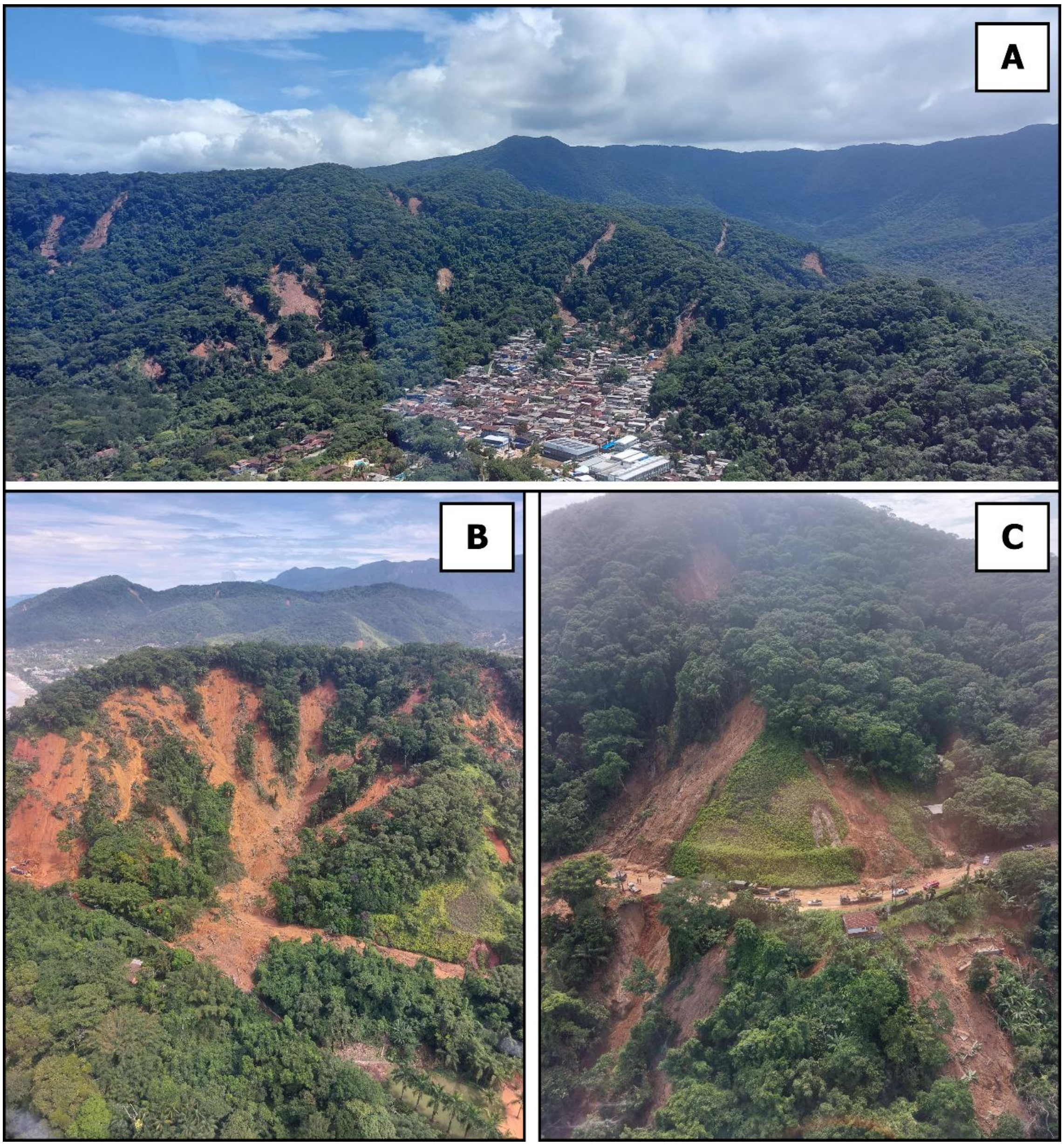


Figure 60 - Aerial image records of the disaster area in Vila Sahy, São Sebastião. A) Record of several landslides along the Serra do Mar, including the one that claimed multiple families. B) Landslide on a section of the highway, resulting in its obstruction. C) Landslide on another section of the highway, causing blockage.

4. Discussions

The forecasting and monitoring of mass movements are complex tasks that present significant challenges, particularly in densely populated urban areas. Therefore, this study aimed to integrate critical precipitation thresholds with automated systems to facilitate real-time monitoring of natural disasters associated with gravitational mass movements.

The real-time precipitation monitoring system was successfully demonstrated in the cities of Cubatão and São Sebastião, located in the state of São Paulo. It exhibited satisfactory performance during the validation phase, which occurred during the rainy seasons of 2023 and 2024.

The municipalities of Cubatão and São Sebastião were chosen as study areas for testing due to their geomorphological and geological characteristics, which render them susceptible to landslides and other natural disasters. They have a significant history of geodynamic events, particularly during periods of heavy rainfall. The proximity to the Serra do Mar, which enhances orographic rainfall, adds complexity to local climatic phenomena, thereby justifying the need for a localized monitoring system.

In Cubatão, the system proved effective in monitoring rainfall, although there were no records of significant increases in precipitation volumes during the rainy seasons of 2023 and 2024. The three rain gauges utilized for monitoring recorded similar precipitation volumes and patterns, which remained stable, with no intensity peaks that would necessitate a change in operational status to Alert or Watch during the four days of monitoring.

In São Sebastião, the quality of rainfall monitoring played a crucial role in tracking and responding to the disaster that occurred on February 19, 2023. The real-time monitoring system tested in the region enabled the collection of accurate data on the intensity and duration of the rainfall, which are essential factors for predicting landslides.

During the event, the rain gauges recorded unprecedented precipitation levels, with intensity peaks surpassing 100 mm/h in certain areas, such as Vila do Sahy. This data was essential for issuing emergency alerts, enabling local authorities and the community to prepare for the event's consequences. The capacity to monitor weather conditions in real time facilitated a more prompt and informed response, although the scale of the disaster exceeded expectations.

Furthermore, the quality of the monitoring was demonstrated by its ability to swiftly identify the most affected areas. The analysis of the collected data revealed that regions such as Barra do Una and Toque Toque Pequeno were in a state of maximum alert.

However, the event also highlighted certain limitations of the monitoring system. Despite the quality of the data, the intensity and speed of the event surpassed predictions, emphasizing the need to enhance alert thresholds and incorporate additional factors, such as soil moisture and local geology, for a more comprehensive assessment of landslide risk.

Among the system's primary strengths is its ability to instantly integrate data collected in real time by automatic rain gauges, a critical feature for any tool designed for civil protection (Hurlimann, 2003; Itakura et al., 2005). This functionality enables an immediate and informed response to adverse weather conditions, which is essential for effective disaster monitoring.

The efficient collection and processing of data related to critical precipitation thresholds, customized to the specific characteristics of the study areas, has proven to be highly effective, particularly using visualization panels and localized monitoring scales. This approach not only enhances the accuracy of forecasts but also improves the effectiveness of preventive measures, enabling better monitoring of extreme precipitation events. It provides essential lead time for decision-making, facilitating the implementation of preventive strategies such as evacuating residents and closing roads (Suwa et al., 2000).

The ability to conduct local-scale monitoring is essential, as precipitation distribution can vary significantly over small areas, particularly due to orographic factors. Consequently, the effectiveness of the system relies on a well-distributed network of automatic rain gauges that can adequately cover the areas of interest. It has become clear that a local scale is the most suitable for supporting strategic decision-making, including interventions in high-risk areas, relocation of residents, and other non-structural measures based on Preventive Civil Defense Plans.

However, certain aspects require improvement, particularly the expansion of the network of automatic rain gauges in the Serra do Mar, especially in areas with a significant history of debris flows. These rain gauges should be strategically placed near drainage headwaters in basins with higher population densities to enhance the accuracy of forecasts in adjacent regions.

Continuous updates to critical precipitation thresholds are essential for maintaining the relevance and effectiveness of the system, particularly in the face of climate change and emerging precipitation patterns. Furthermore, ongoing training for professionals and raising public awareness about the system and the risks associated with landslides are vital for optimizing the effectiveness of monitoring and emergency response efforts.

Another critical area for improvement in future research is the incorporation of soil moisture, vibration, and inertial sensors, particularly in situations where structural measures are not feasible. This approach aims to provide a comprehensive understanding of all parameters related to slope instability by correlating precipitation with the geotechnical properties of slopes (Okuda 1980; Zhang 1993; Suwa et al. 2000; Marchi et al. 2002; Hurlimann 2003; Imazumi et al. 2005; Hurlimann et al. 2014; Mendes et al. 2015; Gregoretti et al. 2016; Hurlimann et al. 2019).

5. Conclusions

The proposed precipitation monitoring system for Cubatão and São Sebastião has significant potential for expansion to other areas vulnerable to landslides and extreme weather events, owing to its low development and implementation costs, as well as its scalable monitoring capabilities. The methodology employed, which integrates historical data, collection and visualization technology, and real-time analysis on a local scale, can be adapted to various geographic and climatic contexts, including mountainous regions, coastal areas prone to heavy rainfall, and densely populated urban centers. The experience gained in Cubatão and São Sebastião can serve as a model for other locations, fostering knowledge exchange and promoting best practices in natural risk management.

The implementation of such systems would not only enhance the safety of populations in vulnerable areas but also foster a culture of prevention and resilience against natural disasters. This is particularly crucial in the context of climate change and the increasing frequency of extreme events. It is essential to disseminate these monitoring models, as their application is economically viable and can be highly beneficial for civil defense agents in making decisions that preserve infrastructure and save lives.

As a recommendation for future studies, it is advisable to implement this system in high-risk areas during the operation of Civil Defense Preventive Plans. This can be achieved by updating local critical precipitation thresholds and incorporating additional sensors that measure a broader range of geotechnical parameters, thereby enhancing the system's redundancy.

It is emphasized that monitoring the extreme weather event that occurred in February 2023 in São Sebastião underscores the importance of robust monitoring systems and the need for rapid response and mitigation strategies for natural disasters to ensure the safety of populations. Additionally, the significance of ongoing studies on climate patterns and their impacts on coastal regions is highlighted, with the goal of enhancing predictability and risk management associated with intense rainfall events.

3 Thesis Conclusions

This work aimed to develop a hazard index for the occurrence of debris flows to be incorporated into the mapping of the Environmental Sensitivity Index to oil spills in pipeline crossing sections in mountainous areas. The four presented chapters converge on the need to improve and, most importantly, implement methodologies for environmental risk mapping and monitoring, with an urgent focus on the prevention and mitigation of natural and environmental disasters.

The use of the Hazard Index for the Occurrence of Debris Flows in pipeline crossing sections has proven feasible for incorporation into the mapping of the Oil Spill Sensitivity Index (SSI) or Cartas SAO, being a fundamental tool in enhancing contingency plans specific to areas subject to natural disasters such as debris flows.

Its adherence stood out as a viable solution to define which watersheds are most critical from the perspective of the possibility of potential events, ensuring that structural and non-structural prevention measures are better specifically targeted. This highlights the need to consider the phenomenology of the geodynamic process and the relationship between susceptibility and vulnerability.

This methodology was validated in the Toque Toque Grande watershed, São Sebastião – SP, where a debris flow occurred during the fieldwork, demonstrating the urgency of structural protection measures and the importance of a multidisciplinary approach in risk management. The recorded debris flow occurred between February 18 and 19, 2023, during the largest 24-hour rainfall event ever recorded in Brazil since historical records began. In various parts of the municipality of São Sebastião, there were 65 deaths and more than 1,000 displaced people, resulting in damages amounting to USD $122.4 million.

Additionally, with the aim of proposing a solution for dynamic monitoring, a real-time monitoring system for one of the main conditioning agents of mass gravitational movements, rainfall, was proposed. To this end, through data collection and data processing tools, a solution in the form of a real-time rainfall monitoring system for the municipalities of Cubatão and São Sebastião was developed.

The integration of critical precipitation thresholds with automated data collection and visualization systems proved satisfactory, and the data visualized during its validation in an event were reliable, making it an important instrument in the Preventive Civil Defense Plans. The strength of this system is its simplicity and low operational cost, but its efficiency depends on an adequate network of automatic rain gauges and the continuous updating of critical precipitation thresholds for each monitored area. For this, it is essential to maintain the policy of managing historical and current data, as one of the major problems in Brazil is the lack of historical information for certain areas, largely due to discontinuities in government policies. Thus, the objective of integrating quantitative mappings of the physical environment with dynamic mappings proved to be feasible from an operational standpoint, much more than that, achievable in these sections, and could be of great value for contingency plans for these areas.

It is recommended that for future studies, watersheds classified with a High Debris Flow Occurrence Hazard Index (H3) undergo complementary research using appropriate instrumentation. These studies should encompass not only precipitation monitoring but also early detection of potential debris flows at the drainage heads of the watersheds. To achieve this, the use of flow meters, humidity sensors, and devices for monitoring slope movement is advisable. These instruments should be cost-effective and capable of remote data transmission.

The results presented reinforce that the state-of-the-art methods and techniques applied to the management of natural and environmental disasters can offer more suitable responses than those observed and recently adopted by managers and policymakers.

From an academic and technical standpoint, there exists a solid foundation built over decades, continuously evolving, capable of addressing needs and providing solutions to the challenges at hand. Therefore, public governance acceptance is crucial for the success of any policy related to disaster prevention and management, through its role in policy implementation and resource allocation.

It is crucial to recognize that investment in prevention is a strategic policy that needs to be incorporated into both public and private agendas worldwide, aiming to protect populations, the environment, and the economy. Preventive measures not only save lives and reduce costs but also promote sustainable and resilient development, preparing nations to face future challenges more effectively.

Allocating and transparently applying resources to policies for the prevention and reduction of natural and environmental disasters should not be seen as an expense, but rather as an investment in sovereignty, population security, the economy, the environment, and long-term sustainability.

The challenges for the coming decades, given climate change, are numerous and complex, impacting society as a whole and the global production chain. To address them, a serious and integrated approach is vital, leaving no room for denialism. Government officials, technicians, and universities must work together, utilizing scientific knowledge for the benefit of society. Collaboration, technological innovation, and social equity are fundamental pillars for confronting these challenges and ensuring a sustainable future for the next generations.

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