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A SPATIALLY INTEGRATED MODELLING APPROACH TO LANDSLIDE RISK ASSESSMENT: A CASE STUDY OF THE NOVA FRIBURGO DISASTER - RJ, BRAZIL

Claudia Paola Cardozo

Doctorate Thesis of the Graduate Course in Remote Sensing, guided by Drs. Eymar Silva Sampaio Lopes, and Antônio Miguel Vieira Monteiro, approved in February 27, 2018.

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Este trabalho foi aprovado por:

( ) maioria simples

(X) unanimidade

São José dos Campos, 27 de fevereiro de 2018

¡No! Permanecer y transcurrir
No es perdurar, no es existir
¡Ni honrar la vida!
Hay tantas maneras de no ser,
Tanta conciencia sin saber
Adormecida

Merecer la vida no es callar y consentir,
Tantas injusticias repetidas...
¡Es una virtud, es dignidad!
Y es la actitud de identidad ¡más definida!

Eso de durar y transcurrir
No nos da derecho a presumir.
Porque no es lo mismo que vivir
¡Honrar la vida!

¡No! Permanecer y transcurrir
No siempre quiere sugerir
¡Honrar la vida!
Hay tanta pequeña vanidad,
En nuestra tonta humanidad
Enceguecida

Merecer la vida es erguirse vertical,
Más allá del mal, de las caídas...
Es igual que darle a la verdad,
Y a nuestra propia libertad
¡La bienvenida!

Eso de durar y transcurrir
No nos da derecho a presumir.
Porque no es lo mismo que vivir
¡Honrar la vida!

Eladia Blázquez

A mis queridos padres Yonne y Carlos

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ABSTRACT

Landslides cause enormous economic damage and fatalities worldwide. The “2011 Mega disaster” in the Rio de Janeiro mountainous region is considered the worst landslide disaster in Brazilian history. Traditionally, risk topic has been analyzed from a purely engineering-based perspective, which has proved to have an ineffective response to face the challenges posed by physical and social factors, especially in low-income countries. This thesis introduces a conceptual framework for an integrated risk assessment and undertakes the proposal in a practical way in the Nova Friburgo municipality, as a case study. In the first part of this research, an assessment of the physical component of risk was addressed. Three scenarios of landslide susceptibility were performed using a 10m-resolution DEM, geotechnical data and a landslide inventory. Findings suggest that the scenario with a wide range of cohesion parameter values was able to predict almost 70% of the inventoried landslides and about 50% of the territory with landslide-prone areas. In the second part of this thesis, a deep analysis of human component of risk is performed. A social vulnerability assessment- using the SoVI method- and data collection disaggregated by age, sex and race/ethnicity of the 2011 landslide-related fatalities were conducted. Results reveal differential social vulnerability among census tracts. Most of them were classified as moderately vulnerable. Although highly social vulnerable areas were not widely distributed in the territory, they are important because of their location and implications for the municipality economic matrix. Regarding the 2011 landslide-related fatalities, 434 casualties were registered. Spatial analysis indicates that the highest mortality was located at the northwest and central municipality zones. Landslide disaster affected males and females differently. In most age groups, landslides have killed more men and boys than women and girls. Fifty percent of those who lost their lives were the youngest and the elderly. The black population had a slightly higher mortality rate than either the brown (Pardos) and white ones. Data did not reveal a discernible trend in the association between social vulnerability and casualties. It seems that the landslide quantity and magnitude was so great that all of Nova Friburgo inhabitants were equally reached, beyond the inequalities expressed by their social vulnerability. In the third part of this inquiry, to predict landslide risk probability, the social vulnerability and the landslide susceptibility predictors were combined using the Generalized Additive Model (GAM). Findings suggest that in instable terrains, is enough a moderate social vulnerability level to increase the probability of landslide risk. Results also highlight model capacity to uncover hidden patterns in the dataset, capturing a nonlinear effect of social vulnerability predictor and a linear effect of terrain stability predictor. In conclusion, the proposed conceptual framework is generic and flexible, so can be applied to other areas, analysis scales and natural hazard types although some adaptation would be necessary depending on available data. Furthermore, the integrated approach performed in this thesis highlights that it is feasible and necessary linking data from different science domains to better understand disaster risk complexity, reducing risk and curbing losses of both human lives and economic assets through knowledge-based actions. It should be noted that this thesis research complies with guidelines given at the first priority area for action of the Sendai Framework for Disaster Risk Reduction 2015-2030, which outlines the importance of “Understanding disaster risk”. Finally, resulting knowledge provides Nova Friburgo community, organizations and governments with a basis to comprehend the risk related to a specific natural hazard: “the landslides” which can be leveraged to achieve an effective preparation and response to future disasters and also to promote disaster-resilient societies.

Key-words: Landslides. Modelling. Risk. Disaster. Integrated approach. Nova Friburgo.

MODELAGEM ESPACIAL INTEGRADA PARA A AVALIAÇÃO DO RISCO DE DESLIZAMENTOS: UM ESTUDO DE CASO DO DESASTRE EM NOVA FRIBURGO, RIO DE JANEIRO

RESUMO

Os deslizamentos de terra causam enormes prejuízos econômicos e mortes em todo o mundo. O "Mega desastre 2011" na região montanhosa do Rio de Janeiro é considerado o pior desastre na história do Brasil. Tradicionalmente, o tópico de risco foi analisado a partir de uma perspectiva puramente baseada na engenharia que provou ter uma resposta ineficaz para enfrentar os desafios impostos por fatores físicos e sociais, especialmente em países de baixa renda. Esta tese apresenta um marco conceitual para uma avaliação integrada do risco e realiza a proposta de maneira prática no município de Nova Friburgo, como um estudo de caso. Na primeira parte desta pesquisa, uma avaliação do componente físico do risco foi abordada. Três cenários de suscetibilidade a escorregamentos foram realizados usando um DEM de 10m de resolução espacial, dados geotécnicos e um inventário de deslizamentos. Os resultados sugerem que o cenário que utilizou uma ampla gama de valores de coesão foi capaz de prever quase 70% dos deslizamentos de terra inventariados e cerca de 50% do território com áreas propensas a deslizamentos. Na segunda parte desta tese, se analisou o componente humano de risco. Uma avaliação de vulnerabilidade social - usando o método SoVI - e a coleta de dados desagregados por idade, sexo e raça/etnia dos óbitos provocados pelos deslizamentos de 2011 foram realizados. Os resultados revelam uma vulnerabilidade social diferenciada entre os setores censitários. A maioria deles foi classificada como moderadamente vulnerável. Embora as áreas altamente vulneráveis não sejam amplamente distribuídas no território, elas são importantes devido à sua localização e implicações para a matriz econômica do município. Em relação aos óbitos por deslizamentos de terra, foram registradas434 vítimas. A análise espacial indica que a maior mortalidade se localizou nas zonas do noroeste e centro do município. O desastre provocado pelos deslizamentos de terra afetou aos homens e mulheres de maneira diferente. Na maioria das faixas etárias, morreram mais homens e meninos do que mulheres e meninas. Cinquenta por cento daqueles que perderam suas vidas eram os mais jovens e os idosos. A população negra teve uma taxa de mortalidade ligeiramente maior do que os Pardos e brancos. Os dados não revelaram uma tendência discernível na associação entre vulnerabilidade social e óbitos. Parece que a magnitude dos deslizamentos foi tão grande que todos os habitantes de Nova Friburgo foram igualmente atingidos, além das desigualdades expressas por sua vulnerabilidade social. Na terceira parte desta investigação, determinou-se a probabilidade de risco de deslizamento, para isso a vulnerabilidade social e a susceptibilidade aos deslizamentos de terra foram combinados usando o Modelo Aditivo Generalizado (GAM). Os resultados sugerem que, em terrenos instáveis, basta um nível moderado de vulnerabilidade social para aumentar a probabilidade de risco de deslizamento. Os resultados também destacam a capacidade do modelo de descobrir padrões oculto no conjunto de dados, capturando um efeito não linear da variável "vulnerabilidade social" e um efeito linear da variável "estabilidade do terreno". Em conclusão, o marco conceptual proposto é genérico e flexível pelo que pode ser aplicado a outras áreas, escalas de análise e tipos de perigos naturais, embora seja necessária alguma adaptação, dependendo dos dados disponíveis. Além disso, a abordagem integrada desta tese destaca que é viável e necessário vincular dados de diferentes domínios científicos para melhor compreender o risco de desastres, reduzir riscos e reduzir perdas de vidas humanas e ativos econômicos por meio de ações baseadas em conhecimento. Deve-se notar que esta pesquisa está em conformidade com as diretrizes dadas na primeira área prioritária para a ação do Marco de Sendai para a Redução de Riscos de Desastres 2015-2030, que descreve a importância de "Compreender o risco de desastres". Finalmente, o conhecimento resultante desta pesquisa fornece à comunidade, às organizações e ao governo de Nova Friburgo uma base para compreender o risco relacionado a um perigo natural específico: "os deslizamentos" que podem ser aproveitados para obter uma preparação melhor e respostas eficazes a desastres futuros e também para promover sociedades resilientes aos desastres.

Palavras-chave: Deslizamentos de terra. Modelagem. Risco. Desastre. Abordagem integrada. Nova Friburgo

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1 INTRODUCTION

1.1 Problem statement

Disasters have increased over the past 50 years, not only in numbers, but also in frequency and severity due to a diversity of conjugated factors including climate changes and human actions. *Disasters* appear on the news headlines almost every day. Most happen in far-away places and are rapidly forgotten by the media. Others keep the attention of the world media for a longer period of time. The events that receive maximum media attention are those that hit instantaneously and cause widespread losses and human suffering, such as earthquakes, tsunamis, landslides, floods and hurricanes (VAN WESTEN, 2013).

Some late examples of disasters are the Indian Ocean tsunami (2004); the earthquakes in Pakistan (2005), Indonesia (2006), China (2008) and Haiti (2010); the hurricanes in the Caribbean and in USA (2005, 2008); the earthquake in Italy (2009); the tsunami and earthquake in Chile (2010); the landslides in Brazil (2011); the earthquake and tsunami in Japan (2011); the typhoon Haiyan in Philippines (2013); the earthquakes in Nepal (2015), Italy and Ecuador (2016); the hurricane in the Caribbean belt (2016); the landslides in Colombia (2017); the landslides and flooding in the Republic of *Sierra Leone and Perú (2017),* the hurricane in USA (2017) and the latest earthquakes that struck Mexico and the border of Iran and Iraq (2017). Moreover, there are many serious *hazards* that have a slow onset such as drought, soil erosion, land degradation, desertification, glacial retreat, sea level rise, loss of biodiversity, etc. Although they may cause much larger impacts on the long run, they receive less government and media attention (VAN WESTEN, 2013).

Until recently, *disaster risk* was considered a residual problem of territorial development, therefore it has been included as an unpredictable contingency that requires an emergency response. This idea has been modified considering that the social and economic cost of *disaster* far outweigh their “residual” status. For this reason, it was necessary to incorporate *risk* dimension in the planning processes to enable either mitigation or control of their effects on population, economic activities and human installations (FERNANDEZ BUSSY et al., 2010).

The Centre for Research on the Epidemiology of Disasters (CRED) of the Catholic University of Louvain (Brussels) has been developing the International Disaster Database (EM-DAT) from 1900 on. The CRED EM-DAT database provides an evidence base to the international community for humanitarian assistance and priority setting. It distinguishes between two generic categories for *disasters*: natural and technological. The **natural disaster** category is divided into 5 sub-groups, which in turn cover 15 disaster types, while the **technological disaster** category is divided into 3 main sub-groups, which in turn, cover 17 disaster types (Table 1.1).

For a disaster to be entered into the database at least one of the following criteria must be fulfilled:

- Ten or more casualties
- Hundred or more people affected
- Emergency state declaration
- Call for international assistance

Between 1960 and 2016, 13,372 *disasters* triggered by natural events occurred in the world affecting 7,791 million people and producing 5,354,947 casualties. The American continent is positioned as the second geographical area with the highest occurrence *disaster* records on the global scale. Asia was most often hit (46.7%), followed by the American continent (24.3%), Africa (16.9%), Europe (8.2%), and Oceania (3.8%) (GUHA-SAPIR et al., 2016). As regards economic damages, Latin America and the Caribbean had losses amounting to US$ 212,561 million, representing 7% of the total recorded worldwide. At the intraregional level, 47% of natural events in this period occurred in South America followed by Central America (23%) and the Caribbean 19% (SELA, 2017).

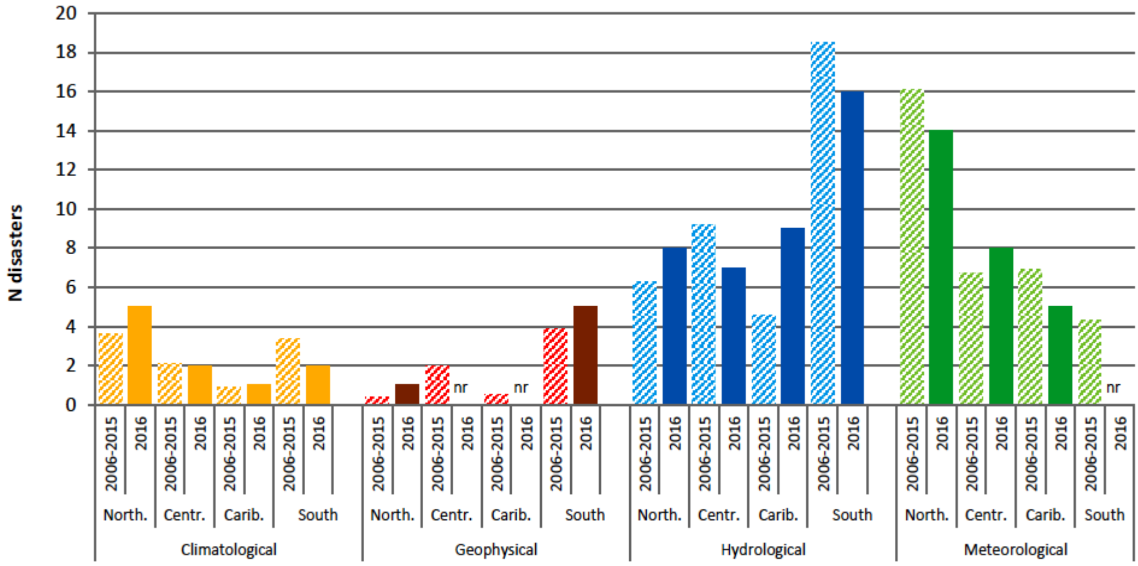
The Annual Disaster Statistical Review (2016) reveals that in the American continent, the most commonly reported *disasters* have a hydrological or meteorological origin, yet are unevenly distributed by region. Hydrological *disasters* are more frequent in Central and South America, while meteorological *disasters* are more frequent in North America (Figure 1.1). In 2016, the number of disasters from floods in South America (16.2) was similar to its 2006-2015 annual average (16), but the absence of landslide *disasters* in this region in 2016 was unusual. Last year, the Caribbean experienced their highest number of floods since 2006 (9), twice the 2006-2015 annual average. Six of these nine floods occurred in Haiti in 2016 and 20 of 45 total during the years 2006-2015. In North America, the number of *disasters* from floods was the third highest since 2006 while no landslide– a very rare event in this region – was reported. In Central America, the number of floods was below its 2006-2015 average, while one landslide was reported, equal to the annual 2006-2015 average (GUHA-SAPIR et al., 2016).

Table 1.1 – General disaster classification.

Disaster group	subgroup	Definition	Disaster main type
Natural	Geophysical	A hazard originating from solid earth. This term is used interchangeably with the term geological hazard.	Earthquake
			Mass movement (dry)
			Volcanic activity
	Meteorological	A hazard caused by short-lived, micro- to meso-scale extreme weather and atmospheric conditions that last from minutes to days.	Extreme temperature
			Fog
			Storm
	Hydrological	A hazard caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater.	Flood
			Landslide
			Wave action
	Climatological	A hazard caused by long-lived, meso- to macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability.	Drought
			Glacial Lake Outburst
			Wildfire
	Biological	A hazard caused by the exposure to living organisms and their toxic substances (e.g. venom, mold) or vector-borne diseases that they may carry.	Epidemic
			Insect infestation
			Animal accident
Technological	Industrial accident		Chemical spill
			Collapse
			Explosion
			Fire
			Gas leak
			Poisoning
			Radiation
			Oil spill
			Other
	Transport accident		Air
			Road
			Rail
			Water
	Miscelleanous accident		Collapse
			Explosion
			Fire
			Other

Source: CRED EM-DAT

Figure 1.1 – Disaster occurrence by type in America. Mean 2006-2015 vs. 2016.



Source: Guha-Sapir et al. (2016).

Because displacement in the context of a *disaster* - including that which occurs across international borders- is already a reality in many parts of the world, 110 countries are endorsing the “Agenda for protection of cross-border displaced persons in the context of natural disasters and climate change” of the Nansen Initiative[1], since October 2015. In 2016, during the World Humanitarian Summit, the Platform on Disaster displacement (PDD) was lunched, follow-up to the Protection Agenda of the Nansen Initiative. Brazil and Costa Rica are the only countries of the American continent that are part of the Platform directive group (RUIZ; OETZEL, 2017).

Brazil has a complex scenario of threats, essentially as a direct result of its size, diversity and both its natural and social heterogeneity. Between 1900-2013 there were around 150 *disaster* records triggered by natural events in the country, whose associated impacts were also alarming: 10,052 casualties, 71 million people affected and a loss of about US$ 16 billion. Floods were the most frequent event (57%), followed by mass movements (11%) (CAMARINHA et al., 2014). Recently, in 2017 the north-eastern and southern Brazil have been reported damages and lost of human lives. In Pernambuco, more than 20 municipalities

1 The overall goal of the Nansen Initiative is to build consensus among States on key principles and elements to protect people displaced across borders in the context of disasters caused by natural hazards, including those linked to climate change. See: https://www.nanseninitiative.org/secretariat/

reported damage caused by heavy rains and landslides that forced the evacuation of at least 30,000 residents and killed eight people. Heavy rains hail and wind also hit southern states of Rio Grande do Sul and Santa Catarina (https://watchers.news).

The so-called “Mega disaster” in the mountainous region of Rio de Janeiro took place on 11th and 12th January, 2011 affecting 23 municipalities, from these 7 were stated in public calamity situation (VASSOLER, 2013): Areal, Bom Jardim, Nova Friburgo, São José do Vale do Rio Preto, Sumidouro, Petrópolis and Teresópolis. This episode is considered the worst *disaster* in Brazilian history (CASTILHO et al., 2012), not only because of the human fatalities that it caused, but also because of the significant losses and economic damage with negative implications on the survivor’s life quality and on the entire region economic activity (WORLD BANK, 2012). Whole areas were covered by mud, hundreds of homes were swept away and hundreds of people were buried. Nova Friburgo, Teresópolis and Petrópolis municipalities recorded the greatest number of casualties. In Nova Friburgo, the greatest impact occurred within the urban area, while in the others areas, the rural outskirts were the most affected (BUSCH; AMORIM, 2011). Government official numbers indicated 918 casualties, 22604 displaced and 8795 homeless in the mega-disaster (FREITAS et al., 2012); however, civil associations point out that the number of fatalities and missing people could be ten times greater. The divergence in numbers can be attributed, in part, to the fact that entire families disappeared and no one claimed for them (MELÂNIA HÖELZ, personal communication, August, 2016).

The 2011 massive landslides were triggered by extreme rainfall conditions: 241.8 mm accumulated in 24 hours, with a peak of 61.8 mm in one hour, and an accumulated rainfall of 573.6 mm between 11th and 12th January (DOURADO et al., 2012). Although this event has been considered the most destructive landslide *disaster* ever registered in Brazil, other events had previously occurred in Rio de Janeiro in 1966, 1967, 1988, 1996 and 2010 (AVELAR et al., 2011) and particularly in Nova Friburgo area in 1924, 1940, 1977, 1979, 2007 (DRM-RJ, 2015).

The Rio de Janeiro Mineral Resources Department identified and classified the 2011 mass movements observed in the mountainous region. The main types were: (1) mass flow, debris flow, earth or mud flow; (2) “Parroca”; (3) “Rasteira”; (4) “Vale Suspenso”, and (5) “Catarina” landslide types (Figure 1.2). A more detailed description of each mass movement can be found in Dourado et al., (2012).

Unpreparedness to face natural *hazards* was recognized by the Brazilian authorities in 2009. According to a report sent by the National Civil Defence Secretary to the United

Nations, only 77.4% of municipalities had officially created agencies to deal with *disasters*. The government accepted limitations in financial resources and operative capacity, i.e., limitations on its monitoring capacity, lack of planning and control of human settlements. Disregard of *hazard* prone areas, coupled with local oversight limitations contributed to increase community vulnerability (BUSCH; AMORIM, 2011).

Federal Law Nº 12.608/12 is the main instrument establishing the National Protection and Civil Defence Policy and sets the Brazilian states and municipalities' responsibilities. Article 7 establishes that the states must identify threats, susceptibilities and vulnerabilities. Additionally, they have to conduct the risk areas meteorological, hydrological and geological monitoring. On the other hand, Article 8 points out municipal duties. Two important responsibilities are:

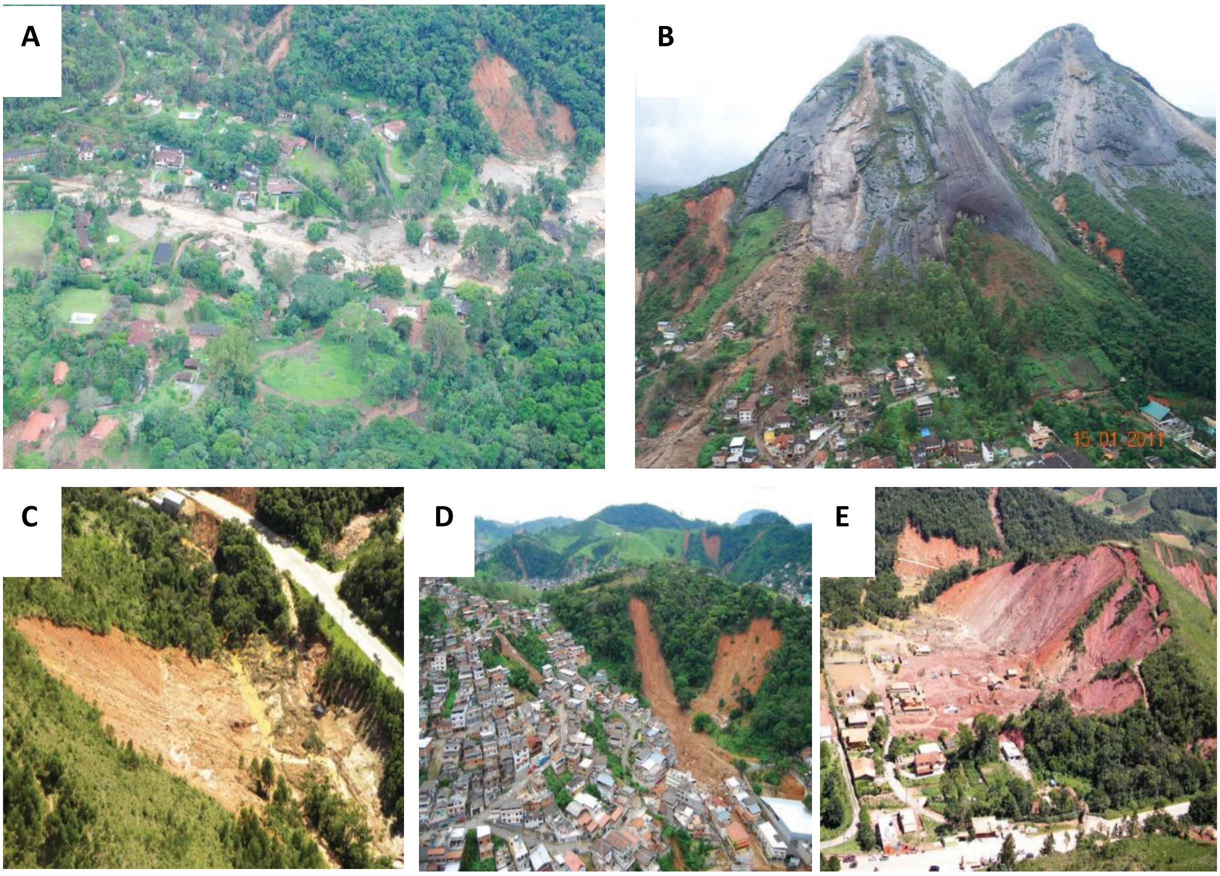
i) to identify and to map *disaster risk* areas and,

ii) to promote the inspection of *risk* prone areas and forbid new human settlements in them. Although this law contains a modern and comprehensive vision seeking to establish the concept of protection to deal with *disaster risk*, in practice, its application has only been partial.

As it can be appreciated, the law does not expressly mention any social vulnerability assessment, i.e., it does not seem to take into account the social dimension of the *disaster*. However, it does highlight other process monitoring, such as meteorological, hydrological and geological. As stated by Valencio (2015) governments programs are being established in municipalities and states with a single purpose: the design and implementation of protection systems based on technical methods that only address the areal physical characteristics while neglecting the social vulnerability.

This approach strengthens the notion of disaster as a punctual episode, dismissing it as a historically and geographically constructed process in which the society participates. Thus, disasters have been interpreted based on the identity [*disaster* == *event*] especially by technicians and hard-sciences researchers but this view is also found among many social science researchers. Monteiro et al., (2015) have revisited disaster literature and then have proposed another systemization to represent the constitutive elements of disasters and their interplay along the space and time. The authors proposed that to look at disasters as a different identity, [disaster == process], could help in moving the focus towards comprehend how disasters are historically constructed on a spatial-temporal scale.

Figure 1.2 – Different types of mass movements in Rio de Janeiro State mountainous region. **A)** Debris flow in Posse, Teresópolis; **B)** "Parroca" landslide type in Córrego Dantas, Nova Friburgo; **C)** "Rasteira" landslide type in Nova Friburgo; **D)** "Vale Suspenso" landslide type in Teresópolis; **E)** "Catarina" landslide type in Nova Friburgo.



Source: Dourado et al. (2012).

In this context, the Social Landscape[2]- usually missed or, at least, not integrated *a priori* in most of disaster risk analyses- becomes a visible component within the set of elements that contribute to shape disasters.

Within the disaster science context, there exists difficulty in establishing a semantic meaning agreement of key concepts, such as *hazard*, *risk*, *disaster*, *vulnerability, resilience*, etc., among the different social actors (e.g., technicians, academic researchers of different

2 The term 'social landscape' refers to the necessity of co-ordination and relationship between places and people. It is an attempt of establishing the *Social* as a constituent part of the whole *Landscape* we examine for *disaster risk* analyses

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science domains, politicians, civil society, etc.). These terms are subject to ambiguity and are thus ascribed different meanings. Each one on its own is a "weak" concept and needs to be negotiated to enable the construction of representations. Those terms represent cases of "boundary concepts" (MOLLINGA, 2008), which make possible the interaction among different interpretations from the parties and further permit the integration of diverse visions for the same problem in a specific context (MONTEIRO et al., 2015).

Science plays a key role in reducing *disaster risk* because it builds an interface between policy and knowledge, which support best-informed decision-making processes. Traditionally, *disaster risk* researches have been performed based on specific discipline predominance, such as sociology, economics, communication, geology, ecology, geography, political science, among others. As a result, the synergy and feedback links existing among *risk* components were overlooked. So, there was an excessive specialization and fragmentation in *disaster risk* studies not contributing to the design of good mitigation strategies, emergency response, neither to promote disaster-resilient societies. According to the Report of the Global Outlook on Disaster Science (2017), nowadays there is an urgent need for integrated, science-based actions to address *risk* and reduce *disaster* impacts on all countries.

The importance of disaster science is reflected in the Sendai Framework for Disaster Risk Reduction 2015-2030, which links research to key priorities, including understanding of all *disaster risk* dimensions: *exposure*, *vulnerability* and *hazard* (UNIDRS, 2015). The Sendai Framework calls for a stronger science and technology role in practical *risk* reduction and in supporting response and recovery after a disaster. To achieve this, collaboration among various stakeholders is indispensable, but it is also a major challenge (HUGGETT, 2017).

Several of the ideas presented in this Thesis have already been published in Monteiro et al., (2015)[3] in which the thesis author has co-authored this book chapter, as well as in Cardozo et al., (2017)[4].

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3 MONTEIRO, M. V.; CARDOZO, C. P.; LOPES, S. E. Sentidos territoriais: a paisagem como mediação em novas abordagens metodológicas para os estudos integrados em riscos de desastres. In: Riscos de desastres relacionados à água: aplicabilidade das bases conceituais das Ciências Humanas e Sociais na análise de casos concretos. A. M. Siqueira, N. Valencio, M. Siena, M. A. Malagodi (Editores). São Carlos: RiMa Ed. ISBN – 978-85-7656-037-1-e-book. 2015.

4 CARDOZO, C. P.; LOPES, S. E.; MONTEIRO, M. V. (in press) Shallow landslide susceptibility assessment using SINMAP in Nova Friburgo (Rio de Janeiro, Brazil). For more details, see Chapter 4.

1.2 Research Objectives

1.2.1 General Objective

The main research objective is to develop an integrated model of landslide disaster risk based on the recognition of the interrelationships existing between physical and human components of risk in Nova Friburgo municipality (Rio de Janeiro State, Brazil) by using Spatial Analysis and Remote Sensing techniques within a Geographic Information System environment.

1.2.2 Specific Objectives

In order to fulfil the main objective, it was necessary to address a set of specific tasks as outlined below.

a) to define the conceptual framework for an integrated disaster risk assessment.

b) to determine the physical component of risk by identifying landslide prone areas.

c) to establish the human component of risk by analysing social vulnerability.

d) to characterize the 2011 landslide-related casualties.

e) to conduct an integrated assessment of landslide disaster risk.

1.3 Thesis Structure

This thesis is organized in seven chapters. The present chapter presents a brief overview of the disasters in the world. Particularly, it introduces Brazil's situation, with special emphasis on the 2011 landslides in Rio de Janeiro mountainous region. The research objectives are also stated.

Chapter 2 provides a theoretical background about topics dealt in this thesis that are regularly used in disaster science.

Chapter 3 gives a methodological proposal for an integrated assessment of landslide disaster risk and also provides the description of the study area by characterizing the environmental and social context of Nova Friburgo municipality.

Chapter 4 gives an estimation of landslide prone areas obtained by a physically based-slope stability model.

Chapter 5 offers an assessment of social vulnerability and the characterization of the 2011 landslides-related casualties in Nova Friburgo. Besides, the role of social vulnerability is explored to explain the fatalities.

Chapter 6 introduces an integrated assessment of landslide risk by a combination of both landslide prone areas and the social vulnerability.

Finally, Chapter 7 summarizes the key findings of this Thesis, limitations and future perspectives.

2 THEORETICAL BACKGROUND

2.1. Natural Hazards, Risks and Disasters: Disentangling the concepts

Within the disaster science, there are several terms, such as *threat*, *vulnerability*, *risk*, *hazard*, *disaster* and others, which are closely related to each other. Despite the efforts to unify concepts by the international organizations, these terms are often used interchangeably both in scientific-technical literature as in everyday speech. Additionally, linguistic problems may amplify confusion since there is no direct translation from many of these words in other languages (SCHNEIDERBAUER; EHRLICH, 2004). Therefore, all this contributes to misunderstanding and harms the communication between politicians, scientists, decision-makers, journalists, civil society and other agents involved around disaster topic.

In 2009, the United Nations International Strategy for Disaster Risk Reduction published a document with this terminology– translated in various languages- which was updated in 2016 (UNISDR, 2009, 2016). But even today one can see that these concepts are used in many different ways and contexts with different meanings. A good use of these terms among social actors is needed to insure an adequate response to the challenges posed by climate change and the new human development schemes.

For many years and even today, there was a current of opinion calling "natural disasters" to events caused by natural *hazards*. This approach conceals the social and political processes that make some people and populations more or less vulnerable to natural *hazards* (COMFORT et al., 1999; GAILLARD et al., 2014). "Natural disasters" are often not perceived as "natural" by people who are victimized (KUMAGAI et al., 2006).

There is nothing "natural" in *disasters* but they are an outcome of both environmental and societal conditions, i.e., human activities play a key role in exacerbating the effects of natural events. As mentioned by Quarantelli (1992) a *disaster* is not a physical happening, there is at most a conjuncture of certain physical happenings and certain social happenings. Thus, it is a misnomer to talk about "natural" *disasters* as if they could exist outside of the actions and decisions of human beings and societies. In this respect, Oliver-Smith (2009) states that the so-called "natural disasters" should be correctly named as "socio-natural events or processes". A term that recognizes that natural *hazards* are environmental systemic elements whose occurrence and expression are deeply affected by social processes and characteristics. This approach has opened important spaces not only for exploring socioeconomic conditions, re-conceptualizing *disaster* and for reducing *disaster risk*, but also for the formation of a new field, the political ecology of *hazards* (GOULD et al., 2016).

The presence of a *hazard* is not an indicative of *risk* existence (LEONI et al., 2011). A *hazard* is a phenomenon or human activity that has the potential to cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage (UNISDR, 2009). In the next section and in the Chapter 4 a particular focus will be placed on landslides, a type of geo-hydrological *hazard* that cause significant societal and economic damage worldwide (SALVATI et al., 2018).

Risk is understood as the possibility of adverse consequences or losses occurring as a result of the interaction between *hazards* and *vulnerable* populations (MASKREY, 1993; NARVAEZ et al., 2009; LAVELL 2000; BLAIKIE et al., 1944; LEONI et al., 2011; VAN WESTEN et al., 2011). In other words, is a combination of the probability of an event and its negative consequences (UNISDR, 2009). Dynamics changes of *vulnerability* and *hazard* phenomena also mean that *risk* is non-static, i.e., it implies that it changes over time (NARVAEZ, et al., 2009; BIRKMANN et al., 2013) as well as in the space (MONTEIRO et al., 2015).

While *risk* and *vulnerability* can be seen as continuums, a *disaster* is but a moment or materialization of these underlying conditions (BIRKMANN et al., 2013). Wilches-Chaux (1993) points out that *disasters* are phenomenon that can be analyzed as processes from Systems Theory point of view. Valencio (2013) describes *disasters* as both a situation and as a process. According to MONTEIRO et al., (2015) technical systems characterize *disasters* as a punctual event, as consequence, objects and features in the territory are represented with a positional cartography. On the other hand, *disaster* conception as a process implies a relational cartography that recognizes that the different relationships among objects, features, groups and their locations in the territory are being modified over time and space.

In section 2.3 and in the Chapter 5, the *vulnerability* concept will be more fully addressed. Likewise, the Section 2.4 and chapter 6 delve into the *disaster risk* concept and its operationalization.

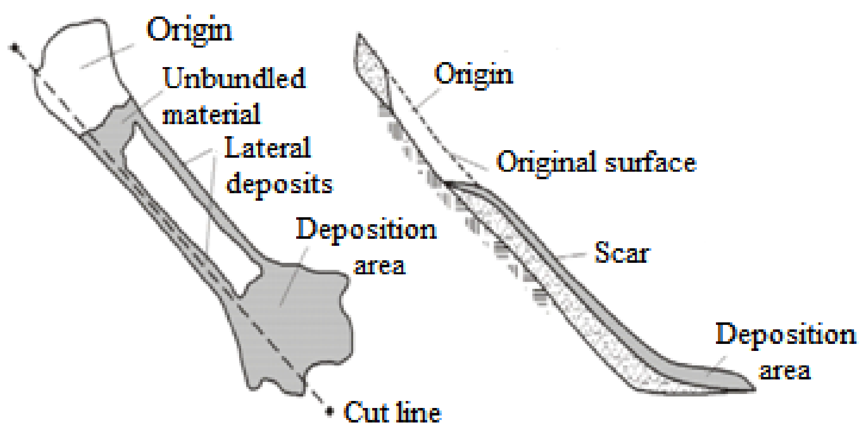
2.2 The Physical Landscape: The nature of landslides

A “landslide” is the movement of a mass of rock, debris, or earth down a slope, under the influence of gravity. Landslides can involve flowing, sliding, toppling, or falling and many landslides exhibit a combination of two or more types of movements, at the same time or during the lifetime of a landslide (CRUDEN; VARNES, 1996).

Landslides are natural processes that are present in all continents and play an important role as landscape-forming mechanism (PETLEY, 2012, GUZZETTI et al., 2012). They are occurring continuously on all slopes; some act very slowly, others occur very suddenly, often with disastrous results (NELSON, 2014) causing directly impact in humans lives (ALEXANDER, 2004; SALVATI et al., 2018).

Landslides usually have common features (Figure 2.1) that permit its visual identification through the discernible scars left in an area, such as: *i)* an origin point, defined for the failure surface; *ii)* a destruction trail in the hillside (scar) and, *iii)* a deposition foot or deposition area where much of the transported mass is deposited (DAI; LEE, 2002).

Figure 2.1 – Typical landslide features.



Source: Marcelino (2004).

In this Thesis, the term "landslide" is adopted in a generic way to refer any downslope movement, independently of the involved material type in which the gravity is the major force implicated.

2.2.1 Classification and Types

Many international and Brazilian systems have been proposed for landslide classification such as, Sharpe, 1938; Freire, 1965; Varnes, 1978; Guidicini and Nieble 1984; Hutchinson, 1988; Cunha, 1991; Filho and Wolle (1996) among others. However, the most commonly adopted system is that proposed by Varnes (1978). This system is based on type of material and type of movement (Table 2.1) and has become the most widely used system in the English language (VARNES, 1958, 1978; CRUDEN; VARNES, 1996). Besides the main types of mass movement, there is one “complex class” which contains a movement with two or more different processes acting together along the downslope movement of the mass. Figure 2.2 helps to understanding this classification.

In 2014, an update to the Varnes's classification has been presented to the scientific community. It has 32 landslide types, each of which is backed by a formal definition (HUNGER et al., 2014).

Table 2.1 – Abbreviated version of landslide classification based on type of movement and on type of material.

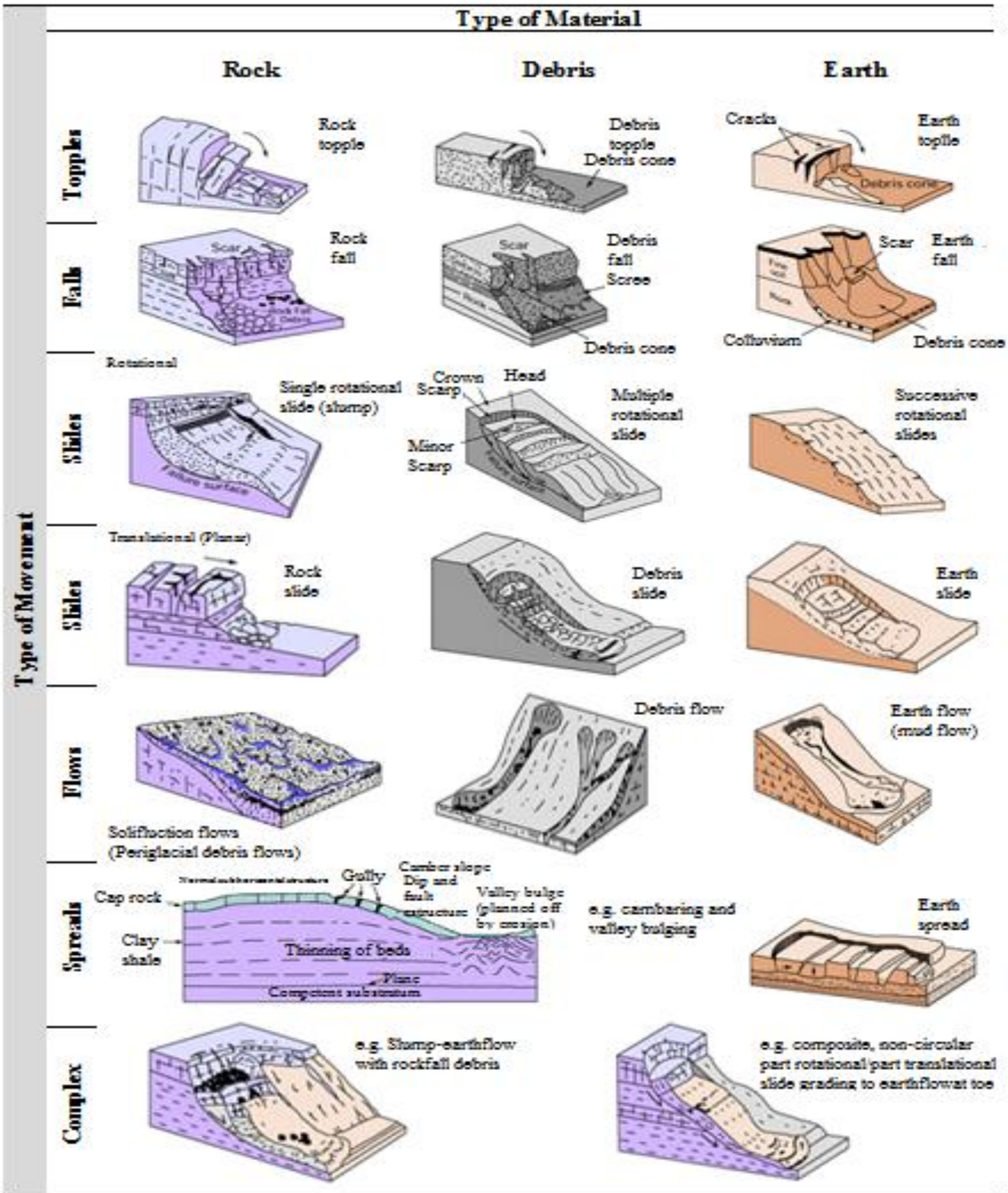
TYPE OF MOVEMENT		**TYPE OF MATERIAL**		
		BEDROCK	**ENGINEERING SOILS**	
			Predominately coarse	Predominately fine
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational / Translational	Rock slide	Debris slide	Earth slide
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow (deep creep)	Debris flow	Earth flow
			(soil creep)	
Complex		Combination of two or more principal types of movement		

Source: Varnes (1978).

As stated by the Geological Society of London, *Rock* is “a hard or firm mass that was intact and in its natural place before the initiation of movement”; *Debris* “contains a significant proportion of coarse material; 20% to 80% of the particles are larger than 2mm, and the remainder are less than 2mm”; *Earth* “describes material in which 80% or more of the particles are smaller than 2 mm, the upper limit of sand sized particles” and, *Soil* is “an aggregate of solid particles, generally of minerals and rocks, that either was transported or was formed by the weathering of rock in place. Gases or liquids filling the pores of the soil form part of the soil”.

The US Geological Survey provides a wide characterization of types of movements, as follows: *Falls* are “abrupt movements of masses of geologic materials, such as rocks and boulders that become detached from steep slopes or cliffs”; *Topples*: the toppling failures are “distinguished by the forward rotation of a unit or units about some pivotal point, below or low

Figure 2.2 – Schematic diagrams of landslide types.



Source: British Geological Survey (2016).

in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks; *Slides*: although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are "*rotational slides*" and "*translational slides*". *Rotational slide* is "a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide". In the *Translational slide* "the landslide mass moves along a roughly planar surface with little rotation or backward tilting"; *Lateral spreads* are "distinctive because they usually occur on very gentle slopes or flat terrain". The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state; Combination of two or more of the above types is known as a *Complex* landslide; *Flows:* there are five basic categories of flows that differ from one another in fundamental ways (For more details, see US Geological Survey, https://pubs.usgs.gov/fs/2004/3072).

2.2.2 Conditioning and Trigger factors

Landslides are produced by an increase of destabilizing forces and/or a reduction of resistance of the involved materials. The factors capable to control such movements are usually those able to modify the internal and external forces acting on the ground (SEISDEDOS SANTOS, 2009). There are two types of factors: Conditioning and triggering. Conditioning factors depend on the nature, structure and shape of the ground, such as topographical, lithological and hydro-geological conditions; stress-strain state; disturbance degree or material weathering and vegetation cover; while triggering factors are external actions producing instability when pre-existing conditions are modified, for example: rainfall; seismicity; earthquakes/vibrations; erosion and anthropogenic factors (SEISDEDOS SANTOS, 2009; HERRERA et al., 2011).

2.2.3 Landslide Susceptibility Mapping

Susceptibility assessment related to the estimation of areas prone to landslides is one of the most useful approaches for risk management. Landslide susceptibility is the likelihood of a landslide occurring in an area based on local terrain conditions (BRABB, 1984). In mathematical language, landslide susceptibility quantifies the spatial probability of landslides occurrence in a mapping unit, not considering the temporal probability of failure or the magnitude of the expected landslides (ROSSI; REICHENBACH, 2016).

Over the last years, in an attempt to find the best approach to evaluate landslide susceptibility, many methods have been developed (FRANCIPANE et al., 2014). Broadly speaking, these methods may be qualitative or quantitative. The first group is mainly based on the site-specific experience of experts with the susceptibility determined directly in the field or by combining different index maps. The approaches of the second group are formally more rigorous (ALEOTTI; CHOWDHURY). Methods for landslide susceptibility evaluation and mapping can be broadly grouped in: i) Geomorphological mapping; ii) Landslide inventory analysis; iii) Heuristic or index-based methods; iv) Statistically-based models and, v) Geotechnical or physically-based models.

Below is a brief description of each method, as stated by Guzzetti et al., (1999). The *Landslide geomorphological mapping* is a direct and qualitative method that relies on the ability of the investigator to estimate actual and potential slope failures. The *Heuristic approach* is based on the a priori knowledge of all causes and instability factors. It is an indirect, mostly qualitative method that depends on how well and how much the investigator understands the geomorphological processes acting upon the terrain. Instability factors are ranked and weighted according to their assumed or expected importance in causing mass movements. All other approaches are indirect and quantitative. For instance, the *landslide inventories analysis* attempts to predict future patterns of instability from the past and present distribution of landslide deposits. On the other hand, the *Statistical approaches* are based on the functional relationships analysis between instability factors and the past and present landslide distribution. Finally, the *Geotechnical or physically-based models* rely upon the understanding of few physical laws controlling slope instability. These models couple shallow subsurface flow i.e., the pore pressure spatial distribution, predicted soil thickness, and landsliding of the soil mantle. Stability conditions are generally evaluated by means of a static model, such as the ‘‘infinite slope model’’, where the local equilibrium along a potential slip surface is considered. According to Aleotti and Chowdhury (1999) such methods are normally applied only in small areas and at details scales. Van westen et al., (2008) point out that this approach is highly applicable to both large and detailed scales of analysis, moderately applicable to medium scales and less applicable to regional scales of analysis.

In this Thesis, the SINMAP methodology- which corresponds to a Geotechnical or physically-based models- is used. It will be more deeply addressed in Chapter 4.

2.3 The Human Landscape: Vulnerability

The history of the term *vulnerability* is long and complex (WISNER, 2016). Multiple definitions and different conceptual frameworks of *vulnerability* exist (VAN WESTEN et al., 2011). The origins of the *vulnerability* approach can be placed in the 1970s when authors began to question the "naturalness" of "*natural disaster*" (BLAIKIE et al., 1994). The report by the *United Nations Disaster Relief Organization* expert group (UNDRO, 1979) was one of the first to address theoretical aspects and to point to the need for *vulnerability* assessment (TAPSELL et al., 2010).

The theory of *vulnerability* has evolved in many fields of knowledge. Although disciplinary approaches originally contributed to overly narrow, dominant theorisations of *hazard* causality, the multi-disciplinary nature of contributions to *vulnerability* theory has led to a particularly wide range of *vulnerability* definitions and to little consensus about its definition (CUTTER, 2006).

There are two perspectives in which *vulnerability* can be viewed and are closely linked with the evolution of the concept (BROOKS, 2003): i) The amount of damage caused to a system by a particular *hazard* (technical or engineering sciences oriented perspective– dominating the *disaster risk* perception in the 1970s) and, ii) A state that exists within a system before it encounters a *hazard* (social sciences oriented perspective– an alternative paradigm which uses *vulnerability* as a starting point for *risk* reduction, since the 1980s). While technical sciences perspective of *vulnerability* focuses primarily on physical aspects, social sciences perspective takes into account various factors and parameters that influence it, such as physical, economic, social, environmental and institutional characteristics. Other approaches emphasize the need to account for additional global factors, such as globalization and climate change (CIUREAN et al., 2013).

As reported by Fuchs et al., (2009) representatives from each discipline define *vulnerability* in a way that fits to their individual disciplinary purposes. By way of example, Table 2.2 provides some *vulnerability* working definitions used in the literature over the last three decades.

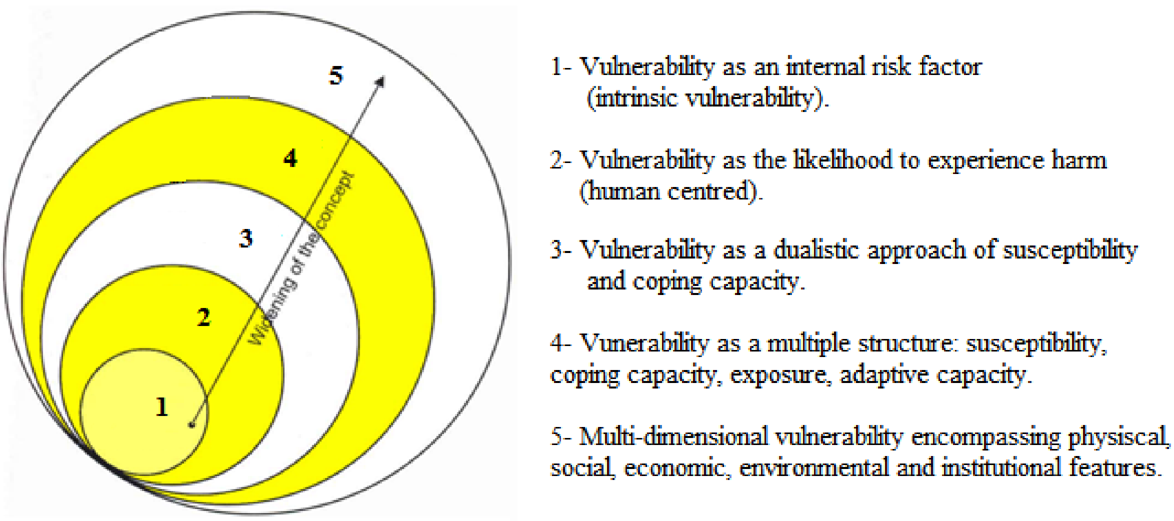
As it can be appreciated in Figure 2.3, the *vulnerability* concept has broadened over the time (BIRKMANN, 2006), by not only looking at buildings and structures (and damages that can suffer) but also to human beings (VAN WESTEN et al., 2011) and their social processes.

Table 2.2 – Vulnerability working definitions.

Vulnerability	Source
The degree of loss to a given element at risk or a set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage).	UNDRO, 1979
Is the potential for loss of property or life from environmental hazards.	CUTTER, 1996
The characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recovery from the impact of a natural hazard.	WISNER et al., 2004
A human condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard.	UNDP, 2004
It is the human dimension of disasters, the result of the whole range of economic, social, cultural, institutional, political and even psychological factors that shape people's lives and create the environment that they live in.	TWIGG, 2004
The intrinsic and dynamic feature of an element at risk that determines the expected damage/harm resulting from a given hazardous event and is often even affected by the harmful event itself. Vulnerability changes continuously over time and is driven by physical, social, economic and environmental factors.	BIRKMANN, 2006
The degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change.	FÜSSEL; KLEIN, 2006
The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.	UNISDR, 2009
The conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards.	UNISDR, 2015

Source: Adapted from Ciurean et al., (2013).

Figure 2.3 – Key spheres of *vulnerability* concept

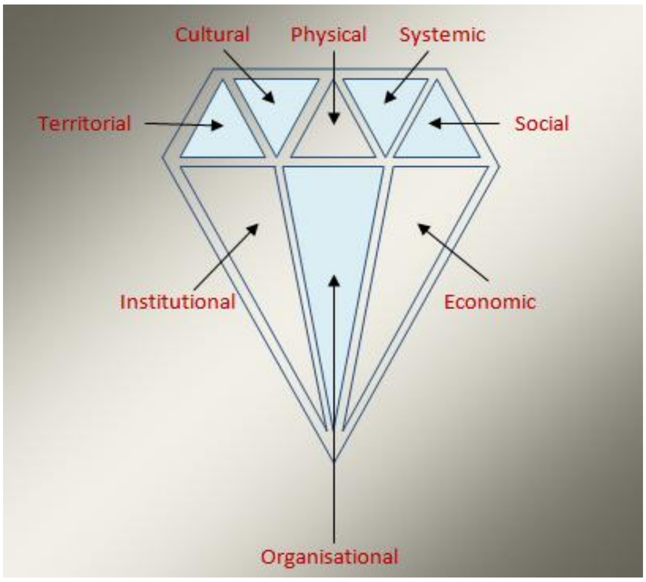


Source: Birkmann (2006).

2.3.1 Multifaceted Nature of Vulnerability

Research literature has identified "*vulnerability*" as essentially an umbrella term for a number of *vulnerability*-types (TAPSELL et al., 2010). Many authors have recognized the multifaceted and articulated nature of the *vulnerability* concept. For instance, Parker et al., (2009) proposed a diamond analogy as a way to illustrate the dimensions or facets of *vulnerability* (Figure 2.4).

Figure 2.4 – The multifaceted nature of *vulnerability*.



Source: Parker et al. (2009).

While the nature and sometimes direction of the relationship between each facet has not yet been clarified in the literature, the diamond analogy recognizes that relationships do exist (TAPSELL et al., 2010). The strength of these relationships and bonds between different dimensions of *vulnerability* vary across the face of *vulnerability* and also through space and time (PARKER et al., 2009).

The number of *vulnerability* facets has been also debated. For example, Fuchs (2009) identified a structural (physical) dimension of *vulnerability* that is complemented by economic, institutional and social dimensions. Parker et al., (2009) extended these dimensions as follows: territorial, cultural, physical, systemic, social, institutional, organisational and economic. On the other hand, Van Westen et al., (2011) defined four main facets of *vulnerability*: physical, economic, social and environmental. Similarly, the Ensure project (https://cordis.europa.eu/publication/rcn/14275_en.html) also visualized *vulnerability* as a multi-faceted concept characterized by physical, economic, cultural, social and systemic dimensions. Sterlacchini (2011) identified the physical/functional, socio-economic, socio-cultural, ecological/environmental and the political/institutional dimensions of *vulnerability*. Menoni et al., (2012) assumed as the main facets being physical (natural and built environment), systemic, social/community/institutional and economic.

2.3.2 Social Vulnerability

Social vulnerability in itself can be also treated as a multifaceted entity, a second diamond structure within the *vulnerability* diamond. It can be characterized by the same attributes on a scale more closely focused on the social; for instance, attributes related to issues of livelihood, housing, income, education, security and gender among many others (TAPSELL et al., 2010).

One central role in *social vulnerability* assessment is attributed to indicator based methods. A *vulnerability* indicator is defined as a variable which is an operational representation of a system characteristic or quality able to provide information regarding the susceptibility, coping capacity and *resilience* of a system to an impact resulting from a natural *hazard* (BIRKMANN, 2006). Tate (2012) provides a classification of *social vulnerability* index configurations widely used in the research: deductive, hierarchical, and inductive structures. *Deductive models* typically contain fewer than ten indicators, which are normalized and aggregated to build the index. This was the most common structure applied to early *social vulnerability* indices. *Hierarchical designs* have employed roughly ten to twenty indicators, separated into groups (sub-indices) that share the same underlying dimension of *vulnerability*.

Individual indicators are aggregated into sub-indices and then are aggregated to the final index. *Inductive approaches* begin with a large set of twenty or more indicators, which are reduced to a smaller set of uncorrelated latent factors using Principal Components Analysis (PCA) (JOLLIFFE, 1986). The factors are then aggregated to build the final index. Inductive methods were popularized by the *Social Vulnerability* Index (SoVI) proposed by Cutter et al., (2003) and form the basis for the majority of more recent *vulnerability* indices in the context of disaster science studies.

In this Thesis, an assessment of *social vulnerability* using the SoVI method is conducted. It will be more deeply addressed in Chapter 5.

2.3.3 Conceptual Frameworks of Vulnerability

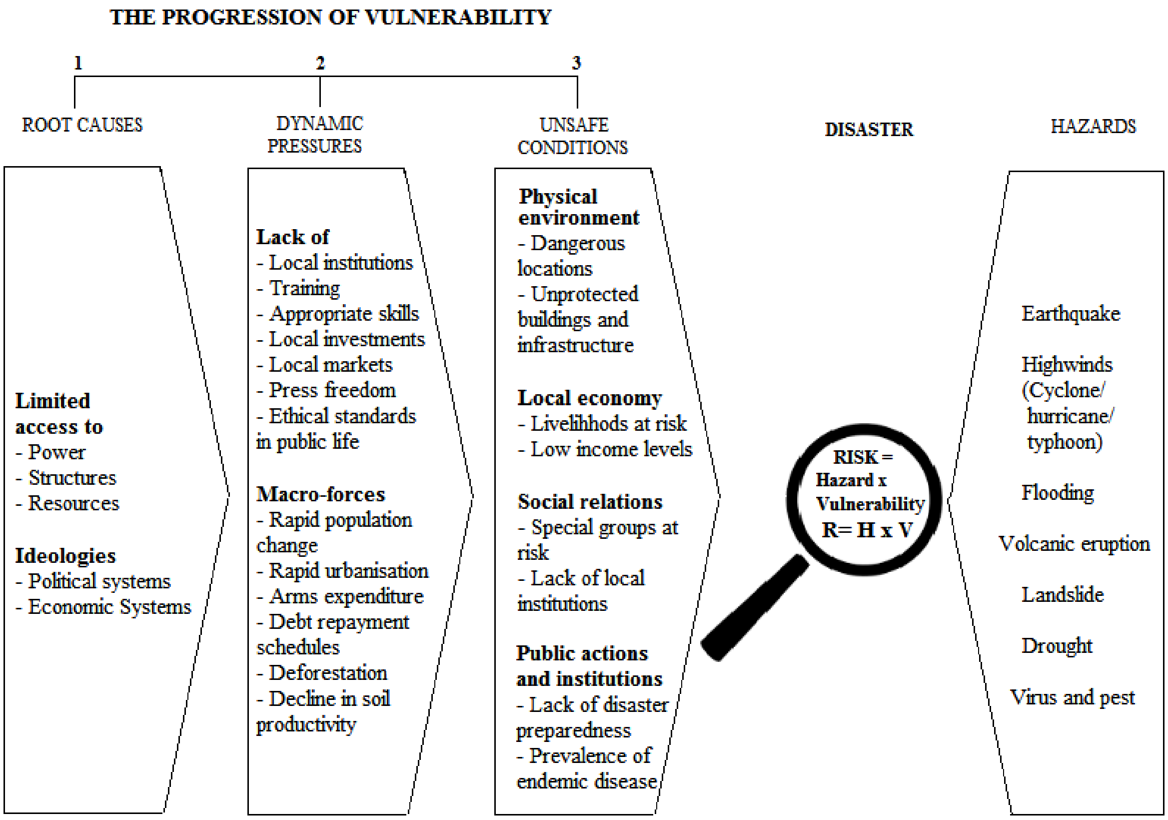
Different conceptual frameworks on *vulnerability* were proposed over the time by different schools of thinking. In this section a short overview of some of the conceptual models is introduced. It is noteworthy that models are tools for representing *vulnerability* but they are inevitably link with the *risk* concept. According to Van Westen et al., (2011) despite the good conceptualization, they show some limitations regarding to how assess their components.

2.3.3.1 Pressure and Release Model (PAR Model)

The Pressure and Release Model (PAR Model) (BLAIKIE et al., 1994; WISNER et al., 2004) is a simple tool for showing how *disasters* occur when natural *hazards* affect vulnerable people. The basis for the PAR idea is that a *disaster* is the intersection of two opposing forces: those processes generating *vulnerability* on one side and the natural *hazard* event (or sometimes a slowly unfolding natural process) on the other (Figure 2.5).

The PAR model states that pressure on people come from their *vulnerability* and from the impact (and severity) of the *hazard*. The 'release' idea is incorporated to conceptualise the reduction of the *disaster*, that is, to relieve the pressure, *vulnerability* has to be reduced. The explanation of *vulnerability* has three sets of links: The *root causes* which are an interrelated set of widespread and general processes within a society and the world economy. On the other hand, *dynamic pressures* are processes and activities that 'translate' the effects of root causes both temporally and spatially into *unsafe conditions.* These are more contemporary or immediate, conjunctural manifestations of general underlying economic, social and political patterns (BLAIKIE et al., 1994).

Figure 2.5 – Pressure and Release Model (PAR model).



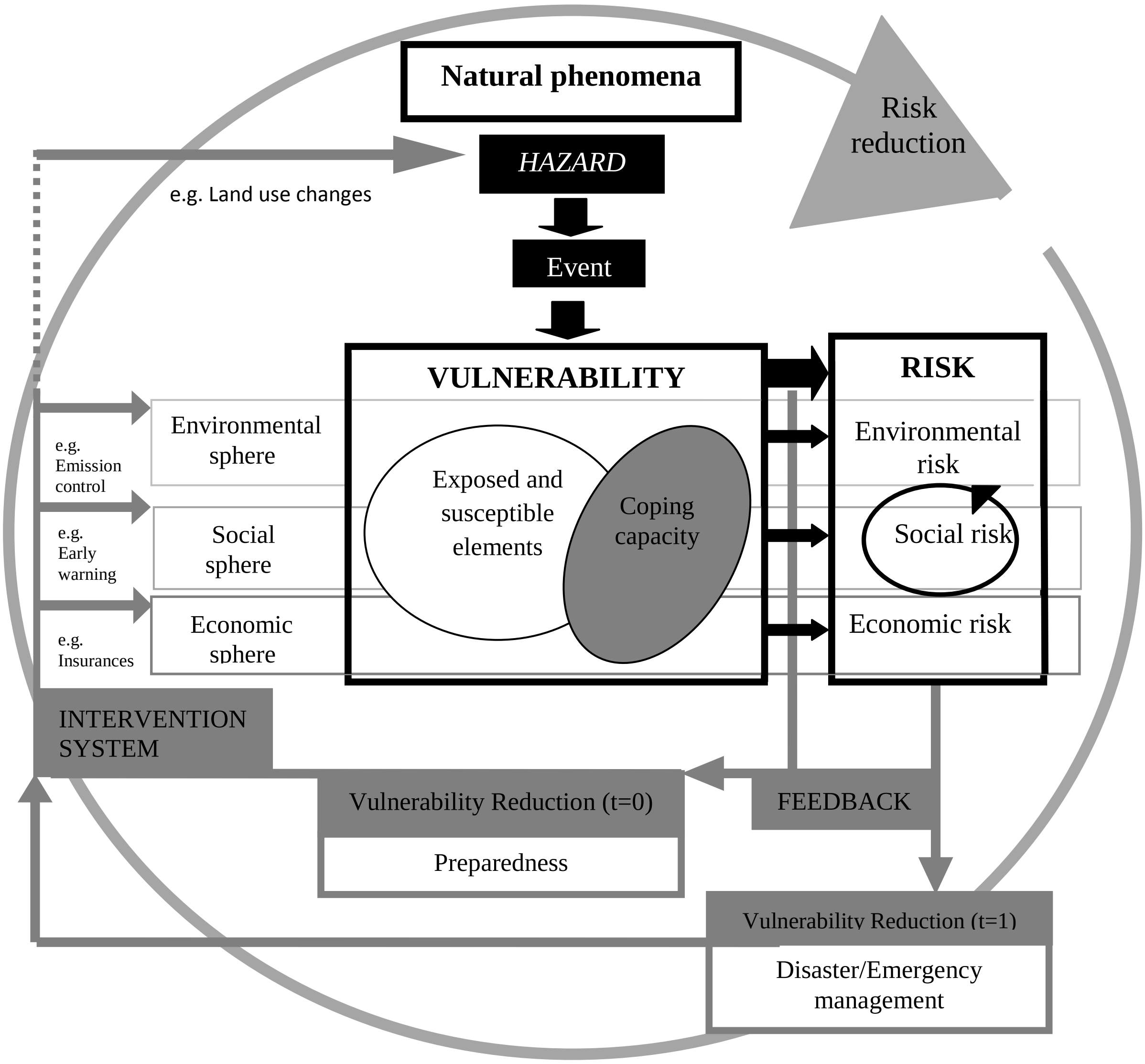
Source: Blaikie et al., (1994).

2.3.3.2 BBC Conceptual Framework

The BBC framework (Figure 2.6) is mainly based on the conceptual work of Bogardi and Birkmann (2004) and Cardona (1999). As stated by Van Westen et al., (2011), it tries to link *vulnerability*, human security and sustainable development. It underlines the need to view *vulnerability* as dynamic, focusing on vulnerabilities, coping capacities and potential intervention tools to reduce it (feedback-loop system). Environmental, social and economic spheres are considered in defining *vulnerability*, coping capacities, *risk* and their *vulnerability/risk* reduction measures.

The BBC conceptual framework stresses the fact that *vulnerability* assessment should take into account exposed-susceptible elements and coping capacities (TAUBENBÖCK et al., 2009). Additionally, it outlines two potential paths for reducing *disaster risk* and *vulnerability*: i) preventive measures such as spatial planning and awareness raising before a *disaster* manifests and, ii) *disaster* management, such as evacuation and emergency response during a disaster (BIRKMANN, 2006).

Figure 2.6 – The BBC conceptual framework.

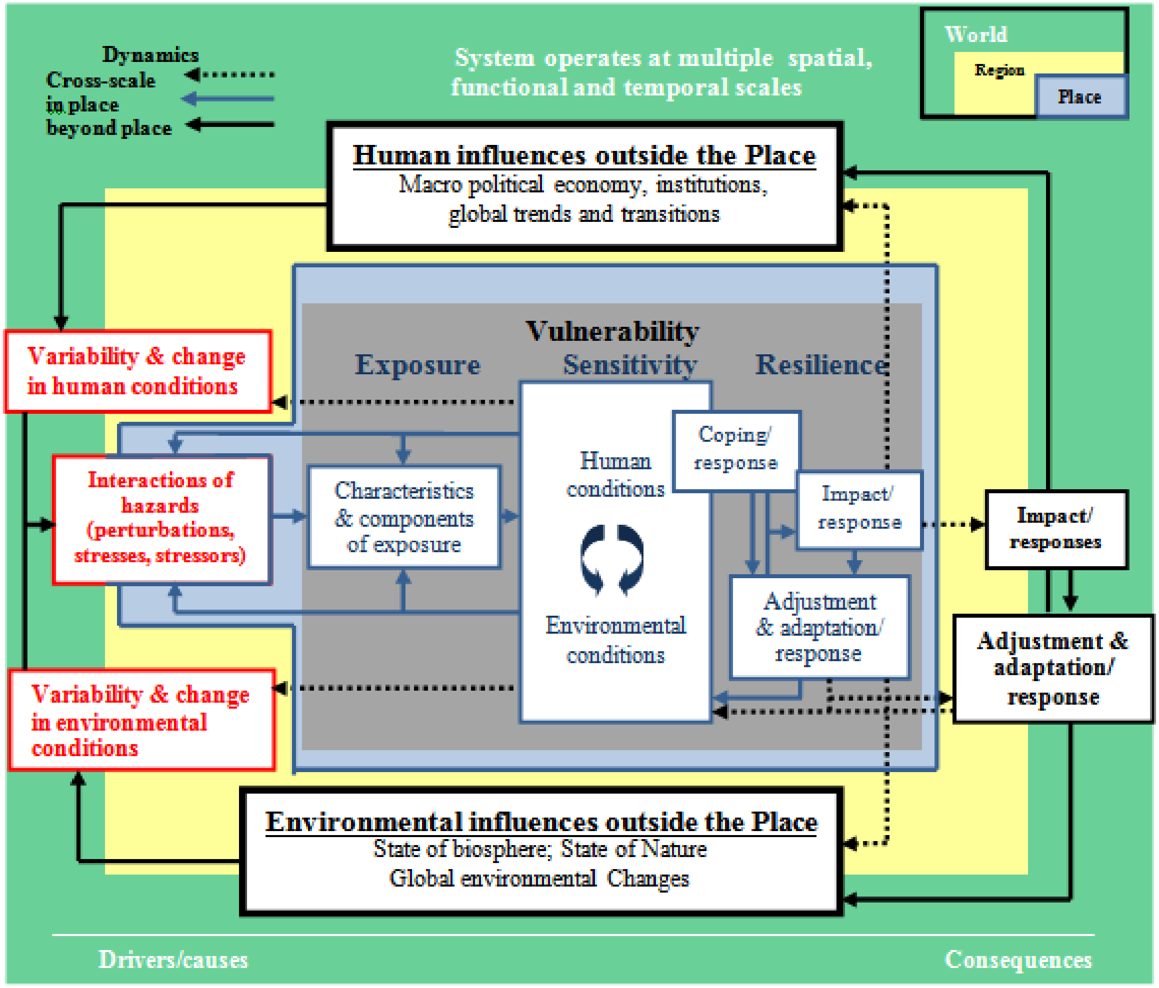


Source: Birkmann (2006).

2.3.3.3 Risk-Hazard (RH) Model

The Risk-Hazard (RH) Model was proposed by Turner et al., (2003). The framework is illustrated in Figure 2.7, by way of spatial scaling, linking places (blue) to regions (yellow) and to global (green) scales. The coupled human–environment system, whatever its spatial dimensions, constitutes the place of analysis. According to the authors, the basic architecture consists of: i) linkages to the broader human and biophysical (environmental) conditions and processes operating on the coupled system in question; ii) perturbations and stressor that emerge from these conditions and processes; and iii) the coupled human–environment system of concern in which *vulnerability* resides, including exposure and responses (i.e., coping, impacts, adjustments, and adaptations). These elements are interactive and scale dependent, such that analysis is affected by the way in which the coupled system is conceptualized and bounded for study. *Vulnerability* is registered by exposure to *hazards* (perturbations and stresses), sensitivity and *resilience* of the system experiencing such *hazards*. The sensitivity to exposure is defined by the human-environmental conditions, e.g. social and biophysical capital, that influence the coping mechanisms when the impact is experienced, as well as those coping mechanisms adjusted or created because of the experience (TURNER et al., 2003).

Figure 2.7 – The Risk-Hazard Model.



Source: Turner et al. (2003).

2.4 Disaster Risk

In popular usage, *risk* means chance or possibility of occurrence of something. There are numerous attempts to define *risk*. According to Narvaez et al., (2009), *risk* definition has historically taken two courses: on the one hand, it puts emphasis on *hazard* occurrence, while on the other hand, it emphasizes on their impacts. By way of example, Table 2.3 shows some *risk* definitions in the *hazard* and *disaster* management literature. Recently, the Second Formal Session of the Open-ended Intergovernmental Expert Working Group on Terminology and Indicators relating to Disaster Risk Reduction defined the term *Disaster risk* as a function of *hazard*, *exposure* and *vulnerability*. It is (normally) expressed as a probability of loss of life, injury or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time (UNIDRS, 2016).

Reducing *risk* from natural *hazards* is a major challenge at present and in the future regarding global environmental change as well as *vulnerability* conditions. Societies will have to live with changing environmental conditions (BIRKMANN et al., 2013). This highlights the need to make people -including government- aware of the *risk* and prepare them for living with it.

Table 2.3 – Risk definitions.

Risk	Source
Implies the possibility of suffering a loss.	BURBY, 1991
The possibility of suffering harm from a hazard.	EASTMAN et al., 1997
Is a function of the probability of the specified natural hazard event and vulnerability of cultural entities.	CHAPMAN, 1994
The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human induced hazards and vulnerable conditions.	UNISDR, 2004
The combination of the probability of an event and its negative consequences.	UNISDR, 2009

Source: Schneiderbauer and Ehrlich (2004).

The United Nations General Assembly designated the 1990s as the International Decade for Disaster Reduction with the aim to promoting awareness of the importance of *disaster* reduction. Despite the efforts devoted to this task, disaster numbers and costs continue to rise, given the increasing *vulnerability* of our societies to natural *hazards*. However, the experience gained during this decade laid the foundations for the subsequent establishment of the three major international frameworks related to Sustainable Development, Climate Change Adaptation and *Disaster Risk Reduction*: *i)* the Sustainable Development Goals (SDG) with time frame of 2015 to 2030; *ii)* the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), and, *iii)* the Sendai Framework for *Disaster Risk Reduction* with a time frame of 2015 to 2030.

2.4.1 The Sendai Framework for Disaster Risk Reduction 2015-2030

The Sendai Framework for Disaster Risk Reduction- the successor of the Hyogo Framework for Action- was adopted by 187 states at the Third United Nations World Conference on Disaster Risk Reduction in Sendai, Japan, in March 2015. This international agreement aims to achieve the substantial reduction of *disaster risk* and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries. In order to attain the expected outcome, it seeks to reduce existing and prevent new *disaster risk* (UNISDR, 2015) thus, seven global targets have been agreed:

i) Substantially reduce global *disaster* mortality by 2030, aiming to lower the average per 100,000 global mortality rate in the decade 2020–2030 compared to the period 2005–2015;

ii) Substantially reduce the number of affected people globally by 2030, aiming to lower the average global figure per 100,000 in the decade 2020–2030 compared to the period 2005–2015;

iii) Reduce direct disaster economic loss in relation to global gross domestic product (GDP) by 2030;

iv) Substantially reduce *disaster* damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their *resilience* by 2030;

v) Substantially increase the number of countries with national and local *disaster risk* reduction strategies by 2020;

vi) Substantially enhance international cooperation to developing countries through adequate and sustainable support to complement their national actions for implementation of the present Framework by 2030;

vii) Substantially increase the availability of and access to multi-*hazard* early warning systems and *disaster risk* information and assessments to people by 2030.

The Sendai Framework also states there is a need for focused action within and across sectors by States at local, national, regional and global levels in the following four priority areas (UNISDR, 2015):

Priority 1: Understanding disaster risk

Policies and practices for disaster *risk* management should be based on an understanding of disaster *risk* in all its dimensions of *vulnerability*, capacity, exposure of persons and assets, *hazard* characteristics and the environment. Such knowledge can be leveraged for the purpose of pre-disaster *risk* assessment, for prevention and mitigation and for the development and implementation of appropriate preparedness and effective response to disasters.

Priority 2: Strengthening disaster risk governance to manage disaster risk

Disaster *risk* governance at the national, regional and global levels is of great importance for an effective and efficient management of disaster *risk*. Clear vision, plans, competence, guidance and coordination within and across sectors, as well as participation of relevant stakeholders, are needed. Strengthening disaster *risk* governance for prevention, mitigation, preparedness, response, recovery and rehabilitation is therefore necessary and fosters collaboration and partnership across mechanisms and institutions for the implementation of instruments relevant to disaster *risk* reduction and sustainable development.

Priority 3: Investing in disaster risk reduction for resilience

Public and private investment in disaster *risk* prevention and reduction through structural and non-structural measures are essential to enhance the economic, social, health and cultural *resilience* of persons, communities, countries and their assets, as well as the environment. These can be drivers of innovation, growth and job creation. Such measures are cost-effective and instrumental to save lives, prevent and reduce losses and ensure effective recovery and rehabilitation.

Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction

The steady growth of disaster *risk*, including the increase of people and assets exposure, combined with the lessons learned from past disasters, indicates the need to further strengthen disaster preparedness for response, take action in anticipation of events, integrate disaster *risk* reduction in response preparedness and ensure that capacities are in place for effective response and recovery at all levels. Empowering women and persons with disabilities to publicly lead and promote gender equitable and universally accessible response, recovery, rehabilitation and reconstruction approaches is key. Disasters have demonstrated that the recovery, rehabilitation and reconstruction phase, which needs to be prepared ahead of a disaster, is a critical opportunity to "Build Back Better", including through integrating disaster *risk* reduction into development measures, making nations and communities resilient to disasters.

2.4.2 Integrated Research on Disaster Risk

Disaster science establishes the need of *disaster risk* transdisciplinary approach which represents a challenge since it requires mobilization of professionals from different knowledge areas in order to integrate the wide range of perspectives and discourses.

Different initiatives have been made to encourage the integrated research on *disaster risk*. For instance, the Integrated Research on Disaster Risk (IRDR) programme envisages an integrated approach to natural and human-induced environmental *hazards* through a combination of natural, socio-economic, health and engineering sciences, including socio-economic analysis, understanding the role of communications, and public and political response to reduce *risk*. Similarly, the Integrated Disaster Risk Management (IDRiM) Society seeks to promote integrated research with an additional focus on the implementation of *disaster* science, research and education in real-world localities, varying in geographic, climatic, political, cultural and social systems (GALL et al., 2015). Recently the United Nations Office for Disaster Risk Reduction (UNISDR) has launched a guidelines on national *disaster risk* assessment (NDRA) intended to: i) motivate and guide countries in establishing a national system for understanding *disaster risk* and, ii) encourage NDRA leaders and implementing entities to aim for holistic assessments that would provide an understanding of many different *disaster risk dimensions* (*hazards*, *exposure*, *vulnerability*, *capacities*) (UNISDR, 2017).

A recent report introduced at the Bosai Global Forum (2017) reveals that despite the key role that science plays in the implementation of the Sendai Framework for Disaster Risk Reduction, *disaster* science represents only 0.22% of the world's total scholarly output. Other important finding highlights that in the period 2012-2016, countries with the highest death tolls from natural *hazards* had the low volumes of *disaster* science scholarly output.

Conversely, countries with the highest economic losses from natural *hazards* had the largest *disaster* science scholarly output. These results point out that there is a need to increase the volume and quality of research being done in the *disaster science* or seek out partnerships to build research capacity in low-income countries, where generally social impacts of *disasters* are the highest (HUGGETT et al., 2017).

In this Thesis an *integrated landslide disaster risk* assessment is performed, based on the First Priority Area of the Sendai Framework. It will more deeply addressed in Chapter 6.

3 CONCEPTUAL FRAMEWORK AND STUDY AREA

3.1 The Conceptual Model: Putting pieces together

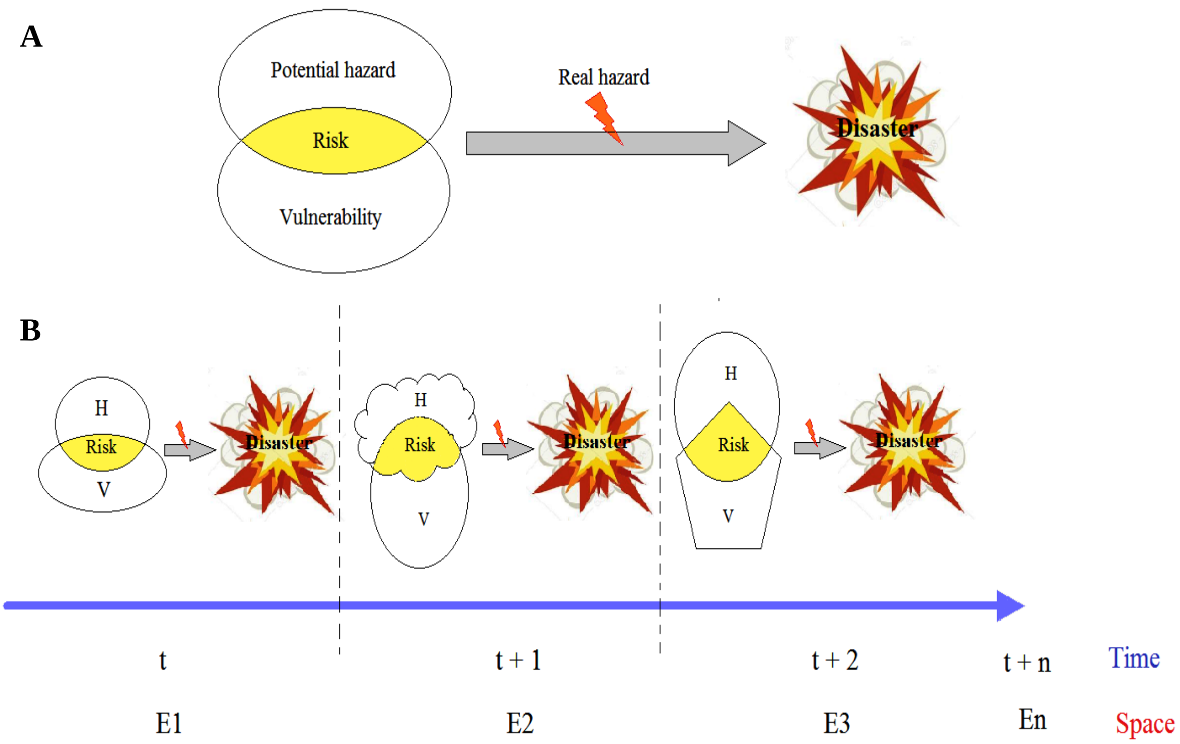
The combination of *hazard*, *exposure* and *vulnerability* has been used to define *risk*. Although the existing literature provides an interesting overview of the *risk* nature, a conceptual framework oriented towards on how to operationally undertake and assemble these concepts is lacking.

In this Chapter a conceptual framework for assessing integrated *disaster risk* is introduced. It identifies key components and looks for structuring them into a consistent system in order to find operational possibilities for a spatio-temporal assessment of *disaster risk*. The proposal is generic enough, therefore, it is applicable to other cases.

Figure 3.1 shows the conceptual framework that can help to develop a better understanding of *disaster risk*. Although this approach is aligned with other proposals (WILCHES-CHAUX, 1993; WISNER et al., 2004; NARVAEZ et al., 2009; VALENCIO, 2013; VAN WESTEN et al., 2011; BIRKMANN et al., 2013), it makes a novel contribution since it emphasizes the non-stationary nature- both over time and space- of the *risk* and the elements that shape it. Furthermore, the way it is proposed enables conversion of this theoretical proposition into a testable form- based on an assessment of the physical and social landscapes- beyond the conceptual level. This will be treated more deeply in the following chapters with a practical case study related to the 2011 landslides in the Nova Friburgo municipality (Rio de Janeiro State). This case study addresses *landslide risk assessment* as a key element of disaster risk management (DRM) at the municipal level. This includes not only the *hazard assessment* (Landslide Susceptibility – Chapter 4) but also, the measurement of the human dimension of *risk* (Social Vulnerability - Chapter 5), paying particular attention to the complex interplay between the physical and the human systems (Landslide Risk Assessment - Chapter 6).

As widely known, the presence of a *hazard* is not considered a *risk* in itself. *Hazards* include latent conditions that may represent a *risk* (VAN WESTEN et al., 2011). When the potential *hazard* becomes a reality in presence of a society with vulnerabilities, the *risk* may become a *disaster* (Figure 3.1-A). In order to understand *disasters*, it is essential to analyze how the conditions producing the *risk* have been formed over time and space. Thus, *risk* (and also disaster) can be seen as a process and not just as a punctual situation. In fact, it can be seen as both: a situation- in a given space and at a given time- and as a process– over a time period and a particular space extension. Figure 3.1-B shows that *hazard* (H), *vulnerability* (V) and *risk* (R) can change along the spatio-temporal scales. Different shapes adopted for H, V and R in the graph highlight their dynamic nature. In this framework, *exposure* concept is considered within the *vulnerability* dimension (see Chapter 6).

Figure 3.1 – Conceptual framework for spatially integrated assessment of disaster risk that combines key concepts. **A)** The hazard (H) and vulnerability (V) interact in a given space (E) and at a given time (t) shaping the risk (R) which may become a disaster. **B)** As hazard (H) and vulnerability (V) can change over time and space then, the produced risk (R) can also change. Symbols t, t+1,..., t+n mean different times "t", with t=1 to n; while E1, E2,…En, refer to different physical spaces "E", with E=1 to n.



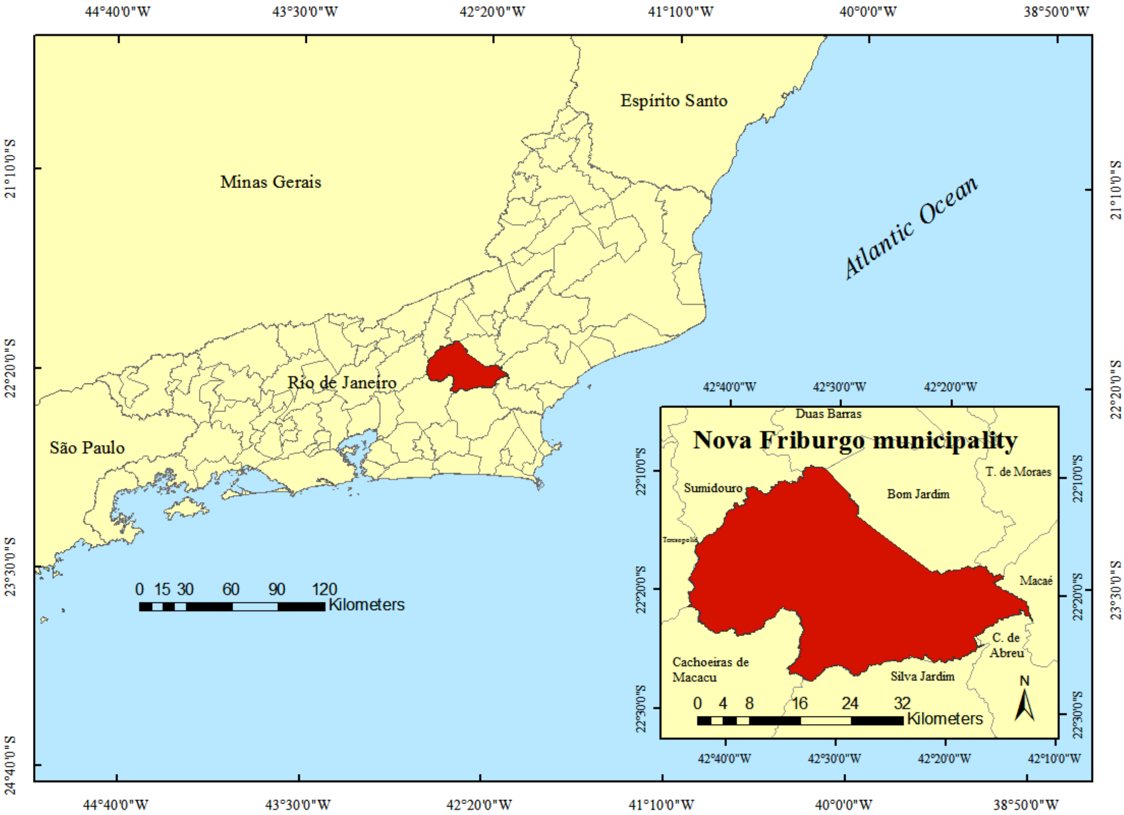
Source: Author's production.

3.2 Study Area

3.2.1 Site Description

Nova Friburgo municipality is located in Rio de Janeiro State mountainous region, Brazil (Figure 3.2). It has approximately 934 km^2 and is situated in the “Serra dos Órgãos”, a local name that designates a higher portion of the mountains called “Serra do Mar”. The elevation ranges from 636 to 1587 meters above sea level.

Figure 3.2 – Localization of Nova Friburgo municipality, Rio de Janeiro State, Brazil.



Source: Author’s production.

3.2.2 Climate and Vegetation

The zone has a predominantly high-altitude tropical climate with an average temperature of 16°C. This area was originally covered by Tropical Atlantic Rainforest, but currently is fragmented and much degraded, especially around urban areas. According to Cardoso and Vieira (2016) the systematic elimination of vegetation arises from the arrival of the Swiss immigrants to the Nova Friburgo city. Nowadays, existing forest patches are represented by a secondary forest. Nova Friburgo is the highest rainfall zone in the State with an average annual precipitation of about 2500 mm in the highest areas, decreasing progressively to 1300 mm to the north (COELHO NETTO et al., 2011).

The “Mega disaster” in the mountainous region of Rio de Janeiro took place on 11th and 12th January 2011 (Figure 3.3). Nova Friburgo municipality was one of the most severely affected zones during the massive 2011 landslides which were triggered by rainfalls. Appendix A provides some selected photographs that may help to illustrate the disaster dimension in Nova Friburgo municipality.

Figure 3.3 – Aereal view of some fresh scars of landslides triggered by rainfalls in the Rio de Janeiro State mountainous region, January 2011.

Source: DRM-RJ (2011).

3.2.3 Geology and Geomorphology

The geology of the Rio de Janeiro State is associated with an ample fold belt from the Proterozoic Era, mainly composed of rocks with high metamorphic grades (gneisses) with well defined foliation in the SW-NE direction and fractures in diverse directions. Sintectonic igneous (granitoid) rocks, generated by anatexis also occur and are oriented in the same way as metamorphic rocks. The geomorphology of the State presents a predominance of hills and coastal plains with isolated rocky massifs, however the mountainous region of Rio de Janeiro contrasts sharply with this group. In the mountainous region, granites (post and tarditectonic), migmatites and gneisses with little foliation compose a province of highly weathering-resistant rocks which regionally produce a mountainous geomorphology called the Serra dos Orgãos. In this mountainous region of Rio de Janeiro, the valley bottoms are narrow and develop along persistent tectonic fractures in which only the larger-sized rivers are able to generate even fluvial deposits where the majority of the population is located. Adjacent to these valleys, escarpments with rocky outcroppings and steep slopes (more than 35 degrees) are common; these can present deposits of talus or colluvium rich in rock blocks at the base.

On the other hand, in the Serra dos Orgãos landscape, there are also many areas where intramontane hills grade to slopes of slighter declivity (between 15 and 35 degrees). In these areas the regolith are composed by thick saprolitic and colluvial deposits that together can reach until 10 meters in depth (AVELAR et al., 2011).

According to Dantas (2001) Nova Friburgo is part of the "Serra Fluminense" which covers the central part of Rio de Janeiro State with an area of 1,552 km^2. It is located in the relief degradation system in the mountainous areas on the back of Serra do Mar with very rough terrain. The slopes are predominantly steep, rectilinear to concave, with top of crest aligned, acute or slightly rounded. The area has a high drainage density with a variable pattern (with occurrence of dendritic or rectangular types). There is a predominance of topographic amplitudes over 400 meters, shallow soils, with rocky outcrops and presence of coluvial and talus deposits

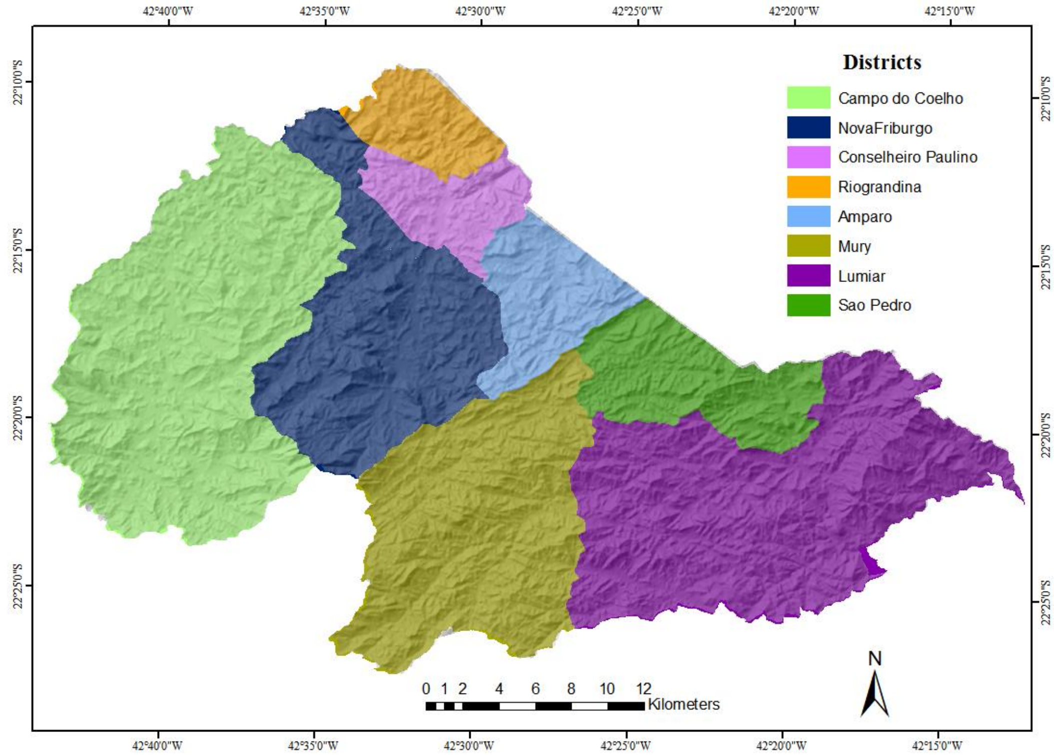
3.2.4 Population and Land Use

In 1890 Nova Friburgo was recognized as a city, which produced great territorial transformations in the municipality. At the end of the 19^{th} Century the city of Nova Friburgo already had a defined urban occupation by Swiss and German settlers. Additionally, arrival of more immigrants such as Italians, Portuguese, Spanish, Lebanese and Japanese occurred. In the 20^{th} Century, Nova Friburgo was characterized by a strong process of industrialization that together with a consolidated urban network attracted people and workers from neighboring cities and regions (DUARTE, 2009).

In 2010, one year before the massive landslide event, Nova Friburgo reached a population of 182,082 inhabitants (195 inhabitants per square kilometer); which represented 4.8% more habitants than in the 2000 census. About 90% (159,372 inhabitants) lived mainly in the urban zones (IBGE, 2010) when the disaster struck.

Nova Friburgo municipality is formed by eight districts (Figure 3.4), "Nova Friburgo" and "Conselheiro Paulino" being the most populated ones. Furthermore, both districts concentrate the main economic activities. "Nova Friburgo" district is characterized by textile industries, while "Conselheiro Paulino" district has an important industrial park in which the metalliferous, mechanical, metallurgical and textile sectors are developed. "Amparo" and "Campo do Coelho" districts are rural but nowadays they have become more important as residential and commercial areas, especially due to its proximity to the central districts. Particularly, Campo do Coelho's economy is based on agriculture and chinchilla and goat breeding. "Riograndina" district, located in the municipality northern border has a remarkable cultural importance. On the other hand, “Mury” district is known as being a gastronomic pole while “Lumiar” and “São Pedro da Serra” districts as being a touristic region (FIRJAN SYSTEM, 2015).

Figure 3.4 – Nova Friburgo districts.



Source: Author’s production.

4 THE PHYSICAL COMPONENT OF RISK[1]

4.1 Landslide Susceptibility

Landslides are one of the major natural *hazards* causing significant damage to buildings, lives and engineering projects in all mountainous areas in the world (MARTHA et al., 2010; SEPÚLVEDA; PETLEY, 2015).

Landslide susceptibility zonation is one of the most important tasks in landslide *risk* assessment. Different mathematical approaches for landslide susceptibility modelling includes: i) Heuristic (e.g., index-based approach and an analytical hierarchical process approach); ii) Statistical (statistical index, certainty factor, probability based methods, weight of evidence modelling, multiple linear regression and logistic regression analysis) and, iii) Deterministic modelling (slope stability factor) (KURIAKOSE, 2010). Some examples of the latter include the SHALSTAB model (MONTGOMERY; DIETRICH, 1994), the Stability INdex MAPping or SINMAP model (PACK et al., 1998) and the TRIGRS model (BAUM et al., 2002).

Physically-based modelling SINMAP has been tested under different geological and hydrological conditions by several authors (MORRISSEY et al., 2001; ZAITCHIK;VAN ES, 2003; CALCATERRA et al., 2004; SILVA, 2006; TAROLLI;TARBOTON, 2006; MEISINA;SCARABELLI, 2007; LOPES et al., 2007; NERY;VIEIRA, 2015; PRETI; LETTERIO, 2015; TERHORST; JAEGER, 2015; ABASCAL;GONZÁLEZ BONORINO, 2015; RABONZA et al., 2016) and it has proved to be highly reliable in predicting slope instability. Performance of SINMAP has also been compared to other models such as SHALSTAB, TRIGRS, and SLIP (ZIZIOLI et al., 2013; MICHEL et al., 2014) resulting in similar global accuracy for all the models.

In Brazil, shallow landslides are typically triggered by rainfalls. According to Nery and Vieira (2015) few studies using mathematical models to assess landslide susceptibility were performed specially in the Serra do Mar

Taking this premise into account, the aim of this study is to assess shallow landslide susceptibility through the SINMAP approach to better understand the slope stability in Nova Friburgo.

1 This chapter is based on the article: CARDOZO, C. P.; LOPES, S. E.; MONTEIRO, M. V. (in press) Shallow landslide susceptibility assessment using SINMAP in Nova Friburgo (Rio de Janeiro, Brazil). *Rev. Brasileira de Cartografia*, Edição Especial: Desastres Naturais no Brasil 2017, v. 69, n. 4. 2017.

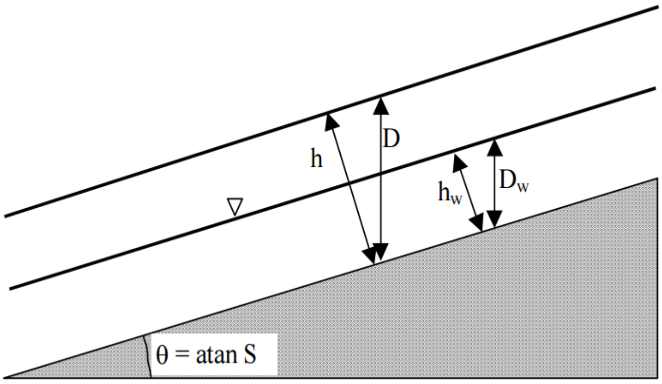
4.2 The Infinite Slope Stability Model

According to Pack et al., (2005) the infinite slope stability model factor of safety (ratio of stabilizing to destabilizing forces) is given by (simplified for wet and dry density the same, from Hammond et al., 1992).

$$FS = \frac{C_r + C_s + \cos^2\theta\left[\rho_s g(D - D_w) + (\rho_s g - \rho_w g)D_w\right]\tan\phi}{D\,\rho_s g\,\sin\theta\cos\theta} \qquad (4.1)$$

where **FS** is Factor of Safety; $\mathbf{C_r}$ is root cohesion [N/m^2]; $\mathbf{C_s}$ is soil cohesion [N/m^2]; $\boldsymbol{\theta}$ is slope angle; $\boldsymbol{\rho_s}$ is wet soil density [kg/m^3]; $\boldsymbol{\rho_w}$ is the density of water [kg/m^3]; **g** is gravitational acceleration [9.81 m/s^2]; **D** is the vertical soil depth [m]; $\mathbf{D_w}$ is the vertical height of the water table within the soil layer [m] and; $\boldsymbol{\phi}$ is the internal friction angle of the soil [°]. The slope angle $\boldsymbol{\theta}$ is the arc tangent of the slope, **S**, expressed as a decimal drop per unit horizontal distance. Figure 4.1 illustrates the geometry assumed in Equation 4.1.

Figure 4.1 – Infinite slope stability model schematic.



Source: Pack et al., (2005).

Soil thickness, h [m] and vertical soil depth, D [m] are related as follows

$h = D\cos\theta$ (4.2)

With this change FS reduces to

$$FS = \frac{C + \cos\theta\,[1 - wr]\tan\phi}{\sin\theta} \qquad (4.3)$$

where

$$w = D_w/D = h_w/h \qquad (4.4)$$

is the relative wetness,

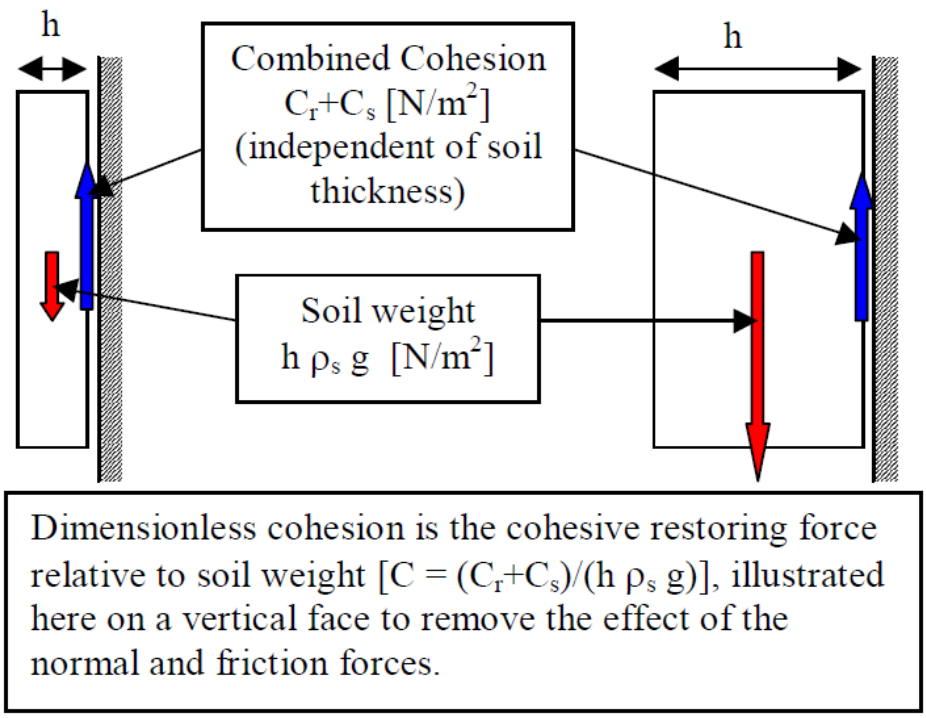
$$C = (C_r + C_s)/(h\,\rho_s g) \qquad (4.5)$$

the combined cohesion made dimensionless relative to the perpendicular soil thickness and the water to soil density ratio.

$$r = \rho_w / \rho_s \qquad (4.6)$$

Equation (4.3) is the dimensionless form of the infinite slope stability model. This is convenient because cohesion (due to soil and root properties) is combined with the soil density and thickness into a dimensionless cohesion factor, C (Eq. 4.5). This may be thought of as the ratio of the cohesive strength relative to the weight of the soil, or the relative contribution to slope stability of the cohesive forces. Figure 4.2 illustrates this concept. The second term in the numerator of Eq. (4.3) quantifies the contribution to stability due to the internal friction of the soil (as quantified by friction angle, φ, or friction coefficient, tanφ). This is reduced as wetness increases due to increasing pore pressures and consequent reductions in the normal force carried by the soil matrix. The sensitivity to this effect is controlled by the density ratio r (Eq. 4.6).

Figure 4.2 – Illustration of dimensionless cohesion factor concept.



Source: Pack et al., (2005).

Practically, the model works by computing slope and wetness at each grid point, but assuming other parameters are constant (or have constant probability distributions) over larger areas. With the form of equation (4.3) this amounts to implicitly assuming that the soil thickness (perpendicular to the slope) is constant.

4.2.1 Topographic Wetness Index

The emergence of the parameter specific catchment area, “a”, defined as upslope area per unit contour length [m^2/m] (see Figure 4.3) has been one of the landmark developments in hydrology, due to Beven and Kirkby (1979). It is tied closely to recent hydrologic models that represent runoff generation by the saturation from below mechanism. These developments follow the field observations that higher soil moisture or areas of surface saturation tend to occur in convergent hollow areas. It has also been reported that landslides most commonly originate in areas of topographic convergence (MONTGOMERY; DIETRICH, 1994).

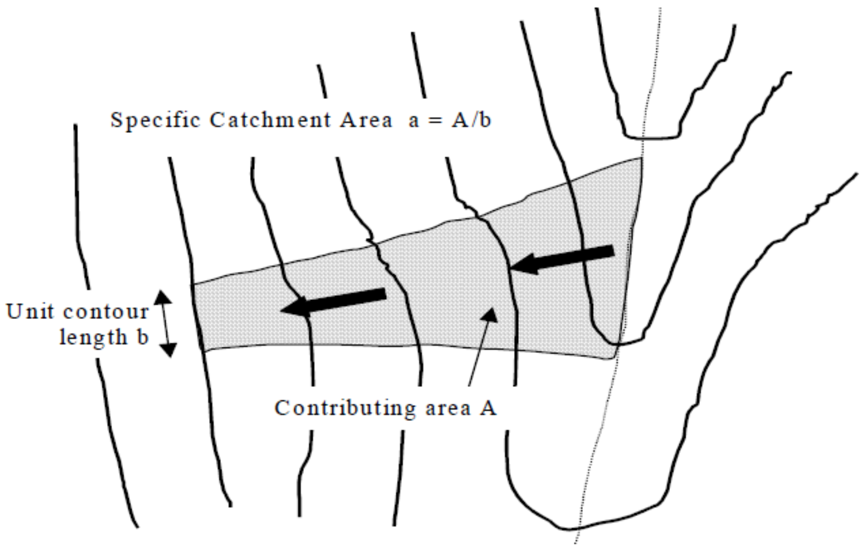
Following TOPMODEL (and other similar topographically based wetness index models) assumptions were made:

(1) Shallow lateral subsurface flow follows topographic gradients. This implies that the contributing area to flow at any point is given by the specific catchment area defined from the surface topography (Figure 4.3).

(2) Lateral discharge at each point is in equilibrium with a steady state recharge R [m/hr].

(3) The capacity for lateral flux at each point is T sinθ, where T is the soil transmissivity [m^2/hr], i.e. hydraulic conductivity [m/hr] times soil thickness, h [m].

Figure 4.3 – Definition of specific catchment area.



Source: Pack et al., (2005).

Assumptions (1) and (2) together imply that lateral discharge q, depth integrated per unit contour length [m^2/hr] is

$$q = R\,a \tag{4.7}$$

With assumption (3) the relative wetness is

$$w = \mathrm{Min}\left(\frac{R\,a}{T\sin\theta}, 1\right) \tag{4.8}$$

The relative wetness has an upper bound of 1 with any excess assumed to form overland flow. As illustrated in Figure 1, the relative wetness defines the relative depth of the perched water table within the soil layer. The ratio R/T in Eq. 4.8, which has units of [m^{-1}], quantifies the relative wetness in terms of assumed steady state recharge relative to the soil's capacity for lateral drainage of water. Although the term 'steady state' is used with lateral flux approximated using Eq. 4.7 the quantity R is not a long term (e.g. annual) average of recharge. Rather it is the effective recharge for a critical period of wet weather likely to trigger landslides. The ratio R/T, which is treated as a single parameter, therefore combines both climate and hydrogeological factors. The quantity (T/R)sinθ [m] may be thought of as the length of hillslope (planar, not convergent) required to develop saturation in the critical wet period being considered. This concept may be useful for establishing field estimates of R/T through the field identification of the limits of surface saturation.

4.2.2 Stability Index Definition

To define the stability index, the wetness index from Eq. 4.8 is incorporated into the dimensionless factor of safety, Eq. 4.3, which becomes

$$FS = \frac{C + \cos\theta\,[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right) r]\tan\phi}{\sin\theta} \tag{4.9}$$

The variables "a" and θ are from the topography with C, tanφ, r and R/T parameters. The density ratio r is treated as essentially constant (with a value of 0.5) but allow uncertainty in the other three quantities through the specification of lower and upper bounds. Formally these bounds define uniform probability distributions over which these quantities are assumed to vary at random. Denote R/T = x, tan φ = t, and the uniform distributions with lower and upper bounds as

$$C \sim U(C_1, C_2)$$

$$x \sim U(x_1, x_2) \quad (4.10)$$

$$t \sim U(t_1, t_2)$$

The smallest C and t, (i.e. C_1 and t_1) together with the largest x (i.e. x_2) defines the worst case (most conservative) scenario under this assumed uncertainty (variability) in the parameters. Areas where under this worst case scenario FS is greater than 1 are in terms of this model, unconditionally stable

$$SI = FS_{min} = \frac{C_1 + \cos\theta\,[1 - \min\left(x_2 \frac{a}{\sin\theta}, 1\right) r]t_1}{\sin\theta} \quad (4.11)$$

For areas where the minimum factor of safety is less than 1, there is a possibility (probability) of failure. This is a spatial probability due to the uncertainty (spatial variability) in C, tanφ and T. This probability does have a temporal element in that R characterizes a wetness that may vary with time. Therefore the uncertainty in x combines both spatial and temporal probabilities. In these regions (with $FS_{min} < 1$):

$$SI = Prob(FS > 1) \quad (4.12)$$

over the distributions of C, x, and t (Eq. 4.10). The best case scenario is when $C=C_2$, $x=x_1$, and $t=t_2$, which leads to:

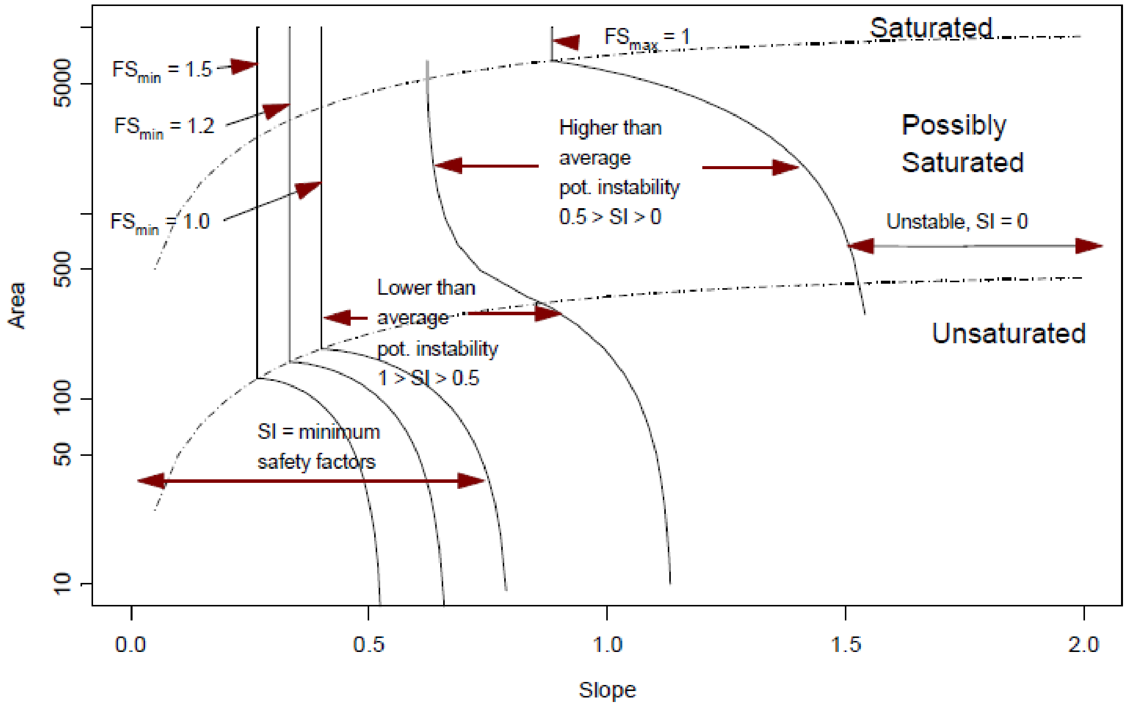
$$FS_{max} = \frac{C_2 + \cos\theta\,[1 - \min\left(x_1 \frac{a}{\sin\theta}, 1\right) r]t_2}{\sin\theta} \quad (4.13)$$

In the case that FSmax < 1, then

$$SI = Prob(FS > 1) = 0 \quad (4.14)$$

Regions with SI > 1 (FSmin > 1), 0 < SI < 1 and SI = 0 (FSmax < 1) are illustrated in Figure 4.4 in a space defined in terms of slope (tanθ) and specific catchment area. This provides a useful visualization medium for understanding this approach.

Figure 4.4 – Stability Index defined in Area-Slope space.



Source: Pack et al., (2005).

The stability classes adopted by SINMAP are shown in Table 4.1.

Table 4.1 – Stability classes in the SINMAP model.

Condition	Predicted state	Parameter range	Possible influence of factors not modelled
SI > 1.5	Stable slope zone	Range cannot model instability	Significant destabilizing factors are required for instability
1.5 > SI > 1.25	Moderately stable zone	Range cannot model instability	Moderate destabilizing factors are required for instability
1.25 > SI > 1.0	Quasi-stable slope zone	Range cannot model instability	Minor destabilizing factors could lead to instability
1.0 > SI > 0.5	Lower threshold slope zone	Pessimistic half of range required for instability	Destabilizing factors are not required for instability
0.5 > SI > 0	Upper threshold slope zone	Optimistic half of range required for stability	Stabilizing factors may be responsible for stability
0 > SI	Defended slope zone	Range cannot model stability	Stabilizing factors are required for stability

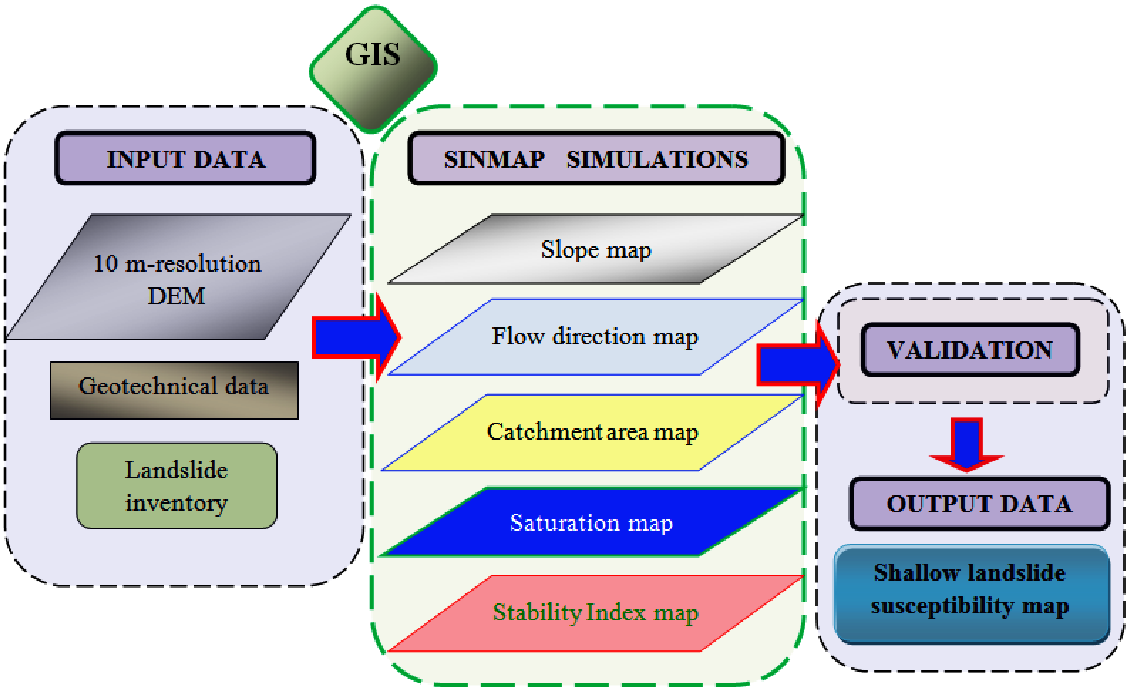
Source: Pack et al.(1998).

4.3 Data Source and Methodology

Figure 4.5 shows the generalized methodology adopted in this study. Tests were performed in SINMAP 2.0- a free extension to ArcView Spatial Analyst GIS software distributed by the Environmental Systems Research Institute (ESRI) (PACK et al., 1998).

To identify the most and least landslide susceptibility zones, Stability Index (SI) was mapped based on six classes: stable, moderately stable, quasi-stable, lower threshold, upper threshold and defended. According to Pack et al., (1998, 2005) "lower threshold" and "upper threshold" characterize regions where, according to the parameter uncertainty ranges quantified by the model, the probability of instability is lower than or higher than 50%, respectively. External factors are not required to bring about instability in these regions. Instability may arise simply due to a combination of parameter values within the bounds quantifying uncertainty and variability. In this scheme, "defended slopes" are also unstable areas.

Figure 4.5 – General methodology adopted in this research.



Source: Author's production.

SINMAP methodology enables adjusting parameters for geographic "calibration regions", based upon soil, vegetation or geologic data. In this study, a single calibration region was used because no detailed geotechnical data were available. However, three susceptibility scenarios were tested by varying soil cohesion and friction internal angle parameters (More details see Section 4.3.3). Calibration procedure involves adjustment of parameters so that the stability map “captures” a high proportion of observed landslides in regions with low stability index, while minimizing the extent of low stability regions and consequent alienation of terrain to regions where landslides have not been observed (PACK et al., 2005).

4.3.1 Landslide Inventory

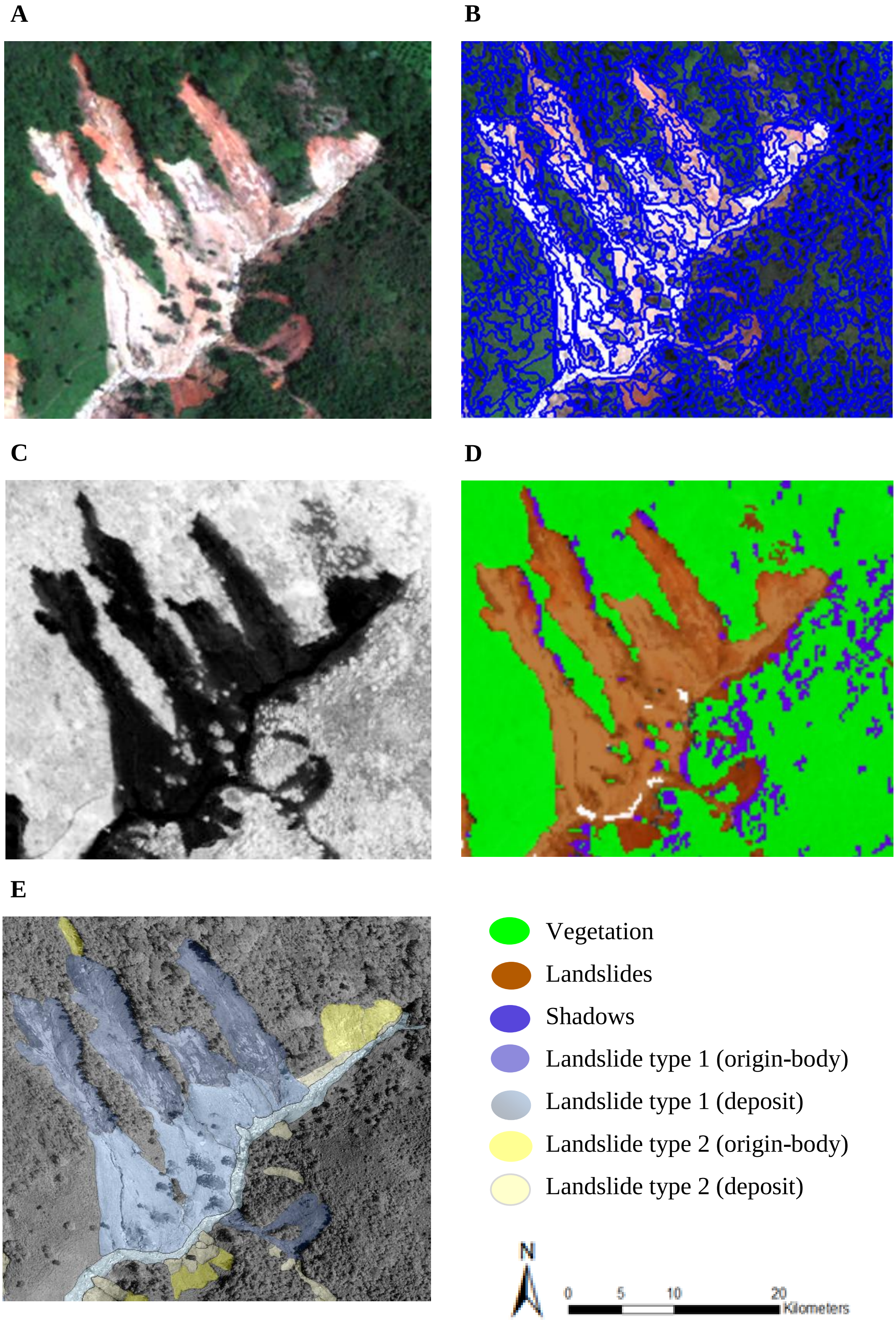
The 2011 landslide recognition by semi-automatic detection with Object-oriented method (OOA) is briefly described below. Landslide classification based on material and movement type is outside the scope of this study.

Two primary data were used. A Geo-Eye-1 satellite data provided by the National Institute for Space Research (INPE) and a Digital Elevation Model (DEM) provided by the Brazilian Institute of Geography and Statistics (IBGE) from which other parameters were automatically derived using a GIS environment. Appendix B shows both satellite dataset.

The multispectral sensor with a panchromatic band (450 to 800 nm) of 0.41 meters and four multispectral bands of 1.84 m spatial resolution (Figure 4.6-A): blue (450 to 510 nm); green (510 to 580 nm); red (655 to 690 nm) and near infra-red (780 to 920 nm)-UTM Datum WGS-84 were acquired on 20th January 2011- with less than 15% of cloud coverage. It was the best available data taken just after the event and it was used to derive landslide spectral characteristics, such as Normalized Difference Vegetation Index *(*NDVI*)* and brightness. The images already had radiometric correction. Additionally, an orthorrectification process was performed in order to remove geometric distortions.

First, with the aim to identify landslide candidates, the image was segmented into objects based on pixel values homogeneity by using the multiresolution segmentation algorithm (Figure 4.6-B). The outcome of this process is controlled by three main factors: (i) the homogeneity criteria or scale parameter that determines the maximum allowed heterogeneity for the resulting image objects, (ii) the weight of colour and shape criteria in the segmentation process, and (iii) the weight of the compactness and smoothness criteria (i.e. the higher the compactness weight, the more compact image objects may be) (DEFINIENS, 200; AGUILAR et al., 2013). In this research, the best settings for segmentation parameters were determined through a combination of trial and error resulting in a scale parameter equal to 20; shape equal to 0.3 and compactness equal to 0.7.

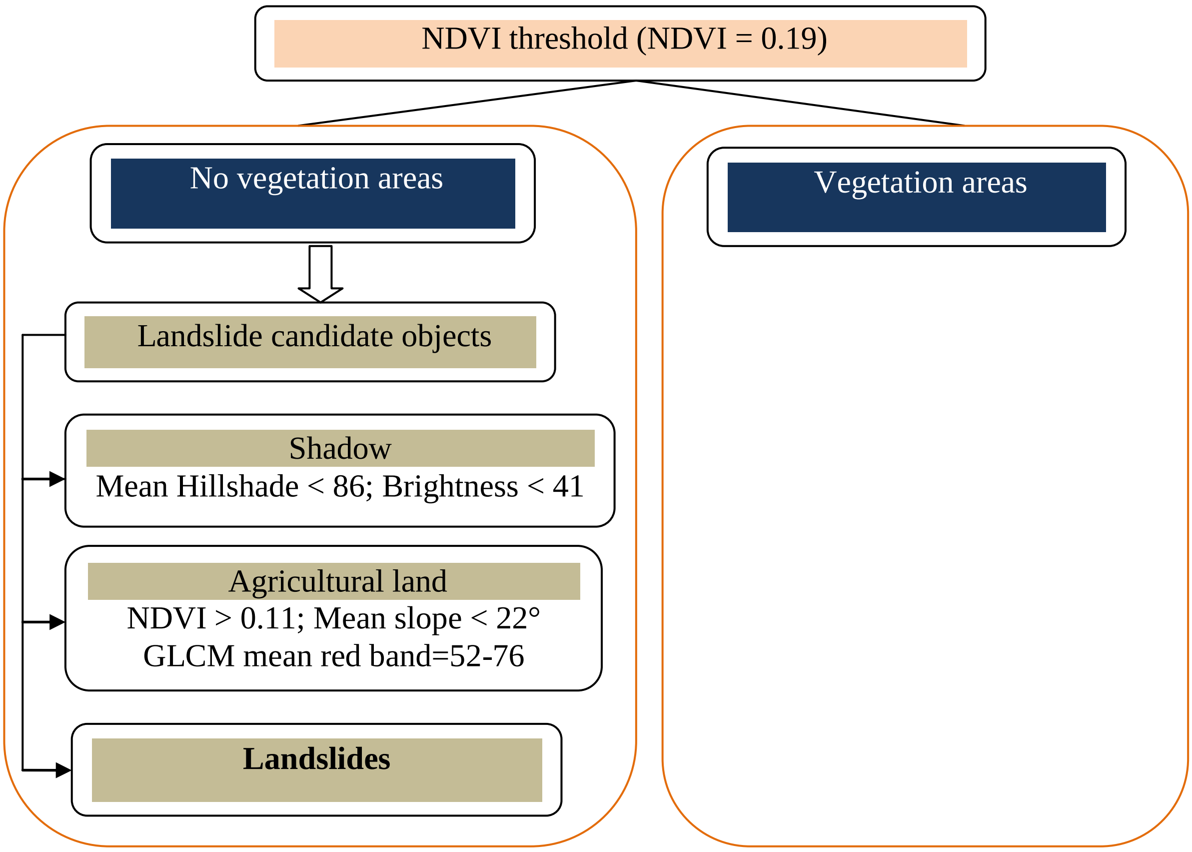
Figure 4.6 – Important stages in landslide identification in OOA. **A)** Geo-Eye-1 image subset (RGB:321) showing landslides, vegetation cover and shadows; **B)** Geo-Eye-1 image after segmentation; **C)** NDVI image; **D)** Classified image into three classes; **E)** Landslides identified and manually mapped.



Second, the NDVI (ROUSE et al., 1974) was calculated to separate landslide candidates from vegetation areas (Figure 4.6-C). NDVI is a function of the red and near-infrared spectral bands (NDVI = NIR - Red / NIR + red) and provides a measure of vegetation presence, as well as its amount and vigour. In this study, an NDVI threshold value equal to 0.19 was useful for object discrimination.

Third, landslide separation from false positives is necessary. According to Martha et al., (2010) since NDVI is used as a cut-off criterion, objects with similar or lower NDVI values are likely to be misclassified as landslides. Because the focus was on landslide classification, other features such as water bodies, roads, built-up areas, riverbeds and barren lands were masked out to avoid misclassification (CARDOZO, 2013). Other possible false positives were eliminated from the landslide class by integrating their spectral, morphometric and contextual information in OOA by using a ruleset (Figure 4.7) which serve to assign objects to classes based on prior knowledge. Hillshade, brightness, NDVI, slope and GLCM were used for the classification. The frequency of combination of grey levels, i.e. texture in an image is calculated using grey level co-occurrence matrix (GLCM).

Figure 4.7 – Quantitative classification criteria for landslide recognition using OOA.



Source: Adapted from Martha et al. (2010).

Finally, a qualitative accuracy assessment was carried out by comparing landslide identified semi-automatically using OOA (Figure 4.6-D) to a landslide sample that was manually mapped by Dr. F. Bucci from the CNR-IRPI-Italy (Figure 4.6-E) using the same dataset. Results suggest that smaller landslide recognition was the very challenging task for the semi-automatic detection. Findings show that about 51% of landslides were correctly identified by OOA. Hence it still needs to be improved. In future research further tests including an extension of the classification criteria could be carried out. Given which and taking into account that a complete landslide inventory is essential for the following research steps, we decided complete the landslide inventory map with data provided by the Nova Friburgo Municipality. Thereby, a total of 2272 fresh scars were detected in the study area corresponding to the 2011 rainfall-triggered landslide event.

4.3.2 Topographic data

The study used the 10 m-resolution digital elevation model (DEM) from which the necessary input information was obtained (slope, flow direction, specific catchment area and saturation). Pits in DEM were eliminated using a "flooding" approach by raising the elevation of each pit grid cell within the DEM to the elevation of the lowest pour point on the pit perimeter (PACK et al., 2005).

4.3.3 Geotechnical and Hydrological data

Since soil sample collection *in situ* and laboratory tests were outside the scope of this research, geotechnical and hydrological parameters (Table 4.2) were obtained from previous studies performed in the Serra do Mar. (i.e., COSTA NUNEZ, 1969; DE CAMPOS *et al*., 1992; WOLLE; CARVALHO, 1994; GUIMARÃES, 2000; AMARAL, 2007; LOPES *et al*., 2007; MENDES, 2008; AVELAR *et al.,* 2011; NERY; VIEIRA, 2015; DOURADO; ROIG, 2013).

In all the simulations tested, a wet soil density value equal to 2000 (kg/m^3) and a gravitational acceleration value equal to 9,81 (m/s^2) were used. Also, a uniform soil thickness value equal to 1.5 m was assumed- according to values suggested by Marques et al., (2017).

Generally, root systems contribute to soil strength by providing an additional cohesion component. Vegetation in the area is mainly represented by forest with root systems that vary widely in both space and time. Coelho Netto et al., (2011) indicate that forest patches are represented by a secondary ecological succession of plants with shallow roots and variable degradation states. Due to the difficulty to find a root cohesion value for the study area, we assumed a value equal to 3 KPa, according to values cited by Wolle and Pedrosa (1981) for the Serra do Mar.

Cohesion parameter (**C**) combines root and soil cohesion (Eq. 4.5). Theoretically, this is the ratio of the roots and soil cohesive strength relative to the weight of soil saturated thickness (PACK et al., 2005).

The internal friction angle (***ϕ***) is a measure of the shear strength of soil due to friction determined in the laboratory using direct shear strength or triaxial stress test (RABONZA et al., 2016).

As mentioned above, the ratio T/R soil transmissivity combines both climate and hydrogeological factors. The transmissivity T represents the water flow within the soil and is derived from the hydraulic conductivity (minimal and maximal) measured in the field. The parameter R is difficult to measure and hard to evaluate the amount of infiltrated subsurface water from the total rainfall measurement. In fact R is influenced by factors like rainfall intensity and duration (MEISINA; SCARABELLI, 2007). The maximum and minimum T/R values were taken from Nery and Vieira (2015). According to Thiebes et al., (2016) the modification of this hydrological factor in calibration procedures only produces small changes in the susceptibility classification. Taking this premise into account, the same T/R value was assumed for all the simulations.

Table 4.2 – Input parameters for SINMAP susceptibility simulations.

Parameters	**Scenarios**		
	1	**2**	**3**
$\boldsymbol{\phi}'_{min}$ [°]	25	30	35
$\boldsymbol{\phi}'_{max}$ [°]	45	49	43
$\mathbf{C}_{min}$ [N/m^2]	0.15	0.27	0.05
$\mathbf{C}_{max}$ [N/m^2]	0.36	0.98	0.75
$\mathbf{T/R}_{min}$ [m]	68	68	68
$\mathbf{T/R}_{max}$ [m]	213	213	213

4.4 Results and Discussion

SINMAP methodology served to test three scenarios using the DEM, geotechnical data and the landslide inventory. The same parameters were used over the whole area (single calibration region) because no detailed geotechnical data were available.

In all the susceptibility scenarios tested around 70% or more of the landslides were correctly identified. Below is an analysis of each simulation result.

The *Scenario #1* identifies that 92.5% of the observed landslides are located in areas classified as unstable (19.4% in the lower threshold, 43.2% in the upper threshold and 29.9% in the defended class) (Table 4.3). In such scenario, however, 78.8% of the considered area is estimated as unstable (23.9% in the lower threshold, 31.2% in the upper threshold and 23.6% in the defended class) and 21.2% as stable (11.5% stable, 3.5% moderately stable and 6.16% quasi-stable) (Figure 4.8-A).

The *Scenario #2* reveals that 86.4% of the observed landslides are located in areas classified as unstable (18.6% in the lower threshold, 37.9% in the upper threshold and 29.9% in the defended class) (Table 4.3). In such scenario, 70.3% of the study area is estimated as unstable (20.6% in the lower threshold, 26.1% in the upper threshold and 23.6% in the defended class) and 29.7% as stable (15.8% stable, 5.1% moderately stable and 8.8% quasi-stable) (Figure 4.8-B).

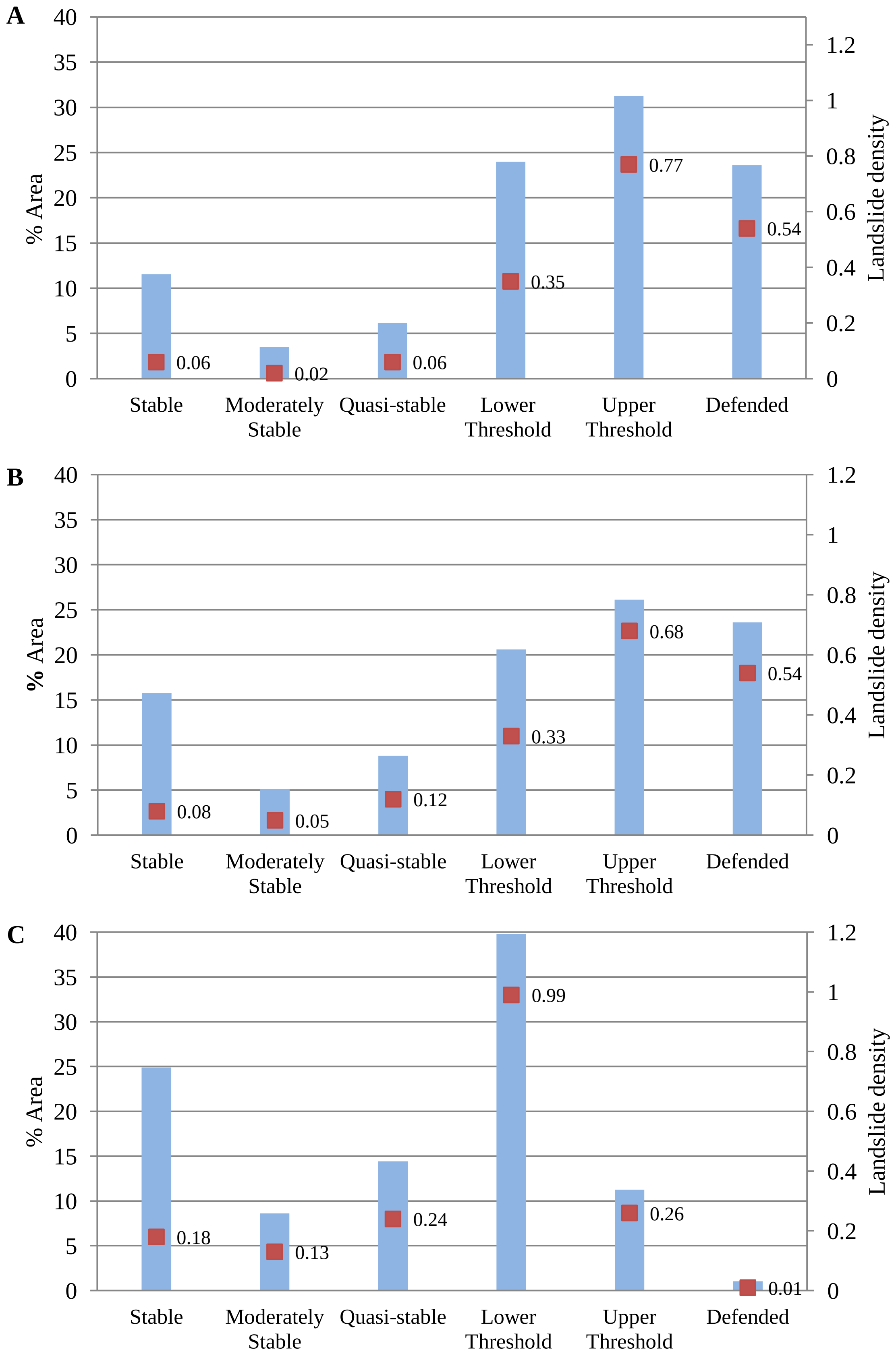
On the other hand, *Scenario #3* indicates that about 70% of the observed landslides are located in areas classified as unstable (55.1% in the lower threshold, 14.3% in the upper threshold and 0.4% in the defended class) (Table 4.3). Figure 4.8-C shows that in such scenario 52.1% of the territory is estimated as unstable (39.8% in the lower threshold, 11.3% in the upper threshold and 1.04% in the defended class) and 47.9% as stable (24.9% stable, 8.6% moderately stable and 14.4% quasi-stable).

Table 4.3 – Landslide percentage observed in each SINMAP simulation class.

# Scenario	Stable SI >1.5	Moderately stable 1.5>SI > 1.25	Quasi-stable 1.25>SI>1.0	Lower threshold 1.0>SI>0.5	Upper threshold 0.5 > SI > 0	Defended SI < 0
1	3.13	0.97	3.43	19.37	43.18	29.93
2	4.31	2.86	6.42	18.57	37.90	29.93
3	9.86	6.95	13.38	55.11	14.30	0.40

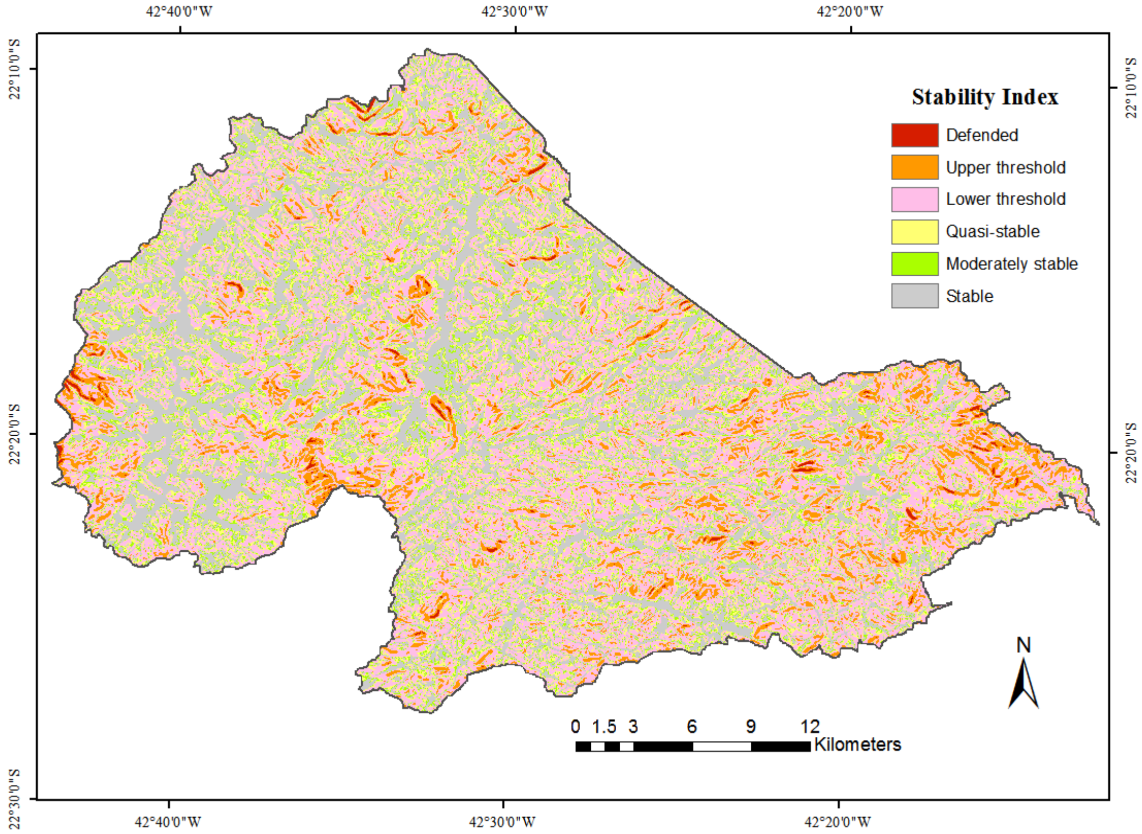
Source: Author’s production.

Figure 4.8 – Prediction accuracy of the SINMAP simulations. **A)** Scenario #1, **B)** Scenario #2 and, **C)** Scenario #3 (Red squares = landslide density; light blue bars = stability class area).



Scenarios #1 and *#2* show landslides in the defended class. According to Pack et al., (1998) "defended slopes" are regions where, according to the model, the slope should be unstable for any parameter within the specified parameter ranges. Where such slopes exist, something other than the modelled parameters is holding the slope in place or the model may be inappropriate. Taking this premise into account and faced with the impossibility of performing field recognition to confirm the findings, we assumed that the most representative landslide susceptibility model is the *Scenario #3* (Figure 4.9) which shows the lowest landslide percentage in the defended slope class (Table 4.3). Furthermore, in such simulation the lower threshold class encompassed the highest percentage of the area is unstable (about 40%) with an average landslide density of 0.99 landslides per square kilometer (Figure 4.8-C). The latter is in agreement with previous findings in the Serra do Mar using SINMAP approach (LOPES et al., 2007 and NERY; VIEIRA, 2015) that show that the highest landslide density is linked to the lower threshold slope zone.

Figure 4.9 – Stability Index map showing the stability classes obtained by SINMAP calculations with a single calibration region in Nova Friburgo municipality.

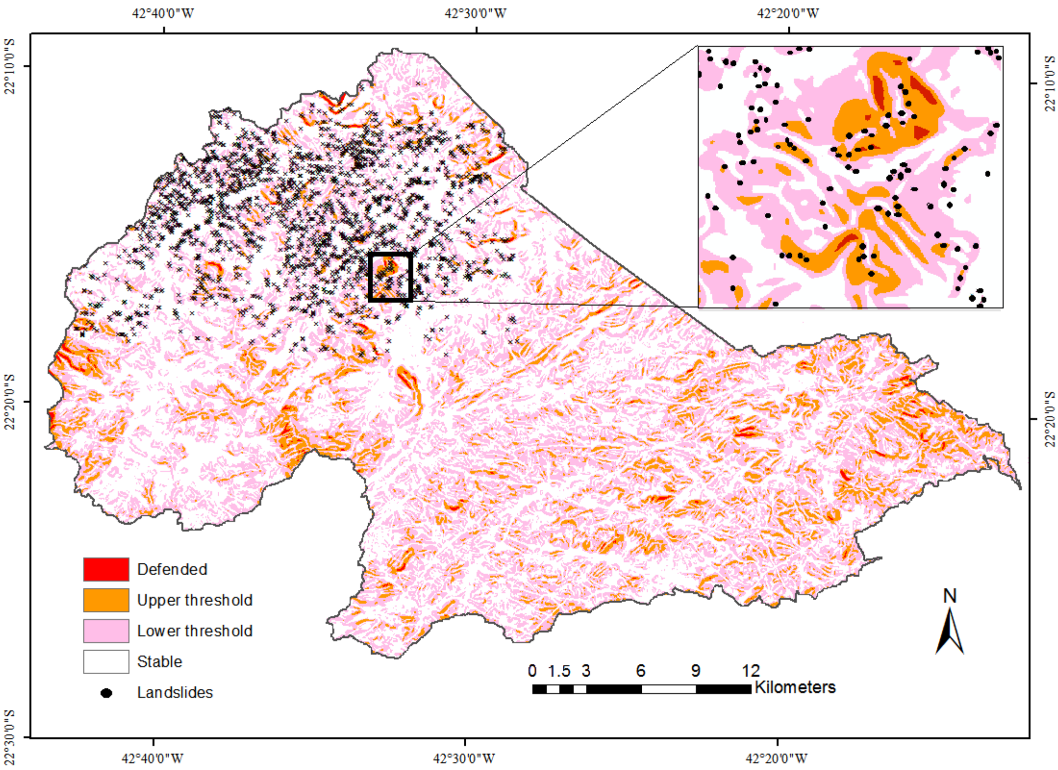


Source: Author's production.

As seen in Figure 4.8, in all the simulations a number of landslides fall within stable classes. According to Pack et al., (2005) the reasons for this may be twofold: i) the bedrock, superficial geology and landslide processes are more complex and, ii) the DEM data fails to pick up many of the small but critical slopes. In addition, it could also be attributed to uncertainties in the accuracy of landslide recognition.

On the other hand, overestimation of unstable areas also was detected. *Scenario #3* shows that many areas classified as unstable were not verified with the 2011 landslides (Figure 4.10). In this regard, it is noteworthy that rainfall (which is the landslide trigger) was spatially non-uniform during January 11th and 12th in Nova Friburgo (COELHO NETTO et al., 2011). According to Bischetti and Chiaradia (2010), any attempt to increase model capability to simulate as unstable locations where landslides have occurred, inevitably leads to simulate all the surrounding areas with similar conditions as unstable. In this study, overestimation may be attributed to the parameter range used- it had to be large enough to cover all the different terrain conditions. In order to improve the susceptibility model predictive performance, more detailed hydrologic and geotechnical data should be available.

Figure 4.10 – Nova Friburgo areas classified as unstable (red=defended, orange=upper threshold, pink=lower threshold) and the 2011 landslide location (black points).

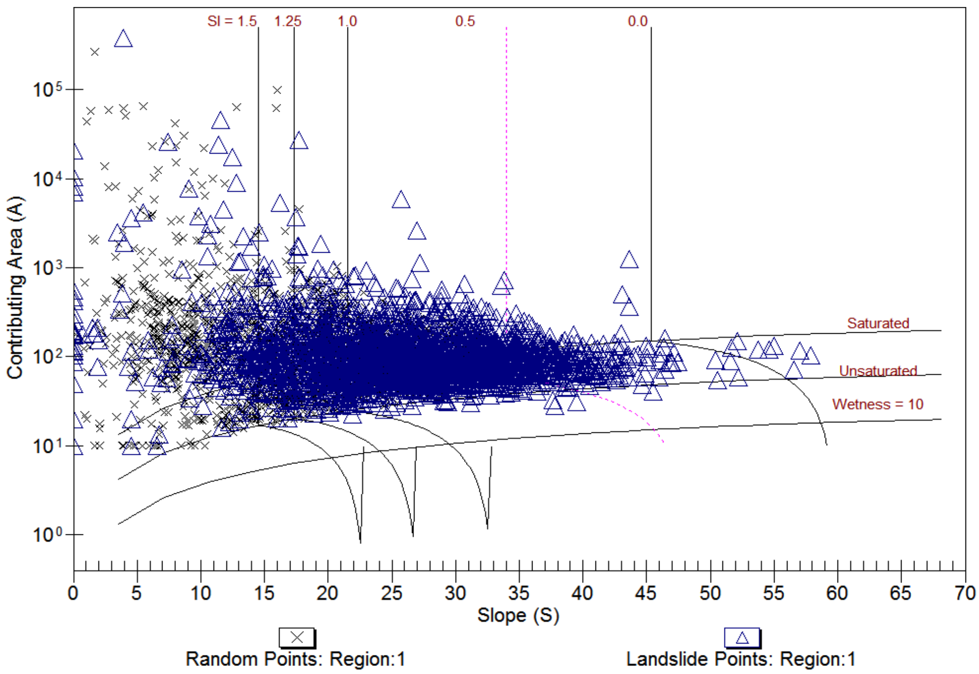


Source: Author's production.

Areas predicted to undergone failure include those with slope angle between 21 and 58 degrees (Factor of safety below 1) and catchment areas below 10^5 m^2 (Figure 4.11). These findings are in agreement with Coelho Netto et al., (2011), who point out that landslides occurred in slope segments with an average slope of 19 degrees and maximum slope of 65 degrees. Particularly, in the D'Antas creek basin- the Nova Friburgo area most affected by landslides- the average slope angle was 32 degrees (COELHO NETTO et al., 2017). Likewise, other zones such as Riogandina and Conselheiro Paulino registered landslides on slopes steeper than 30 degrees (DRM-RJ, 2015).

Inevitably, there are uncertainties in landslide susceptibility assessment. In this study, uncertainties may have arisen from the methodology and the input data used. According to Thiebes et al., (2016) topographic data represent the most important input for the SINMAP methodology. Results suggest that the 10 m-resolution DEM was useful, however, it would be necessary to test whether a more detailed DEM might better capture the study area topographic features and thus, improve the SINMAP outcomes.

Figure 4.11 – Slope-area plot for the single calibration region of scenario 3. Stability index region lines (SI= 1.5, 1.25, 1.0, 0.5, 0.0) provide boundaries for regions within slope-specific catchment area space that have similar potential for stability or instability. Saturation region lines (Saturated, Unsaturated, Wetness=10) provide boundaries for regions within slope-specific catchment area space that have similar wetness potential.



Source: Author's production.

Arguably, one of the most important limitations was given by the selection of geotechnical parameters. Results show that the most sensitive parameter for susceptibility seems to be cohesion. That is, if a wide range of cohesion values- with low values at one end- is taken, then almost 70% of the inventoried landslides are predicted to occur, which is a quite acceptable outcome. The latter is in agreement with Meisina and Scarabelli (2007) who point out that cohesion has a significant influence on stability calculation. Differently, Zaitchick, et al., (2003) indicate that friction angle and hydraulic conductivity play a significant role in the susceptibility analysis; while Nery and Vieira (2015) observe that ratio T/R is the most sensitive factor in their calculations.

4.5 Final Remarks

Based on slope gradient, soil moisture and hydrogeological parameters, several SINMAP simulations with a single calibration region were carried out to determine landslide-prone areas at the Nova Friburgo municipality.

From the three susceptibility scenarios tested with different cohesion and internal friction angle values, the *Scenario #3* showed to be the best, predicting almost 70% of the inventoried landslides. Findings suggest that interaction among relief, water balances and substrate can cause instability in more than 50 percent of the territory.

As widely known, soil and climate properties are highly variable in both space and time. Thus, further researches should introduce calibration regions based on detailed soil maps. Besides, *in situ* geotechnical parameter records and laboratory tests should be performed to provide reliable values that will help get better landslide susceptibility predictions.

Results presented herein are preliminary; nevertheless they provide a baseline for future researches and for landslide *risk* assessments.

5 THE HUMAN COMPONENT OF RISK

5.1 Social Vulnerability and Casualties

Fatalities and economic losses due to *disasters* resulting from natural *hazards* have shown an increase over the past decades, caused by the increase of number of weather-related events, but also due to the increased global society *vulnerability* (VAN WESTEN, 2000). Analysis of human consequences of geo-hydrological *hazards* is important to understand the impact of disastrous events on population (SALVATI et al., 2018). In this regard, Sepúlveda and Petley (2015) point out that acquisition and analysis of casualty data is key for risk evaluation.

The *vulnerability* concept has emerged from notion of everyday language to a more elaborated concept. There is a tendency to use it independently from context, like «the vulnerable people» in general. In fact, *vulnerability* is both context-dependant and subject-dependant: one is vulnerable to something, in a given place and at a given time (NATHAN, 2005). Although there is no universal *vulnerability* definition, various disciplines have developed their own definitions and pre-analytic visions of what *vulnerability* means (BIRKMANN, 2006). *Vulnerability* is the potential to suffer loss or harm (CUTTER, 1996). *Social vulnerability* identifies sensitive populations that may be less likely to prepare, respond, cope with and recover from a *disaster* (CUTTER; FINCH, 2008; FÜSSEL, 2010). According to Aroca-Jimenez et al., (2017) a hybrid approach is currently the one most frequently used for analysing *vulnerability*. This comprises *risk–hazard* approaches, which consider that *vulnerability* depends on biophysical risk factors and the potential loss of a particular exposed population (e.g., the *hazards*-of-place model of *vulnerability*; CUTTER, 1996), and political economic–ecological approaches, which emphasize the political, cultural and socio-economic factors explaining differential exposure, impacts and capacities to recover from an event (e.g., the pressure and release model; BLAIKIE et al., 1994).

Social vulnerability assessment is now recognized as critical to understanding natural *hazard* risks and for developing effective response capabilities (WISNER et al., 2004). This concept has received close attention in *disaster* studies in recent years, though its application in practice is still in its infancy in most countries' *disaster* management activities (PRIOR et al., 2017). Qualitative and quantitative methods have been used to describe *social vulnerability*. One of the most known approaches is the Social Vulnerability Index (SoVI) proposed by Cutter et al., (2003). This is a quantitative methodology to identify and classify *social vulnerability* using census data (WILLIS; FITTON, 2016) making possible to identify the most important drivers across the territory (CUTTER; FINCH, 2008).

Social vulnerability to natural *hazards* has been widely researched by the international scientific community (i.e., WILCHES CHAUX, 1993; CUTTER et al., 2003; NATHAN, 2005; SIERRA; GOMEZ, 2008; ANAZAWA, 2012; ANAZAWA et al., 2012; ABELDAÑO et al., 2013; BAEZ ULLBERG, 2015; CASTRO, 2015; CARDOZO et al., 2015; HUMMEL et al., 2016; WILLIS; FITTON, 2016; RONCANCIO; NARDOCCI, 2016; ROGELIS et al., 2016; AROCA-JIMENEZ et al., 2017; GAUTAM, 2017). However, not many *vulnerability* studies have been focused on geo-hydrological *hazards*. Mass wasting movements are common geomorphological phenomena in mountain regions worldwide and play an important role in landscape evolution. In many areas also pose a serious *threat* to the population (PETLEY, 2012). While there has been an extensive research into quantifying landslide *hazard*, research into consequence analysis and *vulnerability* assessment has been limited (COROMINAS et al., 2014), especially in Latin American countries.

In the context of this Thesis our goals related to the human component of *risk* is threefold: i) to deepen our understanding of *social vulnerability* in the Brazilian municipality of Nova Friburgo, one of the most affected by the 2011 mega-disaster; ii) to characterize the 2011 landslide-related fatalities in this municipality and, iii) to explore the role of *social vulnerability* to explain those casualties.

5.2 Data Source and Methodology

Figure 5.1 shows the general methodology adopted in this study. The approach used in the *social vulnerability* assessment and the 2011 landslide-related fatalities analysis is described in the following sections.

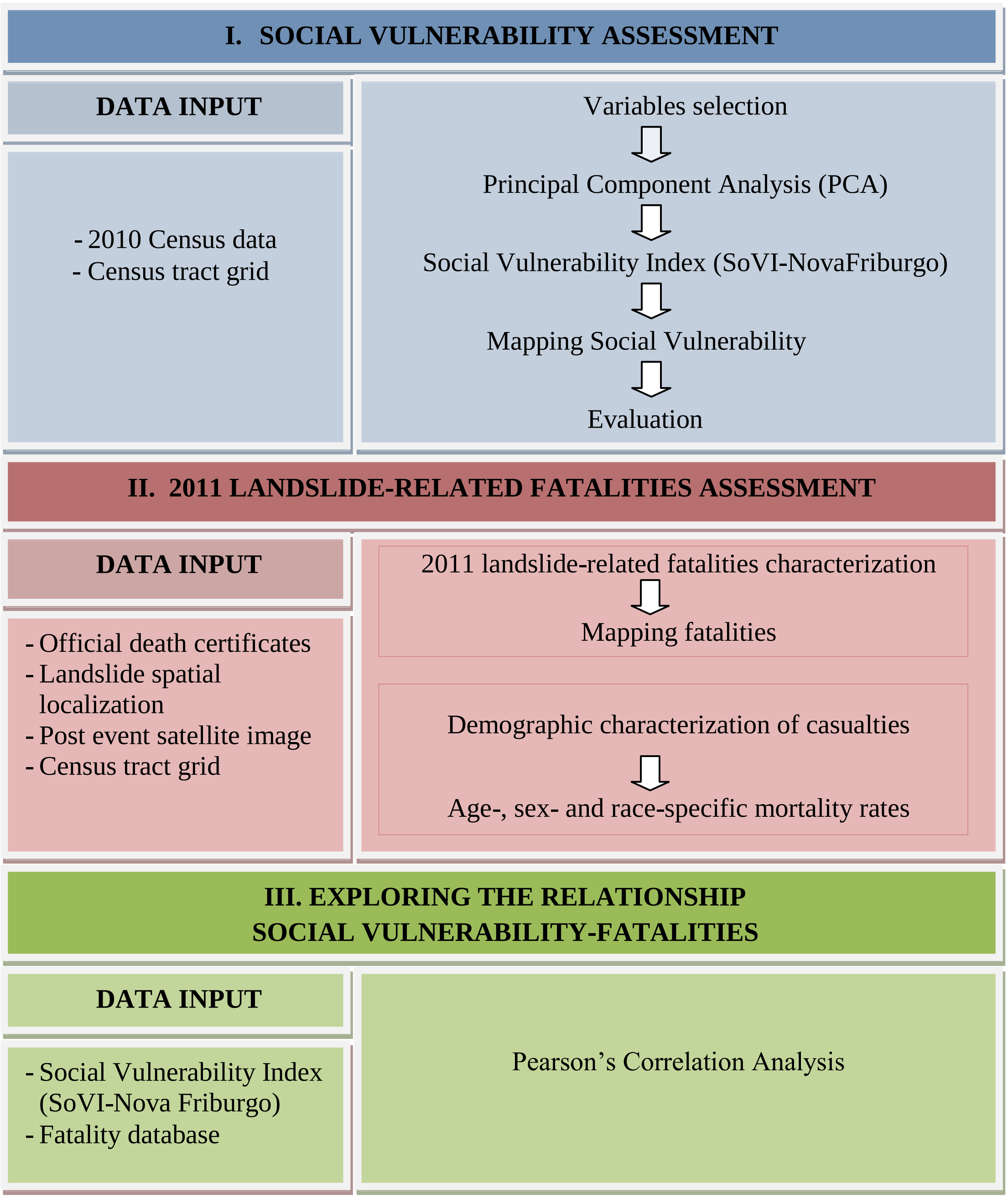
5.2.1 Landslide database

The landslide inventory previously obtained in Chapter 4 was used for the 2011 landslide-related fatalities assessment.

5.2.2 Census database

Data used in the *social vulnerability* assessment were obtained from the 2010 Census provided by the Brazilian Institute of Geography and Statistics (IBGE) (http://www.ibge.gov.br).

Figure 5.1 – General methodology adopted in this research.



Author's production.

5.2.3 Fatality database

In order to characterize the 2011 landslide-related fatalities, death certificates provided by the Nova Friburgo Health Authorities were used. All due data disclosure protocols were attended and the legal and ethical rights to privacy have been fully respected.

5.2.4 Assessing Social Vulnerability

The *social vulnerability* assessment is based on the Social Vulnerability Index (SoVI) proposed by Cutter et al., (2003). The 2010 Census variables were chosen according to: *i)* the available data and, *ii)* their relevance to the Nova Friburgo municipality's context. Census information was originally added in census tracts, therefore, this was the spatial unit of analysis in this study.

Because the original method was conducted at country level, some adaptations were necessary. However, the main concepts defined in the original approach were used. The "Socioeconomic status" and "Quality of the built environment" concepts were subject to main adaptations, i.e., they were defined including the wide spectrum of information provided by the Brazilian census. Table 5.1 shows the adaptations made for the case study of the Nova Friburgo. Additionally, a brief description of the Cutter et al., (2003) *social vulnerability* dimensions related to environmental *hazards* is given over the next paragraphs, which were also used in this inquiry.

The **Socio-economic status concept** represents the ability to absorb losses and enhance resilience to natural *hazard* impacts. Wealth enables communities to absorb and recover from losses more quickly due to insurance, social safety nets and entitlement programs (CUTTER et al., 2003). However, rich people economic losses are also great in a *disaster*. Household monthly income was used to build this concept. According to IBGE (2010), in 2010 the minimum income was equal to 510 reais (reais is the plural noun of real, Brazil national currency). Census information about tenure class housing (owner, renter or rent-free household) was also included in this concept. As stated by Cutter et al., (2003) people that rent do so because they are either transient or do not have the financial resources for home ownership. They often lack access to information about citizen's financial aid during a *disaster* recovery.

The **Quality of the built environment concept** relates to the availability of water supply, paving, electricity and Public Street lighting. In addition, it takes into account toilet availability by household and different ways of sewage disposal.

Table 5.1 – Census variables used in the Social Vulnerability Index (SoVI-Nova Friburgo).

Concept	Variable	Variable description	Increases (+) or decreases (-) Social Vulnerability
Age	0A4	Residents aged 0 to 4	Elderly (+) Children and adolescents (+)
	5A9	aged 5 to 9	
	10A14	aged 10 to 14	
	MAS60	aged 60-and-older	
Socioeconomic Status	SLRO	Households with up to 1/8 of monthly minimum income per capita	High income and house owner (-) Otherwise (+)
		1/8 to 1/4	
		1/4 to 1/2	
		1/2 to 1	
		1 to 2	
		2 to 3	
		3 to 5	
		5 to 10	
		higher than 10	
		no monthly income	
	OCPDOM	Residents in owned house	
		rented house	
		rent-free house	
Urban/Rural	URBRUR	Urban population	Rural (+) Urban (+)
	DNDEMG	Population density	
Education	EDUC	Literate persons aged over 5	Little education (+) Highly educated (-)
Race and Ethnicity	PLPARD	Brown residents	Non white (+) Non Asian (+)
	PLBLAN	White residents	
	PLNEGR	Black residents	
	PLAMAR	Yellow residents (Asian)	
	PLINDG	Indigenous residents	
Density of the built environment	DNAMBC	House density	High density (+) Low density (-)
Gender	RCSEX	Sex ratio	>Females (+)
Quality of the built environment	DOMH2O	Housing with water supply network	Public utilities and toilet (-) No public utilities or toilet provision (+)
		water well system	
		rainfall water supply	
		other types	
	DOMPAV	Housing on paved streets	
		on unpaved streets	
	DOMELE	Housing with electricity service	
		without electricity service	
	DOMIPB	Housing with public street lighting	
		without public street lighting	

Table 5.1 – continued

Concept	Variable	Variable description	Increases (+) or decreases (-) Social Vulnerability
	DOMBN	Housing with toilet	
		sewer system	
		septic system	
		rudimentary cesspit	
		sewage elimination into rivers, lakes or sea	
		other types	
		without toilet or outhouse	

The **Race and ethnicity concept** corresponds to "colour or race" census variables, i.e., white, black, brown (locally named "pardo"), yellow (Asian) and indigenous residents (HUMMELL et al., 2016). The average monthly income for the White and Asian populations is about twice as high as that of the others (IBGE 2011). Cutter et al., (2003) points out that race and ethnicity imposes language and cultural barriers that affect access to post-*disaster* funding and leave certain groups in residential locations in high *hazard* areas. However in the Brazilian case, the barriers are mainly posed because there is a close relationship between skin colour and the socio-economic condition.

Extreme demographic groups are the most affected in *disasters* (CUTTER et al., 2003). It is well known that children are not autonomous but dependent on others. Similarly, the elderly may have physical limitations that influence their inability or unwillingness to comply with mandatory evacuation orders (CUTTER; FINCH, 2008). In brief, they are less able to get out of the damage area on their own. Taking into account these premises, in this research the **Age concept** includes children, adolescents and the elderly.

Brazilian census provides counting information about men and women. Women can have a more difficult time during *disaster* recovery than men, often due to sector-specific employment, lower wages and family care responsibilities (CUTTER et al., 2003). In this context, the **Gender concept** is taken as human sex ratio, which is given as the ratio of males to females.

The spatial patterns in Brazilian cities are explained by the great migration from rural areas to urban centers since the 1930s due to growing industrialization (HUMMELL et al., 2016). Both rural and urban communities face challenges when *hazard* strikes. Rural residents may be more vulnerable due to lower income while high-density areas (urban) complicate evacuation out of affected area (CUTTER et al., 2003). In the context of this study, the

Urban/Rural concept includes population density and urban population percentage variables, following what is stated in Hummell et al., (2016).

The **Education concept** corresponds to the number of literate persons aged 5 on. According to CUTTER et al., (2003) higher educational attainment results in greater lifetime earnings. On the contrary, lower education constrains the ability to understand warning information and access to recovery information.

The **Density of the built environment concept** describes the human-made surroundings that provide the setting for human activity where significant structural losses might be expected derived from natural *hazard* occurrence (CUTTER et al., 2003) and longer-term issues related to the recovery from a *disaster*.

Initially, about 50 census variables were collected and normalized to percentages, natural logarithm or normal probability density function. Then, Pearson's correlation test (PEARSON, 1895) was performed to analyse the correlation between variables. Data provided by the Brazilian census were not in a standardised format. Whilst these original data formats are relevant to their respective measures, they would not be suitable for multivariate analysis. For this purpose, it was necessary to firstly standardise them into a homogenous format. Range standardisation method was applied (Eq. 5.1) to variables composed by a single stratum (for example, variables related to "Age", "Gender", "Urban/Rural", "Education", "Race and Ethnicity" and "Density of the built environment" concepts). The standardised observation (x_n) was calculated as a ratio from the maximum and minimum observations for a given variable. This leads to all observation values being classified between 0 to 1 (WILLIS; FITTON, 2016).

$$Xn = \frac{\mathrm{X{-}Xmin}}{Xmax-Xmin} \tag{5.1}$$

In the variable case composed by several strata (for example variables related to "Socio-economic status" and "Quality of the built environment" concepts) an additional procedure was required. Each variable was built adopting an evolutionary scale to weigh each stratum following the methodology proposed by Anazawa (2012). Thus, higher weight represents the best condition and lower weight the worst one. Table 5.2 provides an example of the evolutionary structure used. Finally, the weighted values obtained for each group were added and classified between 0 and 1 applying Eq. 5.1. The same logic was applied to the remaining multi-stratified variable calculation.

Table 5.2 – Housing tenure class evolutionary structure

Variable	Strata	Evolutionary scale	Meaning
OCPDOM	Residents in rent-free house	**1**	reduced access to opportunities (+ vulnerability)
	Residents in rented house	**2**	↓
	Residents in owned house	**3**	greater access to opportunities (- vulnerability)

Source: Adapted from Anazawa (2012).

In order to provide a robust set of independent factors for the construction of the Social Vulnerability Index -SoVI-Nova Friburgo, a Principal Component Analysis (PCA) was conducted using Varimax rotation with Kaiser Normalization (KAISER, 1958). This technique reduces the dataset dimension consisting in a large number of interrelated variables, while retaining the variation as long as possible. This was achieved by transforming it into a new set of variables- the principal components (PCs)- which are uncorrelated (JOLLIFFE, 2002). The Kaiser criterion (eigenvalues > 1.00, which means that they account for more variability than does a single variable and therefore are retained in the analysis, KAISER, 1960) and Sedimentation graph are the most commonly used approach to selecting the number of components and they are the default in most programs. Hence, they were used to generate the total number of principal components in this study.

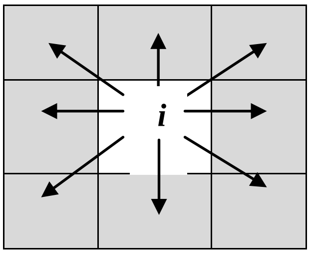
To determine whether the chosen variables were adequate for the statistical analyses, Bartlett's sphericity test (SNEDECOR; COCHRAN, 1989) was used (with $p < 0.005$) and Kaiser-Meyer-Olkim's measure (CERNY; KAISER, 1977), with selection criterion of values above over 0.6. For interpretation purposes, most significant indicators (with correlations over 0.5 and lower than -0.5) were assumed as drivers of each component and provided the rationale for cardinality (±) according to their influence on *social vulnerability*. The overall influence of factors on *social vulnerability* was determined based on positive values that indicated higher levels of vulnerability, while negative ones indicated lower levels (HUMMELL et al., 2016).

Social Vulnerability Indicator -SoVI-Nova Friburgo- was then calculated by assuming an additive model taking into account the principal components (or Factors, F_1, F_2, F_3,…,F_n) previously obtained (Eq. 5.2). According to the original method, in the absence of such theoretical basis for assuming the relative importance of one factor over another in index construction, equal weights were assumed for each factor (CUTTER et al., 2003). To identify the *social vulnerability* spatial distribution, the SoVI-NovaFriburgo scores were mapped based on the Standard Deviation classification method, which finds the mean value of the observations and then places class breaks above and below the mean. This classification method was used in the original approach (CUTTER et al., 2003) and in a previous work in Brazil (HUMMELL et al., 2016).

$$\text{SoVI-Nova Friburgo} = F_1 + F_2 + F_3 + \ldots + F_n \tag{5.2}$$

Finally, the *social vulnerability* spatial autocorrelation was assessed with the Global Moran's test (MORAN, 1948). Moran’s Index tells whether high and low *social vulnerability* are more clustered than expected just by chance (LARA-VALENCIA et al., 2012). Regarding the weight matrix- which serves to evaluate the degree of similarity between localities and values- the queen type pattern was used to define the neighbourhood around each geographical unit (Figure 5.2). Local spatial clusters were also evaluated using the Local Indicators of Spatial Association (LISA) proposed by ANSELIN (1995).

Figure 5.2 – Queen Weight Matrix.



Source: Author’s production.

5.2.5 Characterising landslide-related fatalities

With the aim of describing the distinctive nature of the 2011 landslide-related fatalities, information available in official death certificates, such as age, sex, skin colour, postal address, profession, marital status, education, etc. was registered into an spreadsheet, without victim identification. Victim’s name was taken into account only to determine the sex.

Overall descriptive statistics were estimated. Also age-, race- and sex-specific mortality rates (per 1,000 people) were estimated (Eq. 5.3):

$$\text{specific death rate} = \frac{\text{number of deaths for a specific x group}}{\text{population for that x group}} \tag{5.3}$$

Since landslides occurred during night-time (time that usually begin shortly after dusk and ends shortly after dawn). We assumed for this research, that at that moment, all of the Nova Friburgo inhabitants were in their residences; therefore, casualties occurred in the premises or close to them.

Death certificates did not always have accurate and complete victim's address location. So, in order to build up a reliable casualties geographic location, all data, such as death certificate information (stored in tabular format), landslide spatial localization (produced in vector format), post-event Geoeye-1 satellite image (in raster format- where fresh landslide scars were visible) and a census tract grid were linked and analyzed within a Geographic Information System (GIS) environment. Google Maps also was used to support building a georeferenced database for this research (GOOGLE MAPS, 2011).

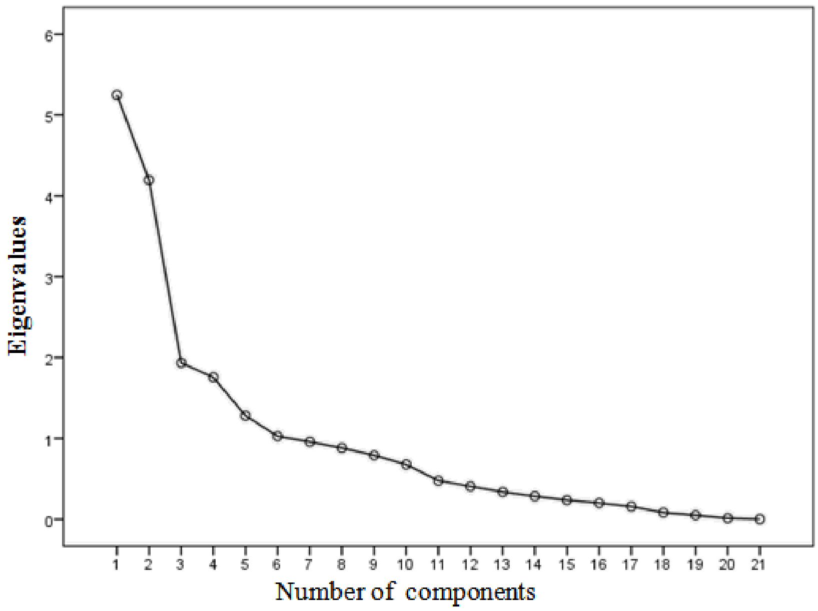
To initially explore the relationship between the landslide-related fatalities and its social vulnerability level (as measured by the SoVI) Pearson's correlation test was used.

5.3 Results and Discussion

5.3.1 Social Vulnerability Index Components

The Principal Components Analysis (PCA) revealed that six factors explaining 73.6% of the data variance (Figure 5.3; Table 5.3). Appendix C shows the relationship between the resulting PCA factors.

Figure 5.3 – Sedimentation graph derived from Principal Component Analysis (PCA).



Source: Author's production.

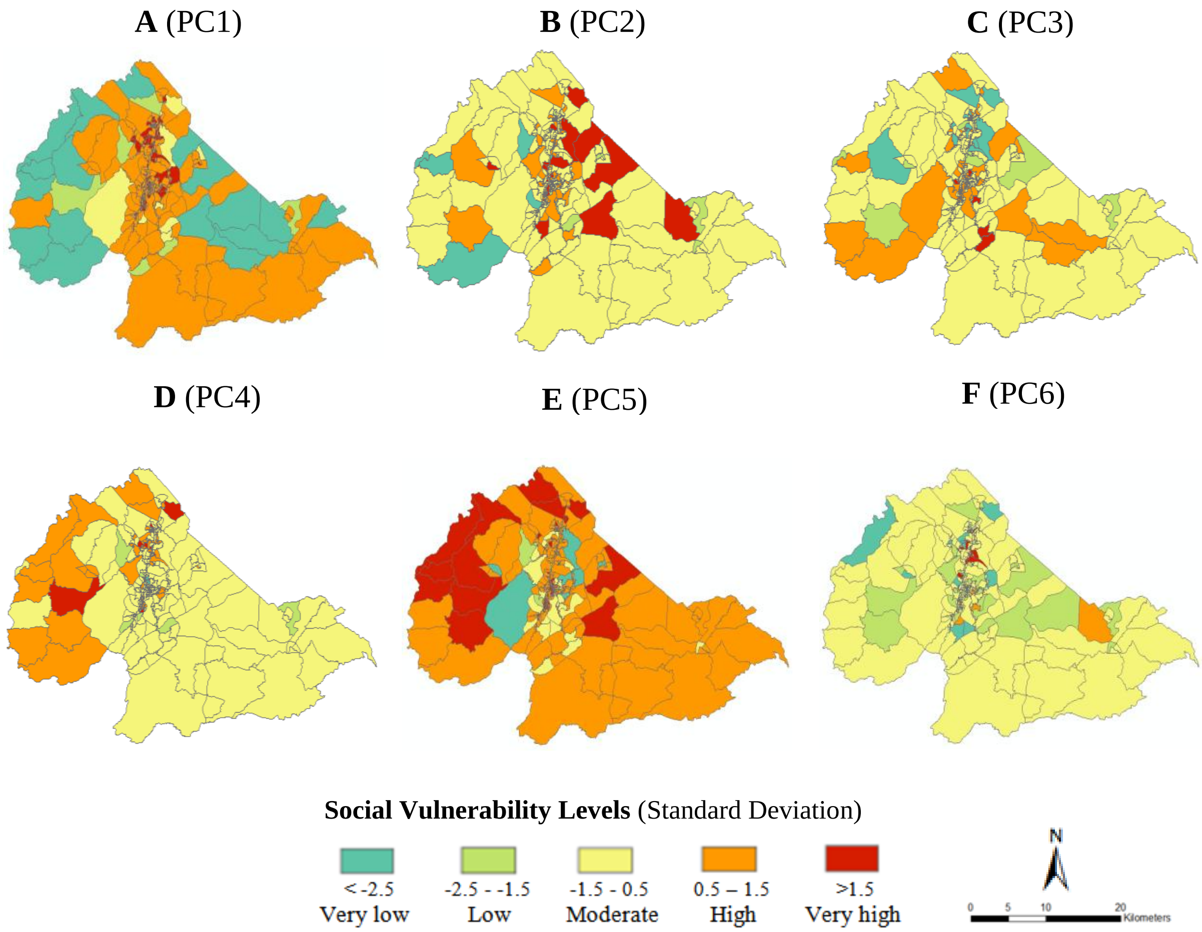
Table 5.3– Components, explained variance percentage, major drivers and involved concepts.

Component	%	Involved concepts	Drivers (Factor correlation)
PC1	25	Urban/Rural Quality of the built environment Density of the built environment	URBRUR (0.87) DOMPAV (0.86) DNAMBC (0.83) DNDEMG (0.83) DOMH2O (0.81) DOMBN (0.55) DOMELE (0.50)
PC2	20	Race and Ethnicity Education Age Socio-economic Status	PLBLAN (0.89) EDUC (0.88) MAS60 (0.87) OCPDOM (0.50)
PC3	9.2	Race and Ethnicity Age	PLPARD (0.90) 10A14 (0.90) 0A4 (0.88)
PC4	8.4	Race and Ethnicity Socio-economic Status Age Gender	PLNEGR (0.86) SLRO (-0.83) 5A9 (0.70) RCSEX (0.55)
PC5	6.1	Quality of the built environment	DOMIPB (0.87)
PC6	4.9	Race and Ethnicity	PLAMAR (0.78)

Figure 5.4 shows the spatial distribution of SoVI-NovaFriburgo in each individual factor or Principal Component (PC).

The first principal component (PC1) explains 25% of the variance and links variables related to concepts: i) Urban/Rural, ii) Quality of the built environment and, iii) D ensity of the built environment, loaded positively. This factor reveals zones with very high *social vulnerability* concentrated in the municipality center, where the population urban density is higher with a high household density too (Figure 5.4A). According to Hummell et al., (2016) a large population in the same area suggests not only that more people might be affected by a *disaster*, but also might have more difficulty in an eventual evacuation or rescue situation making them more vulnerable to the natural *hazards*. Similarly, peripheral urban, south and southeast areas show high *social vulnerability* probably related to the lack of access to water, sewage, electricity and paving. These findings are in agreement with Carmo et al., (2014) who point out that Brazilian urbanization process has not been accompanied by infrastructure and public service investments, which is translated into social inequality.

Figure 5.4 – Geographic distribution of the Social Vulnerability Index (SoVI-NovaFriburgo) in each Principal Component (PC).



The second factor (PC2) explains 20% of the variance. A great deal of the municipality shows moderate *social vulnerability* and hot-spots of very high and high *social vulnerability* (Figure 5.4B). In 2010, the municipal Human Development Index (HDI) was equal to 0.745 (among the highest in the country) (IBGE, 2010). It is noteworthy that index components- income, education and longevity- agreed with the PC2 drivers (white residents, education and elderly over 60); which might explain the moderate levels of vulnerability found. In this regard, it can be argued that racial discrimination in Brazil resulted in the white populations having higher income and education than both the black and brown ones (CAMPANTE et al., 2004). Furthermore, as reported by the Elderly Statute (2003), elderly retirement salary increases family income among the poorest, contributing to reducing poverty levels and thus, their vulnerability.

Variables related to brown-skinned children and adolescents determine the third principal component (PC3) contributing to 9.2% of the overall variance. Although much of the area shows moderate *social vulnerability* (Figure 5.4C), there also exist hot-spots of very high and high *social vulnerability* expressed by social inequality in infancy and adolescence. These findings can probably be explained by child labour. The 2010 census revealed that exist child labour at country level with more than 3 million children and adolescents aged 10 to 17 involved (IBGE, 2010). Nova Friburgo was no exception. Child labour is strongly linked to poverty and, therefore to vulnerability. The need to work affects education access and permanence, so it ends up defining the income a person can earn throughout his/her life. Rural child labour is recurrent in the Nova Friburgo municipality (RIGOUT et al., 2015) and is encouraged by both school and parents- mainly those who are agricultural producers.

The fourth factor explains 8.4% of the data variance. The moderate *social vulnerability* is found in much of the territory. Nevertheless, several western border census tracts- which are rural- and some belonging to the centre- which are urban- show high *social vulnerability* levels (Figure 5.4D). In 2010, sex ratio in Nova Friburgo was equal to 0.92 (IBGE, 2010). As in PC3 case, this factor highlights the presence of a vulnerable group: black children (probably more girls than boys) aged 5 to 9 who have traditionally had difficulty to accessing education- and a well-paid job later- due to racial discrimination (CAMPANTE et al., 2004). These outcomes are in agreement with Ashley and Ashley (2008); Sharif et al., (2015) who suggest that age and gender influence human vulnerability to natural *hazards*. Results also point out monthly income as a driver that decreases vulnerability.

The fifth factor (PC5) explains 6.10% of the variance and is driven by the public lighting system variable (DOMIPB). This component highlights not only a built environment aspect, but also points out the population living conditions. This utility is important in cities with high urbanization rates- as the Brazilian ones. Figure 5.4E shows that very high and high *social vulnerability* are widely distributed throughout the entire study area, including both urban and rural zones. Social inequality becomes evident in this factor suggested by the lack of infrastructure and public services (CARMO et al., 2014). Public lighting system contributes to social and economic development by improving inhabitants' living standards. From the social point of view, it favours public space occupation with licit night activities (preventing crime) while from the economic point of view, it facilitates commerce and tourism- activities strongly developed in Nova Friburgo. It is well known that the public lighting system is normally disrupted when a natural *hazard* strike, however its availability is essential for post-*disaster* activities once it resumes.

The sixth principal component (PC6) explains 4.9% of the variance and is driven by the Asian racial group. Between 2000 and 2010 there was a great expansion of the Asian population in Brazil. In ten years, the "yellow population" increased 177% (IBGE, 2010).

This growth was remarkably higher than that of other ethnic groups in all regions of the country (FERREIRA, 2016). Figure 5.4F shows moderate *social vulnerability* in much of Nova Friburgo. This finding is probably linked to Asian population's monthly income, which is superior to that of the Black, Brown and Indigenous citizens' (IBGE 2011). However, there also exist hot-spots of very high *social vulnerability* in some central census tracts. Cutter et al., (2003) also identifies this racial group as an indicator of *social vulnerability* in USA and point out that race contributes to *social vulnerability* through the lack of access to resources, cultural differences and the social, economic and political marginalization that is often associated with racial disparities. It seems that race and ethnicity diversity plays an important role in Brazilian *social vulnerability*. Hummell et al., (2016) identify that Indigenous and Black populations as the drivers of two factors of *social vulnerability* at country level, while in this research, it is the Asian population one.

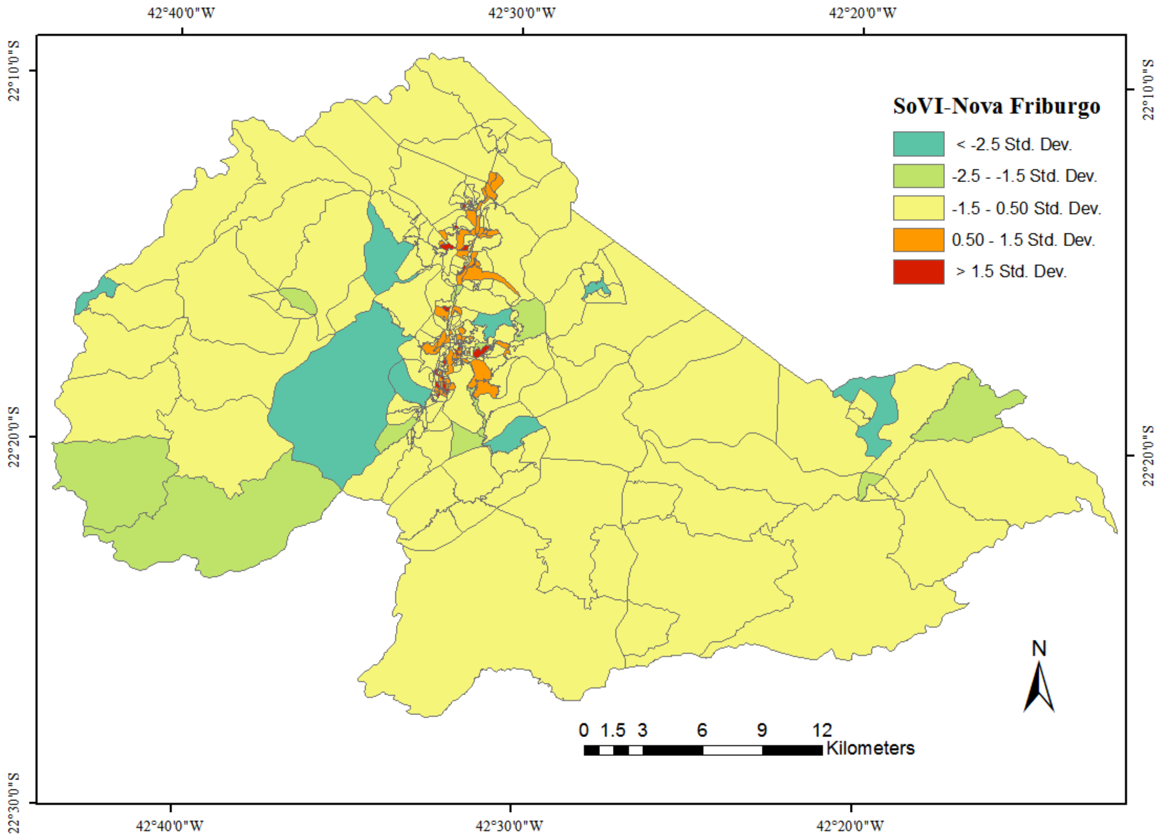
5.3.2 Social Vulnerability Geography in Nova Friburgo

The Social Vulnerability Index, SoVI-Nova Friburgo, is a relative measure of the *social vulnerability* (CUTTER et al., 2003) for each of Nova Friburgo census tracts (Figure 5.5)

SoVI-NovaFriburgo scores range from -7.33 (low *social vulnerability*) to 5.48 (high *social vulnerability*). Census tracts with scores over 1.5 standard deviations are classified with very high *social vulnerability*- in red- representing approximately 0.15% of the total area. Likewise, about 1% of the territory is classified with high *social vulnerability*- in orange- with index scores between 0.5 to 1.5 standard deviations.

Although most vulnerable areas were not widely distributed in the territory, they are important because of their location and implications for Nova Friburgo community's economic growth before and after a landslide *disaster*. In fact, many census tracts of the two most important districts, "Conselheiro Paulino" and "Nova Friburgo" are located within these high *social vulnerability* areas. Most census tracts (83.91%) show moderate levels of *social vulnerability*- in yellow- with index scores between -1.5 to 0.5 standard deviations. Over 8.5% of the municipality includes areas with low *social vulnerability*- in light green- with SoVI-NovaFriburgo scores between -2.5 to -1.5 standard deviations, mainly located in the southwestern border. On the other hand 6.28% of the area is classified with very low *social vulnerability*- in light blue- with index scores under -2.5 standard deviations, located in urban peripheral census tracts.

Figure 5.5 – Geographic pattern of Social Vulnerability based on the SoVI-NovaFriburgo.



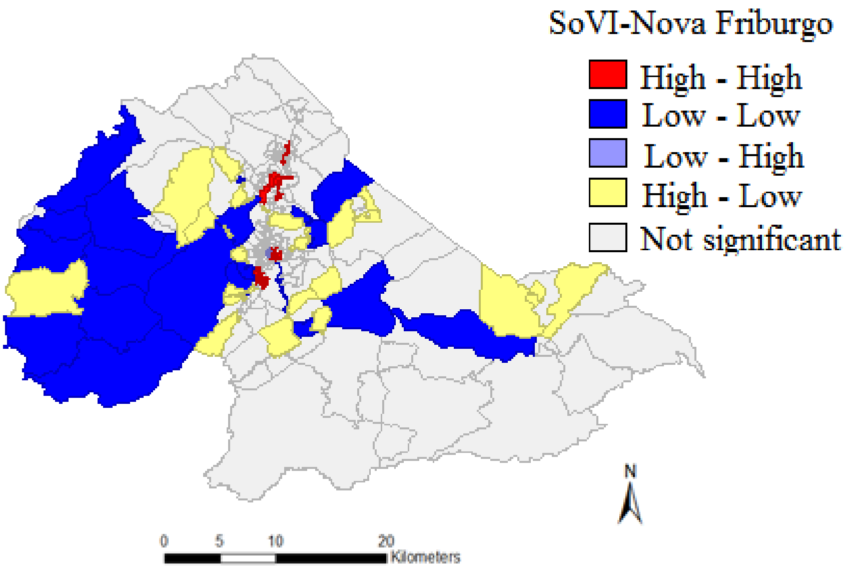
Source: Author's production.

A closer comparison of the results obtained in this study with *social vulnerability* levels estimated by the Atlas of Social Vulnerability in Brazilian Municipalities (2015) and in HUMMELL et al., (2016) reveals differences. Both works identify low *social vulnerability* for the Nova Friburgo area, while we found moderate *social vulnerability* levels all over the municipality with hot-spots of high and very high *social vulnerability*. These outcomes underline the importance of measuring *social vulnerability* at sub-national geography levels and also indicate the importance of customizing indices (HUMMELL et al., 2016) to improve understanding of *social vulnerability* at more fine grained spatial scales. According to Turner et al., (2003) vulnerability analysis usefulness increases when it is capable of providing vulnerability understanding of a particular place.

Data reveal that *social vulnerability* respond to a weak spatial aggregation pattern (Moran's I= 0.266, $p < 0.005$). Figure 5.6 shows that not all regions contribute equally to the global Moran's indicator. Red highlighted regions have high *social vulnerability* values as do neighbouring areas with high values (high-high), located at the municipality centre. Blue areas have both low *social vulnerability* and neighboring zones with low values (low-low), mainly located in the municipality western border. Approximately 0.65% of census tracts exhibit a combination of opposing values (low–high) and 9.94% high–low values. About, 71% of the census tracts do not present local spatial autocorrelation. The latter is in accordance with findings in the city of São Paulo, Brazil (RONCANCIO; NARDOCCI, 2016), showing lack of spatial autocorrelation in much of the territory when using the SoVI methodology with similar variables at basin scale.

In *social vulnerability* assessment, data constraint play an important role and thus, the results may vary according to the number of variables used (GAUTAM, 2017). Although this research offers a sound *social vulnerability* measure, further tests including other variables should be carried out in order to analyze whether the inclusion of more variables might better describe the social reality of the Nova Friburgo municipality.

Figure 5.6 – Local Moran's Index for Social Vulnerability Index.



Source: Author's production.

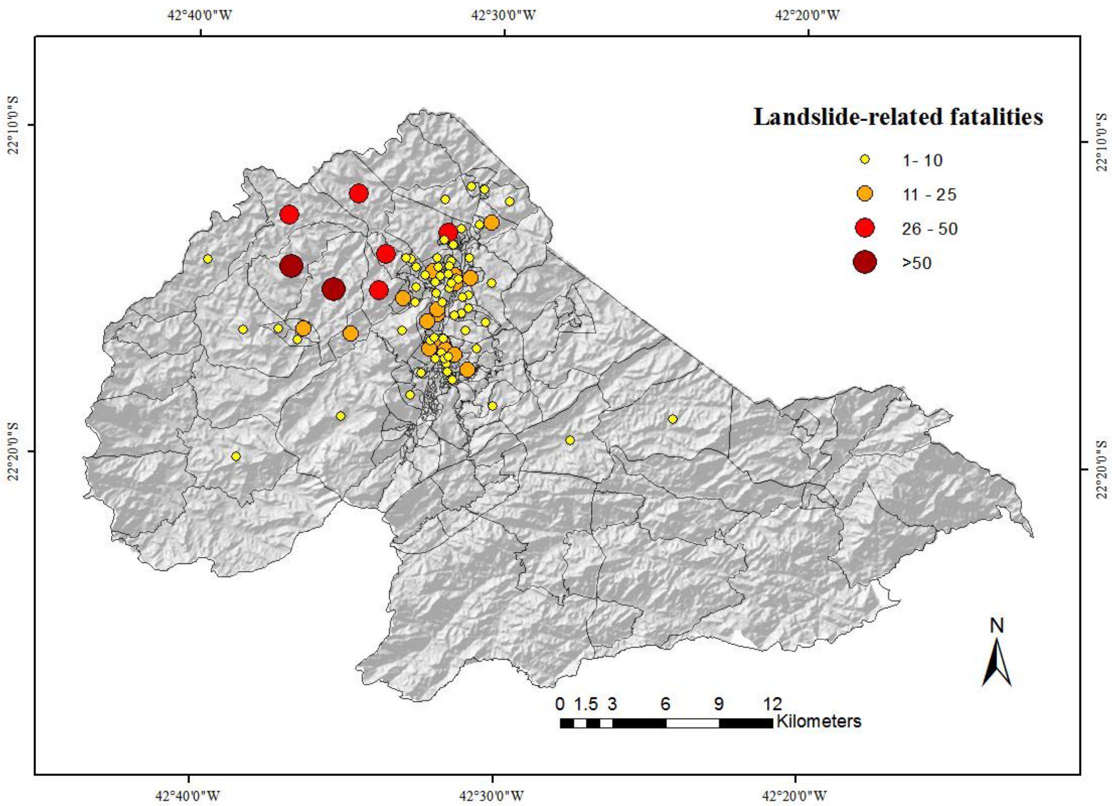
5.3.3 The 2011 landslide-related fatalities

Our findings suggest 434 landslide-related fatalities. This outcome differs from the 429 found by CEPED (2011) and the 349 by SIM (Sistema de Informação sobre Mortalidade, cited by Carmo and Anazawa, 2014). Discrepancy among results may be due to the Nova Friburgo health authorities continued research for fatalities even long after the *disaster* (Melânia Höelz, personal communication, August, 2016).

Cause of death for all the casualties was mechanical asphyxia by burial. Average age was 35-year-old with age range between 0 to 90-year-old. The highest mortality was located mainly in the northwest census tracts and some in the centre (Figure 5.7), including both urban and rural areas. The latter is according to what was stated by the Ministry of Environment in 2011, cited by Carmo and Anazawa (2014) about there being similar damage both in rural and urban areas, equally affecting both low and high income residents.

Data on race/ethnicity were missing for 31 victims (7%). Similarly, age information was missing for 19 victims (4%) and sex for 1 victim (0.2%).

Figure 5.7 – Loss of human lives from the 2011 landslides in Nova Friburgo.

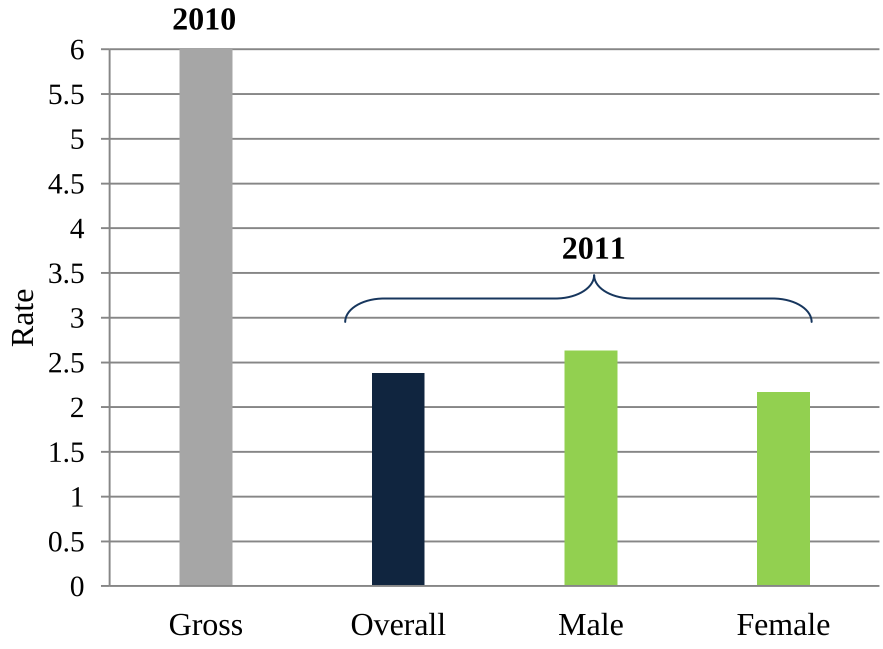


Source: Author's production.

5.3.3.1 Sex and Age

Many researches point out that *disasters* have differential impacts on women and men. Women's mortality during a *disaster* is higher than men's due to the *vulnerability* expressed by the inequitable distribution of rights, assets, resources and power (SHRESTHA et al., 2016) especially in low income countries. In this study, among the 434 landslide related-fatalities, 205 (47,2%) were female and 228 (52,5%) male. Figure 5.8 shows that male mortality rate related to the 2011 landslides was almost half the 2010 gross mortality rate in Nova Friburgo municipality. Furthermore, it was slightly higher than the overall rate and that of females. The latter is in agreement with findings from landslide fatalities in Italy (SALVATI et al., 2018), from floods and landslides casualties in Switzerland (BADOUX et al., 2016) and from Hurricane Katrina related-fatalities in USA (BRUNKARD et al., 2008) that show that males were more affected than women.

Figure 5.8 – Gross mortality rate in 2010 (IBGE, 2010), overall mortality rate and sex-specific mortality rates produced by the 2011 landslides in Nova Friburgo municipality.

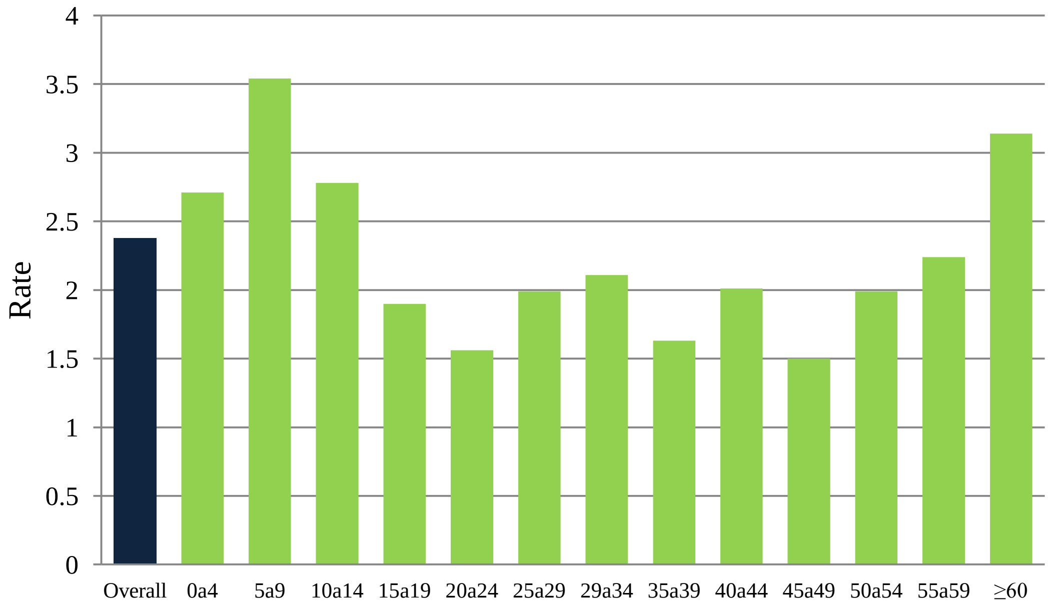


Source: Author's production.

Results also reveal that half the casualties were the youngest and the elderly. That is, about 31% of the casualties were children and adolescents between 0 to 19-years-old. Among these, 10% were children aged 5 to 9. On the other hand, 19% were elderly aged 60-and-older. These findings are in agreement with Cutter et al., (2003) who indicate that extreme age groups are the most affected by *disasters*. Inspection of the age-specific mortality rates (Figure 5.9) highlights this mortality pattern.

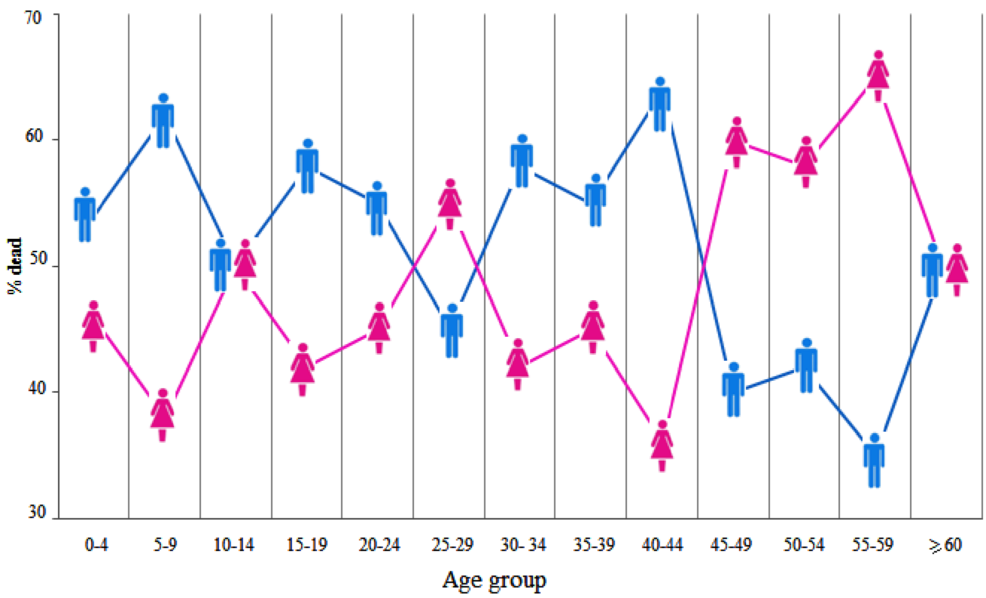
In most age groups, boys and men's mortality was higher than that of girls and women's. However, women aged 45 to 59 showed the highest mortality compared to that of men, being twice as many in the group aged 55 to 59 (Figure 5.10). Men and women may have different behavior patterns to face danger. Generally, women are more prudent and protect themselves and their family avoiding *risk* situations (Fausto Guzzetti, verbal information, 2016). This simple behavior can make the difference between life and death. In Nova Friburgo *disaster* case, landslides happened at night-time and probably all the people were surprised by the landslides while sleeping (CARMO; ANAZAWA, 2014). Hence, independently of age, gender or behavior, all the citizens were affected and much people were unable to escape danger.

Figure 5.9 – Overall rate and age-specific mortality rates produced by the 2011 landslides.



Source: Author’s production.

Figure 5.10 – Percentage of casualties by age in males and females.



Source: Author’s production.

Gender perspective addressed in this research helps to focus attention on the differential landslide impacts on girls, boys, men and women which may serve to redirect public policies to reduce *disaster* mortality. Thus, it is in agreement with the Sendai Framework that highlights the need for explicit gender mainstreaming and gender-disaggregated data collection for *disaster risk* management (UNISDR, 2015).

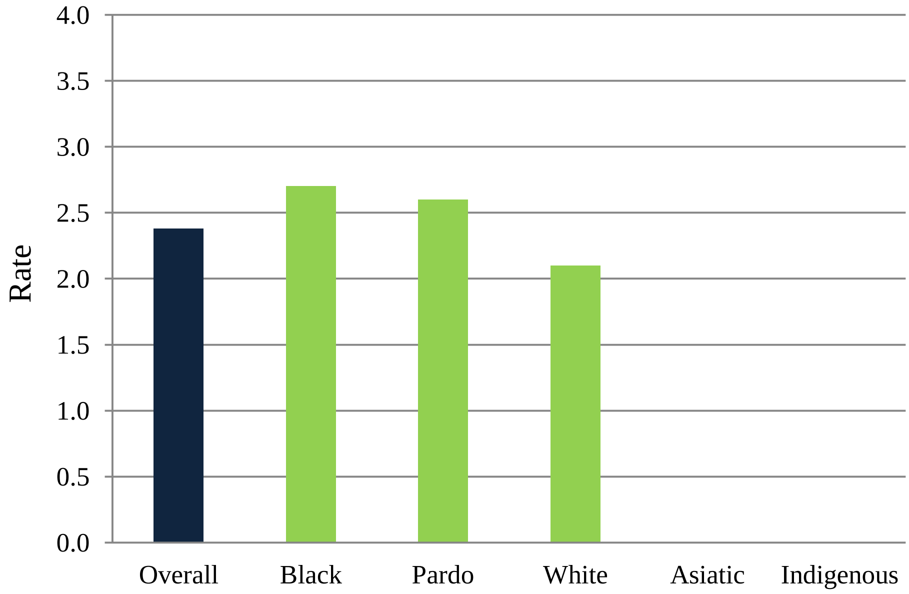
5.3.3.2 Race and Ethnicity

Nova Friburgo municipality is characterized by the predominance of white population as a result of the German and Swiss migration in the nineteenth century. According to the 2010 census data, 72% of the population declared themselves to be white; whereas 18.9% answered they were brown. Also, 8.5% declared themselves to be black, 0.5% yellow and 0.1% indigenous.

In the 2011 landslide *disaster*, 62.7% of the casualties were white, while 20.7% were brown and 9.4% black. Neither Asian nor Indigenous casualties were reported. Considering the 2010 population, results show the black population had a slightly higher mortality rate than either the brown (Pardos) and white ones (Figure 5.11). These findings probably can be explained by the historical social inequality (characterized by poverty, difficult to access to employment, education, health, etc.) among the African descendants and the white population. In this regard, Chor and Risso (2005) point out that there is inequality accumulation evidence based on racial discrimination as the structuring factor underlying the economic and social disadvantages experienced by some ethnic groups in Brazil. However, as mentioned above, taking into consideration the time in which the tragedy happened, probably all the citizens were overwhelmed by the landslides no matter either their race or other characteristics.

In spite of the existing race and ethnic diversity in Brazil and natural *hazards* occurrence, there are not many studies focusing on link these topics. Our research findings provide information contributing to better understanding of landslide impacts over the races and ethnical groups in this particular place, which in turn can steer the development and implementation of efficient *risk* management and mitigation measures. In agreement with Carmo and Anazawa (2014), availability of this type of data is important for governments and other stakeholders to take the proper actions needed.

Figure 5.11 – Overal rate and race-specific mortality rates produced by the 2011 landslides in Nova Friburgo municipality.



Source: Author's production.

5.3.4 SoVI-Nova Friburgo and the 2011 landslide-related fatalities

Pearson's correlation analysis shows a weak linear association ($r = -0.084$, $p > 0.05$) between landslide-related fatalities and SoVI scores. This outcome initially suggests no discernible trend in the relationship between both dataset. The latter is in agreement with findings in USA (CUTTER et al., 2003). Results could reflect some problems with: i) deaths' record accuracy or, ii) missing variables in the *social vulnerability* model. However, it is also possible to hypothesize that landslides' number and magnitude were so great that all Nova Friburgo inhabitants were equally affected beyond the socio-economic inequality expressed by their *social vulnerability*. Environmental degradation and disorderly land occupation patterns might have exacerbated the landslides' impacts (FREITAS et al., 2012). Probably, in Nova Friburgo *social vulnerability* was most apparent after landslides, revealing different suffering and post-*disaster* recovery patterns.

5.4 Final Remarks

This study provided a *social vulnerability* assessment and data collection disaggregated by age, sex and race/ethnicity of the 2011 landslide-related fatalities in Nova Friburgo municipality. The *social vulnerability* assessment was performed by using the SoVI method with customized variables at census tract level, while fatality analysis was conducted using official death certificates.

Results reveal differential *social vulnerability* among census tracts. Most of them were classified as moderately vulnerable. Although highly social vulnerable areas were not widely distributed in the territory, they are important because of their location and implications for the municipality economic matrix. Contributions of this research lie in identifying *social vulnerability* drivers and territories that are priorities for intervention with social policies which in turn can steer the development and implementation of *risk* mitigation measures. According to the conceptual model presented in Chapter 3, the *vulnerability* analysis presented herein defines the social landscape for a specific moment (that is, a photograph of the 2010 social condition). The next step being linking the social landscape to the physical landscape, i.e., landslide prone areas, to achieve an *integrated risk approach*. Future researches will seek to examine how the *social vulnerability*- as measured by the SoVI- can change over time and space.

Regarding the 2011 landslide-related fatalities, 434 casualties were registered. Spatial analysis indicates that the highest mortality was located at the northwest and central municipality zones.

It was possible to collect disaggregated data with more detail than in any previous study. Findings show that the landslide *disaster* affected males and females differently. In most age groups, landslides have killed more men and boys than women and girls. Fifty percent of those who lost their lives were the youngest and the elderly. The black population had a slightly higher mortality rate than either the brown (Pardos) and white ones. We sought to establish whether there was any association between *social vulnerability* and casualties. Data did not reveal a discernible trend. It seems that the landslide quantity and magnitude was so great that all of Nova Friburgo inhabitants were equally reached, beyond the social inequalities expressed by their *social vulnerability*. Probably, *social vulnerability* was most apparent after the landslides, revealing different suffering and recovery patterns among the citizens.

Reducing *disaster* mortality is a priority target of the Sendai Framework 2015-2030 for Disaster Risk Reduction. We expect that the results of this research may contribute to *risk* reduction by providing detailed information to: i) bridge the knowledge gaps about the specific needs and challenges that vulnerable groups are facing, ii) forecast future landslide impacts and, iii) support evidence-based planning.

6 AN INTEGRATED ASSESSMENT OF LANDSLIDE RISK

6.1 Understanding risk

The United Nations Office for Disaster Risk Reduction defines *risk* as “the combination of the probability of an event and its negative consequences” (UNISDR, 2009). *Risk* assessment and *risk* management as a scientific field is not over 30–40 years (AVEN, 2016). The *risk* field as a scientific discipline involves: i) to perform *risk* research related to concepts, theories, frameworks, approaches, principles, methods and models to understand, assess, characterize, communicate and (in a wide sense) manage *risk* and, ii) to use *risk* assessments and *risk* management to deal with the specific *risk* situations (AVEN; ZIO, 2014).

Traditionally, in the *disaster* science domain, *risk* has been analyzed from a purely engineering-based perspective, which has proved to have an ineffective response to face the challenges posed by physical and social factors, especially in low-income countries. Many efforts have been made to analyze physical vulnerability while social vulnerability aspect has often neglected (CUTTER et al., 2003; HUMMELL et al., 2016).

Disaster risk is actually understood as the product of an interaction between the physical process itself and the vulnerable conditions of exposed elements (BIRKMANN; TEICHMAN, 2010; ROGELIS et al., 2016). The *vulnerability* driver is not only climate change but also a range of other stresses that should be considered. Thus, more holistic approaches go further, incorporating social, economic, cultural, institutional and educational aspects, and their interdependence (FUCHS, 2009) in the *vulnerability* assessment.

To manage and reduce *risk* we need to assess it- qualitatively or quantitatively- and visualize it spatially first. *Risk* assessment incorporates three main steps: i) *Risk* identification; ii) *Risk* analysis and, iii) *Risk* evaluation (SEERISK, 2014). In the first step, users identify the context (i.e., objective, working group, *risk* criteria, final users) and the basis (*hazard* type, scale, extent, element at *risk*, *risk* metric). The second step serves to comprehend the nature and level of the *risk*. Thereby, *risk* analysis can be *qualitative* (i.e., based on expert classification schemes, *risk* can be described as high, medium or low); *quantitative* (i.e., *risk* can be described by a specific metric, for example, damage measured in the amount of money lost, potential victims’ number, etc.) or *semi-quantitative* (i.e., it can be described by using indices). The third step, *risk* evaluation is usually implemented simultaneously with the other steps, that is, working group assessing *risk* will have to define assessment criteria to identify high, medium or low *risk* areas. Then, decisions have to be made regarding the different *risk* levels acceptance (SEERISK, 2014; PAPATHOMA-KÖLHE et al., 2016).

Lately different initiatives have been proposed to encourage integrated approach on research *disaster risk* agenda. However, *integrated risk assessment* is not always performed because it requires resources such as, transdisciplinary knowledge- the hardest thing to achieve- time, expertise, and funds that are not always available in most countries. In this respect, in Europe, despite the advice to conduct *integrated risk assessment* and mapping, few countries have done so at national or regional level. For instance, Remondo et al., (2008) have assessed landslide *risk* quantitatively in a region of Spain integrating *hazard* and both direct damage and indirect loss maps. In 2014 the SEERISK project undertook *risk* assessments in nine European countries, such as Austria, Slovakia, Hungary, Croatia, Serbia, Romania, Bulgaria, Slovenia and Bosnia-Herzegovina for different natural *hazard* types, such as heat wave, drought, flood, wildfire and extreme wind. Similarly, some attempts have been performed in Georgia as well as in the South Caucasus generating past events database and existing *hazard*, *risk* and *socio–economic vulnerability* maps. In Brazil, Anazawa et al., (2012) and Cardozo et al., (2015) have made attempts to focus on integrated studies, linking *vulnerability* and different *hazards* such as flooding and landslides. In Central America *risk* mapping has been conducted at national and supra-national levels for earthquakes, volcanic eruptions, tsunamis, landslides and floods (PAPATHOMA-KÖLHE et al., 2016). Recently, in Colombia a regional prioritization for flood *risk* in mountainous areas was carried out (ROGELIS et al., 2016) using a qualitative method for integrating information related to flooding and social vulnerability.

The aim of this chapter is twofold: i) to apply the conceptual framework for *integrated risk assessment* that has been proposed in the Chapter 3 of this Thesis and, ii) to conduct an integrated landslide *risk* assessment combining landslide susceptibility and social vulnerability data (computed previously in Chapters 4 and 5 respectively) using as spatial analysis methodology, the Generalized Additive Model (GAM).

6.2 The Generalized Additive Model (GAM)

Generalized additive models (GAMs) are statistical models in which the conventional linear relationships of multiple regressions are generalized to permit a much broader class of nonlinear, but still additive, relationships between response and predictor variables. GAMs which derives from the work of Hastie and Tibshirani (1986, 1990) provide flexible and effective means of moving out of the “linear rut” in which a considerable amount of statistical modeling is still located. GAM represents an “adaptative” approach in which data help guide the choice of appropriate functional form (JONES; WRIGLEY, 1995). Furthermore, GAM enable the use of several distributions (e.g., Binomial, Logistic, Poisson or Gamma) permitting researchers identify and select the best distribution to fit data, converting the GAM technique into a viable alternative, powerful and yet simple (ANTUNEZ et al., 2017).

The Generalized linear model (GLM) proposed by Nelder and Wedderbum (1972) provides a way of estimating a function of the mean response as a linear combination of a set of predictors X_i (i = 1, 2, …, m) (Eq. 6.1).

$$g(E(Y)) = \beta_0 + \sum_{i=1}^{m} \beta_i \; x_i \tag{6.1}$$

where Y is the dependent variable; $E(Y)$ denotes the expected value; $g(Y)$ is termed the link function (that links the expected value to the predictors X_i), β_0 and β_i are the intercepts and the coefficient estimated for the ith predictor, respectively. ε_i is the error.

The primary restriction of a GLM is the fact that linear predictor is still a linear function of the parameters in the model. The Generalized Additive Model (GAM) extends the GLM by fitting nonparametric functions to estimate relationships between the response and the predictors through the use of smoothing functions (HASTIE; TIBSHIRANI, 1990). In a GAM, the coefficient β_i is replaced by a smoothing function as follows (Eq. 6.2).

$$g(E(Y)) = \beta_0 + \sum_{i=1}^{m} f_i \; x_i \tag{6.2}$$

where f_i corresponds to the nonparametric functions that describe relationship between Y and the ith predictor. ε_i is the error.

In practice, *fi* are estimated from the data by using techniques developed for smoothing scatterplots. According to Yee and Mitchell (1991) there are many types of scatterplot smoothers, e.g., the running lines, running means, running medians, cubic splines, b-splines, the lowess of Cleveland (1979) and the supersmoother of Friedman and Stuetzle (1981). For more details, see Hastie and Tibshirani (1990).

6.3 Data Source and Methodology

Data from different science domains were used to assess landslide *risk* following an integrated approach. For this purpose, a GAM model using logistic regression has been applied.

Because it is difficult to find empirical evidence about *risk* itself, the known landslide casualty occurrence is used to estimate landslide *risk* (i.e., areas with casualties are treated as areas at risk) under the assumption that the dependent variable (i. e., Y= known casualty occurrence) is related to the independent variables *vulnerability* and *hazard*. Dataset were combined using the expression stated in Eq. 6.3:

$$R = H * V \quad (6.3)$$

where *R* is the *risk*; *H* is the *hazard* and *V* is the *vulnerability*.

All the analyses were carried out using the R free software (R DEVELOPMENT CORE TEAM, 2016), using the package "mgcv" (v. 1.8-22; WOOD, 2017).

6.3.1 Landslide Risk Modelling

The logistic regression GAM (Eq. 6.4) used in this research can be expressed as follows:

$$\text{Logit}(P_i) = \log \frac{P_i}{1-P_i} = \beta_0 + f_1(X_1) + f_2(X_2) \quad (6.4)$$

where P_i is the probability of landslide *risk* at the locality *i;* β_0 is the intercept; f_1 and f_2 are unspecified smooth functions of each predictor variable; X_1=*Social vulnerability* predictor and X_2= *Stability terrain* predictor.

It was assumed that landslide susceptibility zonation (or stability terrain condition- that was presented in Chapter 4- represents the *landslide hazard*. While *social vulnerability*- that was presented in Chapter 5- represents the *vulnerability*. The *exposure* concept expressed by "population density" and "house density" (Section 5.2.4, Table 5.1) is assumed as a component within the *vulnerability* concept. According to Turner et al., (2003) it provides a more complete characterization of *vulnerability*.

Both explanatory variables were fitted as smoothers to allow for possible non-linear effects. Functions f_1 and f_2 were determined using cubic spline smoothing. The choice of the cubic spline is based on its proven usefulness and also due to its being less expensive computationally (BRÖMSSEN, 2015).

Finally, the smoothed curves of additive effect related to the individual parameters in the GAM model were plotted. Additionally, plot of the predicted landslide risk was made. In order to analyze the spatial structure of model residuals, the Global Moran's Index was computed.

6.4 Results and Discussion

Landslide *risk* probability was estimated by using a GAM model. Findings reveal that GAM describes 69.5% of the deviance. Both predictors are significant ($p < 0.05$) and contribute to the fitting of the model.

The complexity of the adjusted curves is reflected by the effective freedom degrees (efds). Data suggest that X_1 variable establishes a nonlinear relationship (efd=8) with logit(Pi); while X_2 predictor describes traditional linear regression (edf=1) with the dependent variable (Table 6.1).

Table 6.1 – Results of the GAM model.

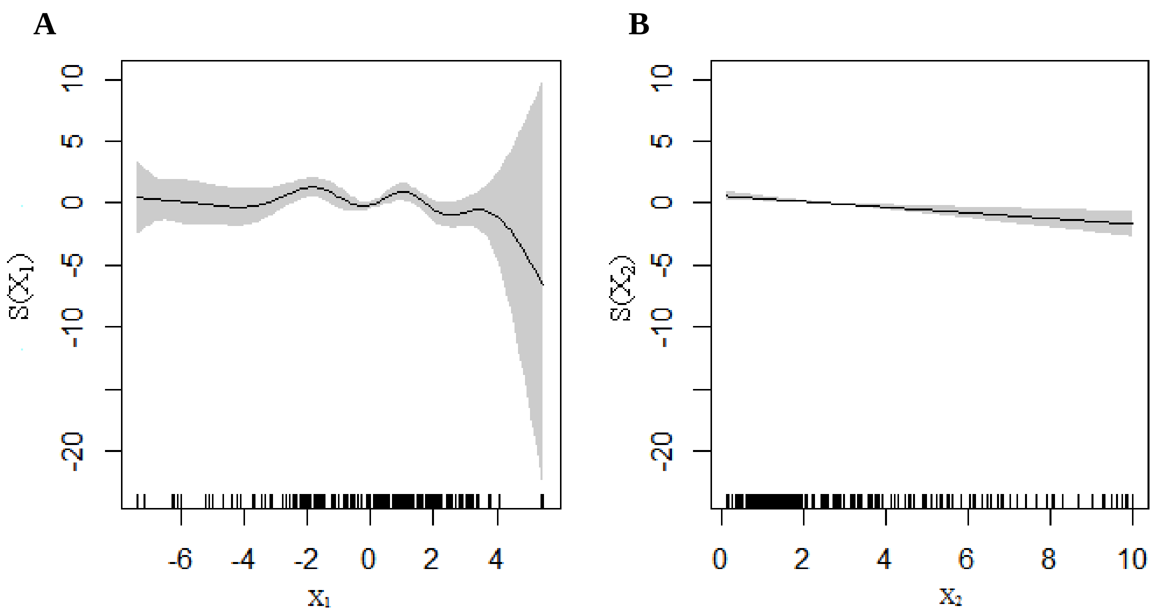
Parametric coefficients:				
	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	-1.1526	0.1547	-7.449	9.41e-14
Approximate significance of smooth terms:				
	Edf	Ref.df	Chi.sq	p-value
s(X_1)	8.122	8.707	18.00	0.028955
s(X_2)	1.000	1.000	10.91	0.000958

Source: Author's production.

Figure 6.1 shows this complexity. Ignoring those plot areas in which there are very few data points and corresponding wide error bands, the model indicates that there is evidence of a nonlinear relationship between X_1 and logit(P_i) -which is estimated by S(X_1) (Figure 6.1-A) and a linear relationship between X_2 and logit(P_i)- which is estimated by S(X_2) (Figure 6.1-B). Thus, GAM results highlight model capacity to uncover hidden patterns in the dataset- that a classic linear model would have missed- capturing nonlinear effect of one of the variables used to predict landslide *risk*. Hence, it proves to be robust and reliable in output predictions. In agreement with Pliscoff et al., (2011) this is attributed to its semi-parametric structure.

According to Jones and Wrigley (1995) the marked inverted U-shape (as those seen in Figure 6.1-A) is exactly the type of relationship that conventional logistic models fail to detect.

Figure 6.1 – Smoothed curves of the additive effect for the individual parameters in the GAM model. Grey zones represent 95% *confidence intervals.* A) Predictor X_1= *Social Vulnerability*. B) Predictor X_2= Terrain stability.

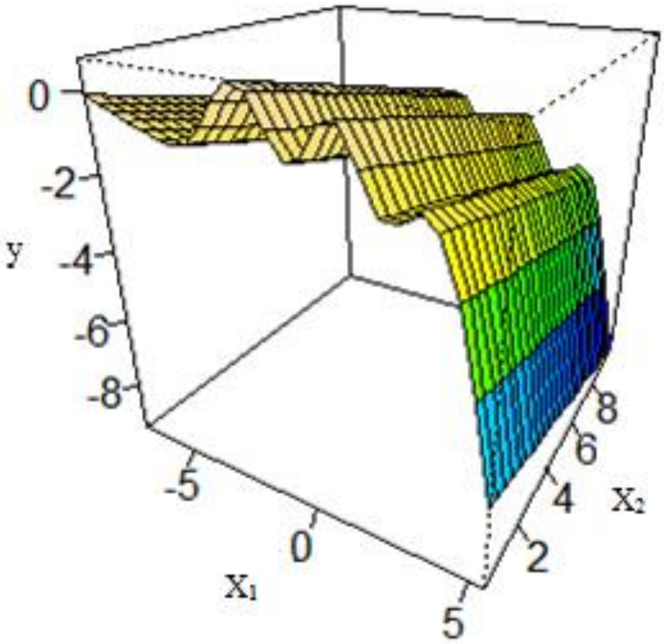


Source: Author's production.

Inspection of the 3D plot reveals that there are at least two peaks of landslide *risk probability* (Figure 6.2). Both occur when X_1 variable adopts values near -2 and 1 (which represent moderate *social vulnerability* level) and the X_2 variable assumes values below 1 (which represent *terrain instability* conditions). Then, these findings suggest that in landslide prone areas, a moderate social vulnerability level is enough to increase the probability of landslide *risk*.

As stated by Larsen (2015), GAM is a non-parametric approach that has interpretability advantages of GLMs, in which contribution of each independent variable to the prediction is clearly encoded, making it easier to examine the role of variables in predicting the response (YEE; MITCHELL, 1991). This aspect is particularly important for those involved in the decision-making process and not necessarily having technical knowledge.

Figure 6.2 – 3D view of fitted value surface according to X_1 and X_2 variables.



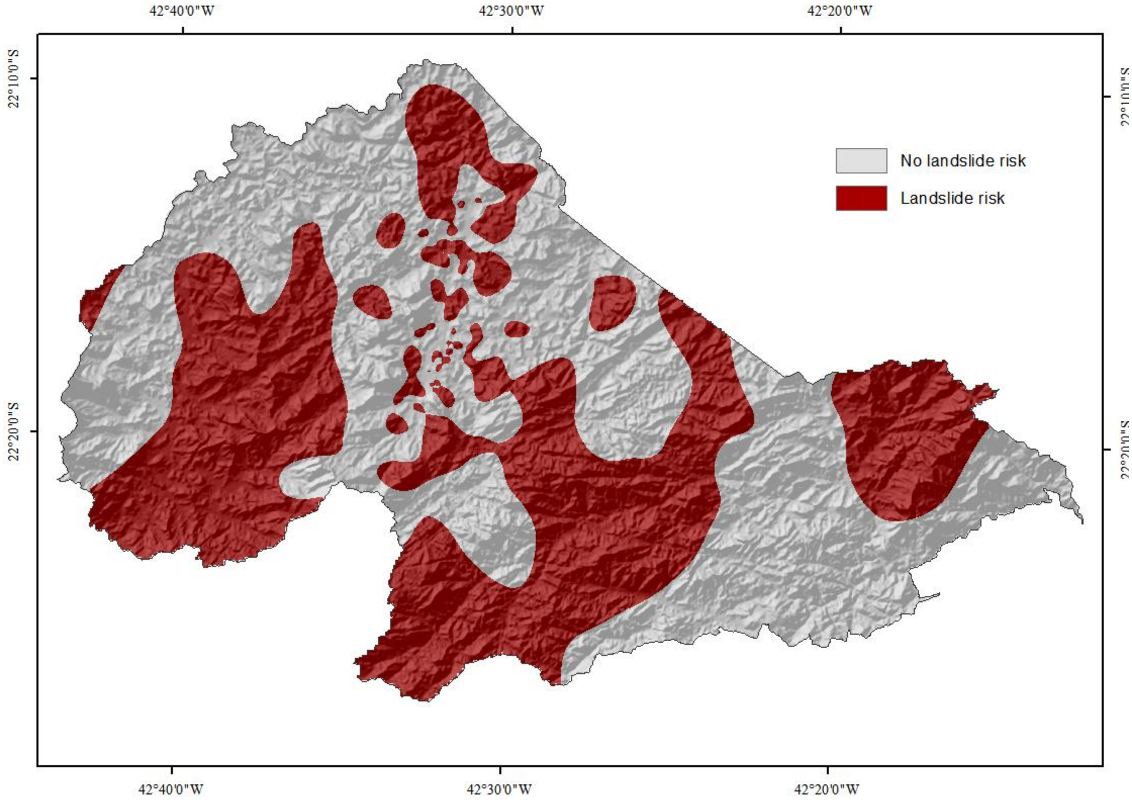
Source: Author's production.

GAM predictions suggest clustered hot-spots of landslide risk mainly in three zones at Nova Friburgo municipality: a belt in the southwest side census tracts; a parallel band in the center-eastern and also in the eastern areas (Figure 6.3). Regarding the spatial structure of residuals, data reveals a positive and weak spatial autocorrelation (Moran's I= 0.192, $p < 0.05$) which suggest an acceptable spatial distribution for the model residuals.

Currently, there is no available information to validate this landslide *risk map*. Hence, this task could be performed considering information from future landslide events.

In agreement with Montgomery (2018) it is high time to get serious about landslide *risk* zoning. These maps could help guide zoning decisions and better inform local government entities, citizens, the private and public sectors of potential *risks*. Without this kind of information, all citizens are physically and financially exposed.

Figure 6.3 – Landslide risk probability predicted from the fitted Generalized Additive Model.



Source: Author's production.

As widely known, proactive measures taken before an emergency or *disaster* occurs are essential to save lives and properties.

Zhang et al., (2005) using ecological data indicated that modeling techniques such GAM may improve model fitting and provide better prediction for the response variable than the Ordinary least-squares (OLS) regression (a special case of GLM modeling technique), however they produce similar spatial patterns for the model residuals as the OLS model does. The authors also highlight that Geographically Weighted Regression (GWR), a local modeling method, produces more accurate predictions for the response variable, as well as more desirable spatial distribution for the model residuals than the ones derived from OLS and GAM modeling techniques.

Taking these insights into account, future researches will seek to assess landslide *risk* using other predictive spatial model types as GWR.

6.5 Final Remarks

Understanding *risk* of a specific natural *hazard* through *integrated risk assessment* is useful to support effective policy design and investment to reduce *risk* and curb losses of both human lives and economic assets.

In this chapter, a spatially integrated modelling approach to landslide *risk assessment* was conducted. This analysis improves previous studies by integrating the physical landscape, approached by a landslide susceptibility zoning model and the human landscape, approached by a social vulnerability model, which might help to better understanding landslide *disaster risk* complexity.

The landslide *risk* modelling strategy introduced herein- using spatial analysis with the GAM technique- has facilitated the identification of value ranges in which predictor variables, such as *social vulnerability* and *terrain stability* produce an effect on response variable. Mapping landslide risk probability predicted form the GAM model enables to recognize geographic variation of landslide risk probability, providing information about where disaster, i.e., great losses of lives and economic assets are likely to happen if landslides strike again in the context of a vulnerable population. Rescue teams might use this map to plan evacuation actions more effectively and establish primary and secondary escape routes for use during landslide emergency times.

The overall knowledge provided in this research can steer implementation and development of efficient landslide *risk* management and mitigation measures by local and national authorities.

This is the start-up point for future researches aimed at monitoring landslide *risk* over space and time in the Nova Friburgo municipality.

Increase of frequency and magnitude of natural *hazards* related to climate change are expected in years to come. Therefore, outcomes derived from integrated approaches, which consider the human and physical dimensions of *disaster* are essential to understand the *risk* complexity and raise the awareness of local communities and governments and also to strengthen their response capacity to efficiently cope with future natural *hazards*.

We expect that the reported findings stated in this chapter may encourage local and national authorities to undertake periodic *integrated landslide disaster risk assessments* to take better preventive action to reduce casualties and the soaring numbers of displaced people every time landslides hit.

7 CONCLUSIONS

To date, most *disaster risk* assessments have focused primarily on estimating the physical aspect of risk and have largely ignored its social facet. This Thesis introduces an analytical framework for *integrated risk assessment* plus a spatial analysis tool to data modelling in this topic. Moreover, the proposal is undertaken in a practical way in the Nova Friburgo municipality (Rio de Janeiro State, Brazil), as a case study. This analysis improves previous studies by integrating information from different scientific fields. The proposed conceptual framework is generic and flexible, so it can be applied to other areas, analysis scales and other natural *hazard* types, although some adaptation would be necessary depending on available data.

The integrated approach conducted in this Thesis highlights that it is feasible and necessary to link data from different science domains to comprehend *disaster risk* complexity, reduce *risk* and curb losses of both human lives and economic assets through knowledge-based actions. We expect that the case study presented herein may encourage other integrated assessments of *disaster risk* aimed to reduce human and financial impacts produced by natural *hazard*s in the country. Likewise, we expect that results of our analysis will be helpful to design recommendations for self-protecting actions and civil protection plans.

7.1 Benefits and Contributions

Although this research was carried out using a number of assumptions which may have introduced a certain uncertainty level, its advantages outweigh disadvantages since was possible tackle it with the available data at this moment and additionally it provides information contributing meaningfully to the existing body of knowledge.

While the proposed analytical framework poses spatio-temporal changes in *risk* (and also of the elements that shape it). The spatially *integrated landslide risk modelling* introduced herein is focused only for a specific time mainly due to the limited availability of complete historical data concerning the frequency of landslides together with social data at the same level of detail.

It is noteworthy that one of the great contributions made in this Thesis is about the “know-how”, i.e., it shows and explain how to make operative key concepts, such as *vulnerability*, *hazard* and *risk*, a characteristic that is often lacking in disaster science.

Regarding *vulnerability*, this research focused on a specific aspect- *social vulnerability*- using a local adaptation of the SoVI Index. Findings provide useful spatial information about critical zones that need to be prioritized by public policies at the Nova Friburgo municipality. Bearing in mind that human actions play an important role in shaping and modifying *risk* conditions, a broader *vulnerability* characterization would be necessary, i.e., a multidimensional approach including ecological, cultural, economic, educational, institutional, *risk* perception aspects and their interdependences should be addressed. Thus, in future researches attempts to capture these *vulnerability* aspects will be performed. Additionally, thesis outcomes underline the importance of measuring *social vulnerability* at sub-national (intra-municipal) geography levels customizing indices in order to produce valuable information to the *vulnerability* understanding of a particular place.

Concerning landslides, this study identifies and map landslide-prone areas which can be useful for land-use planning and also can help urban planners prioritize response measures.

Another point to keep in mind is that the resulting *landslide risk map* provides useful spatial information which can help steer development and implementation of efficient *risk* management and mitigation measures by local authorities. Furthermore, rescue teams may also use it to plan evacuation actions more effectively and establish primary and secondary escape routes for use during landslide emergency times.

Disaster risk information at national level is important but not enough for effective decision making. On the contrary, information at local level is critical, especially taking into account that natural *hazard* impacts are different even among communities, groups and individuals. Understanding what is lost or affected is essential if we are to succeed in mitigating future *disasters* impacts. In this respect, this research provides a characterization of the 2011 landslide-related fatalities disaggregated by sex, age and race/ethnicity which enable unmask mortality underlying trends. These findings can serve government to measure true progress in reducing mortality from landslide *disasters*.

Finally, it should be noted that this research is aligned with guidelines given at the first priority area for action included in the Sendai Framework for Disaster Risk Reduction 2015-2030: "*Understanding disaster risk*". Thereby, resulting knowledge at local scale about *social vulnerability*, *landslide susceptibility* and *risk* provides Nova Friburgo community, civil organizations and local government with a basis to better understand *disaster risk* related to a specific natural *hazard*: "the *landslides*". Consequently it can be used to achieve effective preparation and response to future landslide *disasters* and also to promote *disaster*-resilient societies.

7.2 Limitations and Future Perspectives

During this thesis development some restrictions were faced, however they were solved. One of them is related to geologic data availability, in particular lack of geotechnical and hydrological parameters by soil types- which might have compromised the landslide susceptibility analysis- however it has not hindered its implementation in the SINMAP methodology. Geotechnical parameter records and laboratory tests should be performed to help get better landslide susceptibility predictions using the SINMAP approach or other deterministic modelling. Despite the resulting *landslide susceptibility map* being preliminary and requiring some adjustments, it was very useful and adequate for *landslide risk assessment* in this inquiry.

Another drawback is linked to the incomplete record of the 2011 landslide-related fatalities in the official death certificates. First, it is possible that some people who died during the landslides were never found or documented. Second, some casualties demographic and general characteristics were not reported, revealing different medical criteria for identification. All of which may have put a degree of uncertainty in our analysis. Evidently, the tragedy caused a high number of casualties in short time generating troubles at both social and sanitary levels in Nova Friburgo. In order to assist local authorities in data collection, emergency forensic medical teams should be trained in the preparation of accurate mortality reports and victim identification. This will not only leave a written record of what was done as a legal evidence element, but also will aid to a standardized register, which will undoubtedly provide support for future epidemiological studies.

This research identified possible tasks for future studies as outlined below:

(i) Exploiting the potentialities of the proposed analytical framework by assessing risk in other natural *hazard* contexts, exposure and vulnerability conditions.

(ii) Exploring other spatial analysis techniques for modelling risk and comparing their performance with the GAM model successfully used in this research.

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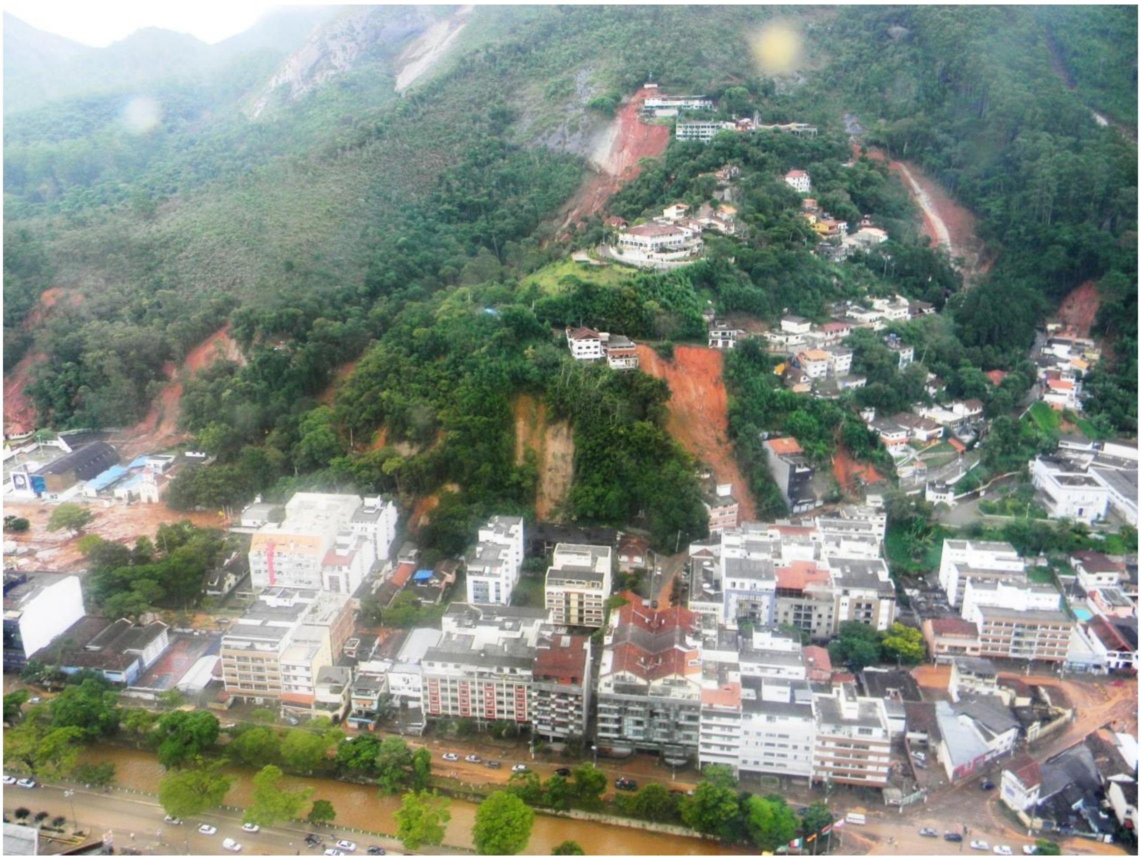
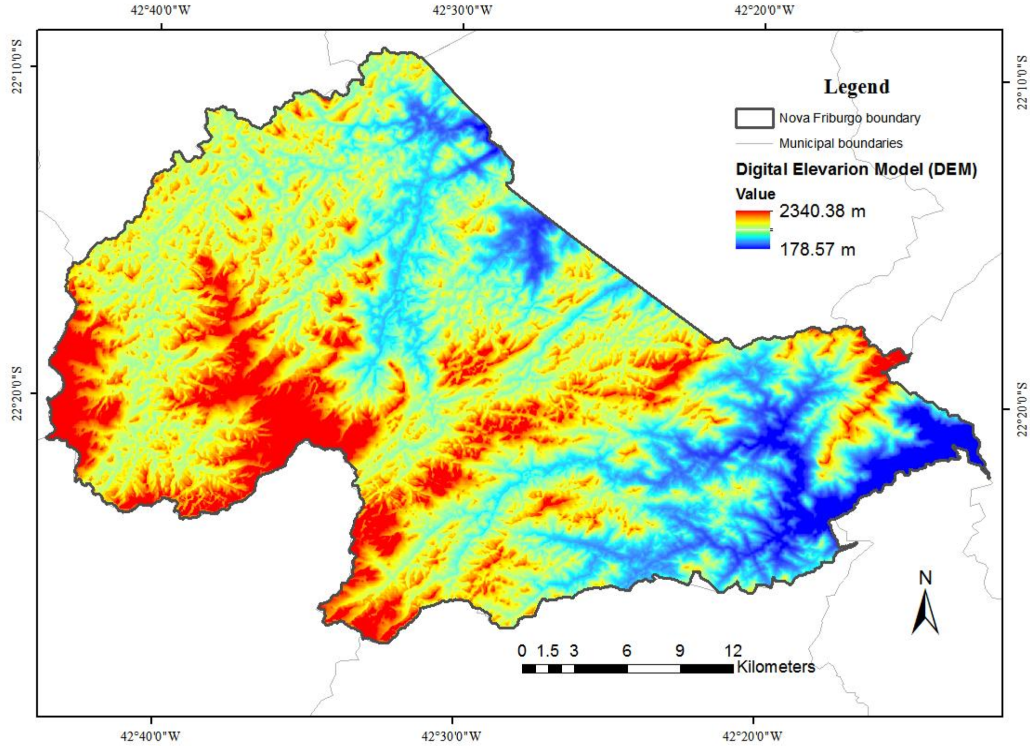
APPENDIX A[1] – Photographs of landlides and its effects in Nova Friburgo municipality.

1 All the photographs were provided by the authorities of Nova Friburgo municipality.



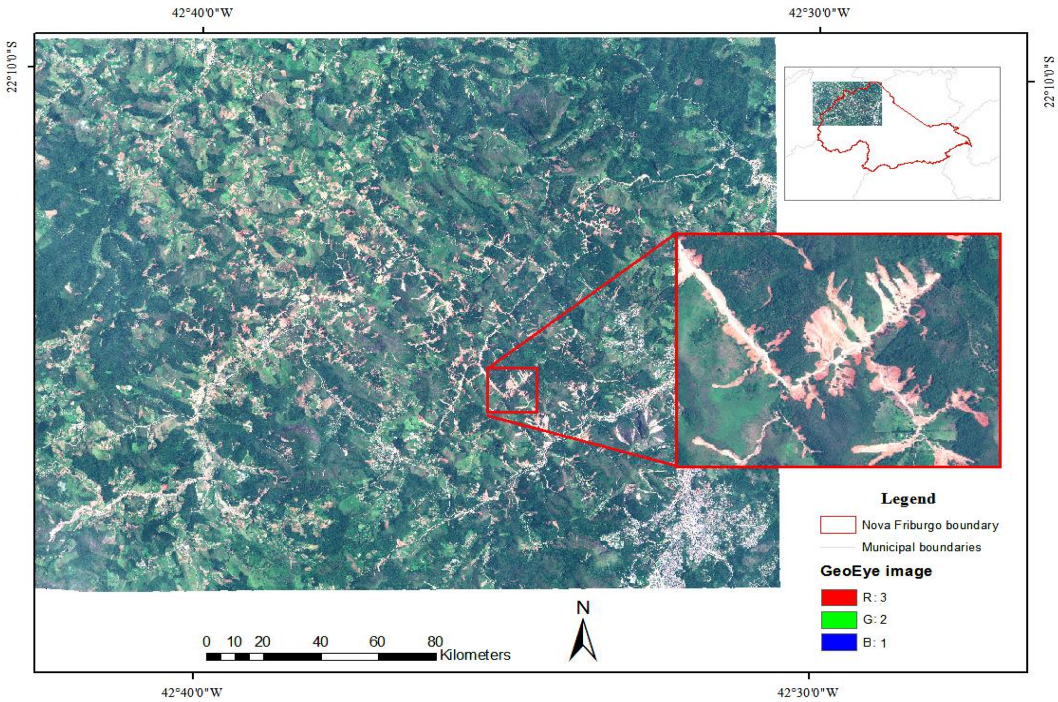
APPENDIX B – Satellite dataset used in this research.

Digital Elevation Model (DEM) of Nova Friburgo municipality.



Source: Brazilian Institute of Geography and Statistics (IBGE).

Geo-Eye-1 satellite data.



Source: National Institute for Space Research (INPE).

APPENDIX C – Scatter Plot Matrix of resulting factors in the Principal Components Analysis (PCA).