

UNIVERSIDADE ESTADUAL PAULISTA
“Júlio de Mesquita Filho”
Instituto de Geociências e Ciências Exatas
Câmpus de Rio Claro

THE OCCURRENCE, IMPACTS AND DYNAMICS OF DEBRIS FLOWS IN BRAZIL

VICTOR CARVALHO CABRAL

Tese de Doutorado em cotutela com a Universidade de Tübingen (Alemanha)

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Abstract

Among the landslide types, debris flows represent a greater hazard to society due to their high destruction potential. In Brazil, debris-flow studies are still incipient when compared to other hydrogeomorphic processes and a good understanding of their dynamics is fundamental to supporting hazard and risk assessment studies. In particular, determining the spatialization of events and the extent of the impacts that the phenomenon represents in the country is crucial to supporting targeted and more in-depth studies. In this context, the main objectives of this thesis are to assess the societal impact of debris flows in Brazil and to propose a methodology that aims at reducing the potential damage that future events can cause in susceptible regions. A detailed post-event characterization of a debris-flow event is also conducted, as it is a fundamental step to understanding the phenomenon's dynamics and can further support the proposal of the hazard assessment methodology. To determine the societal impact of debris flows, a catalogue of events that have caused fatalities and/or economic losses between 1920 and 2021 was created, which supported the debris-flow Mortality Rate (MR) calculation and the application of the so-called F-N Curves (Frequency of events vs. Number of Fatalities). In total, 45 debris-flow events were documented in the considered period, having caused more than 5,773 fatalities and 5.4 billion USD in economic losses. The city of Cubatão (state of São Paulo) shows the highest number of recorded events in the considered period (9), consolidating the status as the most debris-flow prone region in the country. A multi-step hazard assessment is, then, proposed using Cubatão as the test-site, based on the combination of Logistic Regression (LR) analysis, numerical simulation and rainfall back-analysis. The LR results highlight that rainfall is the main influencing factor in debris-flow initiation in the region and indicate the catchments more susceptible to the phenomenon. The simulation results, performed in the catchments indicated by the LR, show that the average runout distance in the region is 470 m, with an average peak flow height of 5 m and a peak velocity of 23 m s^{-1} , according to the calibration based on two past debris-flow events. These results are comparable to the debris-flow event of February 2017 that occurred in the Pedra Branca catchment (Guaratuba, state of Paraná), in which a detailed post-event geomorphological characterization was conducted to estimate the event's magnitude. The Guaratuba event was of a large-sized stony debris flow, with a total magnitude of $120,195 \text{ m}^3$, a peak flow height of 7 m and a peak velocity of 26.5 m s^{-1} . Debris-flow events both in Cubatão and Guaratuba are generally triggered by short duration ($<48 \text{ h}$), high-intensity ($>200 \text{ mm}$) precipitation, with return periods that vary from 3 to 15 years. Five levels of hazard (very low to very high) are, then, proposed in our hazard assessment method, based mainly on the 48-h accumulated rainfall, flow properties (height, velocity) and the spatial analysis of the elements (infrastructures, houses, etc.) at hazard. In

Cubatão, industrial and residential areas in the projected debris-flow route generally exhibit the highest overall hazard levels, as many were developed in the depositional area of the phenomenon and near fluvial courses, where associated floods and flash floods may occur. As pointed out by recent studies, an increase in the frequency of extreme precipitation events is projected in the Serra do Mar region and when the general short return period of the debris-flow triggering rainfall is considered (< 20 years), large magnitude ($>10^5 \text{ m}^3$) events are likely to occur in the next decade in the portions of the mountain range located in the states of São Paulo and Paraná. This thesis, therefore, is a contribution to better understanding the dynamics of debris flows in Brazil and is a step towards the prevention of future disasters.

Keywords: Landslides, Geological hazards, Multivariate statistics, Natural disasters.

Resumo

Entre os tipos de movimentos de massa, os fluxos de detritos representam um risco maior à sociedade devido ao seu alto potencial de destruição. No Brasil, os estudos de fluxos de detritos ainda são incipientes quando comparados a outros processos hidrogeomorfológicos e uma melhor compreensão da sua dinâmica é fundamental para subsidiar estudos de avaliação de perigos e riscos. A estimativa da extensão dos impactos que o fenômeno representa no país é, particularmente, fundamental para subsidiar estudos direcionados e mais aprofundados. Nesse contexto, os principais objetivos desta tese são de espacializar os eventos de fluxos de detritos e avaliar o impacto socioeconômico do fenômeno no Brasil, além de propor uma metodologia que tem como objetivo reduzir os danos potenciais que eventos futuros podem causar nas regiões mais suscetíveis. A caracterização detalhada pós-evento de um fluxo de detritos também é conduzida, uma vez que é um passo fundamental na compreensão da dinâmica do fenômeno e dá suporte à proposta de metodologia de avaliação de perigo. Para determinar o impacto socioeconômico dos fluxos de detritos, foi criado um banco de dados dos eventos que causaram fatalidades e/ou perdas econômicas entre 1920 e 2021, que serviu de base para o cálculo da Taxa de Mortalidade (TM) e a aplicação de Curvas F-N (Frequência de eventos vs. Número de Fatalidades). No total, 45 eventos de fluxo de detritos foram documentados no período considerado, causando mais de 5.773 mortes e US\$ 5,4 bilhões em perdas econômicas. A cidade de Cubatão (SP) apresenta o maior número de eventos, consolidando-se como a região mais propensa a fluxos de detritos no país. Consequentemente, a proposta de uma metodologia de avaliação de perigo a fluxos de detritos em várias etapas é feita utilizando Cubatão como área piloto, que tem como base a combinação de análise de Regressão Logística (LR), simulação numérica e retro análise de eventos de chuva. Os resultados da LR destacam que a chuva é o principal fator de influência no início do fluxo de detritos na região, além de também indicarem as bacias mais suscetíveis ao fenômeno no local de estudo. Os resultados da simulação de fluxos de detritos nas bacias indicadas pelo LR mostram que a distância média de *runout* na região é de 470 m, com altura média do pico do fluxo de 5 m e velocidade de pico de 23 m s^{-1} . Esses resultados são comparáveis ao evento de fluxo de detritos de fevereiro de 2017 que ocorreu na bacia hidrográfica de Pedra Branca (Guaratuba, estado do Paraná), no qual uma caracterização geomorfológica pós-evento detalhada foi realizada com o objetivo de estimar a magnitude do evento. O evento de Guaratuba foi um fluxo de detritos “rochoso” (*stony debris flow*) de grande porte, com magnitude total de 120.195 m^3 , altura do pico de vazão de 7 m e pico de velocidade de $26,5 \text{ m s}^{-1}$. Os eventos de fluxo de detritos em Cubatão e Guaratuba são, de uma forma geral, desencadeados por precipitação de curta duração (<48 h), alta intensidade (>200 mm), com períodos de retorno que variam de 3 a 15 anos. Cinco níveis de risco (muito baixo a muito

alto) foram, então, propostos em nosso método de avaliação de perigo, baseado principalmente na chuva acumulada em 48 horas, propriedades cinemáticas do fluxo (altura de vazão, velocidade) e nos elementos no raio de perigo (infraestruturas, casas, etc.). As áreas industriais e residenciais na rota estimada de fluxo de detritos geralmente exibem os mais altos níveis de perigo geral na área piloto, uma vez que se desenvolveram na área de deposição do fenômeno e perto de cursos fluviais, onde podem ocorrer inundações e enxurradas associadas. Conforme apontado por estudos recentes, projeta-se um aumento na frequência de eventos extremos de precipitação na região da Serra do Mar e, quando se considera o curto período geral de retorno das chuvas desencadeadoras do fenômeno (< 20 anos), eventos de fluxos de detritos de alta magnitude ($> 10^5 \text{ m}^3$) podem ocorrer na próxima década nas áreas consideradas nesta tese, localizadas na região da Serra do Mar paulista e paranaense. Esta tese, portanto, contribui para a melhor compreensão da dinâmica dos fluxos de detritos no Brasil e para a prevenção de futuros desastres.

Palavras-chave: Movimentos de Massa, Perigos geológicos, Estatística multivariada, Desastres naturais.

Zusammenfassung

Unter den Rutschungsarten stellen Murgänge aufgrund ihres hohen Zerstörungspotentials eine größere Gefahr für die Gesellschaft dar. In Brasilien sind Murgangstudien im Vergleich zu anderen hydrogeomorphen Prozessen noch am Anfang und ein gutes Verständnis ihrer Dynamik ist essentiell für die Erstellung von Gefahren- und Risikobewertungsstudien. Insbesondere ist die Bestimmung des Ausmaßes der Auswirkungen, die das Phänomen in einer Region oder einem Land darstellt, von wesentlicher Bedeutung für gezielte und eingehendere Studien. In diesem Zusammenhang besteht das Hauptziel dieser Arbeit darin, die gesellschaftlichen Auswirkungen von Murgängen in Brasilien zu bewerten und eine Methodik vorzuschlagen, die darauf abzielt, den potenziellen Schaden zu verringern, den zukünftige Ereignisse in anfälligen Regionen verursachen können. Eine detaillierte Nachuntersuchung eines Murgangereignisses wird ebenfalls durchgeführt, da dies ein grundlegender Schritt zum Verständnis der Dynamik des Phänomens ist und den Vorschlag der Gefahrenbewertungsmethodik weiter unterstützen kann. Um die gesellschaftlichen Auswirkungen von Murgängen zu bestimmen, wurde ein Katalog von Ereignissen erstellt, die zwischen 1920 und 2021 Todesopfer und/oder wirtschaftliche Schäden verursacht haben, was die Berechnung der Murgangmortalitätsrate (MR) und die Anwendung der sogenannten F-N unterstützten Kurven (Häufigkeit von Ereignissen vs. Anzahl Todesfälle) ermöglicht. Insgesamt wurden im betrachteten Zeitraum 45 Murgangereignisse dokumentiert, die mehr als 5.773 Todesopfer und 5,4 Milliarden US-Dollar an wirtschaftlichen Schäden verursachten. Die Stadt Cubatão (Bundesstaat São Paulo) weist die meisten Ereignisse auf und festigt damit ihren Status als die am stärksten von Murgängen bedrohte Region des Landes. Daher wird eine mehrstufige Gefährdungsbeurteilung vorgeschlagen und am Beispiel von Cubatão getestet, basierend auf einer Kombination von logistischer Regressionsanalyse (LR), numerischer Simulation und Niederschlagsrückanalyse. Die LR-Ergebnisse verdeutlichen, dass Niederschlag der Haupteinflussfaktor bei der Entstehung von Murgängen in der Region ist und zeigen die Einzugsgebiete, die für das Phänomen in der Region anfälliger sind. Die Simulationsergebnisse von zwei Murgangereignissen, die in diesen Einzugsgebieten durchgeführt wurden, zeigen, dass die durchschnittliche Auslaufstrecke in der Region 470 m beträgt, mit einer durchschnittlichen Fließhöhe von 5 m und einer Spitzengeschwindigkeit von 23 m s⁻¹. Diese Ergebnisse sind vergleichbar mit dem Murgangereignis vom Februar 2017 im Einzugsgebiet von Pedra Branca (Guaratuba, Bundesstaat Paraná), bei dem eine detaillierte geomorphologische Charakterisierung nach dem Ereignis durchgeführt wurde, um das Ausmaß des Ereignisses abzuschätzen. Bei dem Guaratuba-Ereignis handelte es sich um einen großen steinigen Schuttstrom mit einer Gesamtgröße von 120.195 m³, einem Spitzenabfluss von 2.146,7 m³ s⁻¹ und einer Spitzengeschwindigkeit von 26,5 m s⁻¹.

Murgangereignisse in Cubatão und Guaratuba wurden durch Niederschläge von kurzer Dauer (< 48 h) und hoher Intensität (> 200 mm) mit Wiederkehrperioden von 3 bis 15 Jahren ausgelöst. Fünf Gefahrenstufen (sehr gering bis sehr hoch) werden dann in unserer Gefahrenbewertungsmethode vorgeschlagen, die hauptsächlich auf den Niederschlägen über 48 Stunden und Strömungseigenschaften basiert. In Cubatão weisen Industrie- und Wohngebiete in der prognostizierten Murgangroute im Allgemeinen die höchsten Gesamtgefahrenstufen auf, da diese sich überwiegend im Ablagerungsgebiet des Phänomens und in der Nähe von Flussläufen befinden, wo damit verbundene Überschwemmungen und Sturzfluten auftreten können. Wie neuere Studien zeigen, wird in der Region Serra do Mar eine Zunahme der Häufigkeit extremer Niederschlagsereignisse prognostiziert; unter Berücksichtigung der allgemein kurzen Wiederkehrperiode (< 20 Jahre) von Murgang auslösenden Niederschlägen, können Ereignisse großen Ausmaßes (> 105 m³) im nächsten Jahrzehnt in Teilen der Bergkette in den Bundesstaaten São Paulo und Paraná auftreten. Diese Arbeit trägt daher zum besseren Verständnis der Dynamik von Murgängen in Brasilien bei und ist ein Schritt zur Vermeidung zukünftiger Katastrophen.

Keywords: Erdbeben, Geologische Gefahren, Multivariate Statistik, Naturkatastrophen.

List of Figures

Figure 3-1. Geographic distribution of reported debris-flow events in Brazil. The reported events are more often associated to the mountain ranges of Serra do Mar, Serra da Mantiqueira and Serra Geral. The underlying Digital Elevation Model (DEM) is created using GTOPO30 data retrieved from Earth Explorer (USGS, 2021).	20
Figure 3-2. Mortality rate (MR) and demographic analysis. A) Average national debris-flow MR (red bar) through the decades, compared to the debris-flow MR of the Southeastern (blue), Northeastern (green), and Southern (yellow) region. B) Populational growth of Brazil according to census year, compared to the average mortality rate through the decades comprising all death causes (dark red bar). The number of people living in urban areas has been steadily increasing since 1960. The Demographic and average MR data for Brazil is retrieved from IBGE (2019; 2021).	22
Figure 3-3. Mortality Rate (MR) per 100,000 people per year of different death causes in Brazil. The average mortality rates for the last decade (2011-2020) are based on data from the Global Burden of Diseases (VOS et al., 2020). The MR of coronavirus in Brazil is based on data from the Brazilian Health Ministry (BRASIL, 2021c). The figure is based on Strouth and McDougall (2021).	24
Figure 3-4. F-N curves of debris-flow events in Brazil compared to other countries. Debris flows represent a higher societal risk than landslide events (also comprising debris flows) in China (TIANCHI et al., 1989), Japan (CASCINI et al., 2008), Hong Kong (HO; KO, 2009), and Italy (GUZZETTI, 2000).	25
Figure 3-5. Societal risk thresholds adopted by Hong Kong, which commissioned the creation of the criterions specifically for landslides (ERM 1998).	26
Figure 3-6. Location of the study area, where the hazard assessment is conducted, as well as the analysis of the factors that influence debris-flow initiation in a catchment. A) The study area (Cubatão, São Paulo State), located in the Serra do Mar Mountain Range, Brazil. B) Overview of the analyzed catchments (numbers in white circles), located at the central and northeastern hillslopes of Cubatão (2022).	28
Figure 3-7: Occurrence of debris-flow according to month. Debris flows are more common in summer months (December – March).	33
Figure 3-8. Average rainfall indices for Brazil, based on the climate data from Brazil’s pluviometric atlas (CPRM, 2021). Debris flows generally occur in areas with average annual rainfall higher than 1,650 mm.	34
Figure 3-9. Daily rainfall indices up to 4 days (96 hours) prior to debris-flow events in the region of Cubatão (blue bars). The phenomenon’s initiation is more strongly influenced by the rainfall accumulated 48 hours prior to an event, as highlighted by the cumulative percentage graph (orange lines).	35
Figure 3-10. Rainfall event that triggered the February 2017 debris flow in Guaratuba (state of Paraná). A) Hourly precipitation for February 11 and 12, 2017, according to the three nearest rain gauges. Rain gauge ‘Arteris’ is located 1 km from Pedra Branca catchment, while ‘Garuva’ and ‘Estrada Geral Quiriri’ are located at approximately 10 km and 30 km away, respectively. B) Precipitation recorded every 15 minutes by the rain gauges ‘Arteris’ and ‘Garuva’ between 18:00 LT (2100 UTC) and 23:00 (0200 UTC).	35
Figure 3-11. Rainfall analysis. a) Relationship between 24-h accumulated rainfall and magnitude. B) Relationship between hourly rainfall and magnitude. C) Relationship between daily rainfall and economic losses. D) Relationship between hourly rainfall and economic losses. E) Relationship between 24-h accumulated precipitation and number of fatalities. F) Relationship between hourly rainfall and number of fatalities.	37
Figure 3-12. Correlation between rainfall and landslide volume (left) and rainfall and estimated debris-flow magnitudes (right), for the catchments located in Cubatão. The correlation is based on data from the 1985 and 1994 landslide and debris-flow events and the different rainfall indices are based on the spatial distribution of the rain event in the region. A) Correlation between 48-h accumulated rainfall and landslide volume – 1985. B) Correlation between 48-accumulated rainfall and landslide volume – 1994. C) Correlation between 48-h accumulated rainfall and estimated debris-flow magnitude – 1985. D) Correlation between 48-h accumulated rainfall and estimated debris-flow magnitude – 1994.	38
Figure 3-13. Pedra Branca catchment (right) in the municipality of Guaratuba, State of Paraná, Brazil. At the top left, the extension of the Serra do Mar mountain range. At the bottom left, the Digital Terrain Model (DTM) for the broader region of the catchment with the location of the three nearest rain gauges.	39
Figure 3-14. A) Pronounced erosion and scour of channel bed is observed at the upstream section – 1.8 m human profile for scaling. B) Intense accumulation of debris at the middle section– in detail, a 1.75 m human profile for scaling. C) Accumulation of debris at the downstream section, with smaller sized-boulders than in the middle section - 1.75 m human profile for scaling. D) Reversely graded pattern observed in debris dams. E) Debouchment of the Pedra Branca river into the São João River, where flow height reached up to 2 m. F) São João river, which received sediments from the Pedra Branca debris flow (photo from August 2017).	41
Figure 3-15. Debris deposition and jam formation. A) Large wood forming a jam that was later broken by the flow’s passage (SG1). B) Mixture of woody and stony debris and formation of debris dams (SG12) – 1.75 m	

human profile for scaling. C) Plot showing the Pedra Branca channel profile and the volume of deposited debris along the debris flow route. Debris deposition is higher in the middle section of the channel (SG19 to SG11).	42
Figure 3-16. Mapping of entrainment and deposition areas based on the orthophotos acquired using UAV. Areas in shades of blue represent debris-accumulation areas and areas in shades of red represent entrainment areas.	43
Figure 3-17. Characteristics of the 2017 debris flow. A) Distribution of on-channel debris volume along the debris flow path in relation to channel slope B) Erosion depth distribution along the debris flow path in relation to channel slope C) Scatterplot showing the relationship between on-channel debris volume and channel slope. D) Scatterplot showing the relationship between erosion depth and channel slope. Bedrock and loose debris refer to the on-channel material post-event. E) Maximum debris size (D_{90}) distribution along the debris flow path in relation to channel slope (measured between every two cross-sections). F) Peak flow height distribution in relation to channel slope.	44
Figure 3-18. A) Location of the 28 cross-sections made along the debris-flow path that supported the magnitude estimation. B) Overview of the headwaters' region of the catchment, highlighting the three landslide scars that initiated the debris flow. C) Longitudinal profile of Pedra Branca catchment with the tentative location of the cross-sections. Channel in blue and slopes in brown.	45
Figure 3-19. Discharge and flow velocity pattern along the debris flow path.	46
Figure 3-20. Debris-flow dynamics. A) Scheme of a debris flow in gullies/catchments, triggered by shallow landslides in the headwaters' region. B) the 1975 debris-flow event that occurred in one of the streams of catchment 1 in Cubatão. Photo from Prof. Dr. Milton Kanji, retrieved from Gramani (2001). C) Overview of the stream where the 1975 debris-flow event occurred, showing intense accumulation of rock boulders in the channel (Coordinates: 365926.79 m E, 7368058.54 m S). D) Upstream view of catchment 20 in Cubatão, showing intense stony debris accumulation in the channel, as well as Large Wood (Coordinates: 350665.03 m E, 7358314.49 m S).	48
Figure 3-21. Debris-flow dynamics. A) Scheme of the initiation mechanism of the 1985 and 1994 debris-flow events in Cubatão, characterized by multiple source areas. B) Upstream view of catchment 7 in Cubatão, showing intense stony debris accumulation in the channel, as well as fractured bedrock outcrops in the margins (Coordinates: 360256.69 m E, 7367963.72 m S) C) Overview of the upstream section of catchment 19 in Cubatão, showing intense stony debris accumulation in a channel. A strong structural control is observed in the catchment (Coordinates: 350847.96 m E, 7360336.15 m S). D) Downstream view of the upstream section of catchment 7 in Cubatão, showing area with less accumulation of debris in the channel. Areas with intense stony and woody debris deposition are intercalated with areas with few accumulations along the catchment, suggesting that smaller debris-flow might have occurred more recently in small gullies or that slope failures occurred but did not trigger a debris-flow event, accumulating the material in the channel. (Coordinates: 360256.69 m E, 7367963.72 m S).	49
Figure 3-22. Recent debris flow in Cubatão and retention structures installed in Catchment 17. A) The tributary of Catchment 17 before the March 2022 event. Photo from 2014. B) The tributary after the debris-flow event, showing the intense erosion of the channel and vegetation. The measured post-event channel width is of 7 m. Photo from July 2022. C) Photo of the debris-flow event on the day after its occurrence (March 30, 2022). Photo from Maicon, one of the monitors of the "Caminhos do Mar" Park. D) Retention structures installed in the downstream portion of catchment 17, to protect the oil refinery from debris-flow events. Photo from Marcelo Gramani. E) Detail of two Sabo dams located in catchment 17. Photo from Marcelo Gramani.	54
Figure 3-23. Map showing the overall susceptibility to debris-flow initiation of the 20 catchments at the study area, based on the LR model.	56
Figure 3-24. Calibration using the coverage index (Ω) of the debris-flow simulations for the selected catchments at the study area. The closer the coverage index is to 1, the more representative the simulation.	57
Figure 3-25. Comparison between modeled and observed run-out distance of the 1994 debris-flow event for the selected catchments.	59
Figure 3-26. Comparison between modeled and observed run-out distances of the 1985 debris-flow event for the selected catchments.	60
Figure 3-27. RAMMS modeling results showing maximum flow height. A) Catchment 7 (1985). B) Catchment 8 (1985). C) Catchments 9 and 10 (1985). D) Catchment 15 and 16 (1994). E) Catchment 14 (1994). F) Catchments 14 and 12 (1985).	61
Figure 3-28. RAMMS modeling results showing maximum flow height. A) Catchment 17 (1994). B) Catchment 19 (1994). C) Catchment 1 (1985).	62
Figure 3-29. Debris-flow hazard zonation, based mainly on flow properties and on rainfall intensity (> 200 mm in 48 h), as well as on the analysis of the elements at hazard.	65

List of Tables

Table 3-1: Analysis of debris-flow related damages according to state. Fatalities include missing people. Avg. = average, N/A = not available.	19
Table 3-2: Analysis of debris-flow related damages according to municipality. Fatalities include reported cases of dead and missing people. N/A = not available.	21
Table 3-3. Influencing factors analyzed in this study.	29
Table 3-4. Results of the ROC analysis of the validation tests of the LR models, according to the Area Under the Curve (AUC) of the ROC Curve.	30
Table 3-5. Statistical validation of the LR models, showing the regression coefficients (B) and relevant statistical parameters.	32
Table 3-6. Morphometric parameters of the catchments located in Cubatão (Southeastern portion of Serra do Mar). Catch. = Catchment.	50
Table 3-7. Morphometric parameters of the catchment located in Guaratuba (Southern portion of Serra do Mar), where a debris flow occurred in February 2017. Catch. = Catchment.	50
Table 3-8. Morphometric Parameters of debris-flow prone catchments worldwide, adapted from Dias <i>et al.</i> (2022).	51
Table 3-9. Debris flow events recorded in Cubatão since 1975, updated based on Gramani (2001).	52
Table 3-10. RAMMS-2D results and characteristics of the debris flows. Est. = estimated, Max. = maximum...	57
Table 3-11. Hazard level matrix developed for the study area, based on different rainfall indices and the impacts on infrastructures and population.	63
Table 3-8. Infrastructures, both public and private, at hazard in each catchment and overall hazard level, for a 200 mm rainfall in 48 h.	64

Table of Contents

List of accepted publications.....	13
1. Introduction	14
2. Objectives.....	18
3. Results and discussions	19
3.1. <i>The impact of debris flows in Brazil.....</i>	<i>19</i>
3.2. <i>The main factors that initiate a debris flow in a catchment</i>	<i>27</i>
3.3. <i>Rainfall analysis and correlation with the consequences of a debris-flow event.....</i>	<i>32</i>
3.4. <i>A detailed field characterization of a debris-flow event</i>	<i>38</i>
3.5. <i>Differences and similarities of debris-flow prone catchments at Serra do Mar</i>	<i>46</i>
3.6. <i>A multi-step hazard assessment methodology for debris-flow prone areas influenced by hydroclimatic events</i>	<i>55</i>
4. Final considerations	66
Bibliography	68
APPENDIX A - Accepted manuscripts.....	88

List of accepted publications

- I. **Cabral VC**, Reis FAV, Veloso V, Corrêa CV, Kuhn C, Zarfl C (2022) The consequences of debris flows in Brazil: a historical analysis based on recorded events in the last 100 years. *Landslides*. Doi: <https://doi.org/10.1007/s10346-022-01984-7>.

Individual contributions: Victor Cabral designed the concept of this study with the support of Fábio Reis. Victor Cabral reviewed literature and wrote the manuscript with the support of Christiane Zarfl. Vinicius Veloso, Christiane Zarfl, Claudia dos Santos Corrêa and Caiubi Kuhn supported the analysis of the data.

- II. **Cabral VC**, Reis FAV, D’Affonseca FM, Lucía A, ..., Zarfl C (2021) Characterization of a landslide-triggered debris flow at a rainforest-covered mountain region in Brazil. *Natural Hazards* 108: 3021 – 3043. Doi: <https://doi.org/10.1007/s11069-021-04811-9>.

Individual contributions: Victor Cabral and Fábio Reis designed the concept of this study. Victor Cabral reviewed literature and wrote the manuscript with the support of Ana Lucía, Christiane Zarfl and Fernando D’Affonseca. Victor Cabral, Claudia Corrêa, Vinicius Veloso, Marcelo Gramani, Agostinho Ogura, Andrea Lazaretti, Felipe Vemado, Augusto José Pereira Filho, Claudia Santos, Eymar Lopes, Lis Rabado and Lucília Giordano supported the collection of the data that sourced the manuscript.

- III. **Cabral VC**, Reis FAV, Veloso V, Ogura AT, Zarfl C (2023) A multi-step hazard assessment for debris-flow prone areas influenced by hydroclimatic events. *Engineering Geology*. Doi: <https://doi.org/10.1016/j.enggeo.2022.106961>

Individual contributions: Victor Cabral designed the concept of this study. Victor Cabral reviewed literature and wrote the manuscript with the support of Christiane Zarfl. Fábio Reis, Christiane Zarfl, Vinicius Veloso and Agostinho Ogura supported the analysis of the data and the final review.

1. Introduction

Debris flows represent great threat to humans and infrastructures in mountain regions worldwide, due mainly to their sudden occurrence and high impact energy that can cause great damage along their path (IVERSON, 2000; BEGUERIA *et al.*, 2009; LUNA *et al.*, 2012). The phenomenon occurs when a mixture of earth material, water and air very rapidly surges down steep drainage paths (VARNES, 1978; TAKAHASHI, 2006; HUNGR *et al.*, 2014), with high-intensity rainfall as the primary triggering factor (MILNE *et al.*, 2008). The increasing frequency of extreme rainfall events on a global scale (BENISTON 2009; GIORGI *et al.*, 2011; BORGA *et al.*, 2014; WESTRA *et al.*, 2014) has been associated to an observed increase in the frequency and magnitude of debris-flow events (STOFFEL; HUGGEL, 2012; WINTER; SHEARER, 2014; BORGA *et al.*, 2014), which, combined with landslides, were responsible for more than 32,000 fatalities between 2004 and 2010 worldwide (PETLEY, 2012; BORGA *et al.*, 2014).

In Brazil, debris flows are mainly initiated by rainfall-triggered landslides (WOLLE; HACHICH, 1989; LACERDA, 2007) and the Serra do Mar Mountain Range is the main site of occurrence, due to its steep slopes and high rainfall rates (VIEIRA *et al.*, 2010; VIEIRA; GRAMANI, 2015). Recent projections in the context of global warming have indicated that the Serra do Mar region may experience a surge in the frequency and magnitude of hydrogeomorphic processes, particularly in scenarios with a 2.0° C increase in Global Warming Levels (GWLs) (MARENGO *et al.*, 2021). More frequent debris-flow events can lead to significant socioeconomic losses, especially in the Global South¹ where little investment is made to prevent natural disasters (PETLEY, 2012; COROMINAS *et al.*, 2013; MARENGO *et al.*, 2021).

According to Bastos *et al.* (2015), landslides and debris flows were responsible for approximately 1,700 deaths in Brazil between 2000 and 2010, affecting almost 8 million people and causing economic losses of 1.5 billion USD (United States Dollar). The increasing urbanization towards mountain regions, especially in south and southeast Brazil, has been highlighted by recent studies (GUERRA *et al.*, 2007; PATEL; BURKE, 2009; LONDE *et al.*, 2018), which can further increase the humanitarian losses that the debris flows can cause, as changes in society and economic development are the main driving forces that can magnify associated damage (ANDRES; BADOUX, 2018).

¹ According to the definition of the United Nations Finance Center for South-South Cooperation (UN FCSSC, 2022)

Despite this extensive history of damage and destruction related to debris flows, quantitative studies about the phenomenon in Brazil are still scarce when compared to other hydrogeomorphic processes. As a result, a reliable estimative of the damage that the phenomenon represents to the society is not yet determined, mostly due to the poor monitoring and documentation of events, which can further be linked to the irregular occurrence of debris flows (KEAN *et al.*, 2013; GREGORETTI *et al.*, 2018; DESTRO *et al.*, 2018). Moreover, the difficult access to debris-flow prone catchments also represents a challenge for the acquisition of good-quality data, which is a prerequisite for reliable risk and hazard studies, as well as for understanding the dynamics and mechanisms of the phenomenon (ÁLVALA *et al.*, 2019).

In Geosciences, hazard can be defined as a process or phenomenon that may cause negative impacts to the society, such as loss of life, injuries, property damages, social and economic disruption or environmental degradation (UNDRR, 2015). Hazard incorporates the concepts of *magnitude* (the intensity), *geographical location* (the place the phenomenon occurred) and *time recurrence* (temporal frequency) (GUZZETTI *et al.*, 1999). Risk considers the probability of the negative effects to occur, as a function of the *hazard*, *exposure* (human assets in the hazard zone), *vulnerability* (the social, physical, economic and environmental conditions) and *capacity* (resources to cope with the consequences) (UNDRR, 2015). Risk assessment studies, therefore, require a more multidisciplinary approach.

The foundation of a hazard assessment that focuses on landslide-triggered debris flows commonly relies on a comprehensive landslide inventory, knowledge of the main controlling and triggering factors that influence their occurrence, as well as the consideration of the elements at hazard (SOETERS; VAN WESTEN, 1996; VAN WESTEN *et al.*, 2008; COROMINAS *et al.*, 2013). Landslide inventories are a critical first step, as they are applied in the investigation of their distribution patterns in relation to environmental variables, as well as in the validation of hazard scenarios (CARDINALI *et al.*, 2002; VAN WESTEN *et al.*, 2008; BĂLTEANU *et al.*, 2010; GUZZETTI *et al.*, 2012; STEGER *et al.*, 2021). The creation of landslide inventories is often dependent on the availability of aerial imagery both prior and after an event, which can represent a serious limiting factor in most regions of Brazil.

The influencing factors are associated to the triggering and controlling parameters that lead to debris-flow occurrence, which can vary according to the characteristics of a region (COROMINAS *et al.*, 2013; NIKOLOVA *et al.*, 2020). Since the study of Melton (1958), several attempts have been made at identifying the critical morphometric variables that control debris-flow initiation in a catchment (e.g., ZHOU *et al.*, 1991; LIN *et al.*, 1993; CHEN; SHIEH, 1993; BOVIS; JAKOB, 1999; LIN *et al.*, 2002; WILFORD *et al.*, 2004; KOVANEN;

SLAYMAKER, 2008; BERTRAND *et al.*, 2013; MEYER *et al.*, 2014; HEISER *et al.*, 2015; LAY *et al.*, 2019; NIKOLOVA *et al.*, 2020), including in Brazil (e.g., DIAS *et al.*, 2016; CERRI *et al.*, 2018; GABELINI *et al.*, 2019, CABRAL *et al.*, 2019; among others). Multivariate statistics analyses have traditionally been applied in this regard, due to their objective evaluation of the relationship between a dependent variable (occurrence or not of an event) and a series of independent variables (i.e., the influencing factors) (SÜZEN; KAYA, 2011; COROMINAS *et al.*, 2013; BUDIMIR *et al.*, 2015).

More recently, numerical and physically-based models have been developed to support hazard and risk analysis, due to their ability to represent important features of the debris-flow dynamics (CROSTA *et al.*, 2003; MEDINA *et al.* 2008; HUSSIN *et al.*, 2012; CASTELLI *et al.*, 2017). These models can predict runout path and distance, velocity, flow height and impact pressure, as well as entrainment rate (FRANK *et al.*, 2017), which are fundamental to estimating hazard intensity and to supporting the dimensioning of protective structures and measures (TAN *et al.*, 2020). Some examples of dynamic models include DAN-3D (HUNGR; MCDOUGALL, 2009; SALVATICI *et al.*, 2017), FLO-2D (MUIR *et al.*, 2006; QUAN LUNA *et al.*, 2011) and RAMMS (FRANK *et al.*, 2015; 2017).

Furthermore, direct field investigations are essential to better understanding the debris-flow dynamics in a catchment (GAUME; BORGA, 2008; BORGA *et al.*, 2014; LUCÍA *et al.*, 2018). Field investigations can also provide a sound knowledge of the magnitude of a debris-flow event (i.e., the total volume of transported debris), which is a prerequisite for quantifying associated hazards (JAKOB, 2005a). Magnitude estimations are more commonly carried out by statistical and empirical methods (e.g., TAKAHASHI, 1992; BIANCO; FRANZI, 2000; MASSAD, 2002; TAKAHASHI, 2006; KANJI *et al.*, 2007; CHANG *et al.*, 2011) or by post-event (forensic) geomorphological investigation of the debris-flow route in a catchment (e.g., MARCHI; D'AGOSTINO, 2004; LIU *et al.*, 2009; GREGORETTI *et al.*, 2018).

Geomorphology-based estimations are considered one of the most accurate, since they are based on direct field evidences (LIU *et al.*, 2009; GREGORETTI *et al.*, 2018) and do not necessarily require information about previous events (MARCHI; D'AGOSTINO, 2004), which can be especially rare in Brazil. By estimating the magnitude, important kinematic parameters such as peak discharge and flow velocity can also be obtained (RICKENMANN, 1999; PAK; LEE, 2008; SANTI *et al.*, 2008; REID *et al.*, 2016), which can greatly support debris-flow hazard assessments (KANJI *et al.*, 2007; SANTI, 2014; GREGORETTI *et al.*, 2018).

In this brief context, the following questions arise:

- What are the societal consequences of debris flows in Brazil?
- What are the most affected regions in the country?
- What are the main characteristics of debris flows in Brazilian catchments and in what way their kinematic parameters influence hazard levels?
- What are the differences and similarities between the dynamics and mechanisms of the phenomenon in different Brazilian catchments?
- What methods can more successfully be applied to mitigate and prevent new losses in the most affected areas?

Three papers have been developed during this research, in the attempt to answering these questions and which results are integrated and discussed in this thesis. Paper I, entitled “*The consequences of debris flows in Brazil: a historical analysis based on recorded events in the last 100 years*”, provides an overview of the damage and losses that the phenomenon has caused so far, based on a comprehensive compilation of recorded events between 1920 and 2021. Paper I also highlights the areas in Brazil where debris flows are more common and have historically caused more negative consequences.

A detailed characterization of a debris-flow event is conducted in Paper II, entitled “*Characterization of a landslide-triggered debris flow at a rainforest-covered mountain range in Brazil*”, to describe the dynamics of the phenomenon in a Brazilian catchment and to contribute to better understanding the hazard that debris flows can represent to the society. A more in-depth analysis and comparison of debris-flow dynamics in different Brazilian catchments is conducted in this thesis.

Furthermore, Paper III proposes a “*multi-step hazard assessment for debris-flow prone areas influenced by hydroclimatic events*”, which is also the title of the study, based on the combination of Logistic Regression analysis, numerical simulation and rainfall back-analysis. The method was developed mainly for tropical and subtropical areas and the region of Cubatão (São Paulo State) is chosen as test site for the study, as it is identified by Paper I as one of the regions most affected by debris flows in Brazil. The results of Paper II are also compared and incorporated in the development of the hazard assessment presented in Paper III. The three papers are available in Appendix A.

2. Objectives

The main objectives are to assess the societal impact of debris flows in Brazil and to propose a methodology that aims at reducing the potential damage that future events can cause in susceptible regions. Another objective is to conduct a detailed post-event characterization of a debris flow, as it is a fundamental step to understanding the phenomenon and can further support the proposal of the hazard assessment methodology. As for the specific objectives, they include:

- To create a comprehensive catalogue of debris-flow events that have caused fatalities and/or economic losses in the last 100 years in Brazil;
- To quantify the social and economic consequences that the phenomenon represents in the country;
- To identify the main factors that influence debris-flow initiation in a catchment;
- To conduct a rainfall back-analysis aimed at identifying precipitation patterns that lead to the phenomenon;
- To correlate rainfall with the magnitude and consequences of a debris-flow event;
- To characterize the dynamics and to estimate the magnitude of a recent debris-flow event, to better comprehend the development of the phenomenon in a Brazilian catchment, which can also further aid the implementation of preventive measures and support hazard assessments;
- To propose a hazard zonation matrix that can be applied in hazard assessment studies of debris-flow prone areas.

The thesis contributes to the effort of better understanding the dynamics of debris flows in Brazil and is a step towards the prevention of future disasters.

3. Results and discussions

3.1. The impact of debris flows in Brazil

According to the catalogue compiled in our research and presented in Paper I, 45 debris-flow events have occurred in Brazil between 1920 and 2021, which have caused fatalities and/or economic losses. Figure 3.1 shows the spatial distribution of these events, responsible for at least 5.5 billion USD in direct economic losses and over 5,771 fatalities (Table 3.1). According to our estimates, the average fatality rate per event is around 128 (total number of deaths/total number of debris-flow events) and the average economic loss per event is of ca. 122 million USD (total sum of economic losses/total number of debris-flow events).

In total, 64.5% of the recorded debris-flow events occur at the Serra do Mar Mountain range, followed by Serra da Mantiqueira (13.3%) and Serra Geral (13.3%). Southeast Brazil is the most affected region by the phenomenon, both in terms of number of events and socioeconomic losses. This can be related to the highest population density in the southeast (especially in the states of Rio de Janeiro and São Paulo), the intense urbanization of the coast, where the mountain ranges “Serra do Mar” is located.

Table 3-1: Analysis of debris-flow related damages according to state. Fatalities include missing people. Avg. = average, N/A = not available.

State	Number of events	Economic losses (USD)	Fatalities	Avg. Fatality/event	Avg. Economic loss/event (USD)
Bahia (BA)	2	34,884,425	173	87	17,442,212
Ceará (CE)	1	N/A	91	91	N/A
Minas Gerais (MG)	3	718,275	286	95	359,138
Paraná (PR)	2	76,095,510	4	2	38,047,755
Rio de Janeiro (RJ)	13	3,517,256,731	4,353	335	270,558,210
São Paulo (SP)	18	168,802,604	621	35	9,377,922
Santa Catarina (SC)	5	1,693,749,577	243	49	338,749,915
Rio Grande do Sul (RS)	1	24,683,356	0	0	24,683,356
Total:	45	5,516,190,478	5,771	128	122,582,011

São Paulo is the state with the highest number of reported debris-flow events, followed by Rio de Janeiro and Santa Catarina (Table 3.1). The state of Rio de Janeiro is, by far, the most impacted by the phenomenon, with 4,353 fatalities in the last 100 years and ca. 3.5 billion USD in economic losses, which corresponds to approximately 75% of all reported fatalities and 64% of the economic losses reported in the whole country. Among the cities most affected by debris flows, Cubatão (São Paulo) and Petrópolis (Rio de Janeiro) stand out with the highest numbers of events in the considered period (9 and 6 events, respectively).

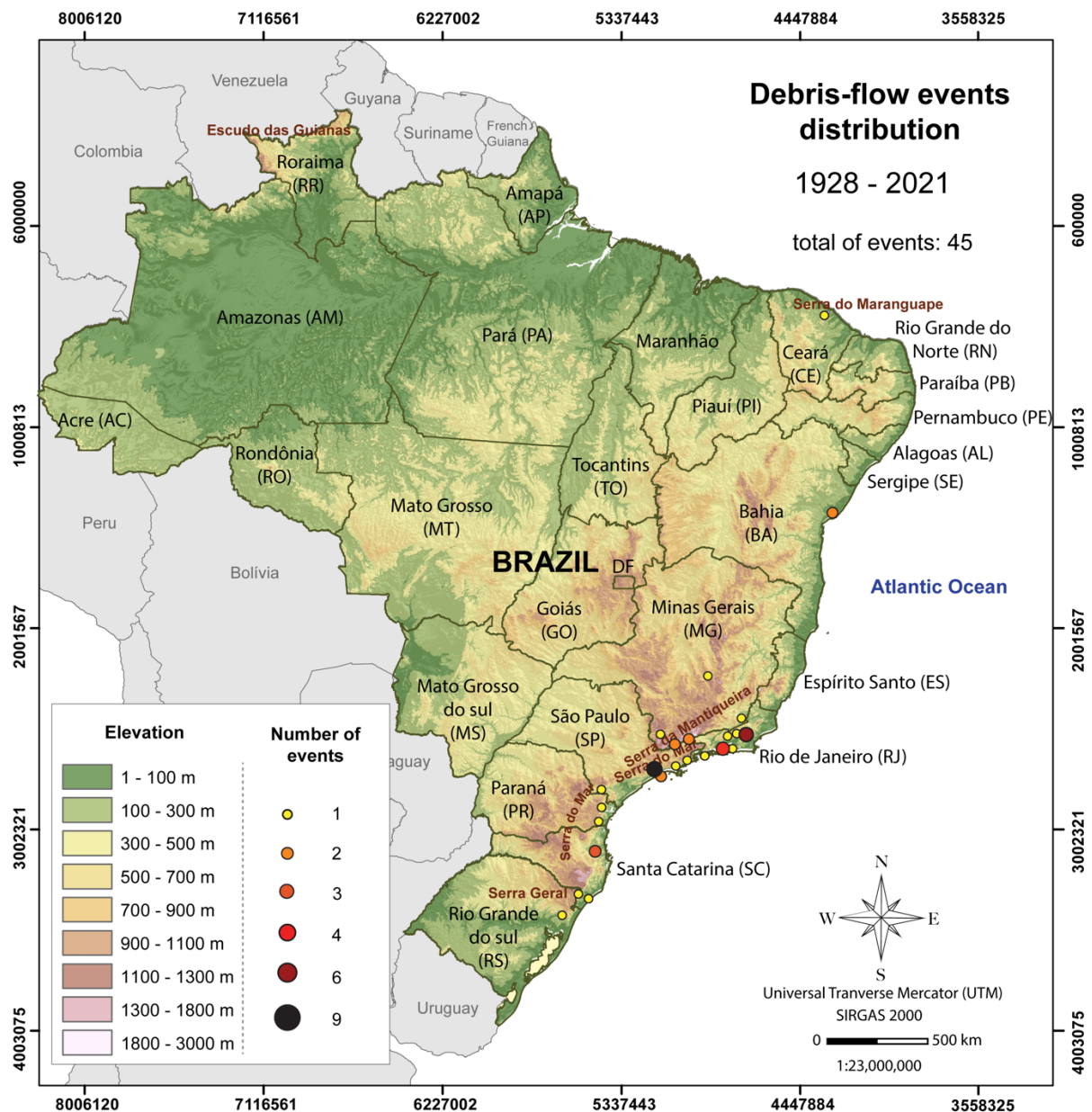


Figure 3-1. Geographic distribution of reported debris-flow events in Brazil. The reported events are more often associated to the mountain ranges of Serra do Mar, Serra da Mantiqueira and Serra Geral. The underlying Digital Elevation Model (DEM) is created using GTOPO30 data retrieved from Earth Explorer (USGS, 2021).

To assess the impact that debris-flows have caused in Brazil in the considered period, we calculated the Mortality Rate (MR) of the phenomenon and we applied the relationship between the frequency of events and their consequences, using the so-called F-N plots. Calculating the MR is a direct method of estimating the debris-flow impact in a country and is expressed as the number of deaths by debris flows per a specified population size in a defined period of time, e.g., a specific year (GUZZETTI, 2000). Here, the MR is calculated per 100,000 people. F-N plots provide the likelihood of multiple fatalities due to a debris-flow event, by plotting the cumulative frequency of events that have cause N or more fatalities (F) with the number of fatalities (N), in a log-log scale (FELL; HARTFORD, 1997).

Table 3-2: Analysis of debris-flow related damages according to municipality. Fatalities include reported cases of dead and missing people. N/A = not available.

Municipality/Region	Number of events	Economic losses (USD)	Fatalities	Material losses (unit)
Além Paraíba (MG) and Volta Grande (MG) region	1	N/A	250	63
Antonina, Morretes (PR)	1	76,095,510	25	223
Bom repouso (MG)	1	718,275	0	11
Campos do Jordão (SP)	2	N/A	27	381
Caraguatatuba (SP)	1	63,449,964	436	400
Contagem (MG)	1	N/A	36	300
Cubatão (SP)	9	73,332,253	11	40
Guaratuba (PR)	1	N/A	0	1
Ilha Grande (RJ)	1	180,668,819	31	8
Itaóca (SP)	1	5,578,975	23	123
Lavrinhas (SP)	2	2,329,412	11	N/A
Maranguape (CE)	1	N/A	91	N/A
Niterói (RJ)	1	146,587,2770	269	62
Nova Friburgo (RJ)	1	1,932,584,390*	392**	N/A
Petrópolis (RJ)	6	322,416,245 + 1,932,584,390*	428**	1,929
Rio de Janeiro (RJ)	4	1,010,547,344	804	> 1,500
Rolante (RS)	1	24,683,356	0	400
Salvador (BA)	2	34,884,425	173	1,401
Santos (SP)	2	24,112,000	102	67
Serra das Araras – Pirai (RJ)	1	N/A	1700	> 100
Teresópolis (RJ)	1	1,932,584,390*	429**	N/A
Timbé do Sul (SC)	1	71,311,286	16	N/A
Tubarão (SC)	1	666,840,081	40	N/A
Ubatuba (SP)	1	N/A	11	30
Vale do Itajaí region (SC)	3	946,442,920	187	5158

* Economic losses associated to the 2011 debris flow event, undistinguished between cities

** +300 missing people, undistinguished between cities

Figure 3.2a shows the average Mortality Rate (MR) of debris flows per 100,000 habitants in Brazil for every decade between 1920 and 2020, whereas the average national MR (combining all death causes) is shown in Figure 3.2b, plotted against the population growth. The results indicate that while the average national MR has been going down since 1920, the national MR of debris flows has been fairly steady through the decades. The comparison between the declining average national MR with the steady debris-flow MR suggests that while

there have been several advances in public health and public security policies in Brazil since 1920, the same is not observed for debris-flow prevention and mitigation measures.

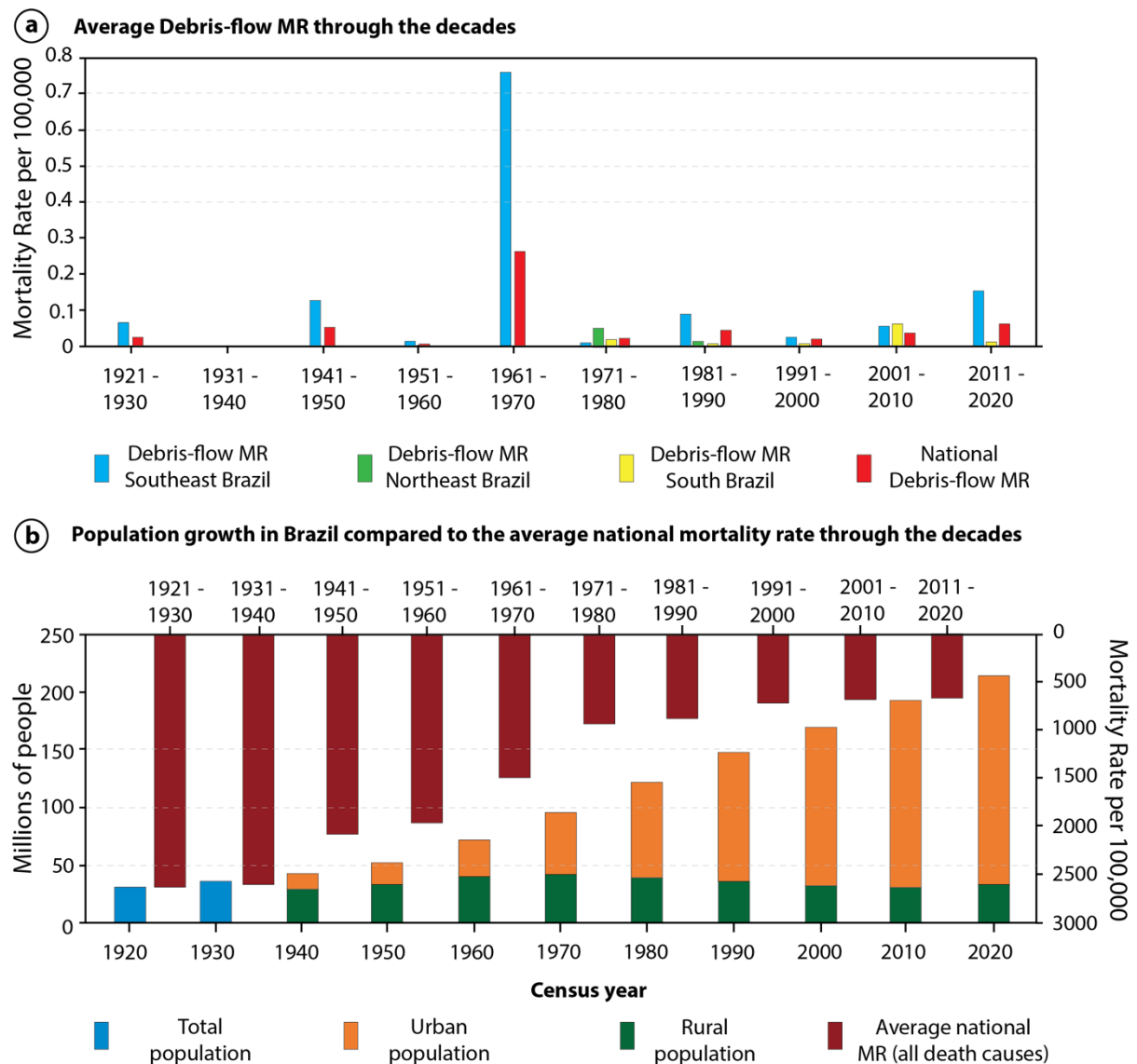


Figure 3-2. Mortality rate (MR) and demographic analysis. A) Average national debris-flow MR (red bar) through the decades, compared to the debris-flow MR of the Southeastern (blue), Northeastern (green), and Southern (yellow) region. B) Populational growth of Brazil according to census year, compared to the average mortality rate through the decades comprising all death causes (dark red bar). The number of people living in urban areas has been steadily increasing since 1960. The Demographic and average MR data for Brazil is retrieved from IBGE (2019; 2021).

Southeast Brazil exhibits the highest debris-flow MR, with debris-flow related fatalities reported in all decades since 1920, except for the 1930s (Figure 3.2a). The average MR in the Southeast ranged from 0.06 in 1920s to 0.76 in the 1960s, decreasing in the 1970s (0.004) and increasing again in the last decade (0.15). In South Brazil, debris-flow related fatalities are recorded every decade since the 1970s, with the highest average debris-flow MR in the 2000s (0.06), due to the debris-flow event in the Itajaí river basin in 2008. In Northeast Brazil, only

in the 1970s and 1980s the region reported debris-flow related deaths, with the highest debris-flow MR in the 1970s (0.05).

The debris-flow MR in the country compared to the MR of other diseases and human-induced causes is shown in Figure 3.3, considering the average MR values for the last decade (2011-2020) according to the Global Burden of Diseases (VOS *et al.*, 2020). Fatalities related to debris flows are rather rare in Brazil when compared to other death causes, with approximately 127 deaths per year during the last decade, while homicides and drowning cause each year approximately 61,000 and 6,380 deaths per year, respectively (Figure 3.3). The primary cause of death in Brazil are diseases, followed by public violence, with COVID-19 related deaths representing the leading cause of fatalities between 2020-2021.

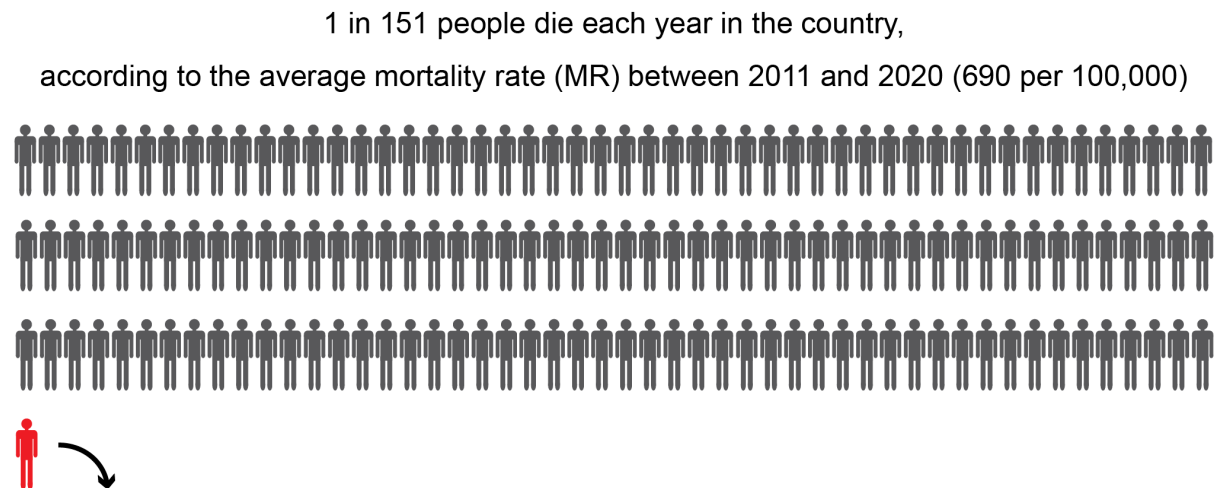
However, when we analyze the plots that considers the Frequency of Events with N or more fatalities (F) and the number fatalities (N) (Figure 3.4), we can observe the high probability of fatal events in the country, which can be directly related to the lack of preparedness and preventive programs to natural disasters. For instance, a debris-flow event with a fatality number of 1,200 or more, such as the one in 2011 in Rio de Janeiro (we refer Paper I, annex A), has a probability of occurring every 50 years, if no preventive measures are adopted, and one with 10 or more fatalities has a probability of occurring every 3 years.

When the fatal consequences of debris flows in Brazil is compared to other countries, the country stands out showing a higher societal impact than in China (TIANCHI *et al.*, 1989), Japan (CASCINI *et al.*, 2008), and Hong Kong (HO; KO, 2009), and a similar societal impact to that of Italy (GUZZETTI, 2000) (Figure 3.4). It is important to point out, however, that our analysis focuses only on debris-flow events, which tend to cause higher number of fatalities and are less frequent than localized fatal landslides (COROMINAS *et al.*, 2013), which is also considered in the other international studies and can potentially impact the slope of the F-N curve. Moreover, Japan, Italy and Hong Kong are much smaller in territorial area than Brazil, which can also potentially affect the probability of fatal events due to scale effect.

F-N plots are commonly applied in landslide studies worldwide (e.g., MACCIOTTA *et al.*, 2015; KELLER, 2017; ZHANG *et al.*, 2019; STROUTH; MCDUGALL, 2021; among others), even though they are not universally acknowledged as a good indicator of risk (EVANS; VERLANDER, 1997; STROUTH; MCDUGALL, 2021). F-N plots have also been applied in the establishment of thresholds of what is deemed as an acceptable risk by society for different types of natural hazards, including specifically for landslides (MALONE, 2005; STROUTH; MCDUGALL, 2021). Hong Kong, through the country's Geotechnical Engineering Office (GEO), established landslide risk thresholds (ERM, 1998) (**Figure 3.6**),

which have been adopted by some countries (e.g., Australia, AGS, 2007; Western Canada, PORTER; MORGENSTERN, 2013), though, as pointed out by Strouth and McDougall (2021), to no great success taking Canada as an example.

CAUSES OF DEATH IN BRAZIL



In a population of 213,460,230 (2020), this is approximately **1.4 million** deaths each year.

The causes of death vary:

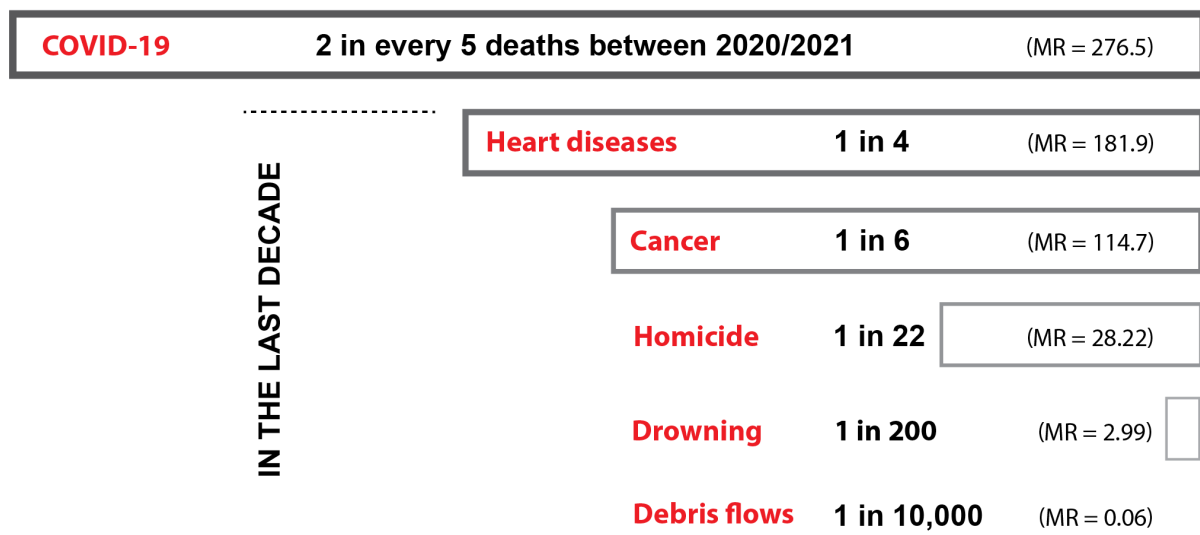


Figure 3-3. Mortality Rate (MR) per 100,000 people per year of different death causes in Brazil. The average mortality rates for the last decade (2011-2020) are based on data from the Global Burden of Diseases (VOS et al., 2020). The MR of coronavirus in Brazil is based on data from data from the Brazilian Health Ministry (BRASIL, 2021c). The figure is based on Strouth and McDougall (2021).

F-N curves can potentially be applied in risk analysis studies at cities with extensive historical incidence of debris-flow events in Brazil, such as Petrópolis and Cubatão, providing a good estimation of the probability of fatal events occurrence, which can later support

decisions about preventive measures. While F-N curves can be useful, the adoption of risk thresholds, such as the one from GEO (ERM, 1998), can be more challenging. Despite similar climate and hydrogeomorphic process dynamics (HO; KO, 2009; LACERDA, 2007), especially in the southeast region of Brazil (sub-tropical climate), economic and cultural differences about the perception of landslide and debris-flow risk are some of the factors that are not easily transferable (STROUTH; MCDOUGALL, 2021).

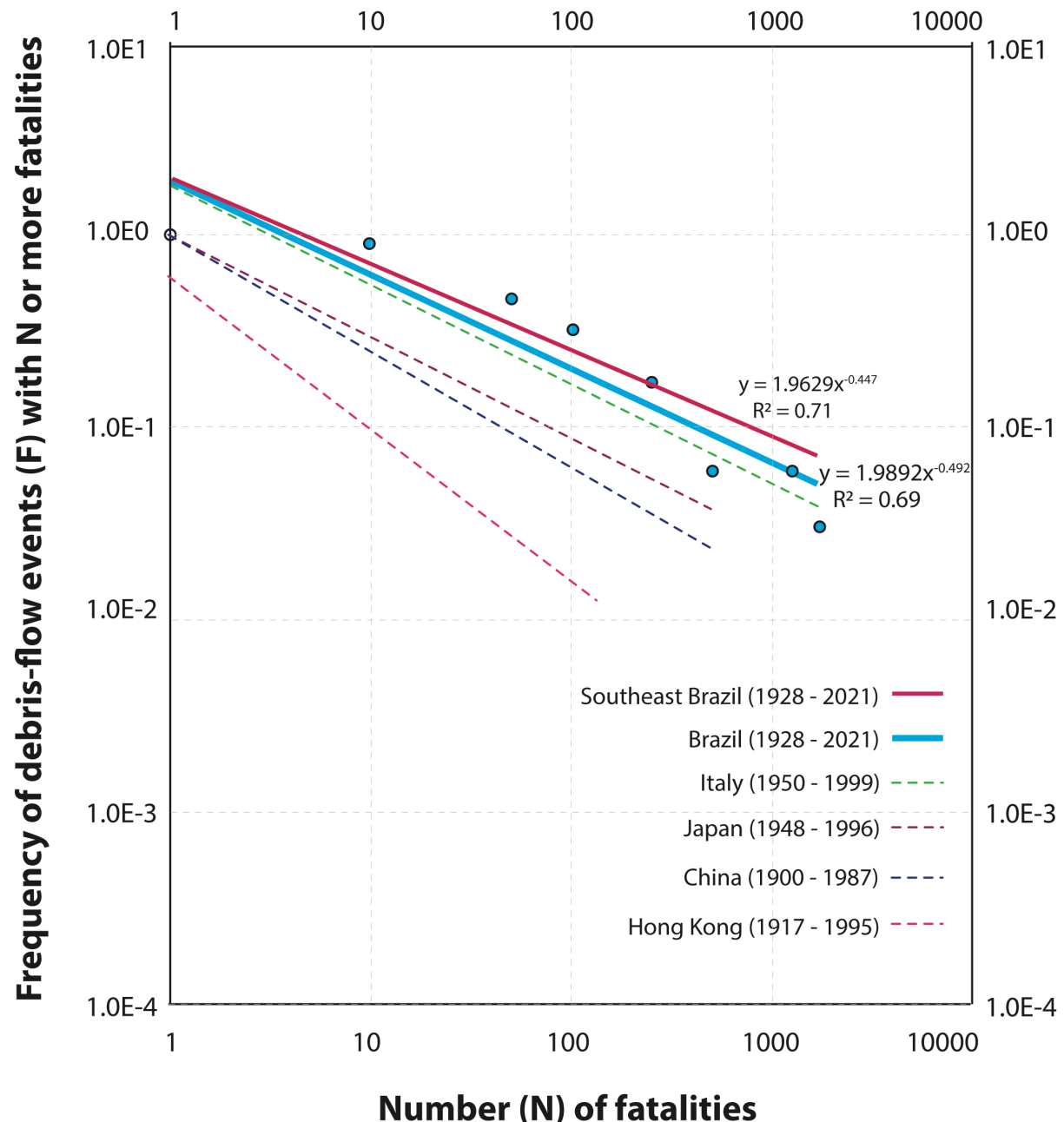


Figure 3-4. F-N curves of debris-flow events in Brazil compared to other countries. Debris flows represent a higher societal risk than landslide events (also comprising debris flows) in China (TIANCHI et al., 1989), Japan (CASCINI et al., 2008), Hong Kong (HO; KO, 2009), and Italy (GUZZETTI, 2000).

For instance, between 2016 and 2017, The Hong Kong Government budget for disaster prevention and preparedness was approximately 396 million USD, with 165 million USD for landslide preventive measures (SIM *et al.*, 2018). In Brazil, the National Center of Monitoring and Early Warning of Natural Disasters (*Centro Nacional de Monitoramento e Alertas de Desastres Naturais* - CEMADEN), responsible for hazard management and monitoring for the whole country, had an annual budget upon its creation of 14 million USD in 2012-2013, which has been successively slashed through the years, reaching approximately 3.7 million USD in 2019-2020 (BRASIL, 2021b).

In addition to very different budgets implemented for natural disasters prevention, there are scale effects in the creation of risk thresholds over F-N plots that should be considered, as the x-axis (N) is affected by the size of the population affected, and the y-axis (F) by the return period of the phenomenon (STROUTH; MCDUGALL, 2021). Comparing the probability of fatal debris-flow events in Brazil with other countries using F-N plots is also subjected to the scale effect, as already pointed out.

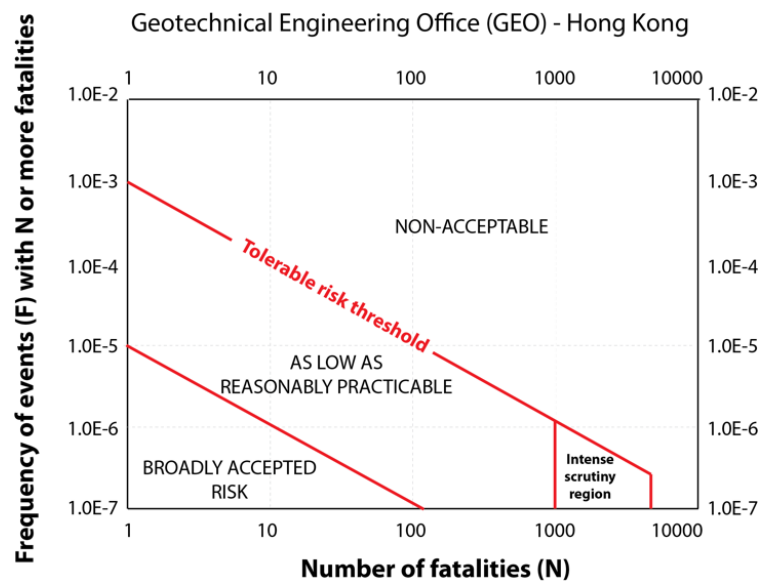


Figure 3-5. Societal risk thresholds adopted by Hong Kong, which commissioned the creation of the criterions specifically for landslides (ERM 1998).

Nonetheless, the use of the F-N plot provides a good indication of the impact that the phenomenon represents in Brazil and the steady debris-flow MR through the decades further shows that little has been made to reduce and prevent their negative impacts in the last 100 years. The temporal and spatial distribution of debris-flow events is a primordial step to understanding the impact of a phenomenon in a country and provides useful information for the definition of areas where mitigative measures must be implemented. Considering that

Brazil's population growth is most concentrated at coastal cities in the southeast (LONDE *et al.*, 2018), which are also the “hotspots” for debris-flow events, disaster prevention measures can and should be implemented in the region, such as local-scale risk analysis, development of early warning systems and installation of retention structures.

The outlook, however, is not promising. The results of the consistent underfunding of CEMADEN and the discontinuation of important disaster-prevention programs have been recently seen in the floods and landslides that struck Petrópolis in February 2022. No warning was issued prior to the catastrophe, causing hundreds of fatalities, despite extensive hazard and risk monitoring programs theoretically present in the municipality.

3.2. The main factors that initiate a debris flow in a catchment

Cubatão in the state of São Paulo is the city where the highest number of debris-flow events were recorded in the last 100 years, as pointed out in the analysis of the phenomenon's impact in Brazil. Cubatão is the largest petrochemical site in Latin America and, during the 1980s, it represented 2.5% of the Brazilian GDP (COSTA-RIBEIRO; MELLO-AWAZU, 1988) and was considered the most polluted city in the world, with very high rates of air and water pollution (COSTA-RIBEIRO; MELLO-AWAZU, 1988; HOGAN, 1988). Since the 1990s, however, the city and the state of São Paulo have implemented environmental monitoring and recuperation programs that have helped to restore acceptable levels of air and water quality in the region (VIEIRA-FILHO *et al.*, 2015; LONDE *et al.*, 2018).

Considering the high environmental and socioeconomic vulnerability of the city, the extensive history of debris-flow events, as well as the availability of high-resolution data, a more detailed analysis is conducted in Cubatão. The city is the test-site in our analysis of the factors that influence debris-flow initiation in a catchment, as well as in our proposal of a hazard assessment methodology presented in Paper III. Even though several landslide and debris-flow events have occurred in the region, the ones from 1985 and 1994 were the most notoriously widespread throughout the hillslopes and catchments of the city and are the events used in our analysis. Figure 3.6 shows the location of the catchments that are our study site.

The selection of the factors that influence debris-flow initiation is based on past studies worldwide and at Serra do Mar (e.g., WILFORD *et al.*, 2004; DIAS *et al.*, 2016; WU *et al.*, 2018; NIKOLOVA *et al.*, 2020), as well as on the factors that are assumed to be critical in the study area based on past events. Two assumptions were made in their selection: (1) new debris flows will occur in similar conditions as past ones and (2) the analyzed factors will not change

for a long period of time. The influencing factors are catchment slope, catchment relief, slope aspect, Stream Power Index (SPI), Topographic Wetness Index (TWI), lithology, soil cover, vegetation and 48-h accumulated rainfall (Table 3.3).

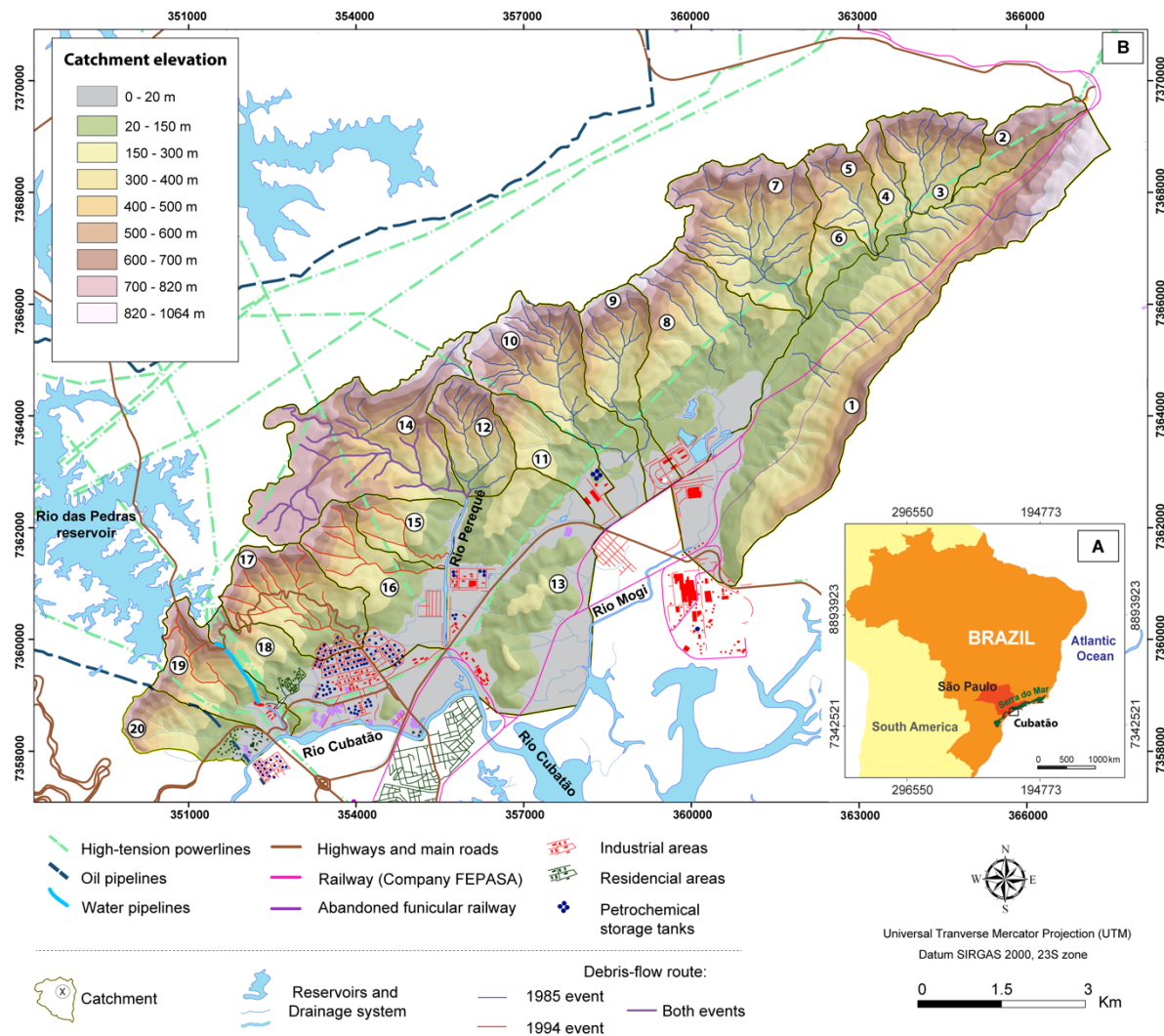


Figure 3-6. Location of the study area, where the hazard assessment is conducted, as well as the analysis of the factors that influence debris-flow initiation in a catchment. A) The study area (Cubatão, São Paulo State), located in the Serra do Mar Mountain Range, Brazil. B) Overview of the analyzed catchments (numbers in white circles), located at the central and northeastern hillslopes of Cubatão (2022).

A reclassification was conducted to standardize the scale of all the factors and facilitate the statistical evaluation. Frequency ratio was applied in the standardization and the statistical evaluation is conducted using Logistic Regression (LR) analysis, which predicts the probability of debris-flow initiation based on the dependent variable (occurrence or not of an event) and a number of independent variables (i.e., influencing factors) that are available in a spatially continuous manner across the region. The independent variables are assessed to establish the LR equation, which can be applied in susceptibility studies.

Table 3-3. Influencing factors analyzed in this study.

Factors	Symbol	Unit	Description
Catchment relief	H	km	The difference between the highest and the lowest elevation point
Catchment slope	SI	%	Slope of the catchment
Slope aspect	Sa	-	The compass direction the slope surface faces
Stream Power Index (SPI)	SPI	-	The erosive power of flowing water
Topographic Wetness Index (TWI)	TWI	-	Terrain-driven variation in soil moisture
Lithology	Lit	-	Geology of the catchment's bedrock
Soil	So	-	The soil cover of the catchment
Vegetation	F	-	The type of vegetation cover of the catchment
48-h accumulated rainfall	P	mm	48-h accumulated rainfall prior to the debris flow

Since the influencing factors can potentially show a high to low correlation with each other, a factor combination was made to determine their degree of contribution to debris-flow initiation. In the first round of the LR, the influencing parameters were added one by one, independently, creating a one-factor model. The factor that showed a more positive effect in the model was retained and added in the following round of LR analysis – creating, then, a two-factor model. The process was repeated until all the influencing factors were combined. The performance validation of our LR analysis was based on a Receiver Operator Characteristics (ROC) analysis, following Fawcett (2006).

Based on the optimal model-fitting results obtained through the LR and on the priority of factors added to the model, the following sequence was established that indicates the order of the factors that most impact debris-flow initiation: (1) Rainfall, (2) Soil cover, (3) Basin slope, (4) SPI, (5) TWI, (6) Forest cover, (7) Lithology, (8) Slope aspect, and (9) Basin relief (Table 3.4).

Several studies at Serra do Mar highlight that rainfall is the main debris-flow initiation factor (LACERDA, 2007; KANJI *et al.*, 2007; VIEIRA *et al.*, 2010, VIEIRA; GRAMANI, 2015) and our analysis statistically corroborates the statement. In total, 10 rainfall index subclasses were identified across the study area, based on the rainfall distribution patterns. For the 1985 events, the subclass 200 – 220 mm is associated with a higher density of debris-flow triggering landslides, while for the 1994 event the subclass 270 – 290 mm is associated with a higher density of landslides. These results potentially indicate that a >200 mm rainfall accumulated in 48 hours can initiate high-magnitude debris flows.

Among the geomorphometric parameters, soil cover shows a stronger influence on debris-flow initiation. Cambisols (Ca2 and Ca3) are associated with a higher tendency to trigger debris flows, which can be related to the high boulder content that can more easily

enable rainfall infiltration (ROSSI; PFEIFER 1991). Ferralsols (LVa1 and LVa3) dominate in the study area, as it is typical of humid tropical and subtropical regions, and do not show a particularly strong tendency to triggering debris flows, which can be related to a more developed and stable soil profile.

Table 3-4. Results of the ROC analysis of the validation tests of the LR models, according to the Area Under the Curve (AUC) of the ROC Curve.

Factors	1 factor model	2 factor model	3 factor model	4 factor model	5 factor model	6 factor model	7 factor model	8 factor model	9 factor model
Rainfall	0.853	-	-	-	-	-	-	-	-
Lithology	0.755	0.768	0.863	0.859	0.876	0.882	0.882	-	-
Slope	0.595	0.853	0.879	-	-	-	-	-	-
Relief	0.641	0.752	0.837	0.84	0.882	0.879	0.869	0.879	0.892
Soil	0.709	0.876	-	-	-	-	-	-	-
Vegetation	0.598	0.859	0.863	0.866	0.873	0.886	-	-	-
TWI	0.605	0.853	0.878	0.876	0.892	-	-	-	-
SPI	0.503	0.846	0.876	0.889	-	-	-	-	-
Slope aspect	0.536	0.683	0.866	0.856	0.882	0.885	0.881	0.886	-

Slope angle is another significant morphometric factor that influences debris-flow initiation, due to the direct influence on surface run-off, vegetation and soil cover, loose material accumulation and groundwater infiltration (LACERDA, 2007). Slope varies from 0 to 172 % in the catchments, with the range of 70 to 90% (35° to 40°) the most prone to triggering debris flows at the study area, followed by the range of > 90% (> 40°). In general terms, the higher the slope the greater the tendency to slope failure, although in very steep slopes (>40°) the accumulation of mobilizable material (i.e., soil) might not be sufficient to initiate debris flows.

The SPI is another strong indicator of debris-flow triggering areas, as it influences the transport and erosion potential of the river/stream (DE ROSA *et al.*, 2019). SPI can be used to characterize debris-flow initiation (Low SPI), transport (High SPI) and deposition areas (Low SPI) (CHEN *et al.*, 2017), and our results show that areas with a low SPI are more prone to debris-flow initiation due very low stream flow in the hillslopes. Areas with a high SPI index (1.5 to 6) can also contribute to the debris-flow development, which can be associated with the erosion of lateral slopes as a result of a stronger flow power. Moreover, the catchments in the region have a moderate drainage density, which suggests a fairly impermeable substratum that results in overland flow that can acquire high erosive power – contributing, thus, to debris-flow entrainment.

The relationship of Topographic Wetness Index (TWI) with debris flows has also been demonstrated by other studies (e.g., NIKOLOVA *et al.*, 2020), with high TWI areas having the ability to collect more surface water, i.e., associated to debris-flow deposition in flatter areas. In the study region, the lower the TWI the higher susceptibility to debris-flows initiation, since the main initiation areas are in steep portions at higher altitudes in the hillslopes.

Based on the LR model results, rainfall, soil, SPI and TWI are the most relevant parameters (Equation 1) that should be used in the prediction of debris-flow initiation in the region, due to a better performance in the output ROC analysis and high-significance of all the variables ($p < 0.05$) in the statistical evaluation of the model (Table 3.5). An LR model with all the influencing factors produced a similar performance in the ROC analysis (Table 3.4), although not all of the variables showed significance in the statistical evaluation (Table 3.5). For susceptibility studies in the region, therefore, we suggest the use of Equation 1.

$$Z = 1.98 + 1.54 TWI + 4.6SPI + 6.47Slope - 4.39Soil - 15.4Precipitation \quad (1)$$

Although with a weaker statistical significance, vegetation is the sixth most influencing factor and is associated with a strong control over the strength of the superficial soil layer, representing a slope-stabilizing parameter, as it can affect surface runoff and create obstacles for flow propagation (LIU *et al.*, 2021). Medium-height broadleaf vegetation (Am), Broadleaf and bush vegetation (AA) and Broadleaf vegetation (Ab2) are associated with a higher predisposition to initiate debris-flow and are weakly (Ab2) to strongly (Am, AA) degraded by the pollution of the region (especially acid rain) (MATTOS; MATSUKUMA, 1990). The effect of pollution on vegetation may contribute to weakening their support of the soil, leading more easily to slope failures.

Lithology is intrinsically associated with the soil type and vegetation of a region, especially in areas with well-developed regolith such as Serra do Mar. Even though a more explicit relationship between lithology and debris-flow initiation is not observed in our statistical analysis, Proterozoic stromatic migmatites (PSeMc), occurring at higher elevations in the catchments, are more prone to debris-flow initiation, accompanied by the other migmatite types (AcMn, AcMp, AcMg) and granitoid rocks (PSEoy). Schists (PSPX) and Phyllites (PSPF) show a lower tendency, which can be related to a more developed and stable regolith, as a result of a weaker strength to weathering.

Slope aspect and relief are the two least relevant factors to triggering debris flows, among the selected influencing parameters. In the study region, the slope direction most prone

to debris-flow initiation varied according to the event, with the eastern and northeastern slopes associated with a higher tendency to initiate debris flows in the 1985 event, and in the 1994 event the northern and northwestern slopes. This is directly related to the rainfall direction of these events: eastern-northeastern in 1985 and western-northwestern in 1994.

The relative relief can control the type of vegetation in the hillslopes, as well as influence both SPI and TWI. In study region, however, relief did not play a prominent role in debris-flow initiation, with the 600 – 700 m elevation range showing a higher tendency to trigger slope failures that can lead to debris flows. This elevation range is associated with stromatitic migmatites (PSeMc) and the 70 – 90% slope range, which show stronger influence on debris-flow initiation.

Table 3-5. Statistical validation of the LR models, showing the regression coefficients (B) and relevant statistical parameters.

	Factor	B	Standard Error	Wald test	Degrees of Freedom	P-value
9-Factor model	Rainfall	-27.758	10.622	6.829	1	0.009
	Soil	-1.117	4.652	0.058	1	0.081
	Basin slope	14.851	9.501	2.443	1	0.011
	SPI	0.214	6.068	0.001	1	0.097
	TWI	2.332	3.667	0.404	1	0.053
	Forest	-17.270	8.846	3.811	1	0.051
	Geology	-3.434	4.994	0.473	1	0.049
	Slope aspect	3.249	8.618	0.142	1	0.071
	Elevation	-6.832	10.188	0.450	1	0.050
	Constant (B ₀)	7.282	3.630	4.025	1	0.045
5-factor model	Rainfall	-15.379	6.195	6.163	1	0.013
	Soil	-4.39	3.596	1.491	1	0.022
	Basin slope	6.468	6.962	0.863	1	0.035
	SPI	4.594	4.332	1.125	1	0.029
	TWI	1.537	2.783	0.305	1	0.048
	Constant (B ₀)	1.978	1.679	1.388	1	0.024

3.3. Rainfall analysis and correlation with the consequences of a debris-flow event

As highlighted by the LR Analysis, rainfall is the main factor that triggers debris flows in catchments, corroborating several other studies (e.g., VIEIRA; GRAMANI, 2015; among many others). Debris-flow events are more common during the summer season (December – March), which is the wettest season in Southeast Brazil, where Serra do Mar and Serra da Mantiqueira are located. Figure 3.7 shows the seasonal distribution of events, with January exhibiting the largest number of debris-flow events, followed by March, February and

December. The phenomena can occasionally occur during winter season in the Southeast due to abnormally rainfall events (SELUCHI *et al.*, 2011).

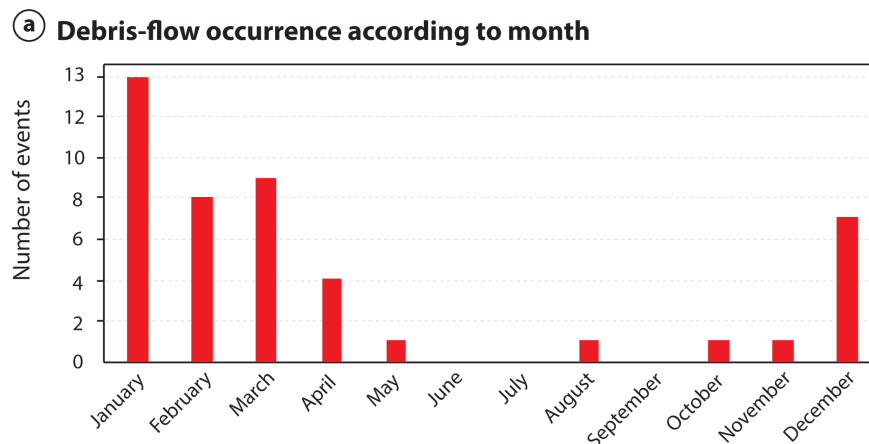


Figure 3-7: Occurrence of debris-flow according to month. Debris flows are more common in summer months (December – March).

Figure 3.8 shows the average annual rainfall indices for Brazil plotted against reported debris-flow events. Debris flows are concentrated in regions with high rainfall rates (> 1600 mm annually) that are also associated with mountain areas, highlighting the strong association between hilly areas and precipitation for their occurrence. In areas with very-high annual precipitation (> 2500 mm) and no debris-flow records, such as the North region of Brazil, the relatively flatter terrain or the remoteness of the mountain areas (e.g., Escudo das Guianas, at the border with Venezuela) can be associated to the lack of recorded events.

When looking specifically at the region of Cubatão, the rainfall patterns that have historically triggered debris flows show that the phenomena are mainly initiated by high-intensity, short-duration rainfall, as also highlighted by other studies in the region (e.g., TATIZANA *et al.*, 1987; KANJI *et al.*, 2007), with the rainfall accumulated 48 h prior to an event suggested as the most critical (Figure 3.9). Such pattern of short-duration/ high-intensity precipitation is also observed in other parts of the world (e.g, Taiwan, Chang et al. 2011; Japan, Fukuoka 1980; New Zealand, Selby 1976).

This pattern is highlighted in a more recent debris-flow event in Guaratuba (state of Paraná), also located in the Serra do Mar Mountain range. According to the testimonies of local farmers, the landslides that triggered the debris flow initiated between 2300 and 0000 UTC (20:00 and 21:00 Local Time – LT) by an accumulated rainfall of 188 mm in 3 hours, with maximum registered intensity of 128 mm h^{-1} , according to the nearest rain gauge data (Figure 3.10a). The recorded antecedent rainfall for the preceding 10 days is estimated at around 88 mm, 23 mm of which (26%) in the 48 hours before the event.

Precipitation recorded by the rain gauges integrated to the Brazilian pluviometer network are notably lower than what the nearest rain gauge documented, suggesting that the extreme rainfall rates were mainly concentrated near the hillslopes of Pedra Branca as a result of orographic effect. The rain gauge ‘Garuva’ recorded 72.8 mm in 12 h (10 km away), with a maximum intensity of 29.2 mm h⁻¹, while the rain gauge ‘Estrada Geral Quiriri’ (30 km away) barely recorded the event (Figure 3.10). While rainfall dynamics in the country can vary greatly according to region (SELUCHI *et al.*, 2011; MARENGO *et al.*, 2021), generally speaking a combination of antecedent, especially in the last 48 h, and high intensity peak precipitation (> 40 mm h⁻¹) is the main rainfall pattern that trigger debris-flow events (KOBİYAMA *et al.*, 2010; DEBORTOLI *et al.*, 2017).

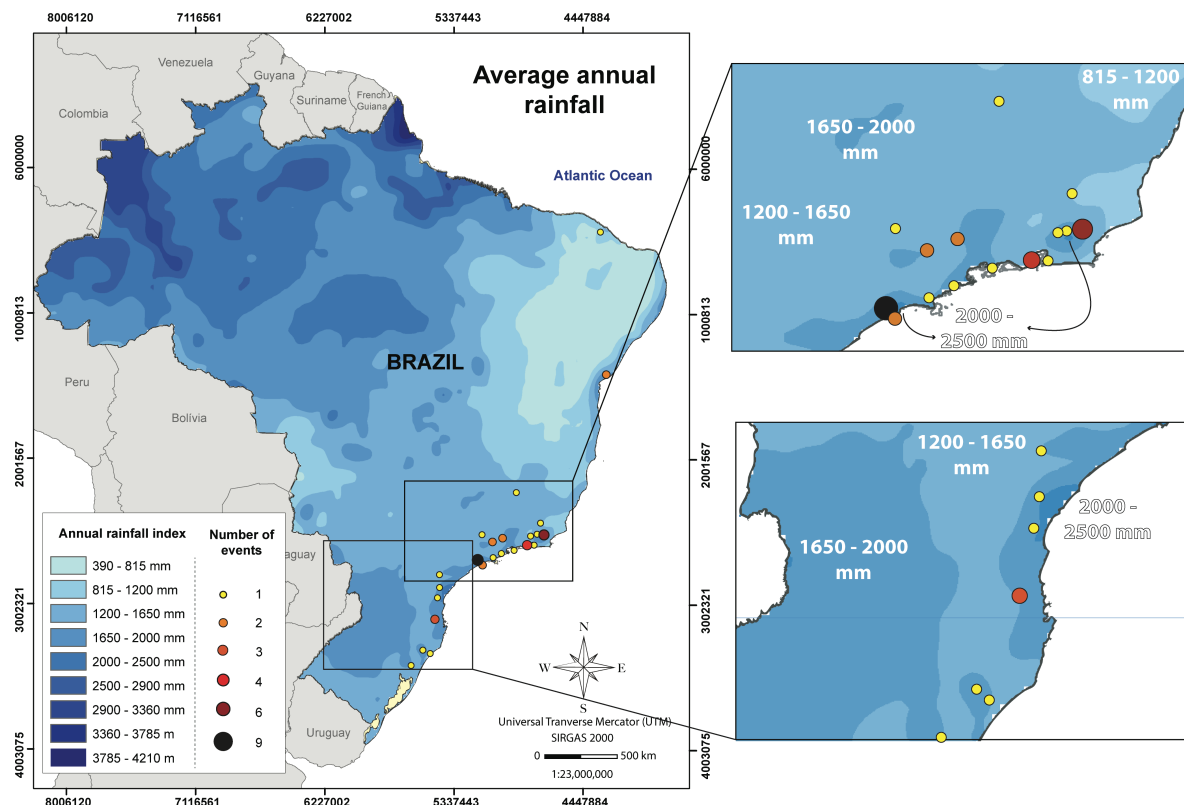


Figure 3-8. Average rainfall indices for Brazil, based on the climate data from Brazil’s pluviometric atlas (CPRM, 2021). Debris flows generally occur in areas with average annual rainfall higher than 1,650 mm.

An important shortcoming in the historical analysis of debris-flow triggering rainfall is the lack of high-quality data with good resolution. Most of the pluviometers prior to 2013 in Brazil only show hourly data, when they are available. Their location can also represent an issue when determining rainfall indices, as most are located in the valley region and not at the top of the hillslopes, where landslides and debris flows initiate. Moreover, debris-flow triggering rainfall can be very localized, as demonstrated by the Guaratuba event, and the

distribution of pluviometers is usually close of urban areas and roads, challenging an accurate analysis as most are far away from the source areas.

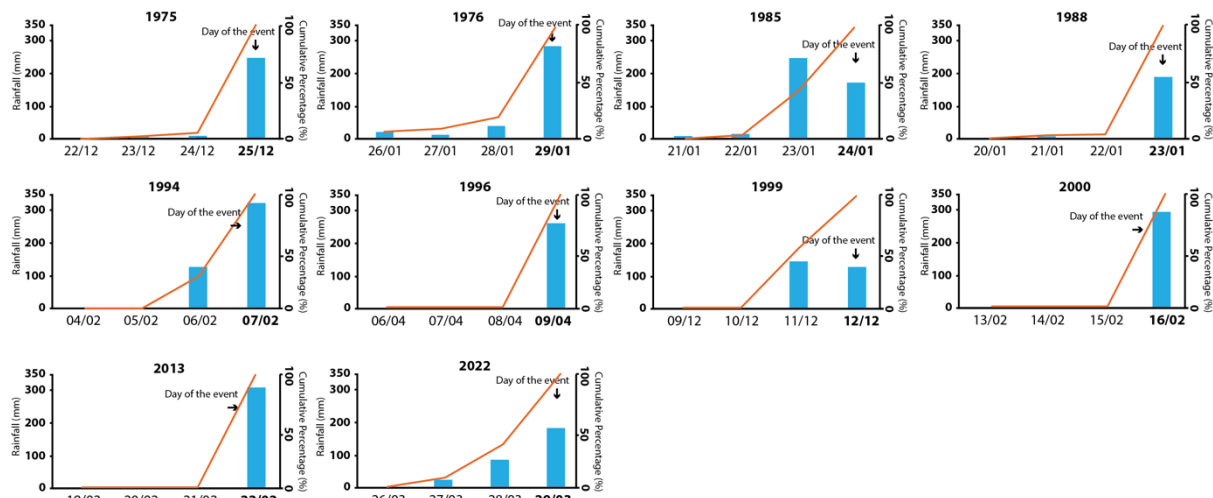


Figure 3-9. Daily rainfall indices up to 4 days (96 hours) prior to debris-flow events in the region of Cubatão (blue bars). The phenomenon's initiation is more strongly influenced by the rainfall accumulated 48 hours prior to an event, as highlighted by the cumulative percentage graph (orange lines).

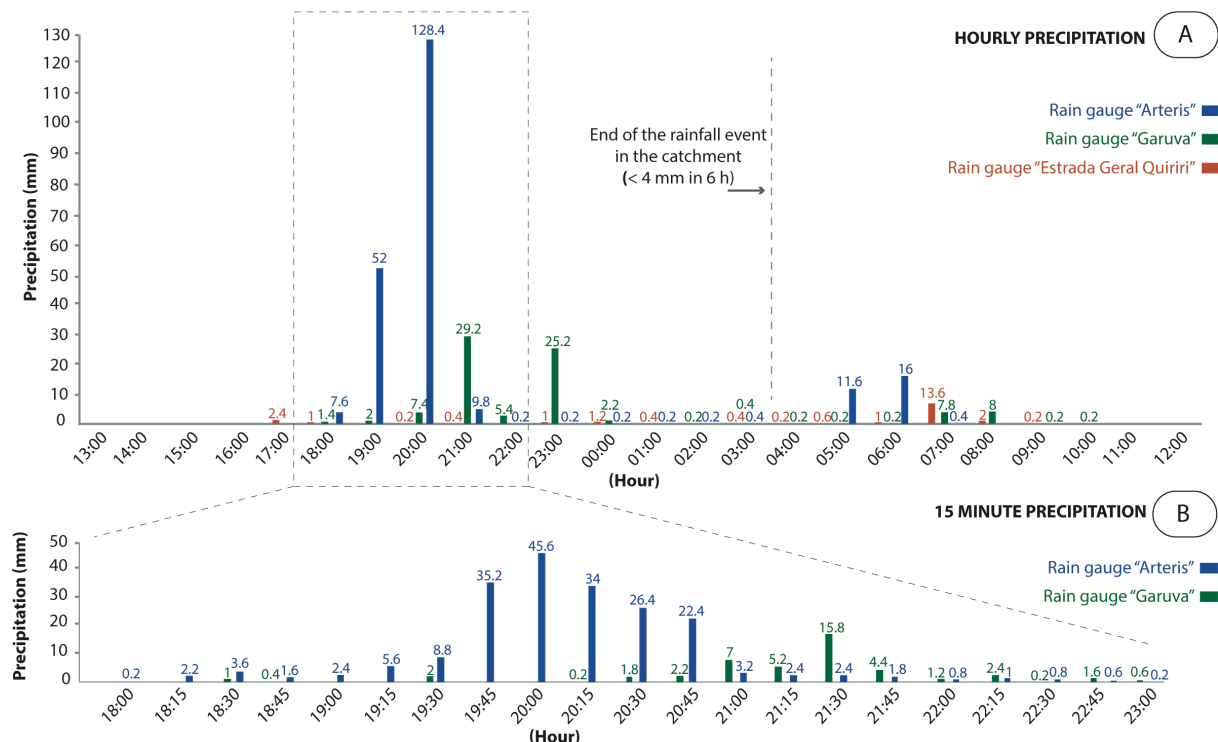


Figure 3-10. Rainfall event that triggered the February 2017 debris flow in Guaratuba (state of Paraná). A) Hourly precipitation for February 11 and 12, 2017, according to the three nearest rain gauges. Rain gauge 'Arteris' is located 1 km from Pedra Branca catchment, while 'Garuva' and 'Estrada Geral Quiriri' are located at approximately 10 km and 30 km away, respectively. B) Precipitation recorded every 15 minutes by the rain gauges 'Arteris' and 'Garuva' between 18:00 LT (2100 UTC) and 23:00 (0200 UTC).

Despite these challenges, we conducted correlations between rainfall and debris-flow impacts and magnitudes, both at a national (Paper I) and at a more local scale in the Cubatão

region (Paper III). At a national scale, comparing the 24-accumulated rainfall with reported data of magnitude, economic losses and fatalities, we can observe a very weak relationship between rainfall and these variables. The relationship between 24-h accumulated rainfall and magnitude, fatality number and economic losses show, respectively, a Spearman correlation coefficient of -0.01 (p-value of 0.52), 0.01 (p-value of 0.51) and -0.25 (p-value of 0.81) (Figure 3.11). In this analysis, the 24-h accumulated rainfall was chosen due to a more consistent historical report of the precipitation data than the 48 h.

When peak rainfall intensity (hourly precipitation) is considered, a stronger positive correlation with magnitude and number of fatalities is observed. The relationship between hourly rainfall and magnitude shows a positive Spearman correlation coefficient of 0.7 (p-value of 0.91), while the relationship between fatality cases and hourly rainfall shows a positive Spearman correlation coefficient of 0.36 (p-value of 0.81). The correlation between daily rainfall and economic losses, on the other hand, is weaker, with a negative Spearman correlation coefficient of -0.2 (p-value 0.63) (Figure 3.11).

Even though hourly rainfall (peak intensity) showed a stronger correlation with magnitude and the number of fatalities, the small sample space of events with complete data of all the considered variables challenges a concrete conclusion about their relationship. It is expected, however, that the more intense the rainfall, the larger the event and, consequently, the larger the associated damage. The available rainfall data, however, is not sufficient to indicate a clear relationship between rainfall indices and these variables. These results can potentially indicate that the damage related to debris-flow events is not only a function of rainfall, but also to social (e.g., urbanization levels, occupation of risk areas) and geomorphic (e.g., vegetation cover, catchment and channel slope, in-channel material) factors.

The effect of the geomorphic aspects on debris-flow development can also be observed when rainfall is correlated with the characteristics of the events that occurred in Cubatão. Considering the effect of the 48-h accumulated rainfall on the volume of material mobilized in the slopes, a positive Spearman correlation between rainfall and landslide magnitude is observed for both 1985 (0.62) and 1994 (0.81) events, highlighting the direct effect of rainfall over slope failure. However, when the effect of rainfall on debris-flow magnitude is considered, such relationship is weaker, showing a low positive Spearman correlation index both for the 1985 event (0.3) and for the 1994 event (0.51) (Figure 3.12). These results can potentially indicate the strong influence of entrainment on debris-flow magnitude in the region, which can potentially also be extrapolated for other mountain areas in Brazil.

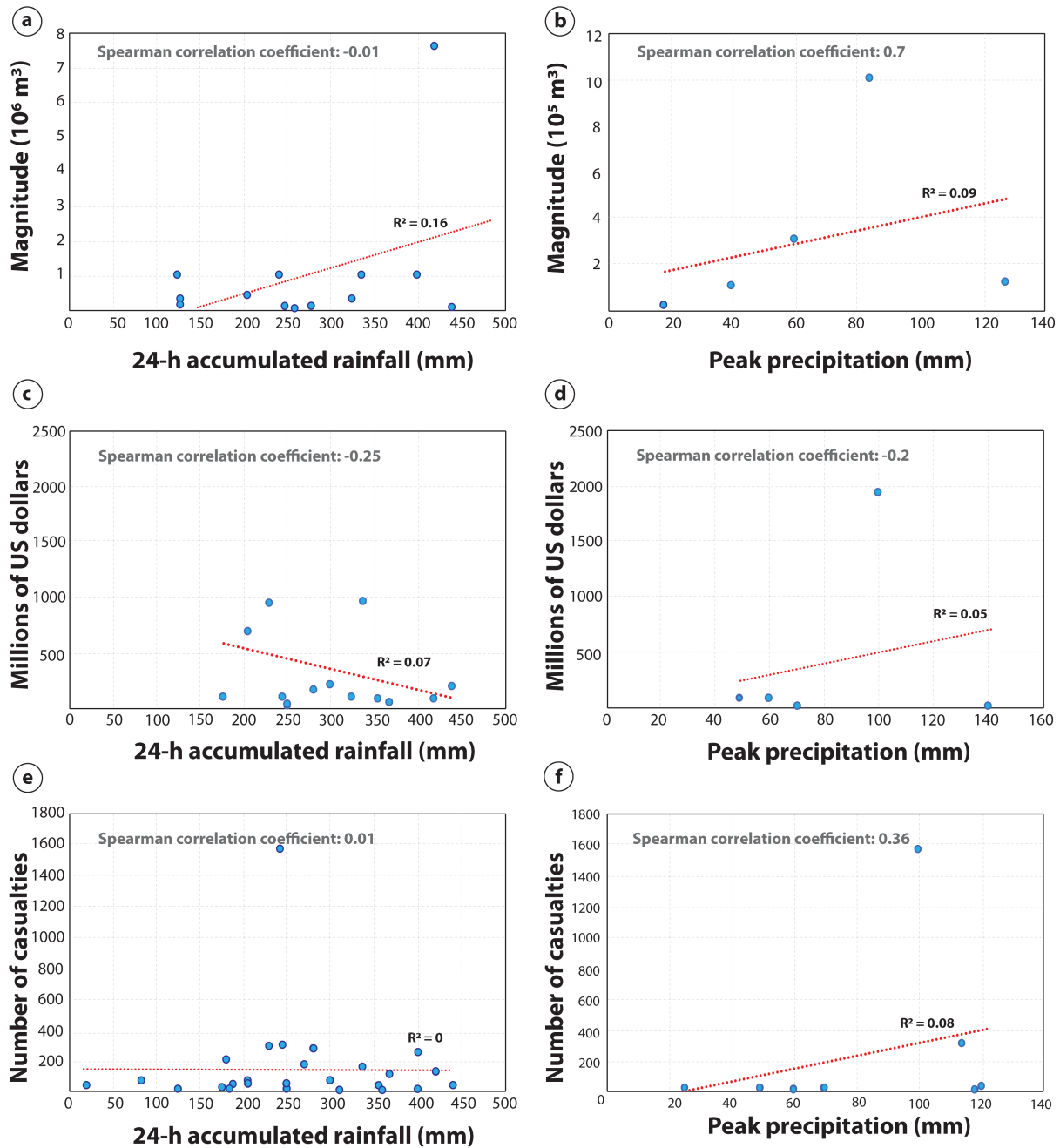


Figure 3-11. Rainfall analysis. a) Relationship between 24-h accumulated rainfall and magnitude. B) Relationship between hourly rainfall and magnitude. C) Relationship between daily rainfall and economic losses. D) Relationship between hourly rainfall and economic losses. E) Relationship between 24-h accumulated precipitation and number of fatalities. F) Relationship between hourly rainfall and number of fatalities.

Consequently, in a possible implementation of an Early Warning Systems in debris-flow prone areas, field information about the catchments should also be considered, due to the intense in-channel debris accumulation that can be remobilized in future events. Moreover, the hazard zonation must also be considered in Early Warning Systems implementation, as it identifies the most sensible areas that should be evacuated/attended first and where preventive measures, such as retention structures, should be installed.

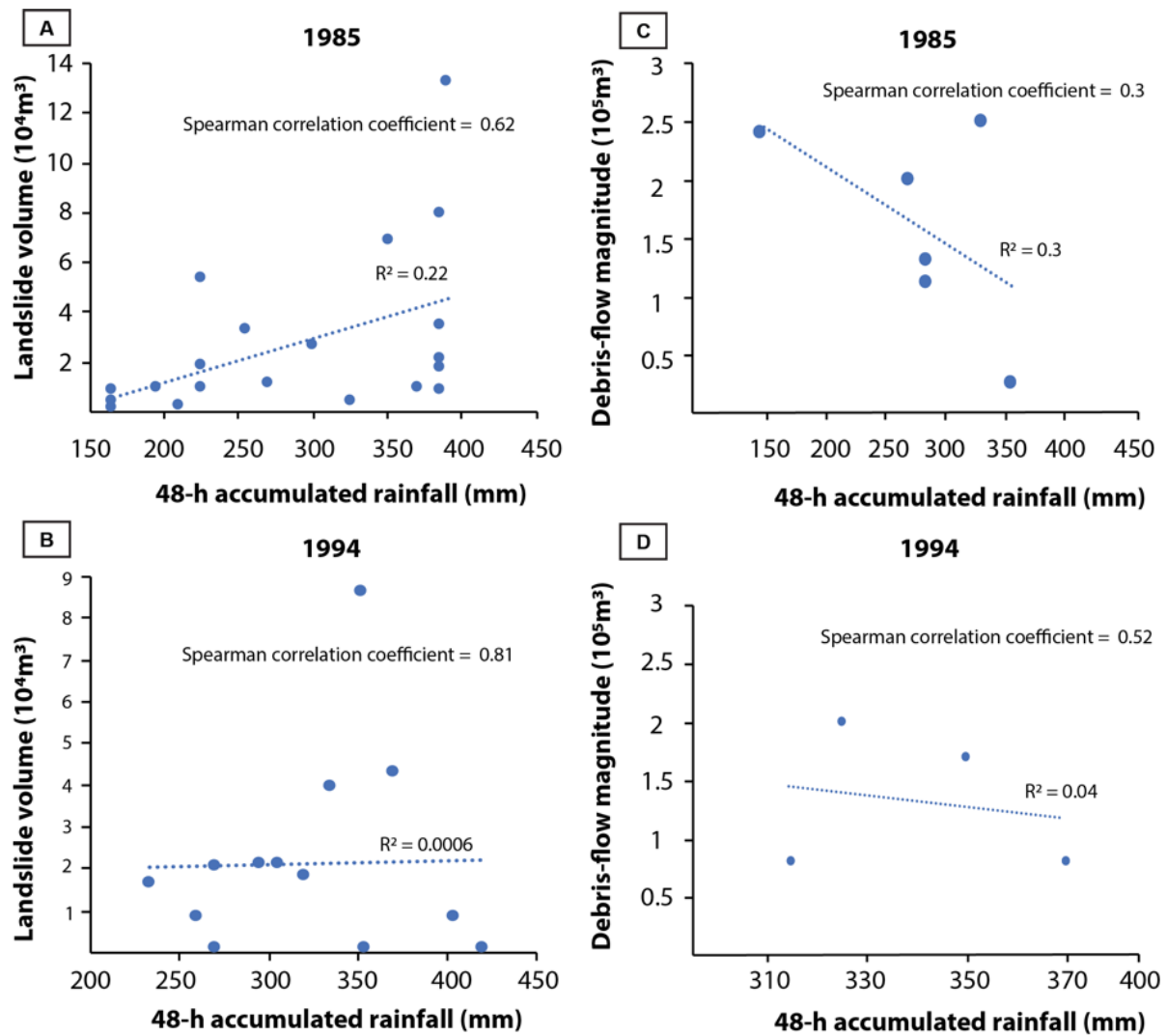


Figure 3-12. Correlation between rainfall and landslide volume (left) and rainfall and estimated debris-flow magnitudes (right), for the catchments located in Cubatão. The correlation is based on data from the 1985 and 1994 landslide and debris-flow events and the different rainfall indices are based on the spatial distribution of the rain event in the region. A) Correlation between 48-h accumulated rainfall and landslide volume – 1985. B) Correlation between 48-accumulated rainfall and landslide volume – 1994. C) Correlation between 48-h accumulated rainfall and estimated debris-flow magnitude – 1985. D) Correlation between 48-h accumulated rainfall and estimated debris-flow magnitude – 1994.

3.4. A detailed field characterization of a debris-flow event

We conducted a comprehensive characterization of the debris-flow event that occurred on February 2017 in the Pedra Branca catchment (Guaratuba, state of Paraná) (Figure 3.13), to characterize the main geomorphological features of a debris flow in Brazil, as well as to estimate important kinematic parameters, such as magnitude, peak discharge and velocity (we refer Paper II). The debris-flow event was triggered by three large landslides, which have their upgradient portions in moderate slopes (38% to 61%, or 21° to 31°). The mobilized material

were mainly residual soil and large wood, which suggest loss of suction as the initiation mechanism at the study area. The debris flow was initiated by first-time movements in the hillslopes, but also carried material (colluvium) from previous landslides, accumulated in upper portions of the channel.

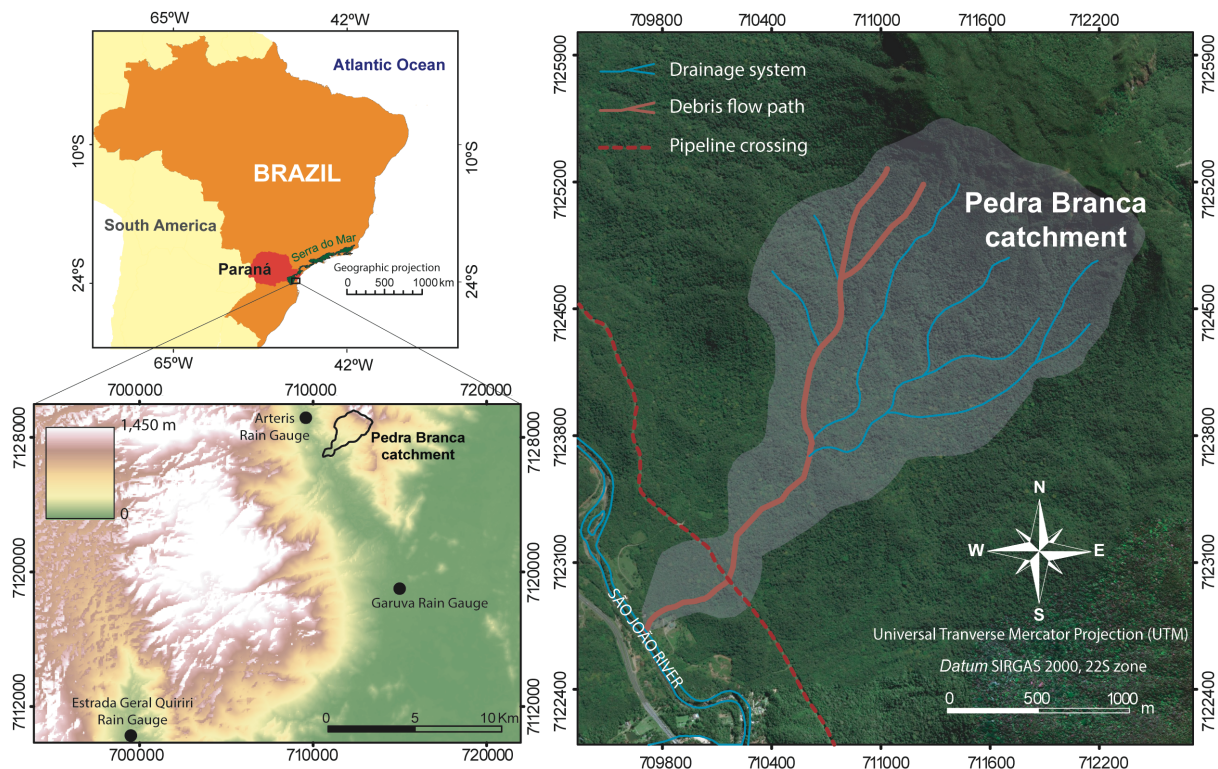


Figure 3-13. Pedra Branca catchment (right) in the municipality of Guaratuba, State of Paraná, Brazil. At the top left, the extension of the Serra do Mar mountain range. At the bottom left, the Digital Terrain Model (DTM) for the broader region of the catchment with the location of the three nearest rain gauges.

The channelization of the material mobilized by the landslides contributed to a magnification of the erosional process, with a pronounced entrainment and scour of debris in the upstream section of the channel. Erosion of the channel bed, lateral slopes and banks by the debris flow progressively decreased towards the outlet region, ranging from an average depth of 3 m at the upstream section to 0.3 m downstream. In bedrock exposed areas, erosion depth was assumed as 0 and these areas are mainly located in steep portions of the channel, near the initiation area and in knickpoints.

In-channel debris in the upstream section consists mainly of large monzogranite boulders (2 to 5 m in diameter), deposited at the perimeter of the flow route or exhumed from colluvial deposits of the lateral slopes (Figure 3.14a). In-channel debris accumulation becomes more frequent towards the catchment's outlet, with the largest volume of debris deposited in the middle portion of the channel (Figure 3.14b) where the average slope is 18.2% (10.3°), i.e.,

within the range of deposition angles for channelized debris flows (from 14% to 21%) (IVERSON *et al.*, 2011). Debris deposition also occurs in the downstream portion of the catchment, although with smaller-sized boulders (<2 m in diameter) and less voluminous deposits than in the middle portion (Figure 3.15c). Recent in-channel debris deposits are easily identified from colluvial deposits due to the lack of pedogenetic evidences and the mixture of fresh wood and stony debris (Figure 3.14d).

Large wood (LW) deposition and accumulation, differently from stony debris, is more frequent in the downstream section of the channel. In this section, the influence of LW in the debris-flow evolution is prominent, with evidences of LW jams that were broken by the flow passage (Figure 3.15a). Debris dams (i.e., areas with intense debris deposition, blocking partially the flow) are observed along the channel and are in their majority clast supported with woody debris (Figure 3.15b), often exhibiting reversely graded patterns. The occurrence of these dams indicates that the debris flow had multiple surges, which is confirmed by the affected farmers that report at least four surges.

The imbricated boulders along the channel's length and the intense debris accumulation along in the middle section of the channel suggest that the event started as a debris flow, evolving into a debris flood as channel slope decreased. In the outlet region, according to testimonies, the flow consisted mainly of muddy water (with sand, silt, clay) mixed with woody debris (Figure 3.14e) and, minorly, by stony debris of up to 1 m. These characteristics indicate that in the final stages the event exhibited characteristics of a flash flood.

The average post-debris-flow width of the channel is ca. 20 m, ten times the previous average width (ca. 2 m) reported by testimonies. No prominent alluvial fan is formed, due to narrow valley and discharge to the larger São João river (Figure 3.14e). In the São João river, large deposits of coarse sand and cobbles are accumulated near the Pedra Branca outlet (Figure 3.14f), as well as small to medium-sized boulders (< 1.5 m in diameters) on the river channel.



Figure 3-14. A) Pronounced erosion and scour of channel bed is observed at the upstream section – 1.8 m human profile for scaling. B) Intense accumulation of debris at the middle section– in detail, a 1.75 m human profile for scaling. C) Accumulation of debris at the downstream section, with smaller sized-boulders than in the middle section - 1.75 m human profile for scaling. D) Reversely graded pattern observed in debris dams. E) Debouchment of the Pedra Branca river into the São João River, where flow height reached up to 2 m. F) São João river, which received sediments from the Pedra Branca debris flow (photo from August 2017).

The mapping of erosional and depositional areas along the Pedra Branca channel is shown in Figure 3.16, based on orthophotos acquired using Unmanned Aerial Vehicle (UAV). Even though debris deposition generally occurs in areas with gentler slope, a direct correlation between these two factors is not observed, with a very weak Spearman correlation coefficient (0.025) and regression line with very low R^2 (0.002) (Figure 3.17a and 3.17c). Debris deposition, therefore, might be influenced by other factors, such as valley width, presence of obstacles and availability of coarse material itself, which can further be related to a less

voluminous deposition in lower reaches of the channel, which show gentler slope angles than in intermediate reaches.

Erosion depth, on the other hand, shows a positive correlation with slope, being deeper near steeper portions of the channel (Figure 3.17b). Excluding areas where bedrock exposure is observed, a correlation between slope and erosion depth shows a weak/moderate positive spearman coefficient (0.39) and a regression line with a weak to moderate R^2 (0.3149) (Figure 3.17d). Hence, erosion is moderately influenced by slope, which can further be associated with a higher momentum of the flow's passage in steeper reaches of the channel. The exclusion of bedrock exposed reaches in the correlation is due to a different incision dynamic than at alluvial-colluvial reaches.

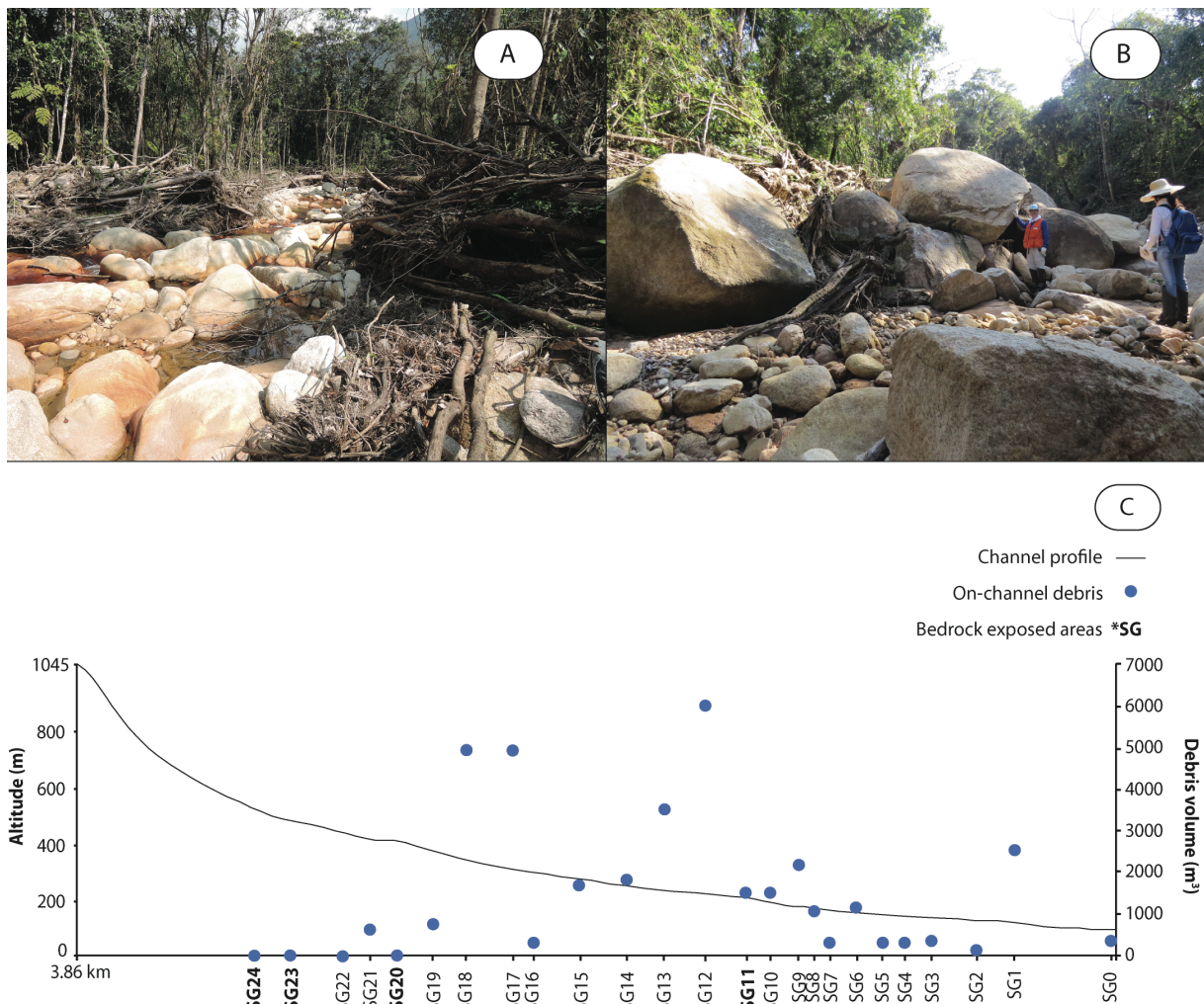


Figure 3-15. Debris deposition and jam formation. A) Large wood forming a jam that was later broken by the flow's passage (SG1). B) Mixture of woody and stony debris and formation of debris dams (SG12) – 1.75 m human profile for scaling. C) Plot showing the Pedra Branca channel profile and the volume of deposited debris along the debris flow route. Debris deposition is higher in the middle section of the channel (SG19 to SG11).

The distribution of maximum grain size (D_{90}) of debris along the debris-flow path shows that debris size decreased by approximately 80% along its trajectory (Figure 3.17e). Sharp reductions in D_{90} along the channel are related to regions where intense debris deposition is observed. Flow heights are generally higher in regions downstream to knickpoints in the channel, with the debris flow reaching a peak height of 7 m (Figure 3.17f). At the debouchment into the larger São João river, flow heights were up to 2 m (Figure 3.17f). Flow height can be affected by areas with intense debris accumulation, which can partially block the flow and raise the flow level. To minimize the uncertainties related to forensic discharge estimations, we documented flow heights in areas that were not directly affected by the intense accumulation of stony and woody debris.

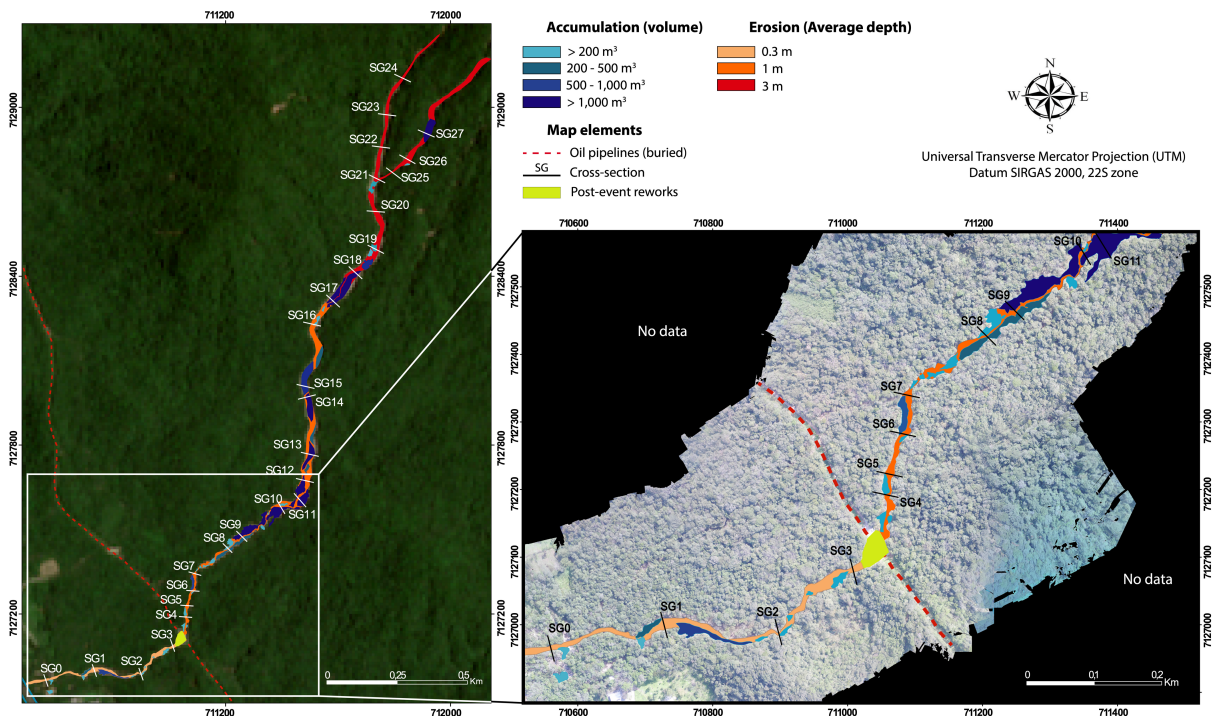


Figure 3-16. Mapping of entrainment and deposition areas based on the orthophotos acquired using UAV. Areas in shades of blue represent debris-accumulation areas and areas in shades of red represent entrainment areas.

The total volume of the debris flow (V_t) is estimated at approximately 120,195 m³, based on the mapping of entrainment and deposition areas (Figure 3.16) and on the landslides that initiated the event (Figure 3.18). Volume entrained by the flow (V_e) is estimated at 121,037 m³, while the volume of debris deposited along the debris flow path (V_d) accumulates to 36,688 m³. The three landslides that initiated the event contributed with 35,846 m³ of earth material. The largest landslide scar contributed with 22,497 m³, while the other two contributed with 7,573 m³ and 5,776 m³, assuming an average depth of 1 m and that the totality of the material reached the channel. Despite the uncertainties associated with erosion depth at the study area,

due to the unknown channel morphology before the event, it is evident that entrainment significantly increased the total magnitude of the process, representing more than 75% of earth material input.

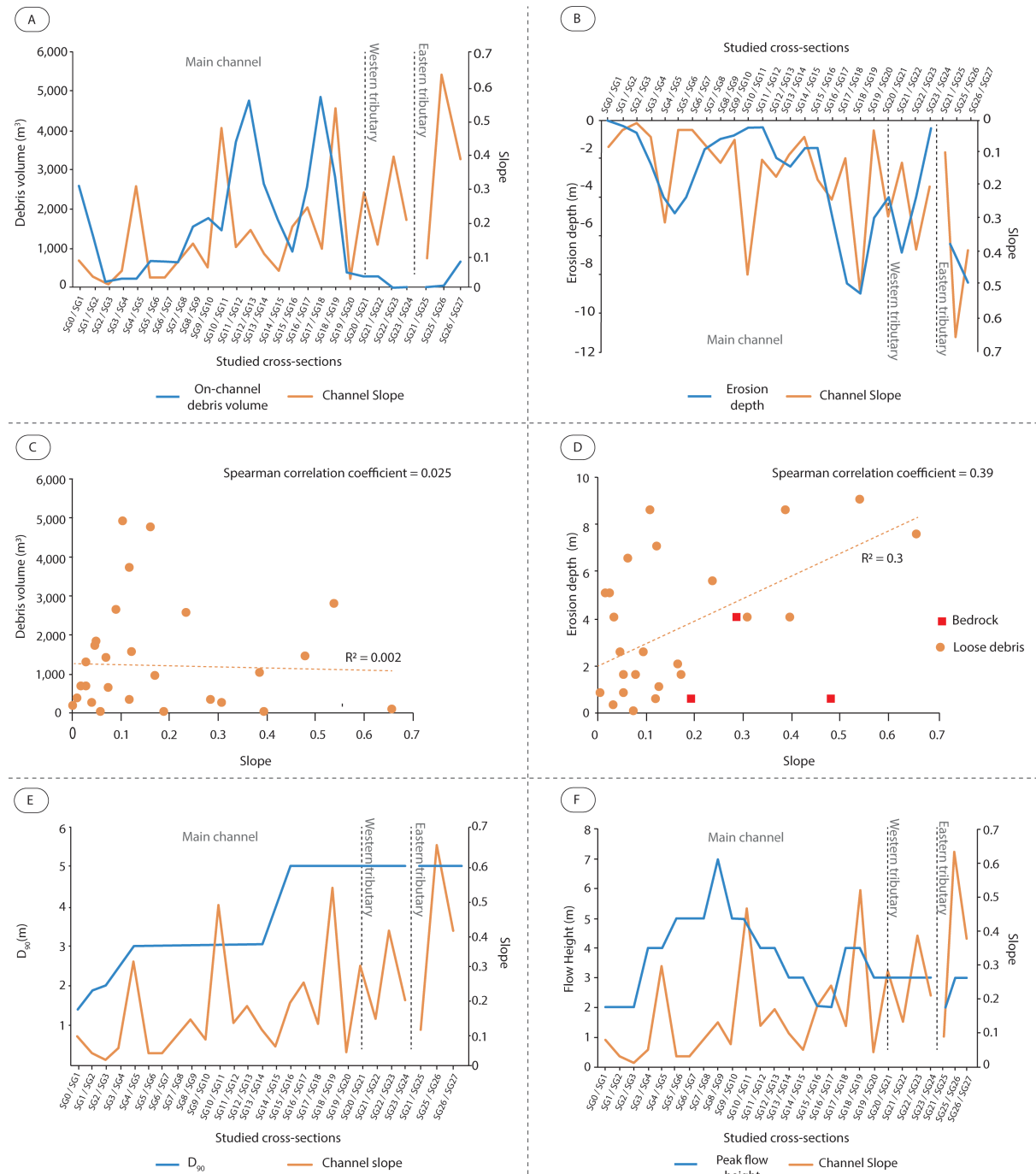


Figure 3-17. Characteristics of the 2017 debris flow. A) Distribution of on-channel debris volume along the debris flow path in relation to channel slope B) Erosion depth distribution along the debris flow path in relation to channel slope C) Scatterplot showing the relationship between on-channel debris volume and channel slope. D) Scatterplot showing the relationship between erosion depth and channel slope. Bedrock and loose debris refer to the on-channel material post-event. E) Maximum debris size (D₉₀) distribution along the debris flow path in relation to channel slope (measured between every two cross-sections). F) Peak flow height distribution in relation to channel slope.

Our estimations, therefore, suggest that the February 2017 debris flow had a large magnitude, within the range of the size-class 5 ($10^5 - 10^6 \text{ m}^3$) proposed by Jakob (2005b). Size-class 5 debris flows can destroy parts of villages and infrastructures, destroy forest of up to 2 km^2 and block creeks and rivers (JAKOB, 2005b).

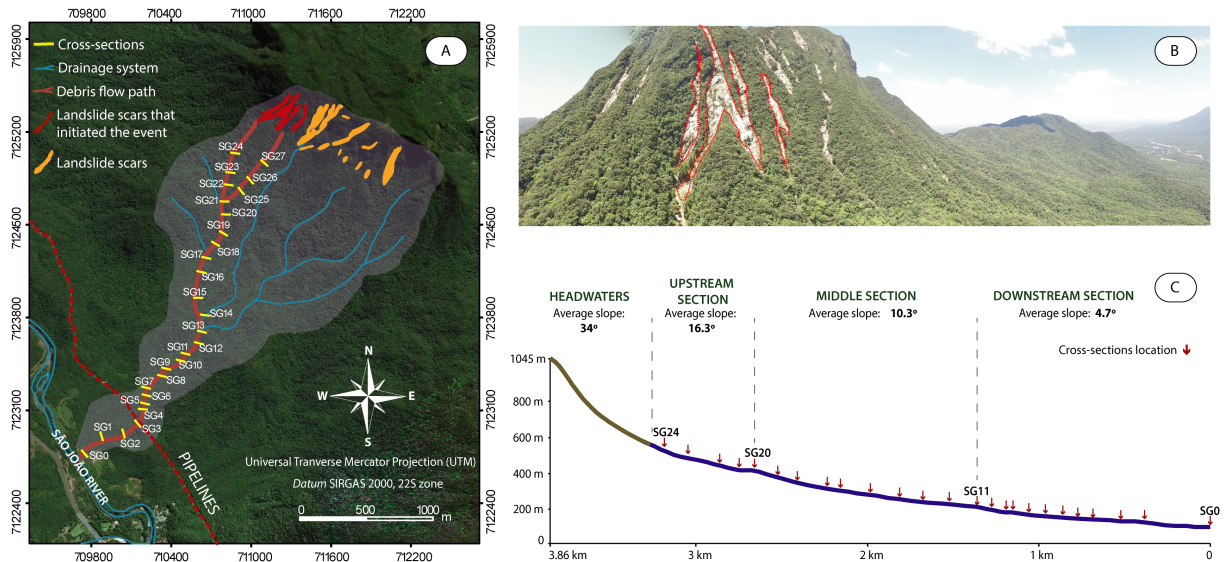


Figure 3-18. A) Location of the 28 cross-sections made along the debris-flow path that supported the magnitude estimation. B) Overview of the headwaters' region of the catchment, highlighting the three landslide scars that initiated the debris flow. C) Longitudinal profile of Pedra Branca catchment with the tentative location of the cross-sections. Channel in blue and slopes in brown.

Peak discharge ($Q_{\max}$) is calculated based on the equation described in Jakob (2005a), as function of the product between the maximum cross-sectional area ($A_{\max}$) of the channel and the mean cross-sectional velocity (v_f). The velocity is calculated following the Manning-Strickler equation, using the Manning coefficient of $0.07 \text{ m}^{1/2}\text{s}^{-1}$ for bedrock rivers in mountain regions (ARCEMENT; SCHNEIDER, 1989; TAKAHASHI, 2006).

Highest discharge and velocity rates are, as expected, observed where channel slope is the steepest and cross-sectional area one of the largest. Discharge, in general, is higher in the immediate region downstream to the initiation area and in the confluency of the two tributaries (Between SG21 to SG17, Figure 3.19), progressively decreasing towards the outlet region (Figure 3.19). Velocity rate patterns are similar to the discharge (Figure 3.19).

It is important to point out, however, that the concurrence of debris flows and debris/flash floods might increase the uncertainty over peak discharge estimations, due to an alteration of the channel cross-section stability with the passage of large sediment volume (AMPONSAH *et al.*, 2016; DESTRO *et al.* 2018).

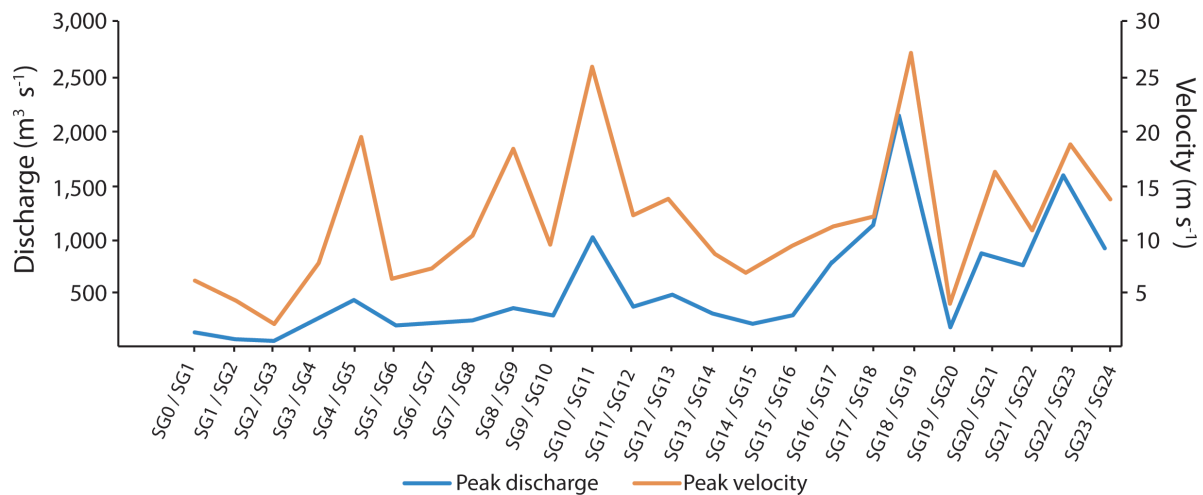


Figure 3-19. Discharge and flow velocity pattern along the debris flow path.

Debris-flow initiation is not controlled solely by rainfall, as it also depends on debris supply and recharge rate, which influences the magnitude and the frequency of new events in a catchment. The debris flow in the Pedra Branca catchment had a magnitude of approximately 120,000 m³, thus a large debris flow. According to Jakob (2005b), such magnitude for a boulder-rich debris flows is atypical, although the statement could be biased due to the general lack of magnitude studies worldwide, especially in mountain areas where debris-flow studies are still incipient. In the Serra do Mar region, based on the few available magnitude estimates (e.g., KANJI *et al.*, 2007; KOBIYAMA *et al.*, 2015), a 10⁵ m³ debris flow is what is usually reported, probably also due to a bias towards reporting and characterizing only larger events and the lack of studies aiming at specifically estimating debris-flow magnitude.

3.5. Differences and similarities of debris-flow prone catchments at Serra do Mar

As pointed out by our historical analysis and other studies in the literature, Serra do Mar is the main site of debris-flow occurrence in Brazil. The initiation of rainfall-triggered debris flows in the region can generally be summarized in three stages, as Lacerda (2007) suggests: (1) rainfall infiltration in the soil that leads to (2) slope failure(s), which further (3) triggers a channelized debris flow. The main process associated with slope failure in the hillslopes of Serra do Mar is loss of suction due to rain infiltration (LACERDA, 2007).

High- to extreme-precipitation events often occur over Serra do Mar catchments (VIEIRA; GRAMANI, 2015), which can trigger large shallow landslides that initiate debris flows in isolated gullies (Figure 3.20a), often remaining unreported. An example is the

February 2017 debris-flow event in Guaratuba (South Brazil), discussed in the previous chapter. The debris flow was triggered by three large landslides (Figures 3.18), which initiating mechanism is interpreted as loss of suction (we refer Paper II). In the region of Cubatão (Southeast Brazil), an example of such an event is the 1975 debris flow in one of the streams of catchment 1 (Figure 3.6), triggered by shallow landslides in the headwater's region (Figure 3.20b).

“Shock wave”, due to the impact of falling rock boulders, is another mechanism that can trigger debris flows in the Serra do Mar region (LACERDA, 2007), as well as dormant landslides, which material can accumulate in upstream reaches and be reactivated by primary landslides or rockfalls in the hillslopes. Debris flows initiated solely by the increase of the discharge in the channel, leading to the mobilization of in-channel material, is not yet reported in Brazil, which can be attribute to the lack of monitoring of catchments prone to the phenomenon.

Large-magnitude debris-flow events ($> 10^5 \text{ m}^3$), such as those in 1985 and 1994 that occurred in Cubatão, are usually characterized by multiple source areas (landslides, rockfalls, in-channel material), both at upstream and middle reaches of the channel (Figure 3.21a). In-channel debris accumulation is an important characteristic that is common in both regions analyzed in this research, which can contribute to increasing the severity of debris flows as these debris' deposits can be remobilized by new events. In-channel debris accumulation can be observed in upstream (Figure 3.21c), middle (Figure 3.14b and Figure 3.20c) and downstream (Figure 3.14f) reaches of catchments, suggesting that these materials are leftovers from past-debris flows (such as the case for Guaratuba) or from recent, localized slope failures along the channel that were not mobilized.

The differences in the initiation mechanism of a debris flow in a catchment is directly related to the geological and morphometric characteristics of each region. For instance, Pedra Branca catchment has a very steep headwaters' region, with gentler side slopes in the intermediate and lower channel reaches. Catchments at the northern slope of the Mogi River in Cubatão (Figure 3.6), on the other hand, show steep side slopes in upper, intermediate and (often) lower reaches of the channel.

As pointed out earlier, both regions exhibit intense in-channel debris deposition, especially of large rock boulders ($>1 \text{ m}$). The in-channel boulders in Cubatão are more sharp-edged when compared to the more round-edged in Guaratuba, which can be related to differences in lithology type (mainly Granite in Guaratuba; mainly Gneiss and Schists in Cubatão). This can also be related to the travel distance from the source areas, with boulders

traveling a longer distance from the headwaters' region (i.e., source area) in Guaratuba, while in Cubatão the boulders in middle and lower reaches can also come from side slopes.

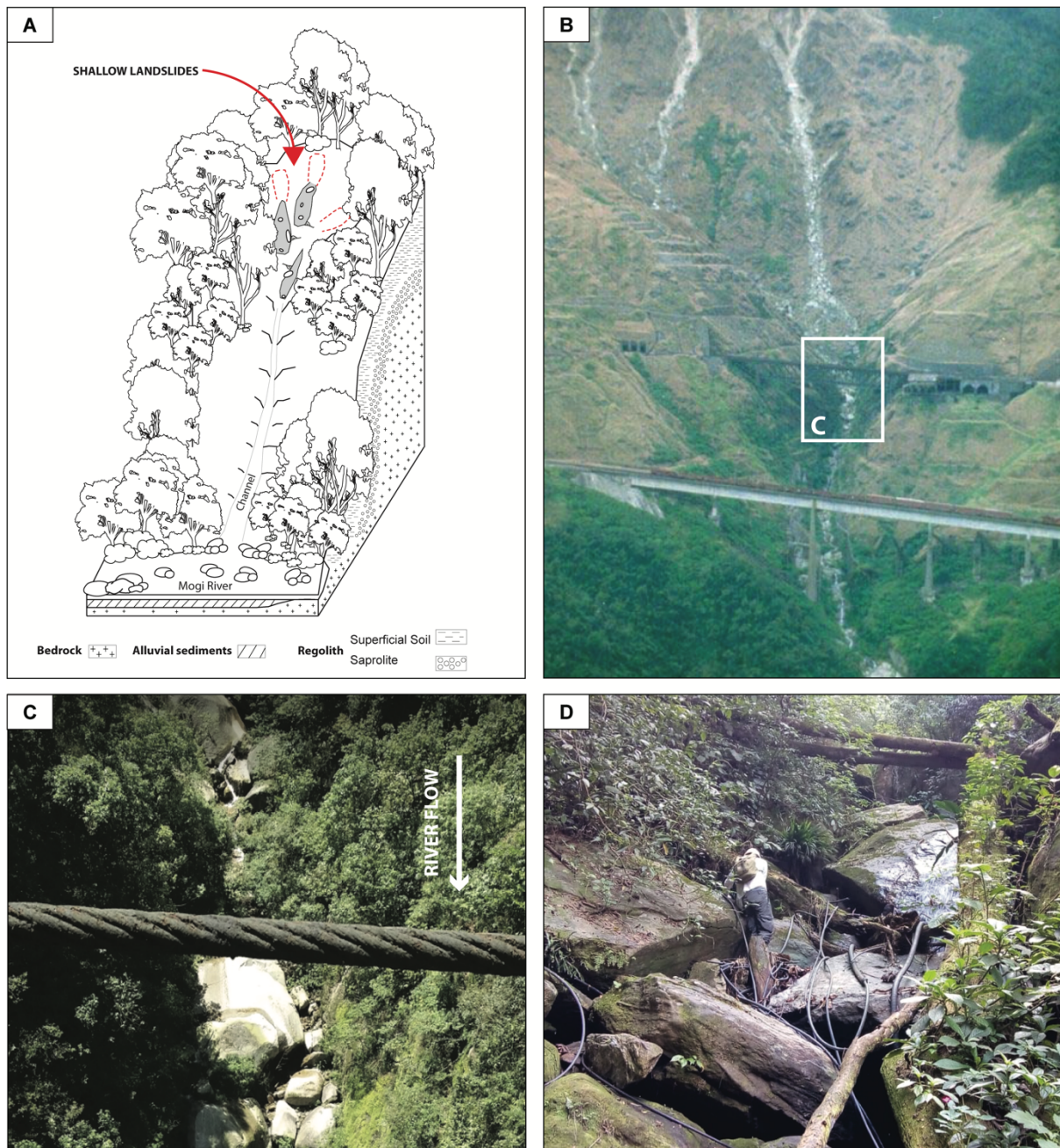


Figure 3-20. Debris-flow dynamics. A) Scheme of a debris flow in gullies/catchments, triggered by shallow landslides in the headwaters' region. B) the 1975 debris-flow event that occurred in one of the streams of catchment 1 in Cubatão. Photo from Prof. Dr. Milton Kanji, retrieved from Gramani (2001). C) Overview of the stream where the 1975 debris-flow event occurred, showing intense accumulation of rock boulders in the channel (Coordinates: 365926.79 m E, 7368058.54 m S). D) Upstream view of catchment 20 in Cubatão, showing intense stony debris accumulation in the channel, as well as Large Wood (Coordinates: 350665.03 m E, 7358314.49 m S).

The evaluation of the morphometric parameters of the catchments in these two different regions can further contribute to understanding their differences and similarities. Tables 3.6

and 3.7 show the main morphometric parameters of the catchments in Cubatão and Guaratuba, respectively, which are more commonly used in debris-flow studies worldwide (e.g., WILFORD *et al.*, 2004, KOVANEN; SLAYMAKER, 2008, ILINCA, 2021; DIAS *et al.*, 2022; among many others). These parameters are: Catchment Area, Relief Ratio, Catchment Relief, Drainage Density, Length and Melton Ration.

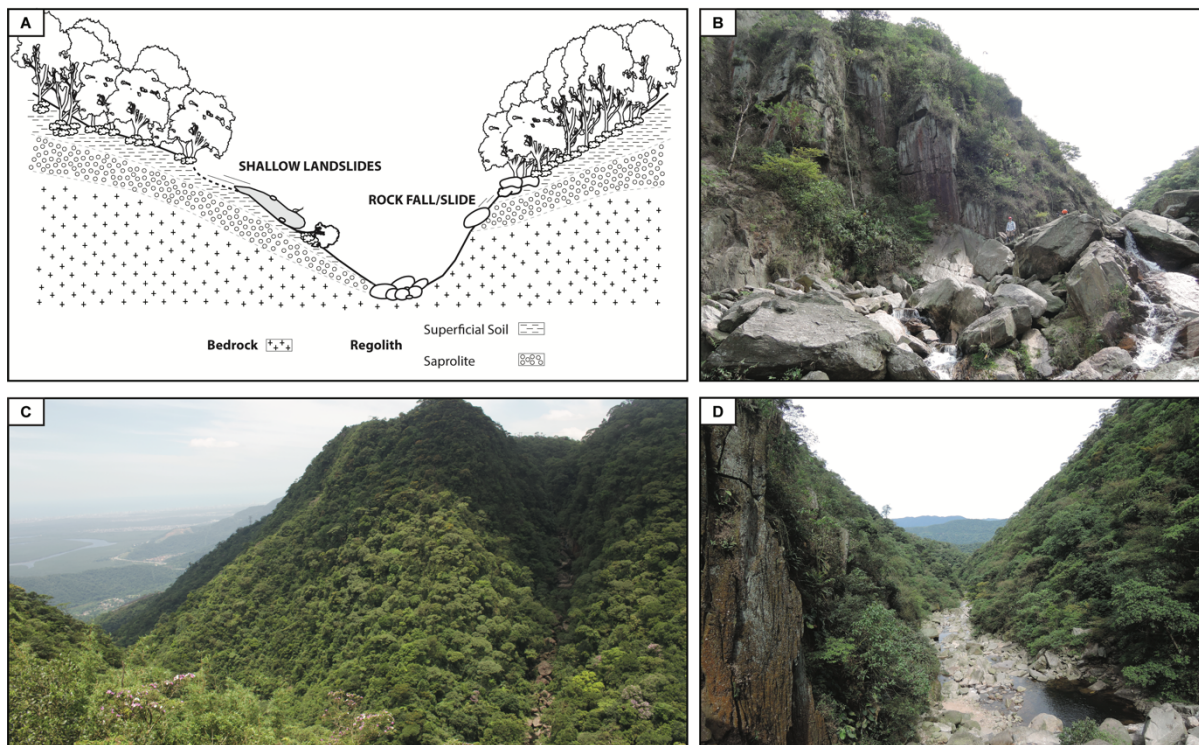


Figure 3-21. Debris-flow dynamics. A) Scheme of the initiation mechanism of the 1985 and 1994 debris-flow events in Cubatão, characterized by multiple source areas. B) Upstream view of catchment 7 in Cubatão, showing intense stony debris accumulation in the channel, as well as fractured bedrock outcrops in the margins (Coordinates: 360256.69 m E, 7367963.72 m S) C) Overview of the upstream section of catchment 19 in Cubatão, showing intense stony debris accumulation in a channel. A strong structural control is observed in the catchment (Coordinates: 350847.96 m E, 7360336.15 m S). D) Downstream view of the upstream section of catchment 7 in Cubatão, showing area with less accumulation of debris in the channel. Areas with intense stony and woody debris deposition are intercalated with areas with few accumulations along the catchment, suggesting that smaller debris-flow might have occurred more recently in small gullies or that slope failures occurred but did not trigger a debris-flow event, accumulating the material in the channel. (Coordinates: 360256.69 m E, 7367963.72 m S).

Generally speaking, debris-flow prone catchments have an area up to 10 km² (SLAYMAKER, 1990) and, on average, both Cubatão and Guaratuba show similar catchment area (ca. 3 km²). A catchment area of 3 km² is what is also observed in other catchments in the Serra do Mar region where debris flows occurred (Table 3.8) and it is within the range of other debris-flow prone catchments worldwide (Table 3.8).

Table 3-6. Morphometric parameters of the catchments located in Cubatão (Southeastern portion of Serra do Mar). Catch. = Catchment.

Catchment	Area (km ²)	Relief ratio	Catch. Relief (km)	Drainage density (km/km ²)	Catch. Length (km)	Melton Ratio
1	1.4	0.51	0.98	1.09	1.91	0.25
7	5.39	0.23	0.75	2.04	3.33	0.32
9	2.94	0.33	0.94	1.42	2.86	0.55
10	4.9	0.28	0.96	2.34	3.42	0.43
12	2.1	0.37	0.8	2.73	2.19	0.53
14	7.19	0.19	0.75	0.88	3.85	0.13
15	2.75	0.24	0.73	1.93	3.06	0.32
16	5.3	0.23	0.74	1.22	3.193	0.44
17	3.53	0.28	0.8	3.74	2.87	0.43
19	1.86	0.35	0.7	4.72	2.01	0.51
20	2.12	0.43	0.76	2.31	1.76	0.52
Average	3.29	0.3	0.71	1.93	2.417	0.42

Table 3-7. Morphometric parameters of the catchment located in Guaratuba (Southern portion of Serra do Mar), where a debris flow occurred in February 2017. Catch. = Catchment.

Catchment	Area (km ²)	Relief ratio	Catch. Relief (km)	Drainage density (km/km ²)	Catch. Length (km)	Melton Ratio
Pedra Branca	3.43	0.35	1.01	3	2.9	0.6

Both regions also show a similar Relief ratio (ca. 0.3), which is related to the production and availability of the sediments (WILFORD *et al.*, 2004). These values are slightly low when compared to other catchments worldwide (Table 3.8), which can potentially be associated to the lower recurrence rate of debris flows both in Cubatão and Guaratuba. These results, however, are similar to other catchments at Serra do Mar (Table 3.8), which also show a slightly lower Relief ratio (ca. 0.25). The Serra do Mar catchments presented in Table 3.8 are located in Itaóca (Guarda-mão catchment, São Paulo state) and in Morretes (Tingidor catchment, Paraná state) (DIAS *et al.*, 2022).

Catchment relief is associated with the intensity and reach of debris flows (NIKOLOVA *et al.*, 2020) and those in the Serra do Mar region are within the range of other catchments worldwide (Table 3.8). Guaratuba shows a higher catchment relief than the average in Cubatão, although catchment 1 in Cubatão shows a comparable relief to that of Guaratuba. Moreover, catchment 1 and Guaratuba also share the similarity of two debris-flow events initiated by large landslides in the headwaters' region, whereas the other catchments in Cubatão have their source areas more spread-out in the hillslopes.

Table 3-8. Morphometric Parameters of debris-flow prone catchments worldwide, adapted from Dias *et al.* (2022).

Location	Catchment Area (km ²)	Relief ratio	Catch. Relief (km)	Catch. Length (km)	Melton Ratio	Reference
Canada	0.2 - 4.1	0.3 - 0.49	0.6 - 1.4	1 - 4.68	0.66 - 1.21	Wilford <i>et al.</i> (2004)
New Zealand	0.18 - 9.66	0.25 - 0.88	0.55 - 1.93	1.05 - 4.5	0.45 - 1.59	Scally <i>et al.</i> (2010)
Bulgaria	0.015 - 39.27	0.05 - 0.68	0.16 - 0.82	0.33 - 15.50	0.13 - 1.59	Nikolova <i>et al.</i> (2020)
Romania	0.005 - 1.02	0.56	-	< 1.7	> 0.55	Ilinca (2021)
Taiwan	0.51 - 8.63	0.20 - 0.44	-	1.54 - 5.75	-	Chen and Yu (2011)
Brazil (Serra do Mar)	2.02 and 3.74	0.23 and 0.25	0.75 and 0.83	3.18 and 3.3	0.39 - 0.58	Dias <i>et al.</i> (2022)

Drainage density is associated to how rapidly a catchment drains the water that flows in their system, with those showing higher density indicating more intense/frequent hydrogeomorphic processes (e.g., floods, flash floods, debris floods, debris flow) (WILFORD *et al.*, 2004). Cubatão (1.92 km/km²), on average, shows a lower Drainage Density than Guaratuba (3 km/km²), as well as the other two catchments at Serra do Mar (5.75 in Itaóca; 4.45 in Morretes), which could potentially indicate less frequent events or events with shorter runout distance. As pointed out by the historical record of debris-flows in Brazil, Cubatão (especially catchment 17) is the main site of debris-flow events, with 9 events between 1920 and 2021 and a more recent one in 2022 (Table 3.9).

Catchment Length is associate to the runout distance of debris flows, with those with a smaller length usually associated with a longer distance (IVERSON *et al.*, 2001). Guaratuba and Cubatão show similar catchment length, which is also within the range of other catchments worldwide and in Serra do Mar (Table 3.9). As pointed out by Dias *et al.* (2022), some studies have suggested that debris-flow prone catchments usually show a length below 2.7 km, with those above this limit more prone to debris floods and other hydrogeomorphic processes (WELSH; DAVIES, 2011; ILINCA, 2021).

Furthermore, the Melton Ration of catchments also indicates a stronger tendency to initiate debris floods and not debris flows in the analyzed catchments. The Melton Ration (MELTON, 1958) has been widely applied in debris-flow studies, as it is suggested as a good indicator of the type of the hydrogeomorphic process that should dominate in a catchment (WILFORD *et al.*, 2004). Debris-flow prone catchments usually show values above 0.6, while those more susceptible to debris floods show values between 0.3 to 0.6 (WILFORD *et al.*, 2004). Guaratuba is on the limit between debris flood and debris flows (0.6), while all the catchments in Cubatão fall into the debris flood range.

Table 3-9. Debris flow events recorded in Cubatão since 1975, updated based on Gramani (2001).

Catchment	Date of the event	24-h accumulated rainfall	48-h accumulated rainfall	Peak rainfall intensity	Return period
1	25/12/1975	247.5 mm	255.5 mm	N/A	N/A
10	29/01/1976	279 mm	315 mm	40 mm h ⁻¹	1.23 years
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14	24/01/1985	242 mm	411 mm	84 mm h ⁻¹	10.4 years
9	24/01/1988	185 mm	186 mm	25 mm h ⁻¹	1 year
14, 15, 16, 17, 18, 19	07/02/1994	325 mm	452 mm	60 mm h ⁻¹	2.7 years
17	09/04/1996	260 mm	265 mm	18 mm h ⁻¹	1 year
Rio Pilões (West of the study area)	12/12/1999	128 mm	274 mm	N/A	N/A
Rio Pilões (West of the study area)	16/02/2000	304 mm	304 mm	118 mm h ⁻¹	90.5 years
Rio Marcolino, Rio Pilões, Ribeirão do cágado (West of the study area)	22/02/2013	312 mm	314 mm	118 mm h ⁻¹	90.5 years
17	29/04/2022	169 mm	248 mm	35 mm h ⁻¹	1 year

These results can potentially indicate that while debris flows can occur, they are not the main geomorphic process. As observed in the geomorphological investigation of the Guaratuba event, and suggested by field campaigns in Cubatão, in-channel accumulation of rock boulders in catchments at Serra do Mar are a common feature, with larger boulders (> 5 m) usually not reaching long distances from the source area, as they deposit along flatter portions of the channel. An evolution from a debris flow, to a debris flood, and, finally, to a flash flood in Guaratuba is suggested, due to the progressive deposition of material along the channel, a direct result of gentler channel slope from the middle section on, as well as to the length of the channel (2,900 m), which decreases the flow momentum.

In Cubatão, this evolution from a debris flows to a debris flood is also suggested by the geomorphological analysis conducted during field campaigns, and this evolution is also observed in other areas in Brazil at Serra do Mar (e.g., LACERDA, 2007; HUNGR *et al.*, 2014; DIAS *et al.*, 2022). The intense boulder accumulation in the channels of both Cubatão and Guaratuba can potentially be remobilized by future events, as erosion and entrainment are important elements of the sediment yield of debris flows in the Serra do Mar Mountain Range. In the estimation of the magnitude of the Guaratuba debris-flow event, approximately 75% of the total magnitude was due to entrainment and erosion. Even though the estimation of eroded material is affected by larger uncertainties than the volume of landslides and the in-channel debris deposits, other studies worldwide have also suggested the strong influence of erosion

on debris-flow magnitude and related impacts (e.g., MARCHI *et al.*, 2009; GABET; STERNBERG, 2008; BENNET *et al.*, 2013; SHEN *et al.*, 2020).

The maximum observed erosion depth in catchments of Cubatão, according to the RAMMS simulation, is of 3.67 m in catchment 7, while in the Pedra Branca catchment (Guaratuba) the maximum erosion depth observed was 10 m. The expressive difference can be mostly related to the resolution of the investigation/estimation. Other kinematic parameters, such as peak velocity, are similar for catchments in Cubatão and Guaratuba, averaging at about 23.1 m s⁻¹ in Cubatão, according to the RAMMS simulation, and 29.04 m s⁻¹ in Guaratuba, according to our field-based estimations.

It is important, however, to point out the bias towards large magnitude events, with smaller debris-flow events often going unnoticed or not investigated. The comparison presented in this study considers high-magnitude ($> 10^5$ m³) events, which is triggered by very-high to extreme precipitation rates. Smaller magnitude events usually go unreported due to the remoteness of upstream reaches of catchments at Serra do Mar, where debris flows are expected to dominate as the main hydrogeomorphic process. The event of March 2022 (Table 3.9) in Cubatão is an exception (Figures 3.22a, 3.22b and 3.22c), because it affected a now tourist attraction, the century-old road that connected the coast to the city of São Paulo (“*Caminhos do Mar*”).

This event occurred in one of the tributaries of catchment 17, where the slopes are very steep ($>30^\circ$, or $>58\%$), but the material did not reach the outlet region near the oil refinery that is located at the downstream area of the catchment. The sediments mobilized by this event most likely deposited along the intermediary reaches of the channel, where the slopes become gentler. Another hypothesis would be that the sediments were trapped by the retention structures (Sabo dams) installed at the downstream portion of the catchment (Figures 3.22d and 3.22e). However, no evidence of a large accumulation of sediments upstream these dams were observed during our field campaigns, which indicates that the sediments deposited in upper portions of the channel.

The return period of the rainfall that triggered this recent debris-flow event in Cubatão is estimated at ca. 1 year, which can indicate that a similar event can potentially occur every year in a tributary of a catchment in Cubatão. However, when we consider the short return period of the rainfall that triggered the 1985 and 1994 debris-flow events (10 and 3.5 years, respectively), the complexity of the interactions between climate and geomorphology is highlighted, as no event of similar magnitude has occurred in the region since then.



Figure 3-22. Recent debris flow in Cubatão and retention structures installed in Catchment 17. A) The tributary of Catchment 17 before the March 2022 event. Photo from 2014. B) The tributary after the debris-flow event, showing the intense erosion of the channel and vegetation. The measured post-event channel width is of 7 m. Photo from July 2022. C) Photo of the debris-flow event on the day after its occurrence (March 30, 2022). Photo from Maicon, one of the monitors of the “Caminhos do Mar” Park. D) Retention structures installed in the downstream portion of catchment 17, to protect the oil refinery from debris-flow events. Photo from Marcelo Gramani. E) Detail of two Sabo dams located in catchment 17. Photo from Marcelo Gramani.

Nonetheless, considering the overall short return period of debris-flow triggering rainfall in Cubatão (Table 3.9) and in Guaratuba (15-20 years), combined with the intense in-channel material accumulation, future large-magnitude events are likely to occur in the next decade or so.

3.6. A multi-step hazard assessment methodology for debris-flow prone areas influenced by hydroclimatic events

Creating tools and methodologies that can be applied in the mitigation of disasters and in disaster-preparedness programs is a primordial and challenging task. Hazard assessment studies are a first step to understanding the potential negative effects that a phenomenon (i.e., debris flows) can cause in a specific region, which can later subsidize in-depth risk analysis. To contribute to the effort of debris-flow risk mitigation in Brazil, our study proposes a hazard assessment methodology to be applied in debris-flow prone areas influenced by high-intensity rain events. As our test-site, 20 catchments located in the region of Cubatão are chosen (Figure 3.6).

In the hazard assessment, we first conduct a data-driven Logistic Regression (LR) analysis to identify the main factors that influence debris-flow initiation in the region (shown in subchapter 3.2), as well as to identify the catchments that are more susceptible to the phenomenon. The most-susceptible catchments are, then, analyzed using the numerical model RAMMS, to simulate past debris-flow that can help to estimate important kinematic parameters about the debris-flow behavior. Based on the outcomes of the simulations and on the analysis of the rain events that led to debris flows in the study site (shown in subchapter 3.3), a hazard matrix is proposed for the creation of a hazard zonation map. The mapping of the infrastructures located in the region is also performed to support the hazard zonation.

Applying the equation based on the LR model (Equation 1) to assess the areas with high susceptibility to debris-flow initiation in the study site, catchments 20, 19, 17, 16, 15, 14, 12, 10, 9 and 7 are those most susceptible overall (Figure 3.23). The northeastern portion of catchment 1 also shows a high percentage of highly susceptible areas (Figure 3.23), which can be related to steeper slopes and the more widespread occurrence of Cambisols in the headwaters' region, which is a significant influencing factor in debris-flow initiation in the region according to the LR analysis.

Based on the susceptibility analysis, catchments 20, 19, 17, 16, 15, 14, 12, 10, 9, 7 and 1 are simulated using RAMMS. The simulations were calibrated based on the debris-flow event of 1985 in catchments 14, 12, 10, 9, 8, 7 and 1, while catchments 14, 15, 16, 17 and 19 were calibrated based on the 1994 debris-flow event. Catchment 20 was not modeled as no debris flow was recorded both in 1985 and 1994 and calibration could not be conducted. The initiation areas were determined according to the landslide inventories that we created using aerial

photographs prior and post event and a bulk density of $1,900 \text{ kg m}^{-3}$ was assumed for the source areas and the entrainment zone.

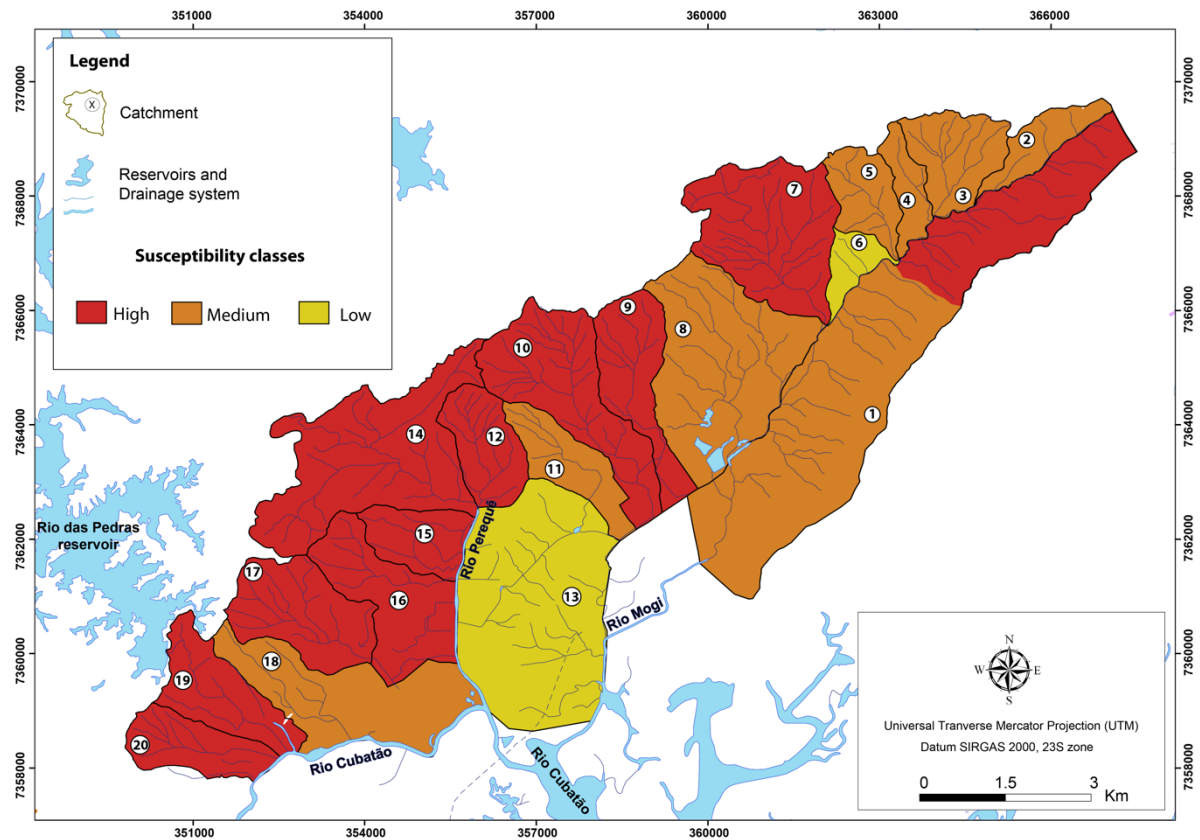


Figure 3-23. Map showing the overall susceptibility to debris-flow initiation of the 20 catchments at the study area, based on the LR model.

The volume of the landslides that initiated the debris flows in each catchment is shown in Table 3.10. Considering the whole study area, the magnitude of the 1985 landslide event is estimated at ca. $540,900 \text{ m}^3$, while the magnitude of the 1994 landslide event is estimated at ca. $227,000 \text{ m}^3$. The magnitude of the debris flows (i.e., volume of sediments mobilized) at each catchment is estimated based on magnitude equations from Marchi *et al.* (2019), as suggested by Cabral *et al.* (2021) for catchments at Serra do Mar (Table 3.10).

Figure 3.24 shows the calibration results based on the coverage index (Ω) (we refer paper III), which aided the identification of the best-matched simulations (Figure 3.25 and 3.26). The calibration is mainly based on the comparison of the observed runout distance with those modeled by RAMMS. One of the parameters subjected to most uncertainties during modeling is erosion depth, as no comprehensive information for any of the modeled catchments was available. In our simulations, we adopted for all the catchments two maximum erosional depths: 4 m at upper and intermediate reaches, and 0.5 at lower reaches of the catchments. A 4

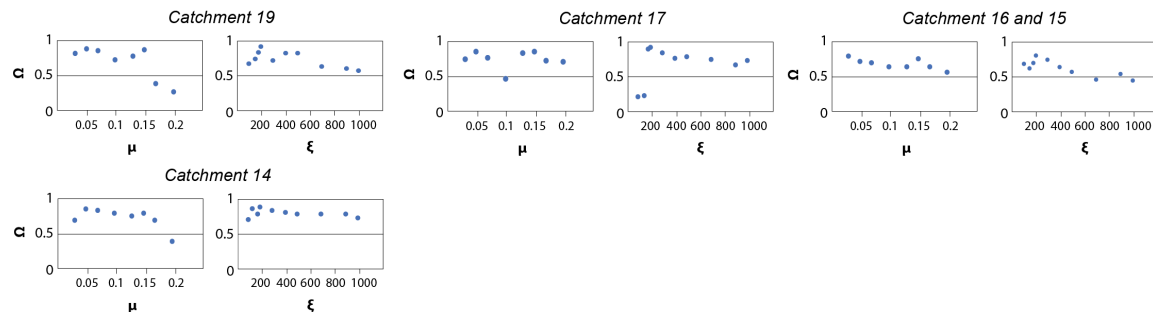
m erosion depth was reported by Kanji *et al.* (2007) in catchment 17 (1994), which we extrapolated for all the other catchments in the study region.

Table 3-10. RAMMS-2D results and characteristics of the debris flows. Est. = estimated, Max. = maximum.

Catchment	Year of the event	Initiation volume (m ³)	Est. Magnitude (m ³)	Runout	Flow parameters					
					μ	ξ (m s ⁻²)	Max. Flow height	Max. erosion depth	Max. velocity	Max. Impact pressure
1	1985	68,422.3*	2.5 x 10 ⁴	N/A*	0.1	300	3.2 m	0.88 m	30.96 m s ⁻¹	1917.55 kPa
7	1985	131,737.6	2.5 x 10 ⁵	N/A*	0.05	200	8.6 m	3.67 m	23.62 m s ⁻¹	1115.38 kPa
8	1985	33,976.8	1.1 x 10 ⁵	480 m	0.05	200	5.5 m	1.3 m	24.25 m s ⁻¹	1175.73 kPa
9	1985	25,740.7	1.3 x 10 ⁵	270 m	0.05	180	4 m	0.74 m	14.04 m s ⁻¹	354.74 kPa
10	1985	78,865.6	2 x 10 ⁵	700 m	0.05	180	4.7 m	1.74 m	14.25 m s ⁻¹	406.1 kPa
12,14	1985	85,409.3	2.4 x 10 ⁵	N/A*	0.05	200	5.4 m	1.59 m	30.87 m s ⁻¹	346.35 kPa
14	1994	82,632.1	2 x 10 ⁵	N/A*	0.05	200	5.6 m	1.8 m	32.93 m s ⁻¹	550.87 kPa
15, 16	1994	10,150.7	0.8 x 10 ⁵	510 m	0.03	200	4.7 m	2.11 m	16.75 m s ⁻¹	561.26 kPa
17	1994	43,702.46	1.7 x 10 ⁵	400 m	0.05	200	5.3 m	2.84 m	12.48 m s ⁻¹	296.13 kPa
19	1994	17,673.8	0.8 x 10 ⁵	N/A*	0.05	200	2.9 m	1.45 m	30.98 m s ⁻¹	1919.97 kPa

* Direct discharge in the drainage system of the region. Indirect effects of debris flows include floods and silting.

Calibration of the debris flows recorded in 1994



Calibration of the debris flows recorded in 1985

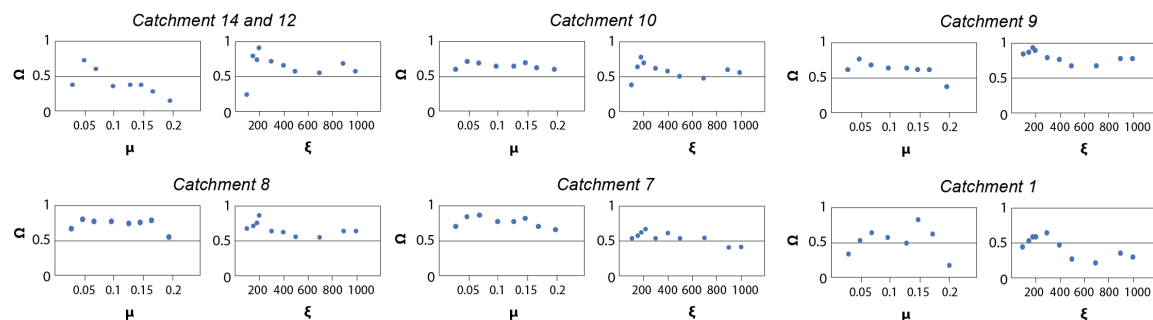


Figure 3-24. Calibration using the coverage index (Ω) of the debris-flow simulations for the selected catchments at the study area. The closer the coverage index is to 1, the more representative the simulation.

Another limitation was the lack of available information about catchments 19, 14, 12, 7 and 1, since no deposition pattern could be interpreted from aerial photographs. Even though

we performed calibrations in these catchments in the same manner as the others, the best matched parameters adopted were those of with μ equal to the channel slope of the downstream portion of the catchment and ξ was assumed to be similar to the general trend of the area ($\xi = 200 \text{ m s}^{-2}$). The lack of depositional fan in these catchments, and in most of the catchments in the study region, is related to the direct debouchment into the rivers Mogi, Perequê and Cubatão, which receive most of the sediments of the 20 studied catchments.

Moreover, even though the debris flows in the study area exhibit a very high content of stony debris, most of the larger boulders ($>1 \text{ m}$) are interpreted to deposit along the debris flow route and are not carried for long distances. Most of the damage in the downstream areas of the catchments is due to the smaller boulders ($< 1 \text{ m}$), fine sediments and woody debris. These interpretations are supported by witnesses of the 1985 and 1994 events and the field campaigns that were conducted in the study area, where intense boulder accumulation in areas with gentler slopes at upper/intermediate reaches of channel were observed. Moreover, the geomorphic characteristics of the studied catchments are similar to others at Serra do Mar, such as Pedra Branca in Guaratuba (Paraná), as discussed in the previous chapter.

The average runout distance, according to the simulations, is ca. 470 m, with the largest distance observed in catchment 10 (700 m) and the shortest in catchment 9 (270 m). Highest flow heights (Figure 3.27 and 3.28) are observed in catchment 7 (8.6 m, 1985) and in catchment 14 (5.6 m, 1994), where the initiation volume is higher. Overall, flow height in the studied catchments averages 5 m. The average peak velocity of the debris flows is 23.1 m s^{-1} , with the highest velocities observed in catchment 14 (30.87 m s^{-1}) and catchment 1 (30.96 m s^{-1}). Maximum impact pressures are observed in catchments where steep knickpoints are observed (catchments 19, 1, 7 and 8).

As discussed in subchapter 3.2 and 3.3, rainfall is identified as the most influencing factor in debris-flow initiation in Cubatão and a hazard zonation matrix is, thus, proposed based on rainfall accumulated in 48 h, as well as the depositional areas and flow behavior patterns modeled by RAMMS. As pointed out in the rainfall analysis, the 48-h accumulated precipitation is more strongly associated to debris-flow initiation in our test-site area and is, as consequence, considered in the hazard matrix.

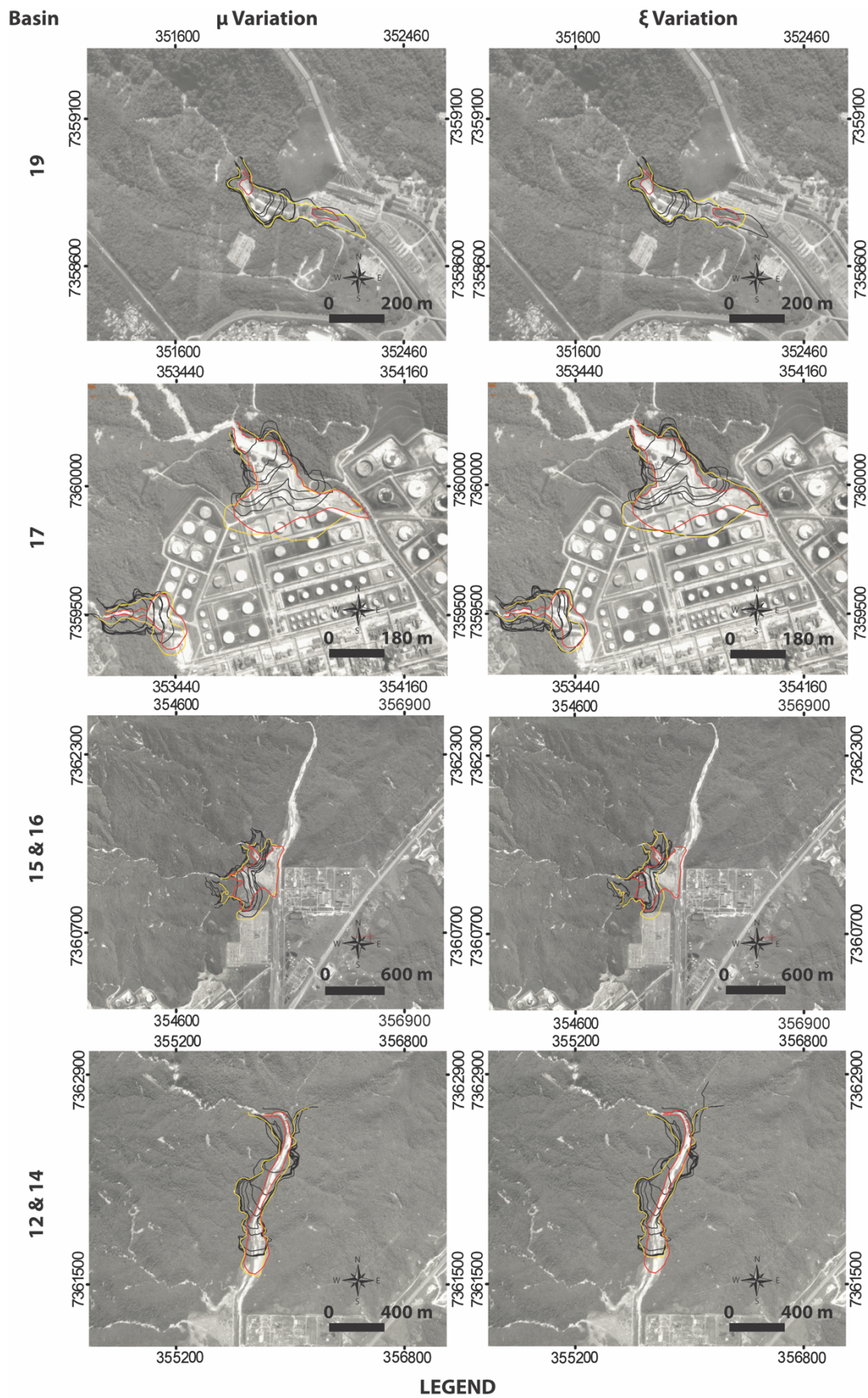


Figure 3-25. Comparison between modeled and observed run-out distance of the 1994 debris-flow event for the selected catchments.

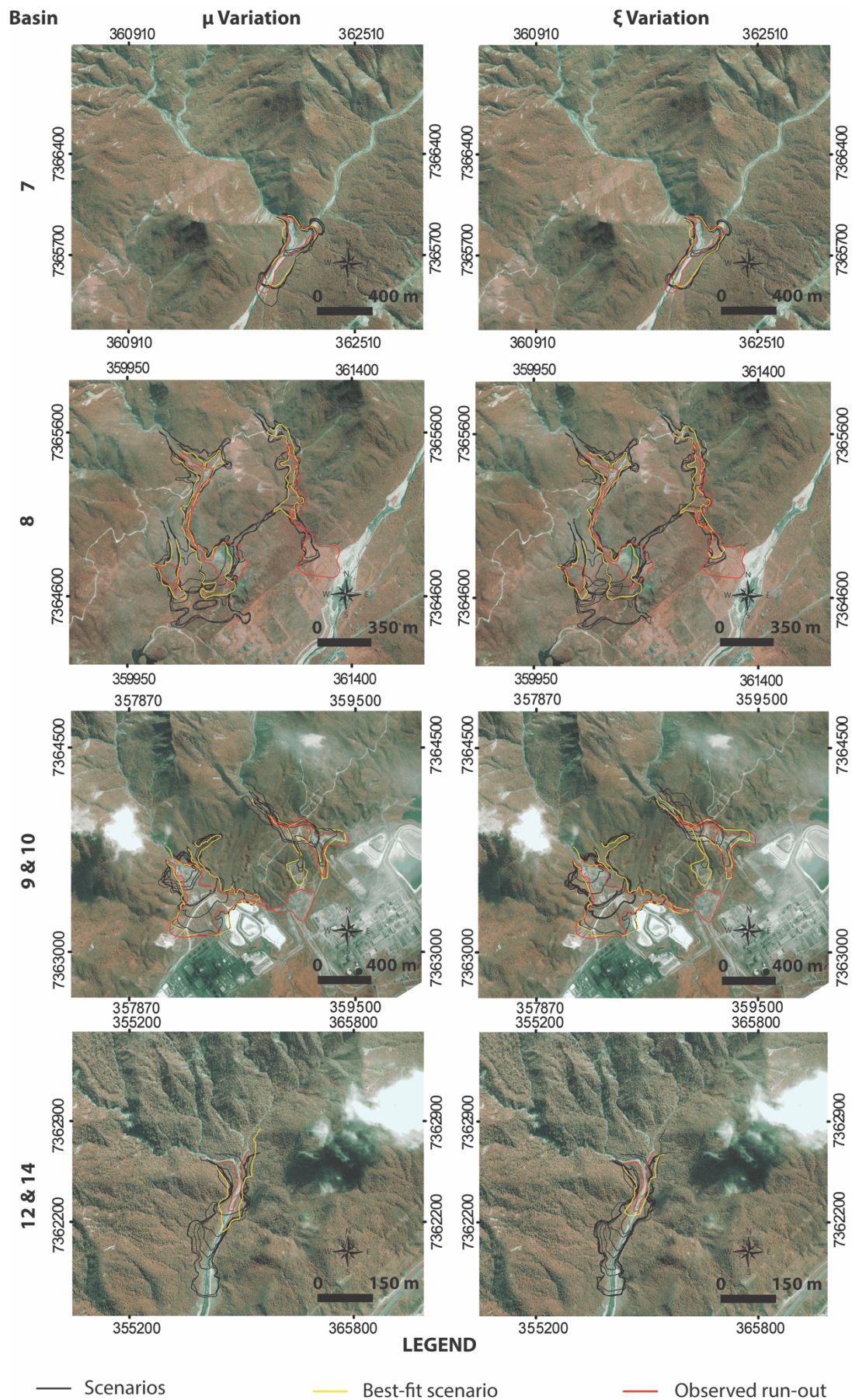


Figure 3-26. Comparison between modeled and observed run-out distances of the 1985 debris-flow event for the selected catchments.

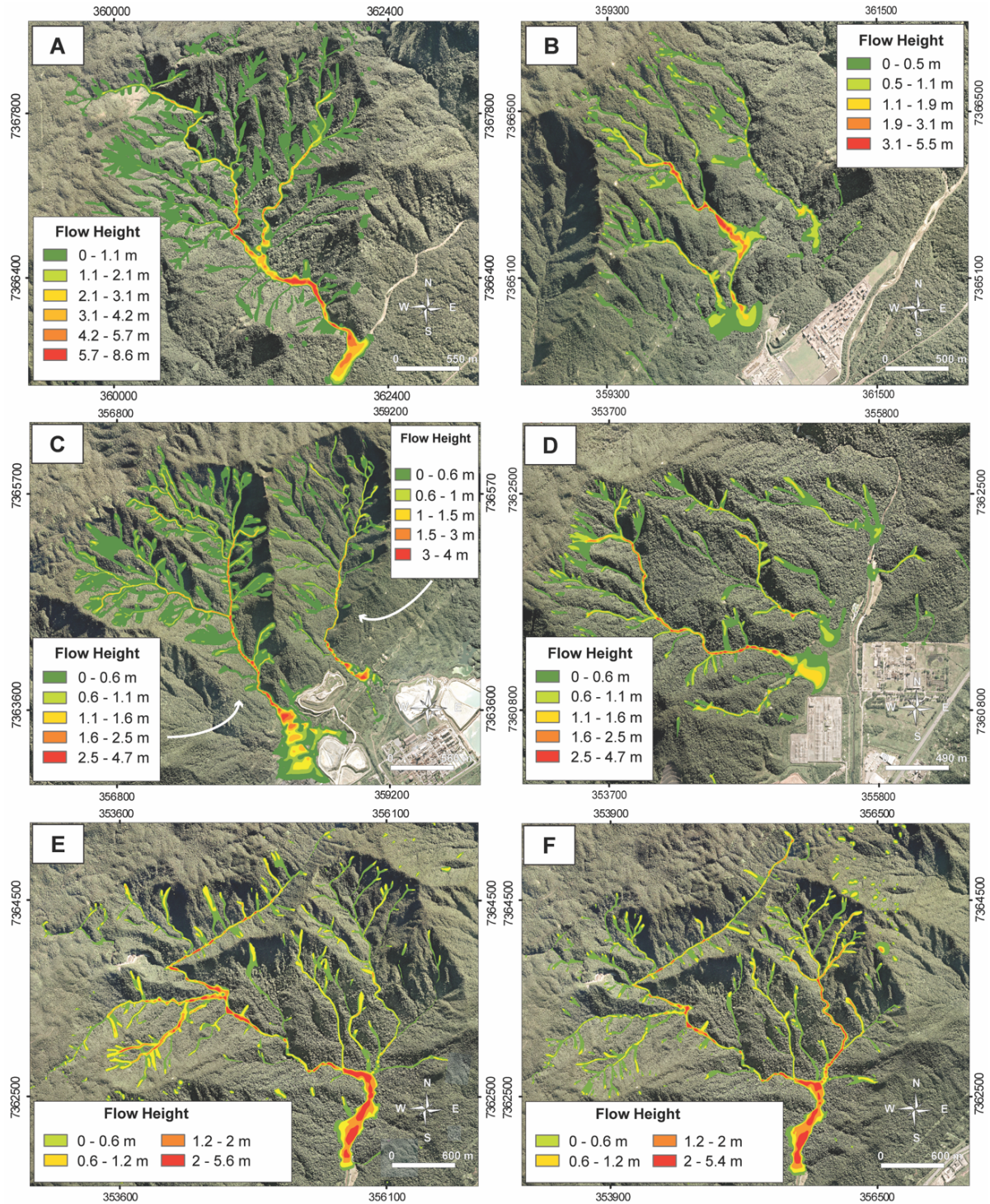


Figure 3-27. RAMMS modeling results showing maximum flow height. A) Catchment 7 (1985). B) Catchment 8 (1985). C) Catchments 9 and 10 (1985). D) Catchment 15 and 16 (1994). E) Catchment 14 (1994). F) Catchments 14 and 12 (1985).

Five levels of hazard are proposed: very high, high, medium, low, and very low (Table 3.11). Very high-hazard areas are those where RAMMS simulated a > 1 m flow height and velocity of $> 1 \text{ m s}^{-1}$, as also proposed by Hürlimann *et al.* (2006), and humans and infrastructures are directly affected. High hazard areas are those where the debris flow runout

can reach up to 1 m in height and velocity of up to 1 m s^{-1} , and infrastructures may be directly impacted. Medium hazard areas are those that are not directly impacted by the sediments transported by a debris flow, but can exhibit flooding or silting that may impact infrastructures. Areas with low hazards are those that can experience some kind of side impacts of the debris flows, such as floods, but are inhabited, or areas with retention structures installed, as it is the case of catchment 19. Areas with very low hazard are those where no impacts of any sort are expected.

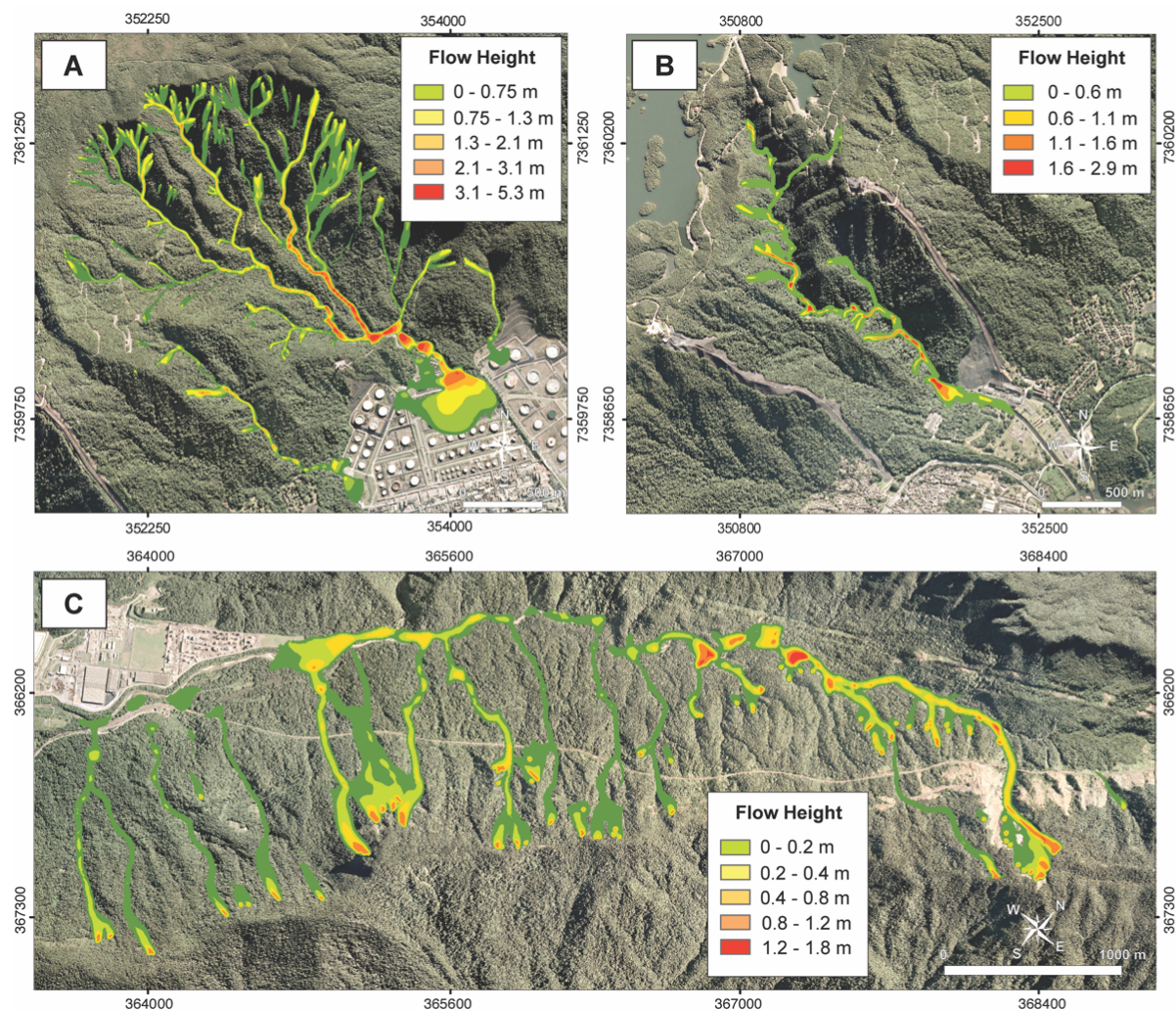


Figure 3-28. RAMMS modeling results showing maximum flow height. A) Catchment 17 (1994). B) Catchment 19 (1994). C) Catchment 1 (1985).

Based on the hazard level matrix and on the infrastructures at hazard in each catchment (Table 3.12), a hazard zonation map was created for the 20 catchments (Figure 3.29). The map of Figure 3.29 shows the zonation based on a rainfall of over $> 200\text{ mm}$ in 48 h, which can be adapted to different hazard levels according to rainfall indices. Catchments 19, 16, 15, 11, 10 and 9 exhibit an overall higher hazard in the region (Table 3.12), due to a higher probability of

debris-flow related damages to humans and infrastructures. Retention structures in such catchments could potentially decrease their hazard level.

Areas that have not shown any history of debris-flow occurrence since 1975, such as catchment 20, were classified as high hazard areas in the context of >200 mm rainfall in 48 h, based on the LR susceptibility analysis. These catchments exhibit intense in-channel stony material accumulation, which contributes to increasing their potential hazard to residential areas and infrastructures that are located within their limits. The average runout distance with a 470 m radius was assumed as a very high hazard area, in catchments where no debris flows were recorded.

Catchment 17, which has an extensive history of debris flows (Table 3.9), is classified with a medium/low hazard level, due mainly to the retention structures installed (Figure 3.22d and 3.22e) and the removal of in-channel debris deposits, promoted after the 1996 debris-flow event.

Table 3-11. Hazard level matrix developed for the study area, based on different rainfall indices and the impacts on infrastructures and population.

			Rainfall index in 48 hours		
			> 200 mm	< 200 mm, > 150 mm	<150 mm, >100 mm
Severity	Direct impacts	flow height $\geq$ 1m; velocity $\geq$ 1 m s ⁻¹	Very high	Very high	High
		flow height < 1m; velocity < 1 m s ⁻¹	High	High	Medium
	Indirect impacts	floods or silting	Medium	Medium	Low
		Areas with retention structures installed; Remote areas	Medium	Low	Very low
	No impacts	-	Very low	Very low	Very low

An integrated analysis of the hazard assessment presented and studies about the economic/social vulnerability of the region is encouraged in future risk analyses. As DeBortoli *et al.* (2017) point out, the mapping of vulnerability of the community is crucial, as it is fundamental to preventing and reducing the risk to which the society is potentially exposed. Such mapping, however, demands a more in-depth and multidisciplinary approach. Moreover, the expansion of the city towards mountain areas, especially by socially vulnerable communities, can increase the risk of new events, even those with smaller magnitudes.

The multi-step hazard assessment here proposed and applied in the hazard zonation of Cubatão joins other studies that aimed at creating new methodologies that can help to mitigate future landslide-related damage, such as the works of Cardinali *et al.* (2022), Hürlihan *et al.* (2006; 2008), Wu *et al.* (2018), Huangfu *et al.* (2021), among many others. When assessing debris-flow hazard, especially in areas where the initiation factor is landslides, it is necessary

to combine analysis of all the factors that can lead to the initiation of the phenomena (STEGER *et al.*, 2021), as well as aspects of their dynamics, represented mainly by the runout distance (COROMINAS *et al.*, 2013; FRANK *et al.*, 2017). The transition from landslides to debris flows occurs especially during periods of heavy rainfall, although, as demonstrated in our analysis and other studies (e.g., TAKAHASHI, 2001; COROMINAS *et al.* 2013; HUNGR, 1997), rainfall intensity is not always directly related to the magnitude of an event.

Table 3-12. Infrastructures, both public and private, at hazard in each catchment and overall hazard level, for a 200 mm rainfall in 48 h.

Catchment	Elements at hazards	Overall Hazard level
1	Railways from the company MRS Logistica; Fertilizer company “Yara Cubatão”, Container storage company “Rodopark”	Medium
2	-	Low
3	-	Low
4	-	Low
5	-	Low
6	-	Low
7	Container storage company “Depotce”	Medium
8	-	High
9	Fertilizer company “Mosaic Fertilizantes do Brasil”	High
10	Petrochemical company “Copebras”; industrial gas company “White Martins”	High
11	Chemical plant “Birla Carbon Brasil”	High
13	Petrochemical company “Braskem”, Logistic company “Brado Logistica”, Chemical industry “Hidromar”, Carbocloro Oxypar Chemical Industries; Industrial gas company “Messer Gases”, Three transportation companies	Low
12, 14, 15,	Electrical substation	High
16		
17	Petrobras oil refinery	Medium/Low
18	Vila Light (Residential area with approximately 140 houses, 60 of which have residents), FAFEN (Oil refinery), Thermoelectric Plant “Euzébio Rocha”; Fertilizers company “Yara Brasil”	High
19	Hydropower plant “Henry Boden”, with electrical substations	High
20	Anchieta and Imigrantes Highway, Vila Fabril (residential area with more than 400 houses), oil pipelines	High

The combination, therefore, of different, data-driven methodologies is fundamental to ensuring the reliability of the hazard evaluation, focusing on the different aspects related to a phenomenon. As pointed out by Wu *et al.* (2018), LR is considered one of the most reliable methods in landslide susceptibility assessment, identifying the main characteristics that influence the phenomenon in a particular region. When combined with the state-of-the-art, numerical model RAMMS, which provides concrete, physically-based results (FRANK *et al.*

2017), the hazard evaluation can reliably represent the potential impact of future debris-flow events in a region. Moreover, the inclusion of the rainfall analysis provides a good indication of future events probability and the different associated hazard levels according to the intensity of the rain event.

This thesis, therefore, is a small contribution to the effort of better understanding the dynamics and impacts of debris flows in Brazil, as well as to the effort of preventing future disasters. As for future studies in Brazil, Large Wood (LW) mobilization in densely forested catchments should be focused, as LW can contribute to significantly increasing debris-flow hazard and risk (LUCÍA *et al.*, 2015; RICKENMANN, 2016).

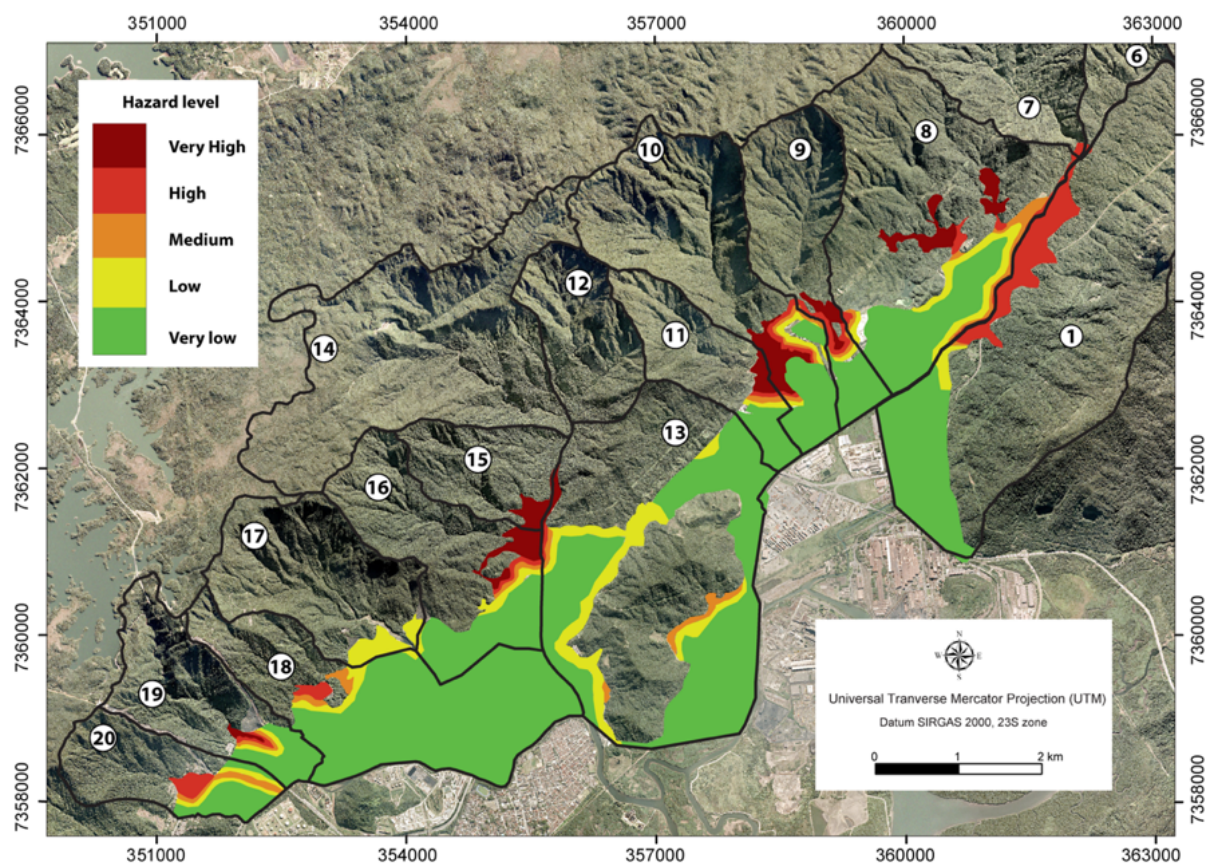


Figure 3-29. Debris-flow hazard zonation, based mainly on flow properties and on rainfall intensity (> 200 mm in 48 h), as well as on the analysis of the elements at hazard.

4. Final considerations

Cataloguing and estimating the consequences that a natural hazard represents based on past events is one of the most effective methods to provide reasonable damage assessments to the society. Our historical analysis shows that debris-flow events are concentrated mostly in the Serra do Mar and Serra da Mantiqueira regions in Southeast Brazil, where population density is higher and occupation of hilly areas is more common. Between 1920 and 2021, debris-flow events were responsible for over 5,771 fatalities and 5.5 billion USD in economic losses in Brazil, most of which in the Southeast region (91% of the fatalities, 67% of the economic losses).

The city of Cubatão, in the state of São Paulo, is one the most affected areas by debris flows in the country, with an extensive history of fatal and destructive events. The region is characterized by high rainfall indices and urban and industrial areas near or at the hilly areas. The city, therefore, was chosen as test-site for our proposed multi-step hazard assessment, based on Logistic Regression (LR) analysis, simulation of flow parameters using numerical model and rainfall back-analysis. The LR analysis highlighted that rainfall is the main influencing factor on the initiation of the phenomenon and the back-analysis of rain events suggests that the precipitation accumulated 48 h prior to the initiation of a debris flow plays a more significant role on their deflagration.

Furthermore, the LR analysis also highlighted the catchments most susceptible to debris-flow initiation, which were further analyzed using the numerical model RAMMS. The simulation using RAMMS aimed at characterizing the kinematic patterns of debris flows in these catchments, as it is a fundamental step when analyzing the hazard that the phenomenon represents. The kinematic parameters of debris flows in Cubatão are similar to those estimated based in the debris-flow event in Guaratuba (February 2017), highlighting an overall similarity between catchments in the Serra do Mar mountain range. Based on the kinematic parameters, the LR and the rainfall back-analysis, a hazard zonation matrix with five levels of hazard (very low to very high) was proposed to assess debris-flow hazard.

The methodology proposed is relevant, as hazard zonation, in conjunction with vulnerability studies, can subsidize the creation of risk management programs for debris-flow prone areas and establish guidelines that should be followed during emergency situations. Such guidelines do not currently exist for Cubatão, as well as for most debris-flow prone regions in Brazil. Moreover, a systematic geomorphological investigation of catchments that show history of debris-flow events, such as the one performed in the Pedra Branca catchment in Guaratuba,

is fundamental to quantifying the potential magnitude of future events, as well as to understanding the type of sediments (e.g., size, woody and/or stony, etc.) that will reach and affect the downstream portions.

Magnitude studies are also a pathway for the development of Frequency-Magnitude relationships that can support reliable monitoring programs and for prioritizing areas where Early Warning Systems should be installed. Considering the short return period of the debris-flow triggering rainfall (between 1 and 15 years) in the sites more profoundly analyzed in the thesis (Cubatão and Guaratuba), new events with large magnitudes ($>10^5 \text{ m}^3$) are likely to occur in the next decade. It is crucial, therefore, that these regions are prepared for emergency situations, with a reliable rain gauge network, hazard zonation maps and an emergency plan for evacuation of the potentially affected areas.

The outlook, however, is not promising. The Brazilian National Center for Monitoring and Warning of Natural Disasters - CEMADEN (*Centro de Monitoramento e Alerta de Desastres Naturais*), responsible for hazard and disaster management in the whole country, has been continuously underfunded in the past 4 years, going from an annual budget of 14 million USD on its creation in 2012-2013 to just over 3 million USD in 2019-2020. The recent landslide and flash flood disaster of February 2022 in Petrópolis (state of Rio de Janeiro), which caused 231 fatalities, is a direct example of how the lack of continuity in public policies and political interest in disaster prevention can be catastrophic. A challenge for the scientific community in Brazil, therefore, is to decrease the distance between politics and science.

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APPENDIX A - Accepted manuscripts

A.1 The consequences of debris flows in Brazil: a historical analysis based on recorded events in the last 100 years

A.2 Characterization of a landslide-triggered debris flow at a rainforest-covered mountain region in Brazil

A.3 A multi-step hazard assessment for debris-flow prone areas influenced by hydroclimatic events