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PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS E MEIO AMBIENTE

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

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Instituto de Geociências e Ciências Exatas
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Rio Claro - SP
2024

UNIVERSIDADE ESTADUAL PAULISTA
“Júlio de Mesquita Filho”
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Câmpus de Rio Claro

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

Rio Claro - SP
2024

V443m

Veloso, Vinicius Queiroz
Methodological proposal for integrating debris flow hazard index with environmental sensitivity index in pipelines / Vinicius Queiroz Veloso. -- Rio Claro, 2024
148 p.

Tese (doutorado) - Universidade Estadual Paulista (UNESP), Instituto de Geociências e Ciências Exatas, Rio Claro
Orientador: Fabio Augusto Gomes Vieira Reis
Coorientador: Artur Agostinho Abreu de Sá

1. Environmental Sensitivity Index. 2. Debris flows. 3. Hazard Management. 4. Natechs. I. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Dados fornecidos pelo autor(a).

UNIVERSIDADE ESTADUAL PAULISTA
“Júlio de Mesquita Filho”
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Rio Claro (SP), 24 de outubro de 2024

Agradecimentos

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001"

Gostaria, primeiramente, de agradecer aos meus orientadores. Ao professor Fabio Reis, por todo o suporte, amizade e confiança ao longo do desenvolvimento desta pesquisa, e ao professor Artur Sá, pela amizade, apoio e por tornar minha estadia em Portugal especial, fazendo com que a distância de casa fosse suportada com boas risadas e momentos inesquecíveis.

Gostaria de estender meus agradecimentos em Portugal à professora Emmaline Rosado, ao professor Nuno Vaz, ao grande e implacável Rui, ao biônico senhor Luis Gonçalves e toda a sua maravilhosa família, à Helena Sá e sua família (inclusive os pets), às atenciosas colegas da biblioteca da UTAD, ao José Gustavo, Renan Gomes e ao Jorginho Malcriado.

Agradeço também a Transpetro nas pessoas de Pedro Mascarenhas e Wanderley Russo por todo apoio e suporte.

Sou muito grato aos meus amigos Adriano Scalzitti, Bruno Parizzotto, Carlos Alberto Fernandes, Marcelo Eric de Almeida Santos, Marcela Barone, Vitor Laubstein, Felipe Vale, Felipe Leite, Renato Peres, Pedro Lazarin, Zito Nunes, Mariano Araujo Gouveia, Igor Zapatta e todo pessoal da 51ª turma e entorno pela ajuda e amizade que remonta a tempos do Brasil Pré-Cabralino.

Agradecimentos especiais são necessários para Victor Cabral, Agostinho Ogura, Marcelo Gramani, Claudia Vanessa e José Zaine, por participarem ativamente do meu processo de formação como ser humano e cientista ao longo desses últimos 10 anos.

Não posso deixar de agradecer à UNESP e a todos os seus funcionários, em especial a alguns, como Lauren, Rodrigo, Clébio, Gilberto Forti, Marie, Gilberto Donizeti Henrique, Rosângela, Dario, Nei, Otávio e João Carvalho, Renan Ramos e Diego Maia que em muitos momentos me tiraram de apuros e me auxiliaram, certamente mais vezes do que eu mereci.

Serei eternamente grato aos meus pais, Maria Aparecida e Valdomiro, que sempre me apoiaram, me inspiraram, a minha irmã Fernanda, Fernando Veloso e Maria Joseli Barreto.

Gostaria de agradecer (muito mesmo) à minha senhora Isadora por todo o apoio e companheirismo; considero fundamental dizer que, sem exagero algum, sem ela nada disso teria sido possível.

E por fim, ao Caetano, que durante todo esse tempo me permitiu crescer ao seu lado, tendo o privilégio de vê-lo se tornar um menino fantástico e muito especial.

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 oilinduced 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.

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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