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CICLO XXXVII

**MULTISCALE APPROACHES FOR EARTHQUAKE-INDUCED
LANDSLIDES (EILs) SUSCEPTIBILITY ASSESSMENT: STUDY CASES
FROM ITALY**

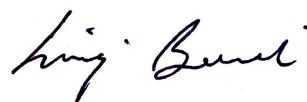
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TABLE OF CONTENTS

ABSTRACT	9
INTRODUCTION	13
1 LANDSLIDES HAZARD IN SEISMIC AREAS	18
1.1 Introduction	18
1.2 Earthquake-Induced Landslides (EILs)	21
1.2.1 <i>Types of Earthquake-Induced Landslides</i>	21
1.2.2 <i>Long-Term Landslide Hazards: The Impact of Seismic and Climatic Interactions</i>	24
1.2.3 <i>Landslide Factors and Triggering Mechanisms in Seismic Areas</i>	26
1.3 EILs Susceptibility and Hazard Assessment Methods	28
1.3.1 <i>Heuristic Methods</i>	30
1.3.2 <i>Probabilistic Methods</i>	31
1.3.3 <i>Statistical and Machine Learning Methods</i>	33
1.3.4 <i>Deterministic Methods</i>	35
1.4 The Role of Empirical Relationships in EILs Hazard Assessment	36
1.5 Multiscale Approach to EILs Susceptibility Assessment	38
2 EMPIRICAL RELATIONSHIPS BETWEEN EARTHQUAKE-INDUCED LANDSLIDES OCCURENCE AND SEISMIC PARAMETERS FROM THE ITALIAN HISTORICAL RECORD	40
2.1 Introduction	40
2.1.1 <i>Study Area</i>	43
2.2 Materials and Methods	44
2.2.1 <i>Datasets</i>	45
2.2.2 <i>Methods</i>	50
2.3 Results: Empirical Relationship	53
2.3.1 <i>Landslide Density vs Epicentral Distance</i>	53
2.3.2 <i>Landslide Density vs Peak Ground Acceleration</i>	55
2.4 Case studies to validate the method	56
2.5 Discussion and Conclusion	62
3 EARTHQUAKE-INDUCED LANDSLIDES SUSCEPTIBILITY EVALUATION: A CASE STUDY FROM THE ABRUZZO REGION (CENTRAL ITALY)	66
3.1 Introduction	66
3.2 Study Area	68
3.2.1 <i>Geological and Geomorphological Setting</i>	68
3.3 Materials and Methods	72
3.3.1 <i>Landslide-Triggering Parameters: Detection and Analysis</i>	73
3.3.2 <i>Unsupervised Classification, Susceptibility Classes Definition, and Map Creation</i>	80
3.4 Results	82
3.4.1 <i>Morphometric Maps</i>	82
3.4.2 <i>Geothematic Maps</i>	84
3.4.3 <i>Susceptibility Map</i>	89
3.5 Discussions and Conclusions	93

4	DEBRIS FLOW ON ACTIVE FAULT ESCARPMENTS ON CARBONATE ROCKS: THE CASE OF THE MONTE MARINE RIDGE (PIZZOLI-BARETE AREA, L'AQUILA CENTRAL ITALY)	96
4.1	Introduction	96
4.2	Study Area	99
4.3	Material and Methods	103
4.4	Results	107
4.4.1	<i>Geomorphological Map</i>	107
4.4.2	<i>Fault-related Morphotectonic Features</i>	122
4.4.3	<i>Debris Flows Mapping and Inventory.</i>	122
4.5	Discussion and Conclusions	125
5	ROCKFALL SUSCEPTIBILITY ASSESSMENT AND LANDSCAPE EVOLUTION OF SAN NICOLA ISLAND (TREMITI ISLANDS, SOUTHERN ADRIATIC SEA, ITALY)	127
5.1	Introduction	127
5.2	Study Area	129
5.3	Materials and Methods	131
5.3.1	<i>Geothematic and Literature Data</i>	132
5.3.2	<i>Rockfall Susceptibility Assessment</i>	135
5.4	Results	137
5.4.1	<i>Geothematic Parameters</i>	137
5.4.2	<i>Rockfall Susceptibility Map</i>	145
5.5	Discussions	146
5.6	Conclusions	153
6	DISCUSSION AND CONCLUSION	157
	REFERENCE	160

ABSTRACT

Studying geomorphological hazards in seismically active areas requires understanding the spatial distribution of Earthquake-Induced Landslides (EILs) and their triggering mechanisms to develop effective risk reduction strategies. EILs pose significant dangers in mountainous regions, causing damage to the environment, infrastructure, and communities. Thus, creating EIL susceptibility and hazard maps is pivotal for risk mitigation and responsible planning, particularly in seismically active countries like Italy. These maps support preventive planning and emergency management by providing essential information to decision-makers and targeted responses. It is crucial to employ appropriate EILs susceptibility and hazard assessment tools to detect potentially unstable areas with adequate detail for each operational scale.

This PhD Thesis presents a comprehensive study on the susceptibility and hazard assessment of Earthquake-Induced Landslides (EILs) using a multi-scalar approach based on geomorphological criteria. It focuses on predisposing factors, defined by physiographic, geological, and geomorphological features, plus seismic triggering factors derived from the seismotectonic context. This multi-scalar approach has been applied to selected case studies at national, regional, and local scales within the Italian territory.

Recently, in Italy and globally, various studies have been conducted at local and regional levels to examine EILs. This research resulted in the creation of databases that facilitate the development of empirical relationships using standardized methodological approaches. Since that, at the national scale, our study has focused on a new empirical relationship between EILs distribution and seismological parameters. Specifically, recently updated data from the Italian Strong Earthquakes Catalogue, the CFTI, were used in this work. The employed dataset consists of 972 EILs associated with 152 different seismic events covering a time span of more than 1000 years. In addition, 39 of these earthquakes have a related shake map derived from the updated INGV shake map database. Using these datasets allowed the development of relationships between landslide density and seismological parameters (magnitude, peak ground acceleration, epicentral distance) based on large, robust, and verified datasets. Considering that in Italy, particular attention has been paid to the analysis of EILs distribution in recent times, the relationships derived from this study contribute to the development of applications for defining pre- and post-earthquake secondary environmental hazard scenarios.

At the regional scale, the research focuses on the Abruzzo Region (Central Italy), which is severely affected by EILs and is linked to geomorphological dynamics and severe seismicity. The distribution, mechanisms, and typology of landslides are strictly related to the different physiographic and geological-structural settings. This case study concerns the realization of an EILs susceptibility map, following a heuristic approach using GIS technology combined with statistical analysis. This approach led to the identification of nine instability factors. These factors were analyzed for the construction of thematic maps. The selected factors were evaluated by assigning appropriate ranks and weights based on a critical analysis of the available literature and data from landslide inventories. These values were then combined to create a preliminary map, where higher numerical values indicate a greater propensity of the slope to fail, while lower values correspond to a lower propensity. Finally, these values were statistically analyzed to define suitable susceptibility classes. Results presented herein highlight the robustness of the approach; remarkably, the applied methodology is suitable even in areas where a detailed landslide catalog is lacking when the same classification and weighting of available parameters was performed. The statistical analyses and adoption of an absolute scale ranging from minimum to maximum potential values ensure the comparability of results among different study areas.

The first case study at the local scale investigates the southwestern slope of Mount Marine, located in the Upper Aterno Valley (Central Italy). This area is shaped by active tectonics and geomorphological processes, including debris flows. By utilizing an integrated approach that combines morphometric, geological, and geomorphological analyses with remote sensing and field surveys, a comprehensive geomorphological map at a scale of 1:5,000 was developed. This map outlines the main landforms of the area, highlighting tectonic, litho-structural, slope, and fluvial features, as well as areas affected by human activities. A total of 32 debris flow systems were mapped, revealing variations in source areas, slope gradients, and depositional zones. These processes are closely associated with the active normal fault system, which drives slope instability by shaping steep gradients, generating structural discontinuities, and influencing sediment dynamics. The study also evaluated the impact of the 2020 wildfire, which exacerbated slope instability and triggered debris flows following intense rainfall. The resulting geomorphological map, combined with the debris flow inventory and susceptibility analyses, offers critical insights into the interaction between tectonic activity, lithology, and slope dynamics. It serves as an essential tool for land-use planning and hazard mitigation, identifying high-risk areas and guiding

strategies to mitigate the impacts of debris flows on infrastructure and communities in tectonically active regions.

The second study case at the local scale focuses on San Nicola Island, pertaining to the Tremiti Archipelago (Southern Adriatic Sea, Italy), which is widely affected by cliff retreat and gravitational phenomena that severely threaten its monumental historical and natural value. In this study, geomorphological features of the area were derived following a stepwise approach, combining multitemporal stereoscopic aerial photo interpretations with morphometric analyses and detailed field surveys. A rockfall susceptibility map was created following a heuristic approach based on morphometric and geothematic parameters, accounting for slope, slope aspect, outcropping lithologies, structural discontinuities density, distance from landslide scarps, and presence of anthropic caves. Cliff sectors set on dolomitic limestones feature the highest susceptibility values, especially along the southeastern sector; medium values, instead, are found along the island flanks and scarps located within the inner sectors, and the lowest values are detected on summit tabular surfaces. The results were compared with historical maps and seismic data derived from local and national archives and catalogs. These analyses allowed us to define the role played by litho-structural and tectonic features on landslide occurrence and distribution and their interplay in driving landscape evolution over centuries. Finally, this study represents a valuable scientific tool to support geomorphological studies for landslide hazard assessment and proper territorial planning in other small insular areas, showing similar geological–geomorphological features and landscape values.

The study's findings demonstrate that statistical techniques at the national level can effectively identify distribution patterns of earthquake-induced landslides (EILs) in relation to major seismological parameters. This highlights the methodology's robustness and applicability, even in regions with incomplete or inaccurate landslide inventories. The research contributes both theoretical insights and practical tools, advancing the understanding of EIL processes and providing a multidisciplinary framework to better assess conditions that could trigger hazards, such as landslides, following an earthquake. Ultimately, this work aims to facilitate sustainable territorial planning, enhance emergency management, and implement effective risk mitigation strategies in seismically active areas.

INTRODUCTION

Earthquakes are among the most dangerous natural phenomena, capable of causing extensive damage and loss of life. However, the dangers associated with earthquakes extend beyond the immediate effects of ground shaking. Secondary phenomena triggered by earthquakes, such as tsunamis, soil liquefaction, and landslides, often significantly contribute to the overall impact of these events. Among these phenomena, earthquake-induced landslides (EILs) are especially significant due to their frequency and destructive potential. These landslides pose considerable risks to human settlements, infrastructure, and activities, particularly in geomorphologically unstable or mountainous regions. Studying these phenomena allows for more accurate predictions of their occurrence, refining hazard models and providing insights to inform policies to reduce vulnerabilities and promote sustainable development in seismically active areas.

In the context of landslide risk analysis, the term susceptibility refers to the likelihood of a landslide occurring in an area based on the distribution of morphological, geological, and geomorphological predisposing factors when a triggering event is present. In the other hand, the concept of hazard encompasses the susceptibility aspect but also integrates the temporal probability, indicating the recurrence interval, and the intensity (or magnitude) of the event. Specifically, hazard analysis quantifies not only *where* a landslide might occur, but also *how large* and *how frequently* it may happen (Corominas et al., 2014; Guzzetti et al., 1999).

In recent years, probabilistic, statistical, and machine learning methods have come to the forefront in the EILs susceptibility and hazard assessment. These approaches seem offer some advantages over traditional methods:

- **Quantitative Analysis:** They provide robust frameworks for assessing the probabilities of landslide occurrences by systematically integrating multiple influencing factors.
- **Uncertainty Estimation:** Such methods enable the quantification of uncertainties, which is crucial for hazard assessment.
- **Reduced Subjectivity:** By relying on algorithms, these techniques minimize the subjectivity inherent in manual interpretations.
- **Computational Efficiency:** Modern algorithms can process large datasets quickly, allowing for a more comprehensive analysis of spatial and temporal factors.

However, a mandatory prerequisite for the effective application of these methods is the availability of a comprehensive and accurate landslide catalogue. The precision of probabilistic and statistical models is heavily dependent on the quality and completeness of the input data. When the landslide inventory is incomplete, inaccurate (see Chapter 3 and 4), or entirely absent (see Chapter 5), the performance of these advanced methods may be significantly compromised.

In such cases, geomorphological criteria, derived from observable field conditions and physical terrain characteristics, continue to provide valuable insights. These criteria serve as an essential alternative tool for assessing landslide susceptibility. They allow researchers to estimate landslide susceptibility based on morphological, geological, and geomorphological factors, even when comprehensive landslide records are not available. This approach offers a pragmatic solution for regions where data limitations pose a significant challenge for an accurate EILs susceptibility evaluation.

This research provides a comprehensive analysis of earthquake-induced landslide (EIL) susceptibility, aiming to enhance land-use planning and risk mitigation through a multi-scalar approach grounded in geomorphological criteria. By examining both the predisposing factors, defined by physiographic, geological, and geomorphological characteristics, and the seismic triggering factors derived from the seismotectonic context, the study deepens the understanding of EIL distribution and mechanisms. Conducted at national, regional, and local scales within selected areas of Italy, it offers valuable insights and reliable tools for improving hazard assessments and developing effective mitigation strategies.

The outcomes of the study demonstrate that statistical techniques at the national level can effectively delineate the distribution patterns of earthquake-induced landslides in relation to major seismological parameters. Geomorphology-based methods, particularly at regional and local scales, enable the development of accurate susceptibility and hazard maps for earthquake-induced landslides, even in contexts where landslide catalogs are absent, incomplete, or inaccurate. This approach provides practical solutions to support land use planning and hazard mitigation across different spatial scales. The multiscale approach bridges the gap between large-scale hazard assessments and detailed site-specific analyses, facilitating more accurate identification of hazard areas and the implementation of strategies for land use planning and post-event emergency management.

The thesis is structured into six chapters, each focusing on a specific aspect of problem.

The first part introduces the topic of EILs and their implications in susceptibility assessment, providing an overview of current knowledge about these phenomena and offering a comprehensive review of the existing literature. It focuses on the interplay between active tectonics, which over the long term creates predisposing geological and morphological factors, and landslide activity, which works to reduce the topographic gradient. Particular attention is given to the analyses of the predisposing factors and triggering mechanisms of EILs, as well as the methods for assessing EILs susceptibility and hazard. Finally the chapter provides an overview of the multiscale approach employed in this Thesis (**Chapter 1**).

In the second part of the Thesis (**Chapters 2 to 5**), the selected case studies are presented from small to large scale of analyses.

The first case study explores new empirical relationships between EILs density and seismological parameters using historical earthquake data from Italy (**Chapter 2**). This research is based on updated datasets and aims to provide more accurate tools for predicting landslide occurrence following seismic events. The main results are under submission to the journal *Geomorphology* (Elsevier) (Cinosi et al., Under Submission). Into detail the contribution I provided to this research encompassed the development and refinement of the methodological framework, data processing, the drafting of the manuscript, and the design and implementation of data visualizations.

The second study case from the Abruzzo region (Italy) reports on developing a susceptibility map for earthquake-induced landslides by combining morphometric, geological, and geomorphological factors (**Chapter 3**). The main results of this research are published in Carabella et al 2022. Into detail the contribution I provided to this research encompassed the development and refinement of the methodological framework, data collection and processing, the drafting of the manuscript, and the design and implementation of data visualizations.

The third case study examines debris flows along active fault escarpments in the Mount Marine Ridge area (Pizzoli (AQ), Abruzzo Region, Italy) by utilizing an integrated approach that combines morphometric, geological, and geomorphological analyses, including remote sensing and field data (**Chapter 4**). This method provides a comprehensive geomorphological characterization of the study area and offers insights into the combined

effects of seismic and hydrological factors on landslide activity. The main results are under submission to the Journal of Maps (Taylor & Francis) (Cinosi et al., Under Submission). into detail the contribution I provided to this research encompassed the development and refinement of the methodological framework, data collection and processing, the drafting of the manuscript, and the design and implementation of data visualizations.

The last case study (**Chapter 5**) focuses on San Nicola Island, located within the Tremiti Islands archipelago in the Adriatic Sea, Italy. This chapter explores the impact of seismic activity on small-scale geomorphological processes in a coastal environment. The primary findings of this research are published in Cinosi et al., 2023. Into detail the contribution I provided to this research encompassed the development and refinement of the methodological framework, data collection and processing, the drafting of the manuscript, and the design and implementation of data visualizations.

Finally, **Chapter 6** synthesizes the overall findings of the research, emphasizing the crucial role of multiscale approaches in understanding EILs and developing effective disaster risk reduction strategies. The conclusions highlight the importance of integrating geotechnical, hydrological, and seismic data across various scales to improve territorial planning and lessen the impact of natural hazards.

This thesis provides theoretical insights and practical methodologies that enhance EILs research and susceptibility assessment, serving as a valuable resource for land management and risk mitigation in seismic contexts regions.

1 LANDSLIDES HAZARD IN SEISMIC AREAS

1.1 Introduction

Natural hazards are processes that can trigger disasters (Chaudhary et al., 2021). Academic research on natural hazards developed in response to the challenges raised by scientific paradigms and focused on two main aspects: the dynamics of natural processes and strategies for adapting to them and the public's perception and understanding of physical phenomena, which can contribute to the development of mitigation measures (Cutter, 2001; Gares et al., 1994; White, 1974). Although different conceptualizations of natural hazards have arisen over time, reflecting the approaches of different disciplines, the field remains characterized by an emphasis on human responses to physical phenomena.

Hazards could be gradual or sudden and could have serious costs for social and environmental systems, such as casualties and economic loss. Reducing damage to human activities and buildings (such as settlements, agriculture, and infrastructure) during natural disasters is an expected outcome of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015). In this context, disaster risk reduction is becoming increasingly important due to environmental changes (Paleari, 2018; Ward et al., 2020) and recent catastrophic events worldwide. Furthermore, analyzing and assessing natural hazards is essential for future research in this expanding field (Assilzadeh et al., 2010; Newman et al., 2017; Youssef et al., 2022).

There is a wide range of geomorphological hazards (e.g., landslides, floods, snow avalanches). They are defined as the potential occurrence of highly dynamic or large-scale destructive phenomena at a specific place and time. The significance of these features lies in the response of the landforms to the processes rather than in their source (Gares et al., 1994).

Landslides are the most widespread natural disasters worldwide and in Italy (Dandridge et al., 2023; Herrera et al., 2018; Petrucci, 2022; Salvati et al., 2010). These result from the dynamic combination of geological, meteorological, and environmental processes, with landscape features under the influence of human activities. Their occurrence may significantly affect human settlements and activities, causing damage to properties and infrastructures, serious injuries and fatalities, and economic losses (Salvati et al., 2018; Summers et al., 2018).

Landslides are among the most important and frequent natural hazards, as they can directly impact people, infrastructures, economic activities, and social and environmental

systems (Haque et al., 2016; Kjekstad and Highland, 2009). Landslides are a landscape modeling process that induces pervasive geomorphic changes with spatiotemporal occurrences regulated by controlling factors (i.e., morphology, litho-structural setting, land use, climate, etc.) and triggering factors (e.g., heavy rainfall events, snowmelt, earthquakes, wildfires, human activities, etc.) (Coco and Buccolini, 2015; Crosta, 1998; Livio and Ferrario, 2020; Rengers et al., 2020). Many of the triggering factors are only sufficient conditions for the occurrence of landslides, which are occasional and sudden. Therefore, it is crucial to consider predisposing factors in landslide analysis to correctly assess the relationships between geological/geomorphological framework, seismotectonic context, and slope instability phenomena.

Seismic events represent one of the most significant natural hazards and could induce a wide range of geomorphological effects on landscapes. These phenomena, referred to as Earthquake Environmental Effects (EEE), include not only surface faulting but also a series of secondary effects such as landslides, liquefaction, ground subsidence, and changes in fluvial dynamics (Guerrieri, 2015; Naik et al., 2023). Among these, Earthquake-Induced Landslides (EILs) are among the most common and damaging secondary hazards in seismic areas (Fan et al., 2019), posing serious risks to human infrastructure and contributing to the long-term evolution of landscapes. Beyond the immediate hazard posed by EILs, seismic activity also plays a critical role in the long-term evolution of landscapes. The process of tectonic uplift creates a steep topography prone to landslides. In contrast, the landslides act as agents of erosion, gradually reducing relief and redistributing sediments across the landscape. Over time, this dynamic interplay between tectonics and erosion shapes the form of mountain ranges, valleys, and plains (Figure 1.1).

In this context, the term geomorphological hazard refers to processes that shape the Earth's surface, driven by exogenic forces such as those related to surface water, aeolian, karts, and weathering process. The interplay between exogenic forces and seismic activity can accelerate and intensify these processes, leading to abrupt and often catastrophic landscape changes. Seismic shaking reduces slope stability, particularly in mountainous or hilly regions where steep topography and weakened geological materials make the landscape more vulnerable due to fractures or weathering. The potential for landslide-triggering increases significantly when strong ground motion interacts with pre-existing geomorphological factors such as slope inclination, soil type, and hydrological conditions (Dahal et al., 2023).

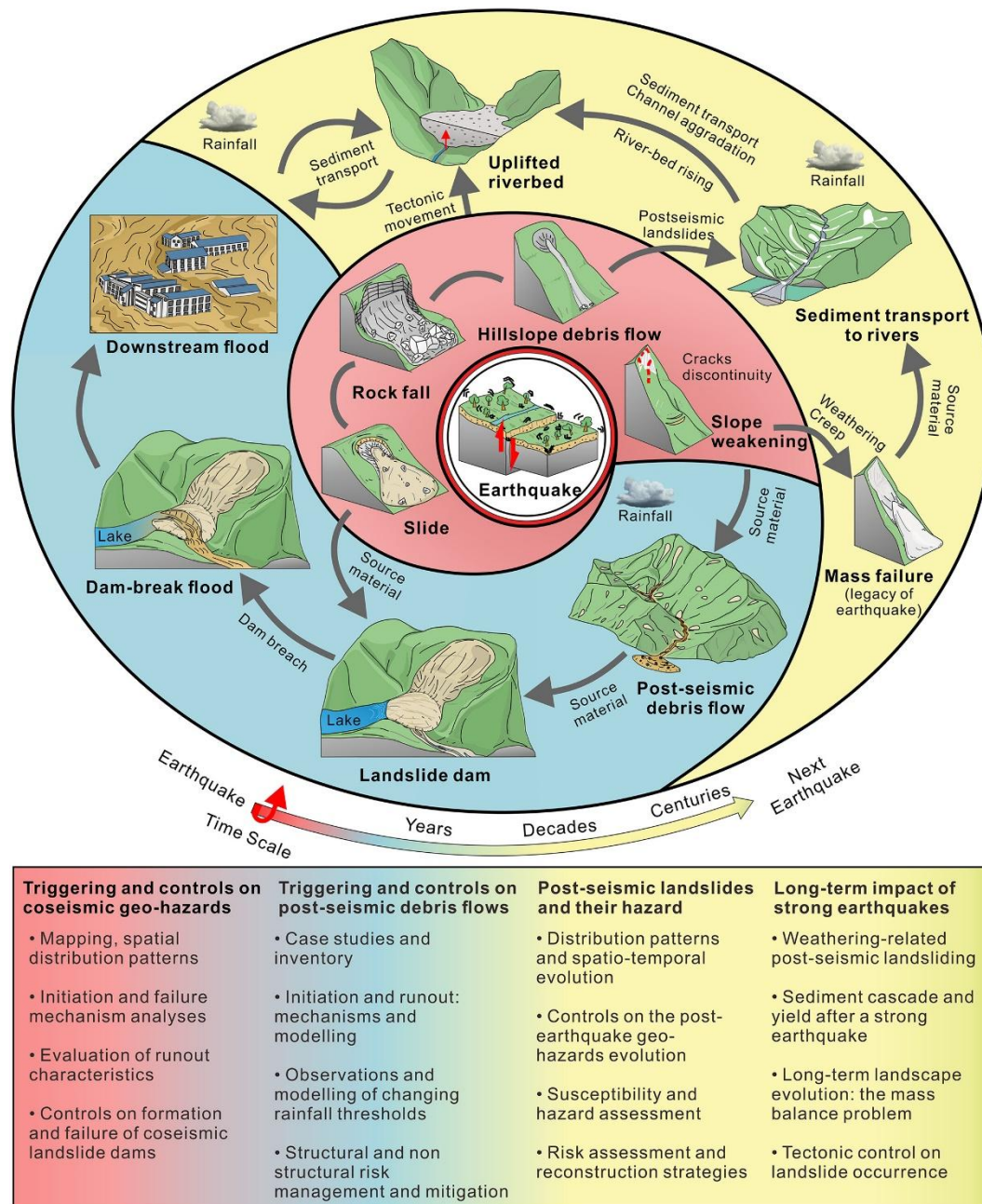


Figure 1.1. The sequence of geological hazards initiated by a strong earthquake is illustrated by arrows indicating the causal links between hazards. The red background highlights the different types of landslides triggered during the seismic event, while the blue background depicts the hazards that emerged in the post-seismic period, from days to years after the earthquake. The yellow background represents the earthquake's long-term effects, spanning years to decades — figure from (Fan et al., 2019).

The study of the influence exerted by seismic activity in slope failure is paramount for understanding the potential risks posed by EILs and the long-term evolution of the Earth's surface in seismic areas. Integrating seismological data, geological surveys, and landslide inventories provides the basis for more accurate susceptibility and hazard assessments and

more effective risk mitigation strategies in regions like Italy, where seismic and geomorphological processes are deeply connected.

A comprehensive understanding of these phenomena is essential for analyzing past events, developing models for predicting landslides, and designing effective mitigation strategies. These analyses typically require mapping, modeling, and developing management strategies, often supported by field surveys, photogrammetry, GIS, and remote sensing (RS) data for identifying and mapping hazard-prone areas.

Modeling approaches seek to integrate past and current event data to facilitate more precise predictions regarding the potential impacts of EILs on specific landscapes. Thematic mapping is the primary method for presenting research results and synthesizing the various techniques to depict hazardous phenomena in natural and urban settings (Lee, 2001). The contemporary cartographic methods employed in the assessment of hazards encompass the generation of input data, including maps of contributing or triggering factors and inventories of past events (e.g., Dai et al., 2011; Farabollini et al., 2021; Hasegawa et al., 2009; Polykretis et al., 2019; Zei et al., 2024a), combining criteria such as resolution, mapping units, classification systems, and validation methods (Bufalini et al., 2021; Martinello et al., 2021). Geomorphological mapping is an effective tool in both academic and applied contexts (Smith et al., 2011). It has reached a level of maturity that allows it to be systematically applied to produce thematic maps that visually represent EILs susceptibility and hazard and facilitate risk assessment (Chelli et al., 2021).

1.2 Earthquake-Induced Landslides (EILs)

1.2.1 Types of Earthquake-Induced Landslides

EILs refer to the displacement of rock, soil, or debris induced or promoted by seismic activity. Earthquakes' ground shaking could reduce slope stability, increasing stress conditions on the slope or lowering the strength of slope materials (Fan et al., 2019; Keefer, 1984, 2002; Kinsey et al., 2021; Livio and Ferrario, 2020; Rodríguez et al., 1999; Tang et al., 2016). Different landslide types could be more or less susceptible to be triggered by earthquakes (Tang et al., 2021); they can range from small rockfalls to massive earth and debris flows, depending on the magnitude of the earthquake and local geological and geomorphological conditions. The most common types of landslides include:

- **Rockfalls:** In steep, rocky slopes, rockfalls are one of the most common EILs types. Seismic shaking could lead to the detachment of rock blocks along pre-

existing discontinuities such as joints, fractures, or bedding planes (Figure 1.2a). The sudden loss of strength along these planes results in the rapid downward movement of these blocks in free fall or bouncing trajectories. Earthquake-induced rockfalls are particularly common in mountainous regions and coastal cliffs characterized by slopes already close to the stability threshold (Meunier et al., 2008; Saroglou, 2019). Given the minimal force required to destabilize unstable blocks, even relatively small earthquakes can lead to falls in these environments.

- **Rock Topples:** In areas characterized by outcrops consisting of high-angle tilted, layered rock or that features high-angle weak planes, toppling, which involves the forward rotation of a block of rock about a pivot point (Figure 1.2b), can be induced by seismic shaking. Topples are often recorded in areas of highly fractured rock masses or steeply dipping strata, where seismic forces can initiate their failure (Guo et al., 2017, 2023)
- **Slides:** Translational slides, which are highly susceptible to earthquake-induced failure, occur when a mass of rock, soil, or debris moves downslope along a planar weak surface (Figure 1.2c). Seismic shaking could reduce the shear strength of these surfaces by inducing shear stresses exceeding material strength or liquefying loose sandy saturated layers (Harp and Jibson, 1995; Nakamura et al., 2014; Xu et al., 2022). Since these mass movements generally involve larger volumes of material and occur over a wider area, they can be more destructive than falls or topples. Earthquake-induced translational slides were widely documented after major seismic events, including the 1999 Chi-Chi earthquake in Taiwan and the 2015 Gorkha earthquake in Nepal (Chen et al., 2006; Roback et al., 2018). On the other hand, rotational slides are less commonly induced by earthquakes because their failure mechanism involves deeper-seated, curved slip surfaces. Rotational slides (Figure 1.2d) require significant displacement along these surfaces, which is not always easily mobilized by seismic shaking alone. However, seismic events can trigger rotational slides if the earthquake magnitude is sufficiently high, and the material is already close to failure. For example, rotational slides were observed in cohesive soils destabilized by protracted wet conditions followed by seismic events (Martino et al., 2022).

- **Lateral spread:** Lateral spreading is another type of landslide, often triggered by large earthquakes. These movements occur when a mass of cohesive soil or rock spreads horizontally over a weaker or liquefiable layer (Figure 1.2e). During earthquakes, the underlying weak layers can lose their strength, causing the overlying material to spread laterally (Lingwall et al., 2018). Notable cases of earthquake-induced lateral spreading include the large ones that occurred after 1964 Alaska and 2011 Christchurch (New Zealand) earthquakes (Araujo and Ledezma, 2020; Cubrinovski et al., 2012; Cubrinovski and Robinson, 2016).
- **Mud/Debris flows:** In areas with extensive deposits of loose, unconsolidated material on steep slopes and with incised morphologies that favor channelization of surface water runoff, earthquakes can help create predisposing conditions for triggering debris and mud flows (Figure 1.2f). Seismic action can destabilize these materials by shaking (He et al., 2022) or by liquefaction of saturated soil (Coviello et al., 2021), resulting in rapid debris flows mixed with water. Debris flows, which are mixtures of soil, unsorted blocks, and water, can be extremely destructive, especially when triggered by the combination of seismic shaking and heavy rainfall or rapid snowmelt (Chen and Petley, 2005; Fan et al., 2019; Pierson et al., 1990). These flows can travel long distances at high velocities and carry large amounts of material in their path, as seen after the 2015 Gorkha earthquake in Nepal (Dahlquist and West, 2019). Similarly, mudflows consisting mainly of finer materials such as silt and clay can also be triggered by earthquakes, especially in volcanic regions or areas with abundant loose, saturated soils (Pu et al., 2021).
- **Complex landslides:** This type of movement involves two or more failure mechanisms (i.e., a slide may transition to a flow as the mass of material disintegrates during movement) and is often triggered by earthquakes. Complex landslides are particularly challenging to predict and manage because the initial failure mechanism can evolve into multiple movement phases, each with different characteristics and hazards. Earthquakes potentially enhance this complexity by triggering multiple simultaneous failure mechanisms.

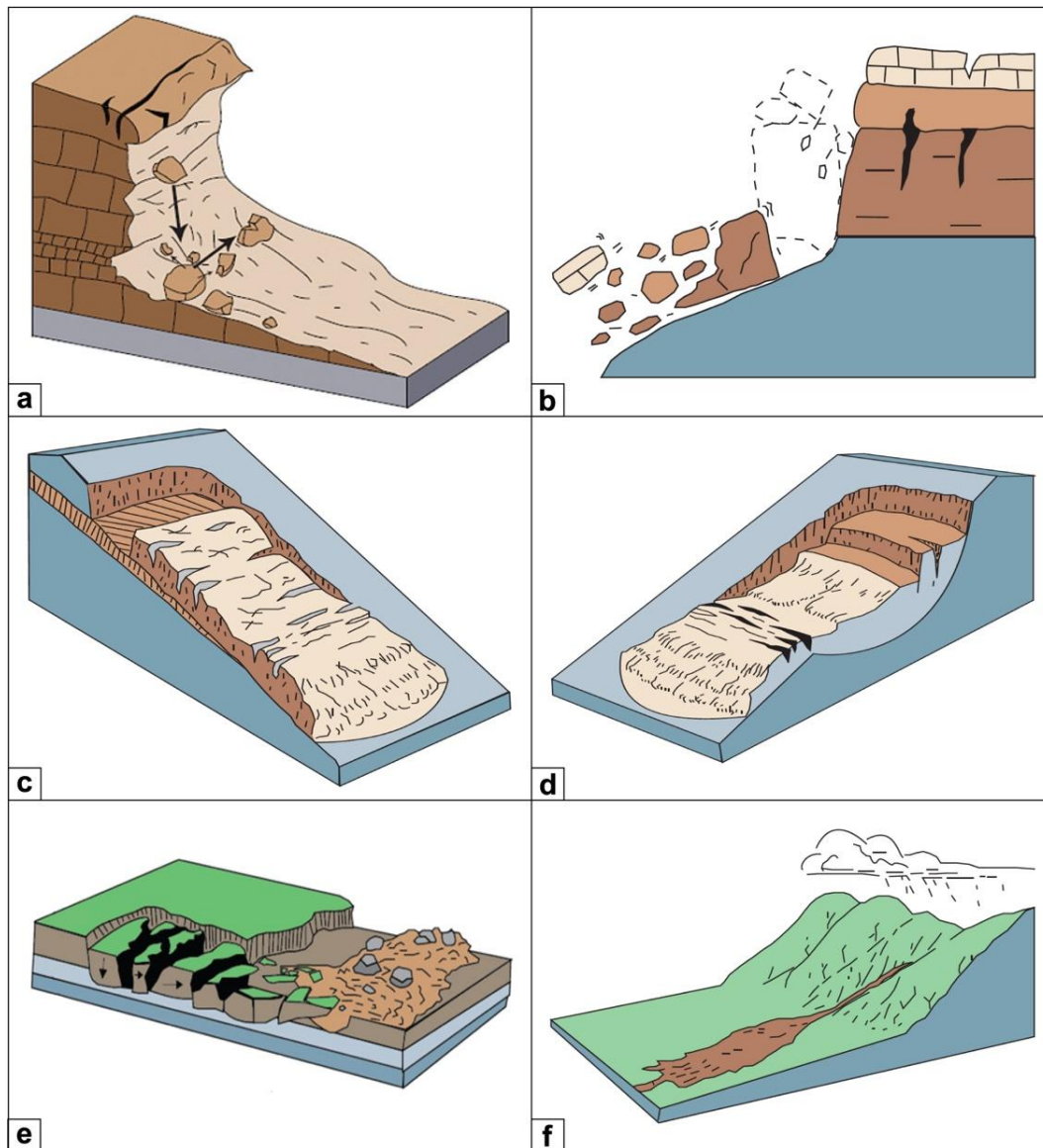


Figure 1.2. Schematic models of principal earthquake-induced landslide types: a) Rockfall; b) Rock topple; c) Translational slide; d) Rotational slide; e) Lateral spread; f) Debris flow (modified from Highland and Bobrowsky, 2008).

1.2.2 Long-Term Landslide Hazards: The Impact of Seismic and Climatic Interactions

The state of landslide activity plays a key role in assessing long-term hazard and reactivation potential. Landslides can be categorized according to their current and potential future activity, as defined by the Working Party on World Landslide Inventory (UNESCO WP\WLI, 1993).

- Active landslide: moving at the time of observation,
- Suspended active landslide: moved in the last seasonal cycle but is currently inactive,
- Reactivated landslide: has moved again after a period of inactivity,

- Inactive landslide: last moved before the previous seasonal cycle. The latter can be further divided into dormant, if the movement can be reactivated by the causes that triggered it; naturally stabilized, if it can no longer be influenced by the original causes, the causes of movement have been naturally removed; artificially stabilized, if it has been stabilized by anthropic measures; relict landslide if it has developed under geomorphologic or climatic conditions significantly different from the present ones.

Seismic activity also plays a critical role in assessing long-term landslide hazards and reactivation potential in both the initiation of new landslides and the reactivation of existing ones. Earthquakes can act as primary triggers or contributing factors to slope failures, particularly in regions where slopes are already susceptible due to geological, geomorphological, or climatic conditions. The interaction between seismic activity and climatic factors such as intense rainfall or rapid snow melt could complicate the assessment of landslide activity, particularly concerning lowering rainfall thresholds for slope failure initiation. In tectonically active regions, the triggering of new landslides by earthquakes was well documented in the scientific literature (Chen et al., 2024; Ma et al., 2023; Seal et al., 2023; Tiwari et al., 2017; Zhang et al., 2019). During an earthquake, ground shaking increases stresses on slopes and can reduce the shear strength of slope materials through dynamic loading, liquefaction, or fracturing of cohesive layers. Large earthquakes greater than magnitude 5.0 are known to trigger several types of landslides, including rockfalls, debris flows, and translational slides, particularly on steep, fractured slopes or in areas of pre-existing weakness (Fan et al., 2019; Keefer, 1984; Nakamura et al., 2014; Sassa et al., 1996). Even moderate earthquakes can induce significant landslide activity in areas with highly weathered materials or weak lithologies.

However, seismically induced landslides are often not limited to the immediate post-earthquake period. The destabilization caused by ground shaking can significantly weaken the slope, leading to slope failures delayed days, weeks, or even years after the seismic event (Dai et al., 2011; Fan et al., 2019; Marc et al., 2015; Tanyaş et al., 2021; Xu et al., 2014).

In areas where slopes have previously moved frequently, seismic activity led to the reactivation of pre-existing landslides, particularly where conditions are near the failure threshold. Seismic shaking can significantly reduce the stability of slopes that have already been weakened by weathering, water table oscillation, or long-term deformation (Ruggeri et al., 2020). These reactivations are particularly common in dormant or inactive landslides

where the original triggers, such as heavy rainfall or tectonic activity, are no longer present. Earthquakes can reinitiate movement by disrupting the slope equilibrium through direct ground shaking or secondary effects such as liquefaction, which can undermine the shear strength of the slope material.

Another relevant aspect is the interaction between seismic activity and climatic factors, particularly precipitation, which significantly influences landslide hazard. Rainfall is widely considered to be the primary driver of slope failure because it contributes to increased pore water pressure, reduces matric suction, and leads to slope saturation, all of which reduce the overall stability of the slope (Lashgari et al., 2024; Mahmood et al., 2016). However, the contribution of seismic shaking can lower the rainfall thresholds required to trigger a landslide. Several studies have shown that in areas hit by an earthquake, slopes become more susceptible to failure even under lower-intensity rainfall events due to the cumulative effects of ground shaking that weakens the structural integrity of the slope (Leshchinsky et al., 2021; Lin et al., 2006; Marc et al., 2015). This phenomenon is particularly evident in regions with frequent seismic activity and high precipitation, where landslides are triggered by moderate rainfall events following an earthquake, compared to the higher rainfall intensities typically required during non-seismic periods (Lin et al., 2006; Liu et al., 2021; Segoni et al., 2014; Yu et al., 2014); on the other hand, heavy or prolonged rainfall can weaken the slopes, making it possible to trigger EILs even with moderate magnitude earthquakes (Martino et al., 2020a).

1.2.3 Landslide Factors and Triggering Mechanisms in Seismic Areas

EILs are mainly triggered by ground acceleration and changes in pore water pressure induced by seismic shaking. Ground acceleration, commonly measured as peak ground acceleration (PGA), directly affects slope stability by applying a dynamic load that can exceed the shear strength of slope materials. In regions exhibiting elevated PGA values, stability condition deterioration in consolidated rock formations and unconsolidated surface materials can result in a spectrum of landslide types, encompassing shallow debris flows and deep-seated slides (Gratchev, 2023). This phenomenon is significant in tectonically active regions, such as the Central Apennines, where the combination of frequent seismicity and steep topography gives rise to an unstable geomorphological setting.

Seismic cyclic loading can induce changes in pore water pressure in saturated loose sandy deposits, which can also significantly impact slope stability. This process results in a reduction of effective stress, which in turn leads to a decrease in shear strength, thereby

enhancing the susceptibility of the slope to failure (Matsunami et al., 2024; Nguyen et al., 2020; Wang and Sassa, 2009). Regions that experience heavy rainfall prior to seismic events are more prone to landslides, as elevated water content further increases the likelihood of failure (Leshchinsky et al., 2021; Martino et al., 2022). Therefore, the combination of seismic acceleration, pre-existing hydrological conditions, and local geotechnical factors such as slope geometry and soil composition exert a critical role in the landslide distribution in seismic areas.

Morphological, lithological, structural, and geomorphological characteristics of the slopes may influence its susceptibility to failure (Table 1.1). The slope exerts significant control over stability conditions, with a higher gradient typically associated with a higher probability of event occurrence (Çevik and Topal, 2003; Yalcin et al., 2011). The slope aspect can also exert an influence on slope stability by affecting the amount of solar radiation intercepted by the surface, which in turn affects the microclimate conditions (Capitani et al., 2013; Pham et al., 2017). Topographic curvature significantly impacts the susceptibility to rockfall events, with convex slopes exhibiting the highest likelihood of such occurrences (Bajni et al., 2023). Additionally, it influences seismic wave propagation and dispersion, directly affecting ground motion (Pischiutta et al., 2017). The intrinsic properties of rock masses exert a direct influence on slope stability, with outcropping lithologies playing a pivotal role in determining landslide typology and distribution (Esposito et al., 2021; Henriques et al., 2015). Structure discontinuities, defined as faults or tectonic fracture systems, natural or anthropogenic caves, and other elements that reduce slope strength, play an indisputable role in hillslope stability. They determine the mechanisms of failure and the geometry of landslides (Khan et al., 2019; Lee and Dan, 2005; Parise and Lollino, 2011). The degree of karstification of carbonate and evaporite rocks also affects landslide susceptibility. Potential caves may collapse in response to earthquakes, as well as exhibit instability phenomena linked to differential erosion rates, sliding along weak surfaces, and other factors (Andriani and Loiotine, 2020; El-Haddad et al., 2022; Santo et al., 2007). The distance from active faults and epicenters also plays a significant role in EILs. There is a discernible decline in the occurrence of triggered phenomena as one moves away from fault traces or epicentral areas, which is attributed to the attenuation of the seismic input (Keefer, 1984, 2002; Livio and Ferrario, 2020; Rodríguez et al., 1999). Moreover, the proximity to faults can affect landslide susceptibility due to the influence of structural discontinuities on rock weathering processes (Conforti et al., 2011).

Table 1.1. Summary of key factors influencing landslide susceptibility.

Macro-category	Factors	Influence on susceptibility	References
Morphological	Slope gradient	Steeper slopes increase failure probability due to gravitational stress.	Çevik and Topal (2003); Yalcin et al. (2011)
	Slope aspect	Orientation affects solar radiation exposure, influencing microclimate (e.g., moisture, ice-thaw cycles).	Capitani et al. (2013); Pham et al. (2017)
	Topographic curvature	Convex slopes promote rockfall; concave slopes may retain debris. Modulates seismic wave propagation.	Bajni et al. (2023); Pischiutta et al. (2017)
Lithological	Rock mechanical properties	Weak or weathered lithologies (e.g., clay, shale) are prone to sliding; resistant rocks favor toppling.	Esposito et al. (2021); Henriques et al. (2015)
	Degree of karstification	Collapse of caves, differential erosion, and sliding along weak surfaces in carbonate/evaporite rocks.	Andriani and Loiotine (2020); El-Haddad et al. (2022)
Seismotectonic	Distance to active faults/epicenters	Higher landslide density near seismic sources due to ground shaking and fault-induced weakening.	Keefer (1984, 2002); Livio and Ferrario (2020)
	Structural discontinuities	Reduce slope stability by creating planes of weakness; could control landslide geometry and mechanisms.	Khan et al. (2019); Parise and Lollino (2011)
	Seismic wave propagation	Amplification of seismic wave due to topographic and stratigraphic factors.	Pischiutta et al. (2017)
Climatic	Microclimatic conditions	Slope aspect-driven solar radiation regulates moisture, freeze-thaw cycles, and soil weathering.	Pham et al. (2017); Capitani et al. (2013)
	Precipitation patterns	Heavy rainfall saturates soils, increasing pore pressure and reducing shear strength.	Guzzetti et al., 2012

1.3 EILs Susceptibility and Hazard Assessment Methods

The study on EILs is primarily concerned with three principal aspects: EILs susceptibility, hazard, and risk evaluation. This work focuses on susceptibility and hazard assessment. EILs susceptibility mapping, or zonation, is the classification of an area into different zones based on the likelihood of landslide events. This process considers factors such as the spatial distribution, size, location, and movement of landslide deposits

(Corominas et al., 2014; Fell et al., 2008; Guzzetti et al., 1999; Shao and Xu, 2022; Varnes, 1984). Similarly, EILs hazard mapping divides an area into zones that reflect both the spatial and temporal probability of landslides induced by an earthquake, providing information on the location, potential volume, and predictions of future landslide events in the region (Fell et al., 2008; Glade et al., 2005; Lu et al., 2024; Shano et al., 2020).

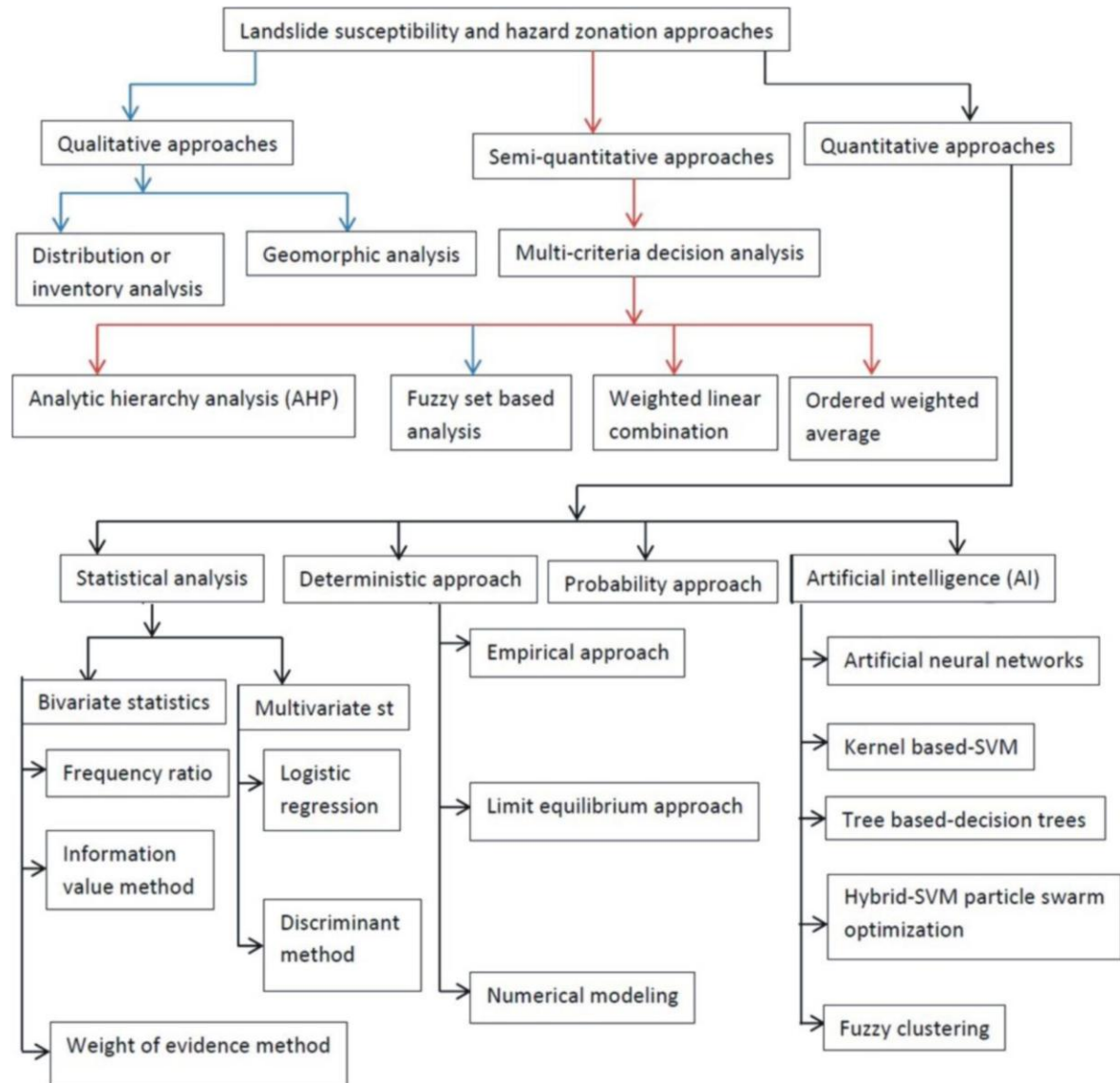


Figure 1.3. Summary chart of the main landslide susceptibility and hazard assessment methods proposed in the literature (Shano et al., 2020).

Different approaches have been developed over the years; these methods could be referred into four main categories: heuristic, probabilistic, statistical (including machine learning), and deterministic (Figure 1.3; Bojadjieva et al., 2018; Guzzetti et al., 1999; Shano et al., 2020). Each method has specific strengths and limitations, depending on the available data, the studied area, the scale of the analysis, and the aims of the works.

1.3.1 Heuristic Methods

Heuristic methods are based on assessing EILs susceptibility or hazard by overlaying thematic maps of the different predisposing and triggering factors and assessing the relative importance of each factor in influencing landslide occurrence. Each parameter (input data) is divided into classes, and each is assigned a numerical weight according to its greater or lesser propensity to cause slope failure (Kouli et al., 2010; Leoni et al., 2015; Magliulo et al., 2009; Raghuvanshi et al., 2015; Ruff and Czurda, 2008; Saha et al., 2002). These methods are based on expert judgment and allow the assessment of seismic landslide susceptibility and hazard at different scales, even when landslide catalogs are absent, scarce, or inaccurate.

Generally, the methodologies adhere to a systematic series of steps, encompassing the identification of parameters that affect slope stability. The selected parameter is divided into an appropriate number of classes, each of which is assigned a weight. The thematic maps for the weighted parameters are then overlaid and summed. This process results in a map with numerical values representing landslide susceptibility or hazard values, which are then divided into classes. The most widely used heuristic method is the Landslide Potential Index (LPI) method (Gholami et al., 2019; Meten et al., 2015) based on a weighted sum of considered factors.

These methods are applicable at any scale and in all contexts. Their primary advantages are that they can be applied even in areas where the amount of information and studies are limited and that the results are not affected by the quality of the catalogs. Conversely, the major disadvantages are related to the subjectivity with which landslide related factors are chosen and weighted within the model and the difficulty of adapting the results obtained in one area to other regions.

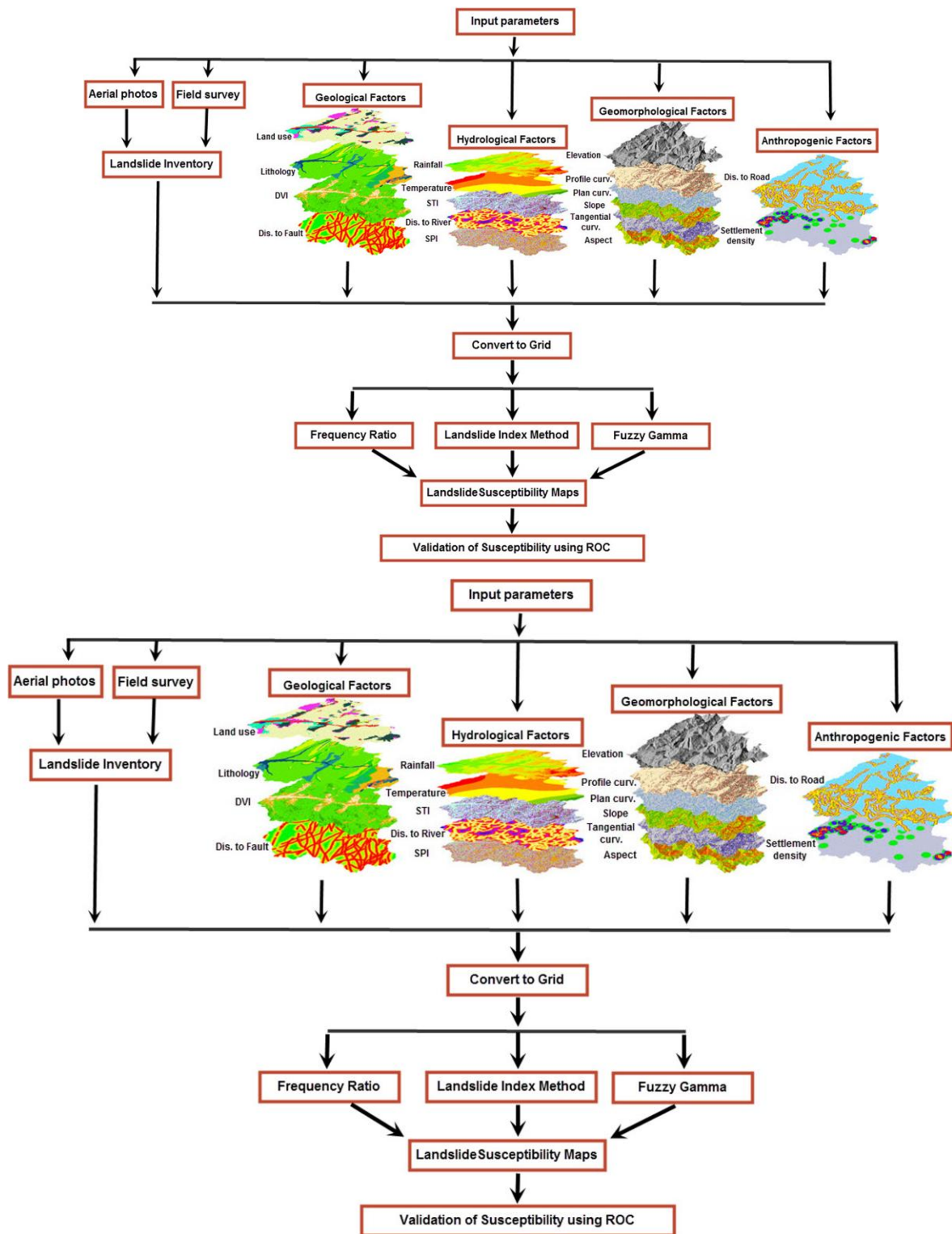


Figure 1.4. Example of a flowchart for landslide susceptibility assessment by heuristic method (Landslide Potential Index; LPI) from Gholami et al. (2019)

1.3.2 Probabilistic Methods

Probabilistic methods assess EILs susceptibility or hazard by estimating the probability of occurrence based on the relationship between past landslides and various triggering factors. These methods integrate uncertainty, making them valuable in regions

prone to seismic activity. The fundamental principle of probabilistic methodologies is integrating historical landslide data with environmental and seismic variables to assess the probability of future landslide occurrences.

These methods typically involve combining landslide inventory data with morphometry, rock and soil type, climatic factors, and seismic activity parameters. The frequency and magnitude of previous seismic events are essential in determining the potential occurrence of future landslides in seismically active areas (Chen et al., 2022; Jibson and Tanyaş, 2020). This probabilistic framework allows for the creation of comprehensive hazard maps that quantify the probability of landslide occurrence within a specified area. Such maps can inform land-use planning and infrastructure development, particularly in regions where seismic activity is a significant factor (Guzzetti et al., 2005).

In recent years, several studies applied probabilistic methods for EILs susceptibility and hazard evaluations (e.g., Caccavale et al., 2017; Rajabi et al., 2013; Refice and Capolongo, 2002; Rodríguez-Peces et al., 2020; Song et al., 2018). These models incorporated seismic data, such as the magnitude and frequency of earthquakes, and terrain features, like slope angle and soil composition. By calculating the probability distribution of landslides triggered by earthquakes, these models (e.g., Figure 1.5) produce hazard maps useful for risk mitigation strategies.

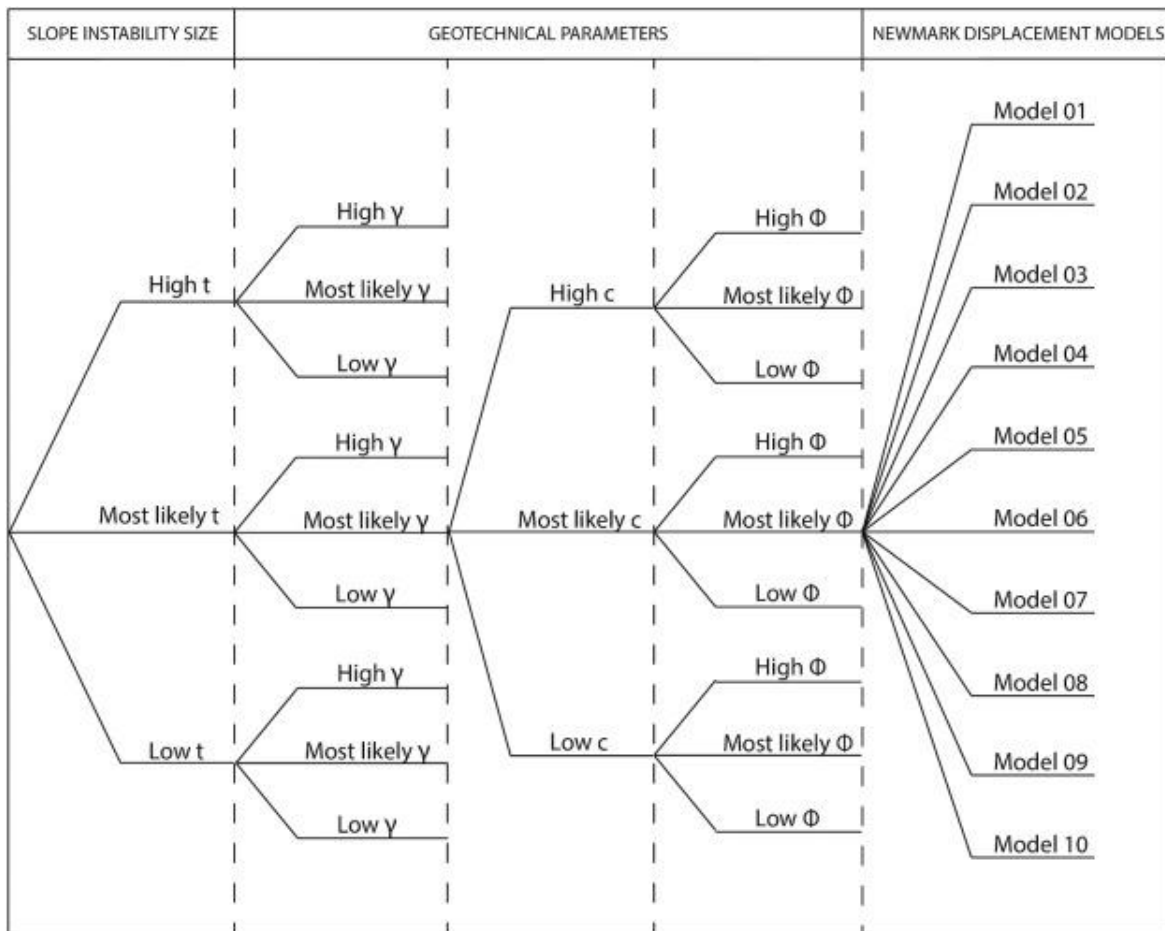


Figure 1.5. Example of a scheme of the structure of a logic tree for a probabilistic landslide hazard assessment from Rodríguez-Peces et al. (2020)

Probabilistic methods are widely recognized for their capability to account for uncertainty in the data and provide a quantitative framework for hazard assessment (Guzzetti et al., 2005; Lari et al., 2014; Lee and Talib, 2005). However, these methods' limitations are that they require comprehensive and high-quality landslide inventories and accurate seismic data, which may not always be readily available. Nevertheless, they offer a robust, data-driven approach to assessing landslide susceptibility in regions with complex triggering factors.

1.3.3 Statistical and Machine Learning Methods

Statistical methods are based on data-driven approaches to assess EILs susceptibility or hazard. This is achieved by evaluating the statistical correlation between the distribution of conditioning factors (e.g., slope, lithology, rainfall, and seismicity) and past landslides. Quantitative assessment of susceptibility/hazard is done by assigning a weight, through statistical analysis, to each class of each parameter that contributes to instability (Carrara et al., 1991; Falaschi et al., 2009; Lee, 2014; Trigila et al., 2015). The weights are calculated

with relationships that consider the spatial relationship between the area occupied by each class and the landslide area in the same class (Marsala et al., 2019; Polykretis et al., 2019). Logistic regression is a common statistical method used to evaluate landslide susceptibility, whereby the probability of a landslide is modeled based on multiple independent factors (Falaschi et al., 2009; Pokharel et al., 2021; Trigila et al., 2015; Yalcin et al., 2011).

In recent years, the development of Machine Learning (ML) techniques has led to significant advances in the field, enabling the identification of complex, non-linear relationships that extend traditional statistical approaches (Pradhan and Lee, 2010).

In general, the methodologies require a series of steps, starting with selecting parameters that influence landslide occurrence. In regions with a high frequency of seismic activity, ML techniques such as Support Vector Machines (SVM) and Artificial Neural Networks (ANN) could outperform traditional methods in complex datasets (Figure 1.6; Colkesen et al., 2016; Karam et al., 2019; Kavzoglu et al., 2014; Lee and Evangelista, 2006; Li et al., 2012; Liang et al., 2020; Merghadi et al., 2020; Sun et al., 2022; Tian et al., 2019; Xie et al., 2018).

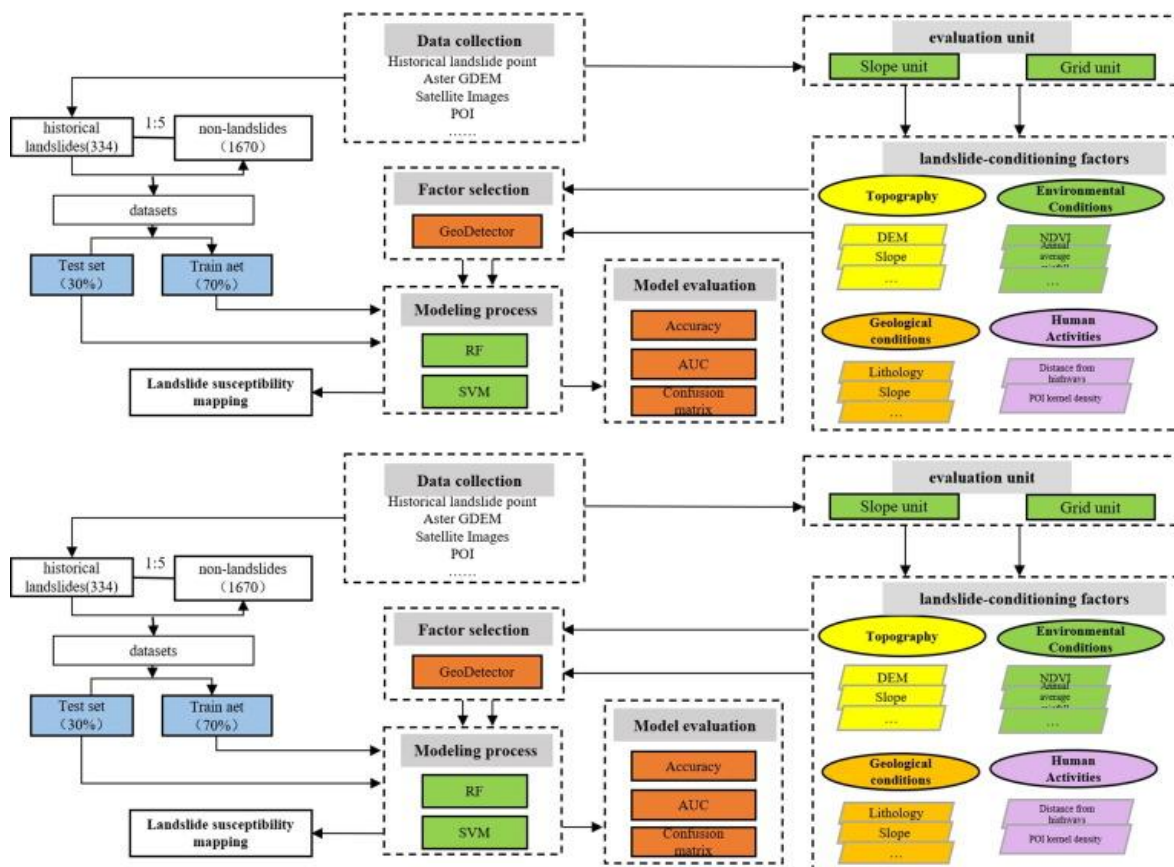


Figure 1.6. Example of a flowchart for landslide susceptibility assessment by different machine learning methods (Random Forest and support vector machine) from Sun et al. (2022).

These methods are particularly valuable in regions with high seismicity, where traditional statistical methods may be inadequate for catching the complex interactions among factors; however, it should be noted that the robustness of these methods depends on the quality of the available data. Furthermore, while ML models offer valuable insights, they typically require extensive training datasets and may be less interpretable than simpler statistical models (Goetz et al., 2015). The primary advantages of these methods lie in their capability to handle complex relationships in large datasets and provide a robust framework for assessing landslide susceptibility. Conversely, the main disadvantages include the dependence on high-quality data and potentially reduced interpretability compared to traditional statistical approaches.

1.3.4 Deterministic Methods

Deterministic methods are based on computing slopes' Factor of Safety (FoS) by applying limit equilibrium stability analysis (Figure 1.7). The deterministic methods may be one-, two-, or three-dimensional, contingent upon the intricacy of the equations utilized to resolve the physical laws delineating the conditions of rupture, displacement, and arrest of landslide bodies. The modeling of landslide phenomena requires the input of slope geometry and local geotechnical data, including cohesion, interstitial pressure and shear strength, water table level, thicknesses of surficial deposits, and, in the case of EILs analysis, the expected seismic acceleration at the site for a reference earthquake (Montgomery and Dietrich, 1994; van Westen and Terlien, 1996; Zizioli et al., 2013). Consequently, comprehensive field surveys and a wide range of in situ and laboratory tests are necessary to obtain these data.

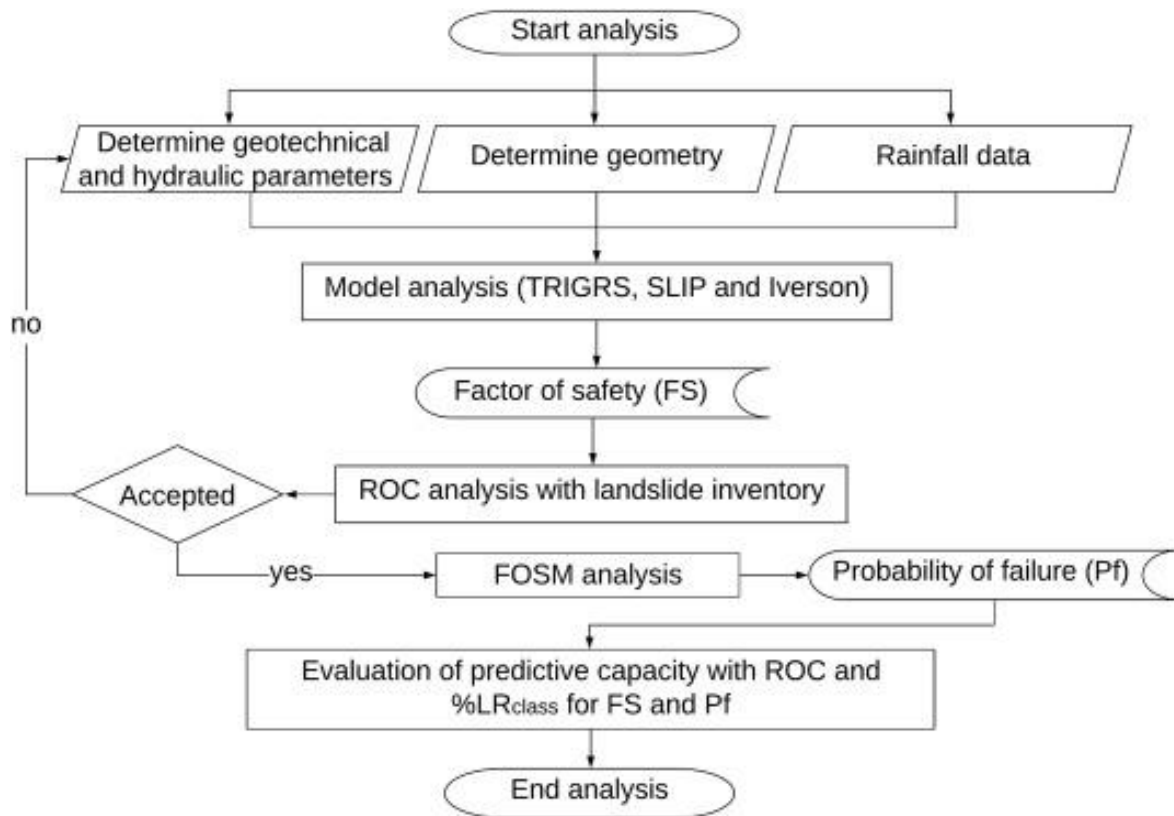


Figure 1.7. Example of a flowchart for landslide hazard assessment by a deterministic approach from Marin et al. (2021).

These methods are of great value in the context of engineering projects and site-specific analyses, as they can be effectively employed to model individual slopes or construction sites where detailed geotechnical data can be gathered. Conversely, the main limitations lie in their feasibility for regional-scale assessments due to the required data and computational resources (Marin et al., 2021).

1.4 The Role of Empirical Relationships in EILs Hazard Assessment

A robust correlation between seismic parameters and the occurrence of earthquake-induced landslides (EILs) has been extensively documented in scientific literature; this is evidenced by several studies, including those by Fan et al. (2019); Jibson (2007); Keefer (1984, 2002); Livio and Ferrario (2020); Rodríguez et al. (1999) and Tanyaş et al. (2017). These studies indicate that earthquakes with magnitudes exceeding 5.0 are capable of triggering landslides, with the frequency, spatial distribution, and scale of such events correlating directly with increasing seismic magnitude. As the earthquake's magnitude increases, the number of triggered landslides rises accordingly, along with the affected area, which influences slope stability and the geomorphological landscape over a broader region. However, the attenuation of seismic energy as a function of distance from the epicenter is of

critical importance. The density of landslides is considerably higher in the proximity of the epicenter, where ground motion is most intense, and it decreases as the distance from the epicenter increases, following well-established attenuation patterns (Keefer, 1984; Livio and Ferrario, 2020; Rodríguez et al., 1999).

However, the study of EILs has been challenged by several factors. A major limitation is the scarcity of data, as most documented EILs occur in association with moderate to high magnitude earthquakes, typically greater than M5-5.5 (Guzzetti et al., 2009; Hancox et al., 2002). Furthermore, the logistical challenges posed by post-earthquake conditions often prevent immediate and comprehensive field assessments in affected areas. In addition, post-earthquake surveys are often conducted along accessible routes such as roads and highways, which can introduce bias into the data and limit the representativeness of landslide distribution and density (Tanyaş et al., 2017).

Despite these limitations, successful attempts have been made to develop empirical relationships between seismic parameters and landslide occurrence. Various approaches have been employed to refine these correlations, including analyzing global and local datasets. Global databases provide a comprehensive range of landslide data across a range of tectonic and geomorphological settings (Keefer, 2002, 1984; Marc et al., 2017; Seal et al., 2023), offering a large repository of information for large-scale hazard mapping and pre/post-earthquake scenario analysis. In contrast, local databases refer to geologically and geomorphologically homogeneous areas, thereby enhancing the accuracy of hazard assessments within defined regions (Alvioli et al., 2023; Livio and Ferrario, 2020). The two types of databases have been instrumental in developing empirical models that relate earthquake characteristics, such as magnitude and PGA, to the spatial distribution of EILs. This has led to an improvement in the prediction of landslide-prone areas.

In addition to magnitude and distance from the epicenter, other factors, such as slope angle, lithology, and hydrological conditions, have been identified as playing a significant role in EIL susceptibility. Integrating these geological and environmental parameters with real-time seismic data has resulted in the development of advanced tools for landslide risk assessment. For example, the combination of shakemaps, which provide near real-time estimates of ground shaking intensity, with landslide susceptibility maps has been demonstrated to be an effective approach for identifying high-risk areas immediately following a seismic event (Cauzzi et al., 2018; Nowicki Jessee et al., 2014). These tools

allow researchers and civil protection agencies to direct their field investigations and relief efforts more precisely, focusing on locations where landslides are most likely to occur.

1.5 Multiscale Approach to EILs Susceptibility Assessment

In the study of geomorphological hazards in seismically active areas, understanding the spatial distribution of earthquake-induced landslides (EILs) and their triggering mechanisms is essential for developing effective risk reduction strategies. EILs are one of the most dangerous consequences of earthquakes in mountainous and hilly regions, capable of causing significant damage to the environment, infrastructure, and communities within it. Therefore, developing EILs susceptibility and hazard maps is a crucial step for risk prevention and responsible regional planning, especially in countries like Italy, where seismic activity is frequent, and the territory is highly prone to landslides. These maps are essential for both preventive planning and post-event emergency management, providing key information for logistical decisions and targeted responses. Given the different scales of land management needs, it is important to apply EILs assessment tools tailored to specific geographical and operational scales, each designed to provide details appropriate to the scale of intervention and the available data (Günther et al., 2013; Hervás et al., 2007).

On a national scale, using landslide and seismic databases allows quantitative analysis of general patterns in EILs distribution. Statistical approaches rely on seismic parameters such as magnitude, epicentral distance, and peak ground acceleration (PGA) to establish correlations between triggering factors and the density of EILs. Including these parameters in statistical models allows the development of predictive scenarios, highlighting high-hazard areas and allowing better land use planning.

At the regional scale, analyses benefit from higher resolution data, including official geological and geothematic maps, together with landslide databases and morphological information on active faults and epicenter distributions. This scale supports more detailed assessments by integrating local data and geomorphological analyses to assess slope stability conditions. GIS tools combined with updated databases produce high-resolution susceptibility maps that allow the identify particularly vulnerable areas and support region-specific preventive measures.

Finally, at the local scale, direct field data collection through detailed geological and geomorphological surveys provides detailed information on lithological features and active geomorphological processes. In situ data collection allows the integration of specific

geological and geomorphological characteristics of the study area, which are essential for accurately assessing landslide susceptibility following a seismic event. These detailed investigations are valuable for monitoring high-risk areas and implementing mitigation measures.

The high seismicity of Italy, particularly in the Apennines, increases the EILs hazards. The interaction between tectonic forces and geomorphological processes is crucial in these regions, where seismic shaking often triggers landslides in sites characterized by faulted bedrock, steep slopes, and loose sediments.

Recent seismic events, such as the 2009 L'Aquila earthquake and the 2016 Central Italy earthquake sequence, show the EILs hazard in the area (Forte et al., 2021; Miccadei et al., 2010; Romeo et al., 2017). These events caused widespread landslides, damaging infrastructure and human activities. The relationships between seismic parameters, such as earthquake magnitude, Peak Ground Acceleration (PGA), epicentral distance, and landslide occurrence, are the main research goals to improve hazard assessment and risk mitigation strategies (Livio and Ferrario, 2020).

This work presents a multiscale approach to assess the spatial distribution of EILs, with practical applications at different scales of analysis. At the national scale (**Chapter 2**), historical data from throughout Italy are integrated to statistically evaluate the distribution of EILs with respect to key seismic parameters. At the regional scale (**Chapter 3**), the analysis focuses on the Abruzzo region, where more detailed data support the development of susceptibility maps that consider the local morphology and geology. Finally, two local case studies (**Chapters 4 and 5**) provide direct applications of the proposed approach: the first examines debris flows associated with the Monte Marine fault (Pizzoli-Barete area, AQ, Italy), and the second focuses on seismically induced rockfalls on the island of San Nicola (Tremi Islands, FG, Italy), a coastal environment with slopes highly prone to landslide events. These examples demonstrate the effectiveness of an approach that integrates data at national, regional, and local scale, offering a flexible tool for assessing the EILs spatial distribution and susceptibility, providing a useful tool for land planning and risk management

2 EMPIRICAL RELATIONSHIPS BETWEEN EARTHQUAKE-INDUCED LANDSLIDES OCCURENCE AND SEISMIC PARAMETERS FROM THE ITALIAN HISTORICAL RECORD

2.1 Introduction

The ground shaking generated by the arrival of seismic waves released during earthquakes, besides generating damages to the urban environment and artificial infrastructures, can trigger widespread co- and post-seismic environmental effects, overall defined as Earthquake Environmental Effects (EEE) in the Environmental Seismic Intensity scale (ESI; Guerrieri, 2015; Michetti et al., 2007). These natural effects, if the area hit by the earthquake is susceptible to landslide occurrence, include above all slope failure that take place almost constantly, regardless of the kinematic characteristics of the triggering earthquakes (e.g., Keefer, 1984; Livio and Ferrario, 2020; Rodríguez et al., 1999). Besides potentially increasing overall earthquake macroseismic damages immediately after the main shock and interfering with post-event rescue operations, Earthquake Induced Landslides (EILs) pose long-lasting secondary hazards to the earthquake-affected areas (e.g., Fan et al., 2019), also driving the long-term morphological evolution of the territory (e.g., Wang et al., 2020).

Because there exists reciprocal feedback between the tectonic activity, which in the long-term creates the predisposing topographic, morphological, and geological factors, and the landslide activity, mainly driven by gravity, and which works for lowering the topographic gradients, EILs are among the most diffused secondary environmental hazard mostly affecting recent, high relief mountain landscapes located along active plate margins (Figure 2.1).

Due to the widespread occurrence of these phenomena, the correlation between the seismic events and the spatial distribution of the triggered landslides has been investigated by several scientific studies using a variety of approaches and datasets (e.g., Alvioli et al., 2023; Fan et al., 2019; Guzzetti et al., 2009; Hancox et al., 2002; Keefer, 2002, 1984; Livio and Ferrario, 2020; Marc et al., 2017; Rodríguez et al., 1999; Tanyaş et al., 2017; Wang et al., 2020). These studies were based on datasets ranging from a worldwide collection of literature data to regional or local, more homogeneous inventories related to individual earthquakes. They developed empirical relationships relating the seismological parameters to the occurrence of EILs, which were used to produce predictive tools for generating landslide scenarios of future seismic events.

The application of these studies spread over different topics, from the regional landslide hazard mapping to the pre- and post-earthquake regional scenarios to the local landslide hazard assessment for urban areas and relevant infrastructures. The landslides databases used for these studies may be divided into global or regional. The former scale has the advantage of including a more significant number of landslide data coming from different tectonic and geomorphological context (e.g., Keefer, 2002, 1984; Marc et al., 2017; Seal et al., 2023), hence providing more general insights into the landslide triggering process, but at the same time, not considering the possible differences (e.g., geological, geomorphological, rainfall pattern) existing among the different regions. The regional and local databases, on the other hand, generally refer to more homogeneous geological, geomorphological, and seismic domains. Thus, their use can improve the reliability and meaning of the results for the specific area despite the possible lower number of available input data.

These studies show a general correlation between the earthquake parameters and the EILs distribution. As a general rule of thumb, the number and density of EILs decrease from the earthquake epicenter following a classic attenuation law. The earthquake magnitude plays a significant role in defining their number and maximum distance of occurrence: an increase in the magnitude of the triggering seismic event is generally associated with a higher number of landslides distributed over a larger area on account of the greater amount of released energy (Harp et al., 2011; Keefer, 1984; Tanyaş et al., 2017). Also, the depth of the earthquake hypocenter is a key parameter in EILs triggering since shallow earthquakes tend to induce more landslides than deeper ones with the same magnitude. This effect is due to the lesser attenuation of the ground motion when hypocenters are closer to the ground surface and is similar to what is observed for the macroseismic intensities associated with earthquakes of similar magnitude localized at different hypocentral depths (e.g., Sbarra et al., 2023).

Concerning ground motion parameters, which include Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Arias Intensity (AI), and are controlled by the characteristics of the earthquake rupture process and by local geologic conditions (site amplifications), they are also closely linked to the likelihood of EILs occurrence. In this context, high PGA values often relate to a remarkable landslide activity, as shown by empirical models developed by Jibson et al. (2000). Also, PGV values are considered critical factors since they indicate the velocity at which ground particles are displaced during seismic shaking, directly influencing the stability of slopes (Newmark, 2015). AI, considering the

whole duration of the ground motion signal, is proportional to the total energy applied by shaking and is often used in conjunction with Newmark's block modeling to analyze the slope stability under dynamic conditions and generate predictive models of EILs hazard (e.g., Chousianitis et al., 2014).

In addition to the control exerted by the earthquake parameters, the actual spatial probability of the EILs occurrence and the density of the slope movements strictly depend on the landslide susceptibility of the terrains experiencing the ground shaking, which depends on the local geological, structural, and geomorphological setting of the area (Gorum et al., 2011). Factors such as the topographic gradient, outcropping lithologies, and the presence of pervasive fracture systems influence slope stability under seismic conditions (Harp et al., 1984). These local conditions, hence, are essential at local scale in modulating the impact of earthquake parameters on landslide occurrence (Carabella et al., 2022; Kritikos et al., 2015; Marc et al., 2016).

In this work, empirical relationships relating to EILs density and earthquake parameters, like the epicentral distance and PGA were developed using the recently released database of earthquake-induced landslides associated with historical Italian earthquakes (CFTI Landslides; Zei et al., 2024a, 2024b). This database includes events that occurred during the last few centuries in Italy. It lists 972 historical EILs associated with 152 individual earthquakes or seismic sequences that occurred between 951 and 1997 CE and was used to calculate the EILs density around the earthquake epicenters. To also consider the relationship with the ground motion, the INGV database of historic event shakemaps, showing PGA values derived from macroseismic data (ShakeMap v4; Michelini et al., 2020) was used to derive information for 39 earthquakes of our dataset.

In doing so, the developed empirical relationships sample at a regional scale the climatic, geologic, tectonic, and geomorphologic variability of the analyzed area covering the Italian territory and provide more reliable evidence of the local earthquake-surface interaction, also thanks to a high number of EILs and earthquakes considered. Besides, historical data and landslide inventories represent a valuable contribution to the detection and comprehension of hidden patterns behind EILs distribution and density, as well as for the improvement of predictive models for future events, especially when working in low tectonic strain rate regions, where the probability of earthquake occurrence is low, so it is necessary to extend into the past the catalogs.

2.1.1 Study Area

The study presented in this chapter is based on historical landslide and seismic datasets covering the Italian territory that lies along the plate margin separating the slowly converging Eurasia and Nubia plates (Figure 2.1). The regional tectonic process, which has been going on at least since the Paleogene (e.g., Faccenna et al., 2014), is responsible for the nowadays seismicity and related seismic hazard (Danciu et al., 2021; Stucchi et al., 2004), that concentrates mainly in the eastern Alps, along the axial and external sectors of the Apennines, and in the Calabrian Arc and eastern Sicily, and includes deep earthquakes associated to the ongoing subduction of the Jonian oceanic lithosphere below Calabria, and intermediate events related to the lower plate monocline below the Northern Apennines (Figure 2.1; ISIDe Working Group, 2007; Latorre et al., 2023). The seismotectonic framework is completed by less frequent but strong seismic events registered in the external areas of the Adriatic foreland, usually connected to the reactivation of inherited faults in the active compressional stress field generated by the plate convergence (e.g., Di Bucci et al., 2010; Zampieri et al., 2021). The historical and instrumental seismic record covers almost 2000 years (Guidoboni et al., 2018) and lists earthquakes with magnitudes up to ~ 7 , generated by extensional and compressional seismogenic faults (DISS Working Group, 2021).

In the long term, the same tectonic process that drives seismicity developed the elevated topography of the Alps and Apennines fold-and-thrust belts and surrounding hilly areas, forming almost 80% of the Italian territory. Italy is characterized by rugged topography, with tectonically controlled steep gradients and significant local relief caused by river incision. This is further compounded by lithological contacts between old, compacted rocks and young, unconsolidated sediments, as well as the widespread outcropping of highly deformed rocks. These factors make the Italian territory highly susceptible to landslides, which are one of the primary geomorphological processes shaping its landscape, as highlighted by landslide indices and susceptibility maps (Günther et al., 2014; Trigila et al., 2010; Wilde et al., 2018). The Italian landslide database (IFFI) lists approximately 620,000 mapped landslides – one of the most significant numbers in Europe – which affect about 8.4% of the national territory that is classified as having a high or very high landslide hazard (data available from the IdroGEO platform, <https://idrogeo.isprambiente.it/app/>, and based on the landslide mapping of the IFFI Project; Iadanza et al., 2021; Trigila et al., 2007).

The comparison between seismic hazard and landslide susceptibility maps corroborates the tight correlation between seismic and landslide activity in terms of driving forces. It highlights the potential triggering mechanism of the former on the latter (Figure 2.1).

Within this seismotectonic and geomorphic framework, many earthquakes acted as landslides triggering factors, as occurred during the last normal-, strike-slip, and thrust-faulting sequences occurred in central and northern Italy (i.e., 1976 Friuli, 1997-98 Umbria-Marche, 2009 L'Aquila and 2016 Central Italy; (Govi, 1977; Guzzetti et al., 2009; Martino et al., 2017, n.d.; Song et al., 2022), as well as during historical ones (Bozzano et al., 2011; Cotecchia, 1986), making the earthquake-induced landslide hazard one of the main natural threat of the Italian territory, like in many other world-wide active plate margins (e.g., Seal et al., 2023).

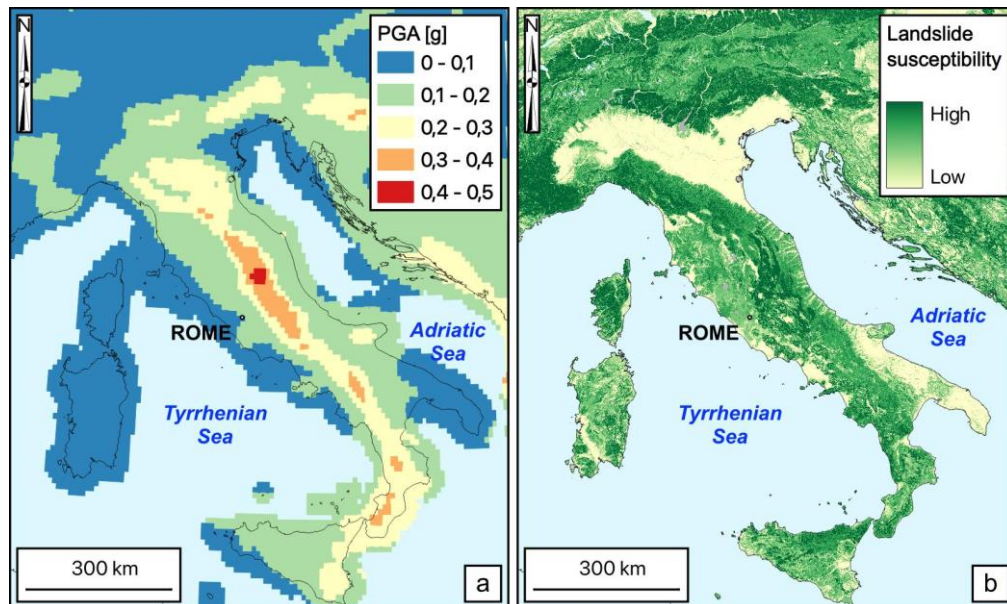


Figure 2.1. Comparison between a) the seismic hazard and b) the landslide susceptibility maps for the Italian territory and conterminous regions. The seismic hazard map is retrieved from the 2020 European Seismic Hazard Model (ESHM20; Danciu et al., 2021) and is available at <http://www.efehr.org/start/>. The landslide susceptibility map is the European Landslide Susceptibility Map v.2 (ELSUS v2; Wilde et al., 2018) and is available at <https://esdac.jrc.ec.europa.eu/>.

2.2 Materials and Methods

This work aims to derive empirical relationships between the EILs distribution and earthquakes and shaking parameters based on extensive, robust, and validated datasets that can serve specific applications, particularly for defining pre- and post-earthquake scenarios. Only public and open-access earthquake databases (Table 2.1) available from the INGV web portal (<https://www.ingv.it/en/resources-and-services/archives-and-databases>) were used in this study. This approach and the developed workflow ensure the repeatability of the method

and the possible update of the derived relationships when new data is available in the input datasets. Besides, the developed workflow is designed to derive regional relationships for other areas with different geological, geomorphological, and tectonic settings based on the availability of rich EIL and seismic datasets.

Specifically, the employed databases are 1) the last version of the CFTI5Med catalog of historical earthquakes (<https://storing.ingv.it/cfti/cfti5/>, Guidoboni et al., 2018), 2) the recently released CFTI landslides database (<https://cfti.ingv.it/landslides/>, Zei et al., 2024b), and 3) the ShakeMap database of ground shakings (<https://shakemap.ingv.it/>; Michelini et al., 2020). We analyzed a dataset comprising 972 EILs connected to 152 different seismic events spanning over 1000 years. For 39 of these events, the corresponding shake maps derived from intensity data points (Oliveti et al., 2023) were also analyzed.

These data allowed to investigate the relationship between landslide density and PGA values for many recent and historical earthquakes.

Table 2.1. Datasets used in this work.

Database name	Dataset description	Web site	Reference
CFTI5Med	Historical earthquakes and their parameters	https://storing.ingv.it/cfti/cfti5/	Guidoboni et al., 2018; 2019
CFTI landslide	Earthquake induced landslides associated to historical earthquakes	https://cfti.ingv.it/landslides/	Zei et al., 2024a, 2024b
Historical shake maps	Shake maps of historical earthquakes from macroseismic intensity data	Michelini et al Oliveti et al., 2023	Michelini et al., 2020; Oliveti et al., 2023

2.2.1 Datasets

2.2.1.1 Earthquake parameters

The seismological parameters, i.e., earthquake epicenters and magnitude, used for calculating the empirical relationships were retrieved from the CFTI5Med historical earthquake catalog (Table 2.1; Guidoboni et al., 2018), which includes over 1,200 seismic events that occurred during the last 2,000 years up to 1997. This analytical catalog is the “parent” database of the CFTI landslides. It offers a complete account of the Italian strongest seismic events, describing their impact on the territory, the coseismic environmental effects of all types, which amount to over 2,300 observations, and the associated social and economic consequences (Guidoboni et al., 2019). In this catalog, the epicentral location and the magnitude of each event, the last parameter expressed as M_e (i.e., equivalent magnitude because based on macroseismic observations), were calculated using the Boxer code

(Gasperini et al., 1999) that uses intensity data point to localize the source of the historical earthquakes, and at the same time, to compute their moment-magnitude and dimensions and probable orientation of the seismogenic sources. The code calculates the macroseismic epicenters as the barycenter of the spatial distribution of the sites that experienced the largest macroseismic intensities. In contrast, based on the average epicentral distance of each intensity level, the magnitude is calibrated using instrumental earthquakes and is equivalent to a moment magnitude.

2.2.1.2 Earthquakes and EILs: the revised CFTI database

The EIL dataset used for this work is taken from the first version of the CFTI landslides database (the Italian database of historical earthquake-induced landslides), recently published by the INGV (Table 1; Zei et al., 2024b). This database was built starting from the review of historical sources, newly found, or already archived in the CFTI5Med catalog (Guidoboni et al., 2018), dealing with the occurrence of coseismic environmental effects and explicitly describing the occurrence of landslides in conjunction with historical earthquakes (Zei et al., 2024a). The historical documentation was integrated with many sources of information derived from the analysis and review of recent scientific articles and technical reports and with a comparison with the list of EILs included in other digital archives, such as the CEDIT (Caprari et al., 2018; Martino et al., 2020b, 2014) and the EEE (Guerrieri, 2012) catalogs. All landslides were georeferenced, interpreting the geographic description given in the sources and making a geographical comparison with different types of datasets, including aerial photographs, geomorphological maps, and landslide maps. However, the level of location accuracy is variable, based on the quality of the historical information and the possibility of identifying the landslide sites on modern maps. Therefore, each EIL record was assigned to one of the following location accuracy classes:

- **Class A**, the landslide is well located, either through a toponym or a detailed indication, and the site of occurrence was identified on modern topographic maps; sometimes the landslide is recognized as one of the IFFI database (11.7% of the landslides).
- **Class B**, the landslide falls in a broad area localized in the modern topographic maps, identified through toponyms or distance, and bearing information relative to an identified locality; sometimes the landslide is recognized as one of the IFFI database (31.8% of the landslides).

- **Class C**, the landslide location corresponds to the nearest locality described in the source because no more specific geographic information is available (56.5% of the landslides).

Of all EILs, 191 events (18.1%) were associated with individual landslides already registered in the IFFI database.

In the workflow that was developed in this study, the geographic location of each individual EIL and the completeness of the effects recorded for each earthquake are of the most significant importance, as these parameters are used to define the distribution of landslides around earthquake epicenters and to calculate the empirical relationships. The location error associated with Class B and Class C landslides could not be quantified; however, it is expected to reach a maximum of a few hundred meters for Class B and a few kilometers for Class C.

When possible, the type of slope movement for each EIL was determined based on contemporary descriptions and in accordance with the landslide classification adopted by the IFFI database. However, due to statistical limitations, this information was not utilized to derive any relationships differentiated by the type of slope movement in the present study.

Concerning datasets used so far in the literature for deriving empirical relationships and based on global or regional compilations (e.g., Keefer, 1984; Livio and Ferrario, 2020; Tanyaş et al., 2017), the used dataset (Figure 2.2) increases the number of available data points, and the number of earthquakes, and all of them are concentrated in a more homogeneous (compared with global catalogs) geologically, geomorphologically and climatic context. Therefore, the empirical relationships derived from this dataset could be more tightly constrained to the specific local conditions.

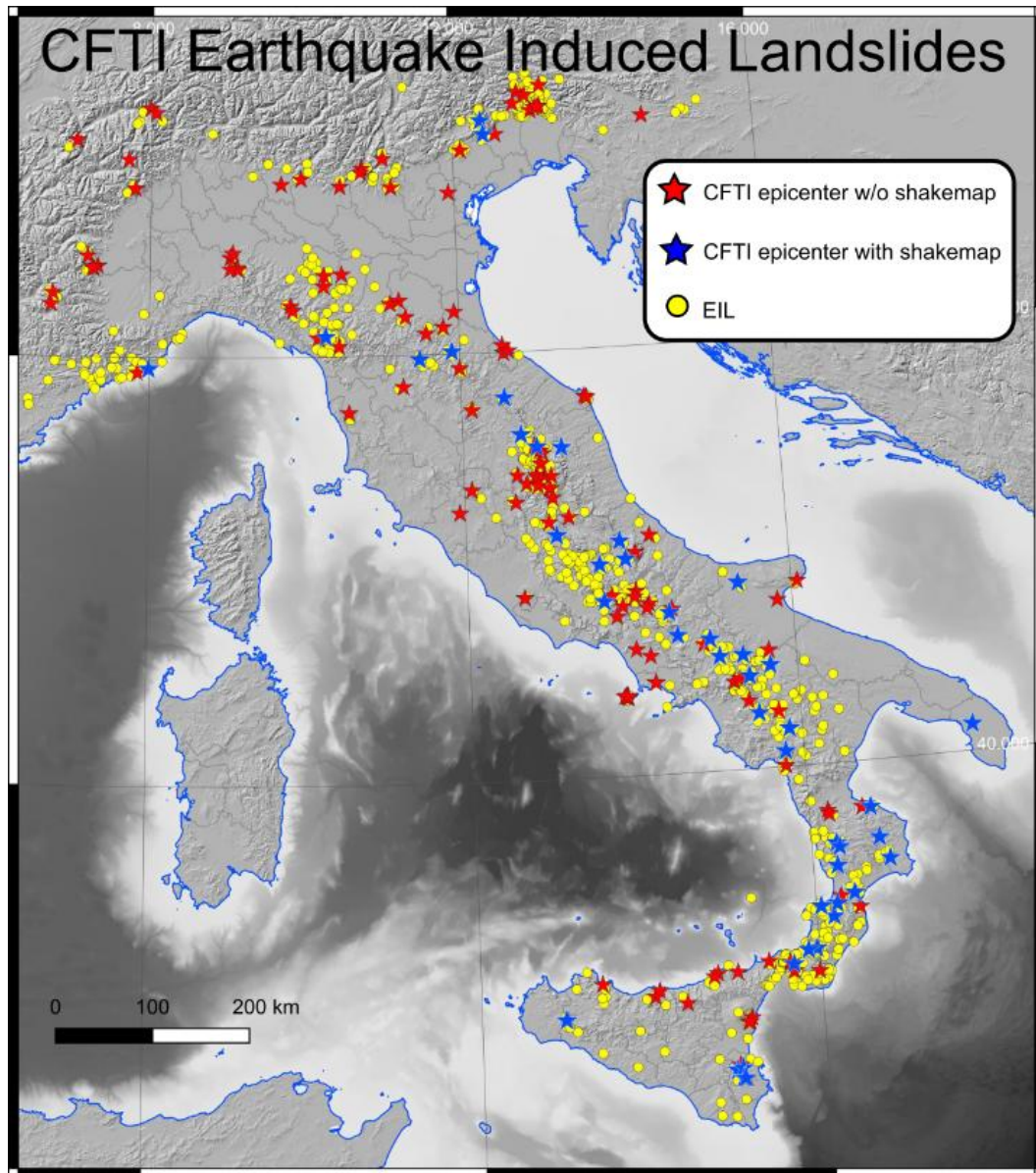


Figure 2.2. Map showing the location of Earthquake Induced Landslides and earthquakes' epicenters from the CFTI catalogs (Guidoboni et al., 2019, 2018; Zei et al., 2024a, 2024b).

Among the selected landslides, 113 EILs were linked to earthquakes of moment magnitude (M) < 5.5 , 312 EILs to events with $5.5 \leq M < 6.5$, and 547 EILs to seismic events of $M \geq 6.5$. (Figure 2.3). The ratio between the number of EILs and the number of associated earthquakes within each class increases as the associated M range rises, moving from 2.5 ($M < 5.5$) to 4.2 ($5.5 \leq M < 6.5$), to 17.1 ($M \geq 6.5$). By analyzing the distribution of EILs over historical time, furthermore a general increase of EILs is observed within each magnitude class moving towards recent times, pointing out a progressively greater amount of available data and, in turn, significant completeness of associated catalogs.

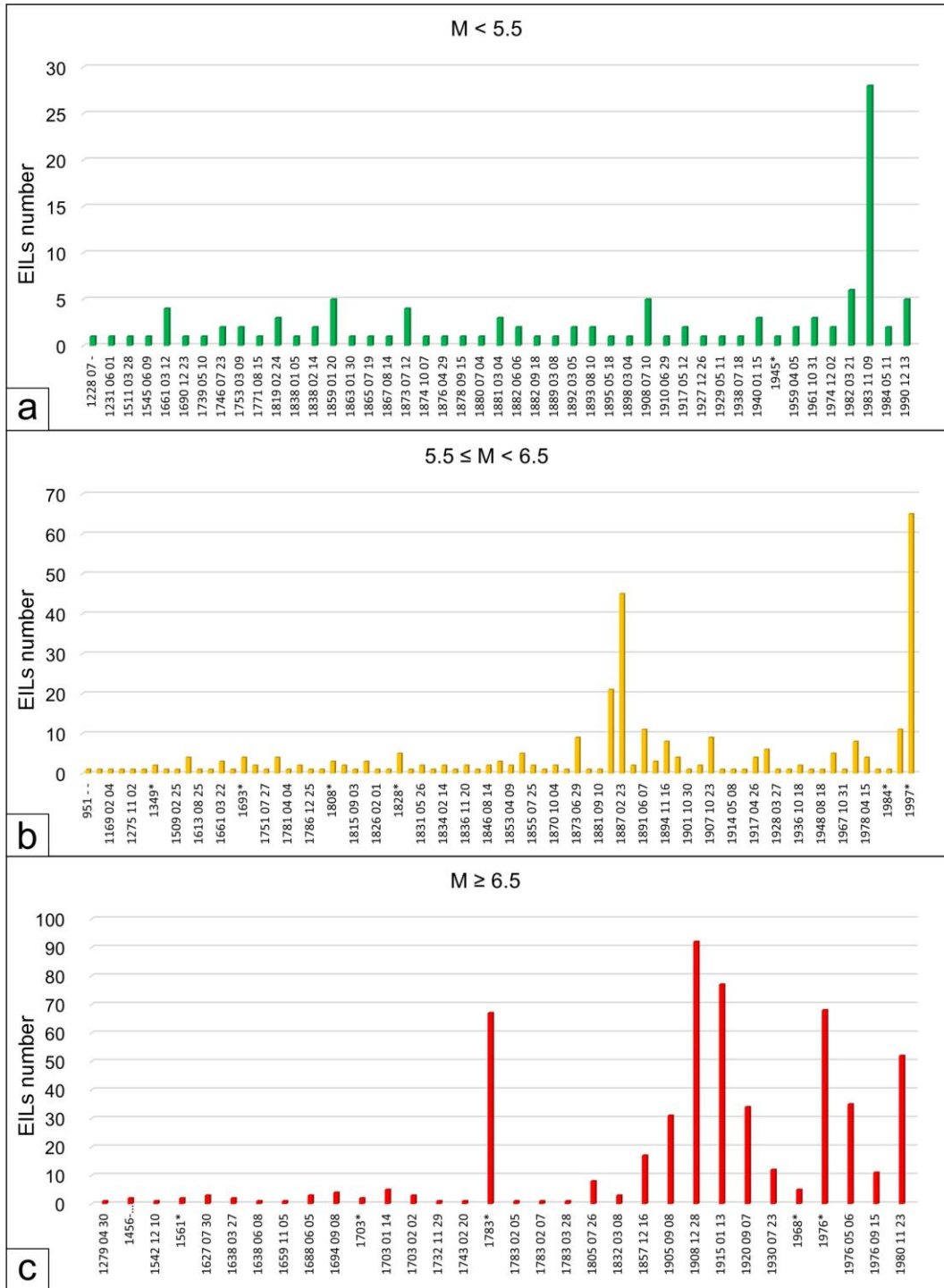


Figure 2.3. EILs distribution over time is divided according to the magnitude of the reference earthquake. The horizontal axis indicates the time of occurrence of the seismic event derived from the CFTI5med catalog. The asterisk (*) marks EILs not associated with a specific seismic sequence event.

2.2.1.3 Earthquake-related shaking: the shake maps database

Another recently updated dataset used to investigate the relationships between the seismological parameters and EILs distribution is the INGV shake maps database (Table 2.1). This database also includes shake maps of historical earthquakes generated from the analysis of the macroseismic intensity observations, collected in the Italian Macroseismic

Database (DBMI15; Locati et al., 2022), and interpreted in terms of ground motion parameters using the relationships developed by Oliveti et al. (2023). The historical shake map database includes 80 earthquakes with a magnitude of 6.0 or higher that occurred before 1980.

These data allow to investigate the relationship between landslide density and PGA values for a large number of recent and historical earthquakes.

2.2.2 Methods

The methodological workflow applied in this study comprised two main steps: i) the definition of the relationships between specific seismological parameters and the EILs distribution and ii) the application of these relationships to case studies of known recent earthquakes within the Italian territory for testing the accuracy of achieved results.

The first step consisted in the definition of new empirical relationships between the EILs density and two seismological parameters: i) the distance from the earthquakes epicenter and ii) the PGA values registered or derived for the location area (Figure 2.4).

Concerning the first step, circular search areas were considered around the reference epicenters with radii values progressively increasing of 5 km. Since EILs can affect areas with variable extent, depending on the amount of energy released by the seismic event (Keefer, 1984; Livio and Ferrario, 2020), landslides were subdivided into three subsets based on the magnitude of the reference earthquake, as follows: Class 1, $M < 5.5$; Class 2, $5.5 \leq M < 6.5$, and Class 3, $M \geq 6.5$ (see Figure 2.3). The number of EILs within each circle was computed in a GIS environment for every earthquake. Subsequently, for each magnitude class, EILs falling within circles with the same radius (R , [m]) were summed, and the landslide density values (d) were derived by dividing the cumulative EILs number (N) by the surface extent of the considered sector. The following equation was applied:

$$d = \frac{N}{n\pi R^2} \quad [2.1]$$

where n is the number of earthquakes falling within the reference magnitude class. Empirical relationships were then derived between this density and the distance from epicenters for each magnitude class in the form of power laws:

$$y = \alpha x^\beta \quad [2.2]$$

where x is the radii length, α , and β are empirical coefficients. The coefficients of determination were calculated to evaluate the reliability of derived laws. The 33rd, 66th, and

95th percentile distances, i.e., the distances within which 33%, 66%, and 95% of EILs are expected to occur, were also computed.

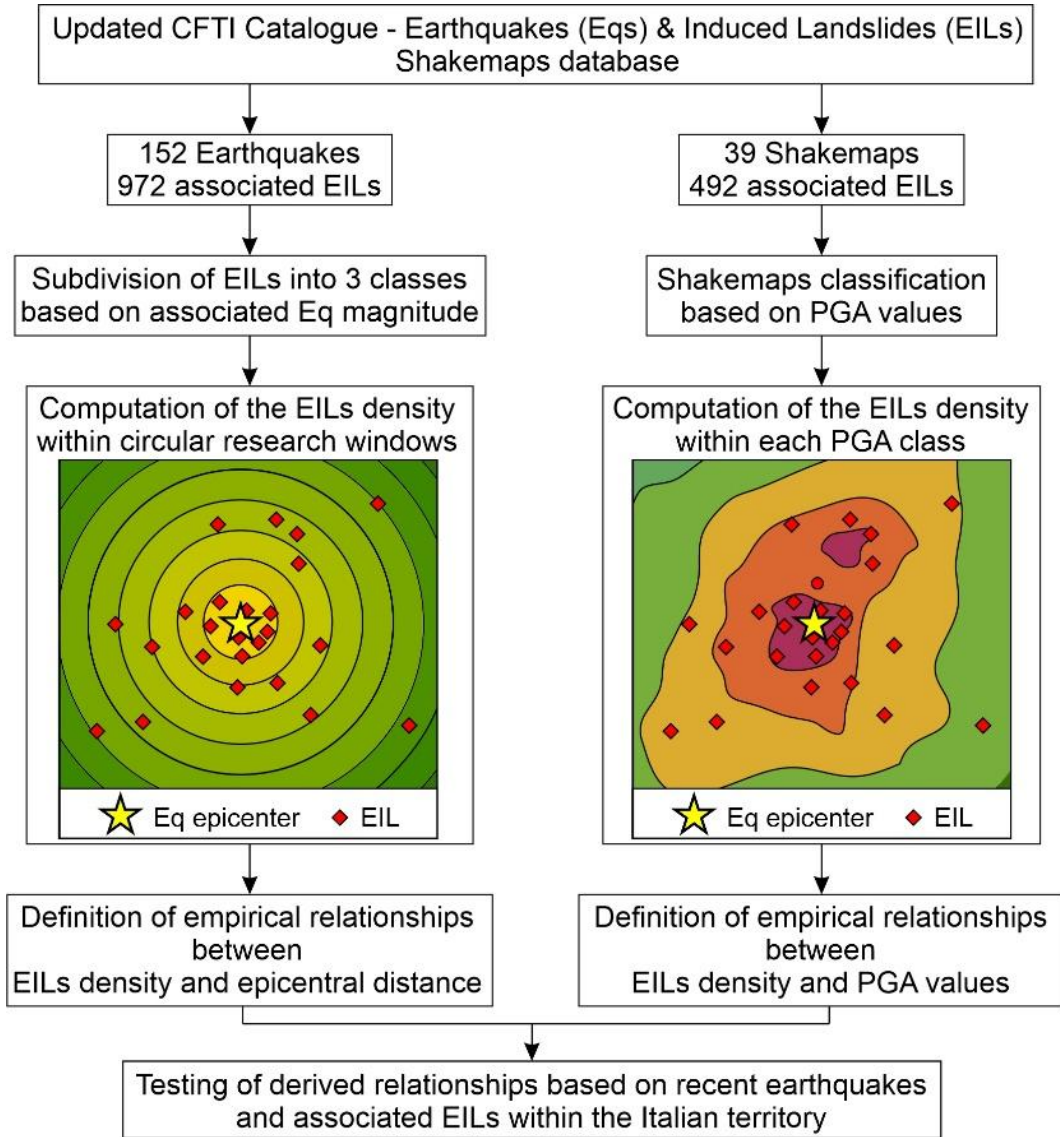


Figure 2.4. Workflow of the applied methodology.

Concerning the first step, circular search areas were considered around the reference epicenters with radii values progressively increasing of 5 km. Since EILs can affect areas with variable extent, depending on the amount of energy released by the seismic event (Keefer, 1984; Livio and Ferrario, 2020), landslides were subdivided into three subsets based on the magnitude of the reference earthquake, as follows: Class 1, $M < 5.5$; Class 2, $5.5 \leq M < 6.5$, and Class 3, $M \geq 6.5$. The number of EILs within each circle was computed in a GIS environment for every earthquake. Subsequently, for each magnitude class, EILs falling within circles with the same radius (R , [m]) were summed, and the landslide density values

(d) were derived by dividing the cumulative EILs number (N) by the surface extent of the considered sector. The following equation was applied:

$$d = \frac{N}{n\pi R^2} \quad [2.3]$$

where n is the number of earthquakes falling within the reference magnitude class. Empirical relationships were then derived between this density and the distance from epicenters for each magnitude class in the form of power laws:

$$y = \alpha x^\beta \quad [2.4]$$

where x is the radii length, α , and β are empirical coefficients. The coefficients of determination were calculated to evaluate the reliability of derived laws. The 33rd, 66th, and 95th percentile distances, i.e., the distances within which 33%, 66%, and 95% of EILs are expected to occur, were also computed.

Concerning the relationship between EILs distribution and PGA values, out of the 152 historical earthquakes used in the previous analytical steps, 39 featured associated shake maps (available at <http://shakemap.ingv.it/shake4/>, accessed on 30th April 2023), which were used for the analysis. Into detail, shake maps were classified into 0.1 g PGA intervals; for all the earthquakes, the number of EILs falling within each class was then computed. As in the previous step, EILs density was calculated for each class by dividing the number of EILs by the total area of the corresponding PGA class. An empirical relationship was then derived between EILs density and PGA values in the form of a power law represented by equation 2, where x is the upper limit [g] of the considered PGA class. The coefficient of determination was calculated to evaluate the accuracy of the regression.

In the final step, two recent earthquakes that occurred within the Italian territory were selected to verify the reliability of computed regressions. Into detail, the seismological parameters of the 6th of April 2009 L'Aquila earthquake and the 30th October 2016 Norcia earthquake (CPTI15 catalog; Rovida et al., 2022) with associated EILs (CEDIT catalog; Caprari et al., 2018; Martino et al., 2020) and shake maps (ShakeMap catalog; Oliveti et al., 2023) were extracted and used for the analysis. As made for historical earthquakes, circular search windows were built around earthquake epicenters with radii values progressively increasing of 5 km, and EILs densities were computed within each sector along with empirical regressions (first step); concerning PGA values, these were classified into 0.1 g classes, and EILs density values were computed for each class (second step). The results

were then compared with those derived from the analysis of historical earthquakes, which accounted for the magnitude class of the considered event.

2.3 Results: Empirical Relationship

2.3.1 Landslide Density vs Epicentral Distance

The number of landslides triggered by earthquake events typically decreases as one moves away from the epicenter. Notably, within the first circle, which spans the area between 0 and 5 km from the epicenter, the number of detected landslides is usually lower than that of landslides found within the second one (Figure 2.5).

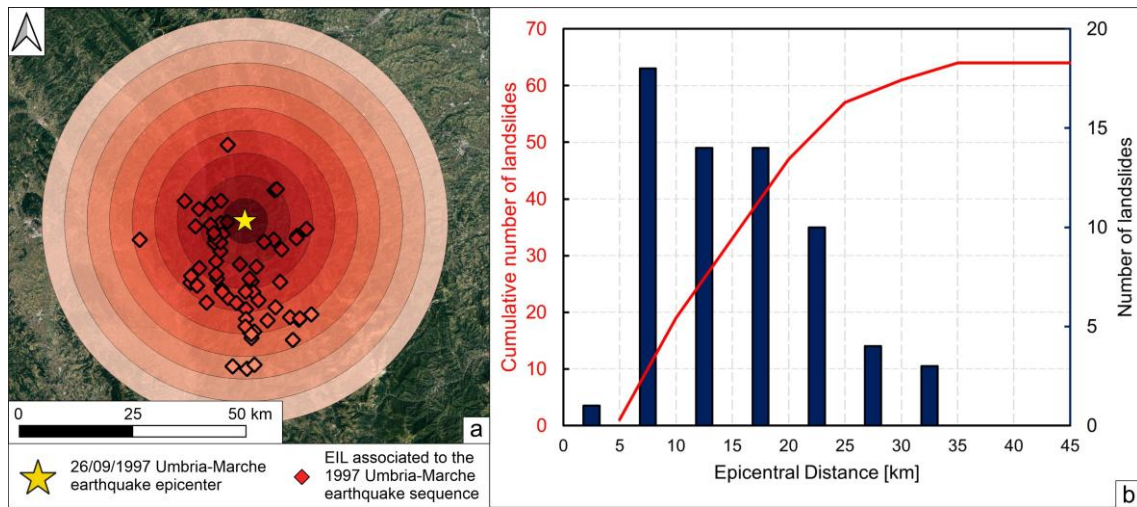


Figure 2.5. Example of distribution of EILs vs the epicentral distance of reference earthquake occurred during the 26 September 1997 Umbria-Marche earthquake.

This fact, which could sound contradictory at first glance, is linked to the minor surface extent of the first section compared to that of the second one, for which fewer landslides commonly result in a higher density, as shown in Figure 2.6. Considering all data gathered for each magnitude class, a decrease in landslide density clearly moves away from the epicenter, following a power law relationship. R-squared values of regressions are always higher than 0.9, with maxima resulting for the $M < 5.5$ class. In detail, regressions computed for the $M < 5.5$ and $5.5 \leq M < 6.5$ classes show values close to the unit; the regression computed for the $M \geq 6.5$ class shows an R-squared value of about 0.91, likely due to the lower number of EILs available for the study.

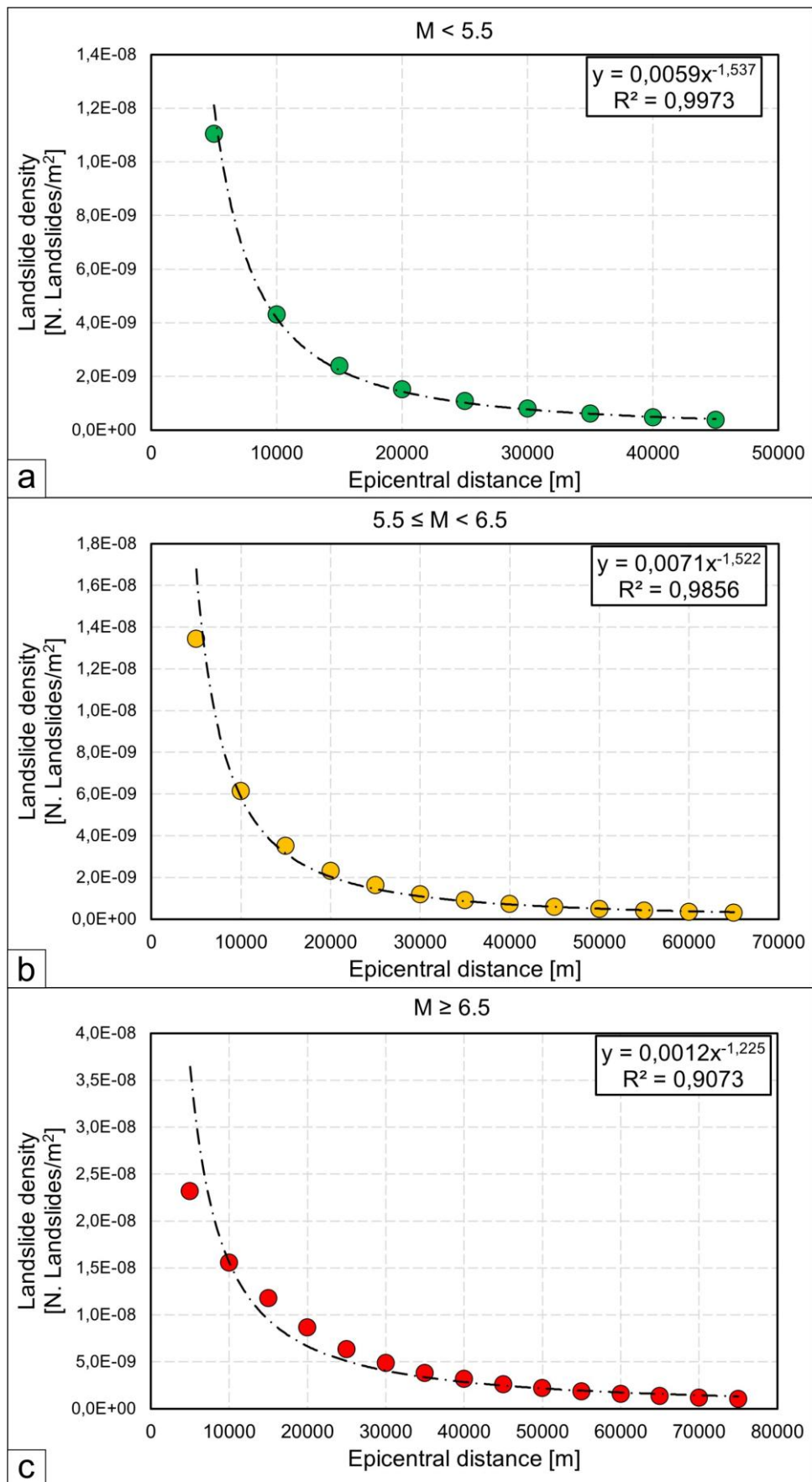


Figure 2.6. Empirical regressions computed for EILs density vs the epicentral distance of associated earthquakes.

Furthermore, it is clear that the extent of the area affected by EILs tends to increase as the magnitude of the reference earthquake increases. In this context, seismic events featuring a magnitude lower than 5.5 results in triggering 95% of EILs within a distance of about 42 km from the epicenter, whereas seismic events with a M greater than 6.5 can trigger the 95% of EILs within a distance of around 77 km from the epicenter (Table 2.2).

Table 2.2. Distances at which 33, 66, and 95% of EILs occur, divided by magnitude class.

Percentile	$M < 5.5$	$5.5 \leq M < 6.5$	$M \geq 6.5$
33	5.0 km	7.2 km	12.9 km
66	14.1 km	19.0 km	26.7 km
95	41.5 km	66.3 km	77.3 km

2.3.2 Landslide Density vs Peak Ground Acceleration

Concerning the link between the number of EILs and PGA values, the lowest EILs values are usually detected in correspondence of the highest and lowest PGA classes; on the other hand, the highest EILs values are found within classes with “intermediate” g values (Figure 2.7). A low EILs number within the highest PGA classes can be linked to the limited surface extension of these last, which minimizes the probability of landslide occurrence within their extent despite the high acceleration values.

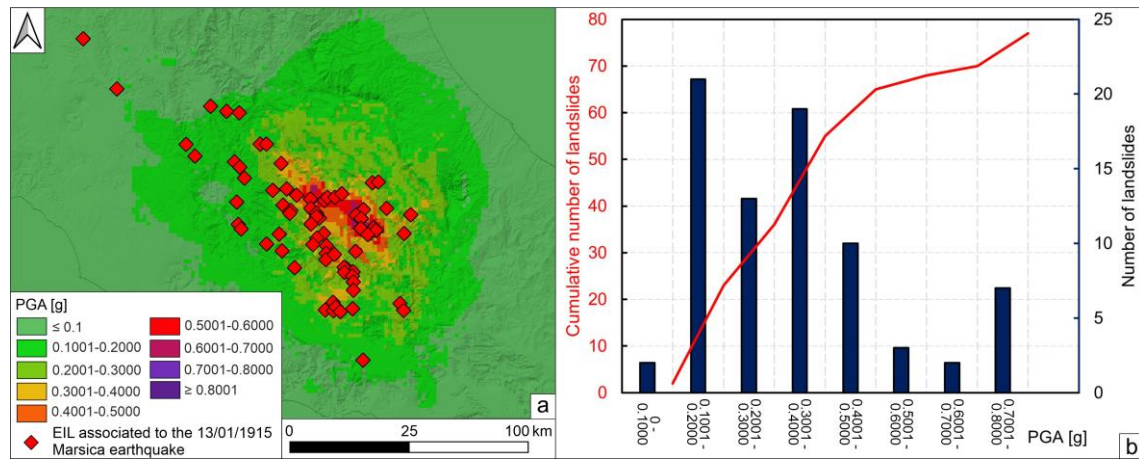


Figure 2.7. Example of distribution of EILs vs PGA values occurred during the 13 January 1915 Marsica earthquake.

EILs densities tend to increase as PGA values increase, pointing out a strong relationship between these parameters (Figure 2.8); values for the $0 < \text{PGA} \leq 0.1 \text{ g}$ class are not reported, given the indefinite extent of the associated area.

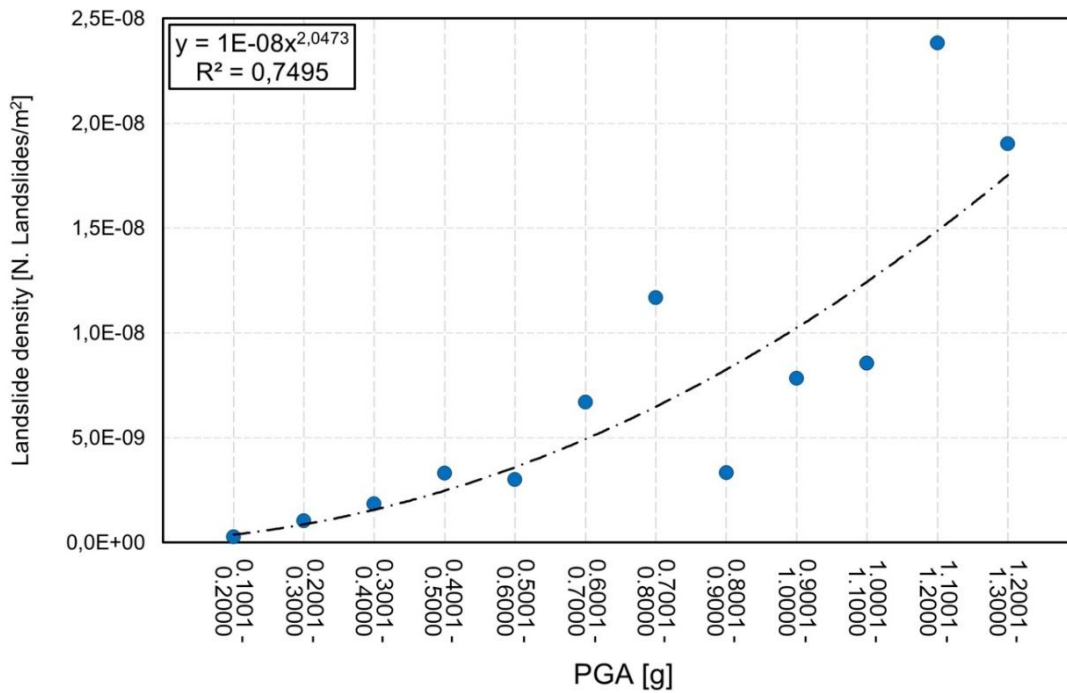


Figure 2.8. Empirical regression computed for EILs density vs PGA values registered or derived for associated earthquakes.

2.4 Case studies to validate the method

The empirical relationships derived from the CFTI landslides database in the previous sections can be used to associate each landslide mapped in the Italian national inventory (ISPRA IFFI Project; Iadanza et al., 2021; Trigila et al., 2007) with individual segments of known seismogenic sources located in Italy or nearby countries, and their potential earthquakes (with a maximum expected magnitude). This association can generally be made to composite seismogenic sources in the DISS database version 3.3.0 (DISS Working Group, 2021), hypothesizing that they may trigger the EILs activation during future earthquakes within maximum distances corresponding to the 95th, 66th, and 33rd percentile distances calculated from the relationships (Table 2.2). However, the association can also be made with recent earthquakes to verify the consistency of the results with mapped EILs and validate the relationships and the method. In this work, the relationships were tested using two recent seismic events in Central Italy, specifically: 1) the 2009 L'Aquila and 2) the 2016-2017 Central Italy seismic sequences.

For the 2009 L'Aquila seismic sequence, the events that occurred between April 6th and 9th were investigated, and EILs densities were computed with reference to the distance from the epicenter as well as to PGA values for the main shock (L'Aquila, Mw 6.3, April 6,

2009). 86 EILs were extracted from the CEDIT catalog (Caprari et al., 2018; Martino et al., 2020) and used for the analysis.

According to the EILs distribution shown in Figure 2.9a, landslides tend to concentrate around the epicentral zone. The highest density is clearly found within the innermost circle ($r = 7.2$ km), corresponding to the area where 33% of the landslides are expected to occur, according to relationships derived in this study for the $5.5 \leq M < 6.5$ class (Table 2.2); fewer EILs are found within the second circle (66th percentile limit, r 19 km) and just a few beyond its limit.

By comparing density values with those derived for historical earthquakes, for the case study, the highest one is derived for the 0-10 km circle and not for the 0-5 km one. This can be linked to local topographical features since the earthquake is enucleated in correspondence with a gently sloping sector, with steep – more susceptible – slopes found at distances of 5 or more kilometers, as shown in the plan and profile (Figure 2.9a, b). In this context, topographical variations occurring in the area are highlighted by swath profiles shown in Figure 2.9b, built considering a total width of 20 km (10 for each side) around the profile trace (Figure 2.9a). Either way, the empirical law derived from available data shows good consistency with results from the analysis of historical events, as highlighted by the proximity of β parameter values [2.4]), which directly determines the shape of the curve (Figure 2.9c; Table 2.4). On the other hand, α parameters feature an appreciable difference; in this context, the higher α value derived for the case study can be related to the higher number of EILs data available for recent earthquakes compared to historical ones (Figure 2.3).

Table 2.3. Comparison between empirical regressions computed based on historical events and equations derived for the 2009 L'Aquila seismic sequence.

	Empirical regressions			Case study	
	$M < 5.5$	$5.5 \leq M < 6.5$	$M \geq 6.5$	06/04/2009 earthquake Mw 6.3	L'Aquila
Equation	$y = 0.0059x^{-1.537}$	$y = 0.0071x^{-1.522}$	$y = 0.0012x^{-1.255}$	$y = 0.3501x^{-1.604}$	
$y = \alpha x^\beta$					
R^2	0.9973	0.9856	0.9073	0.6918	

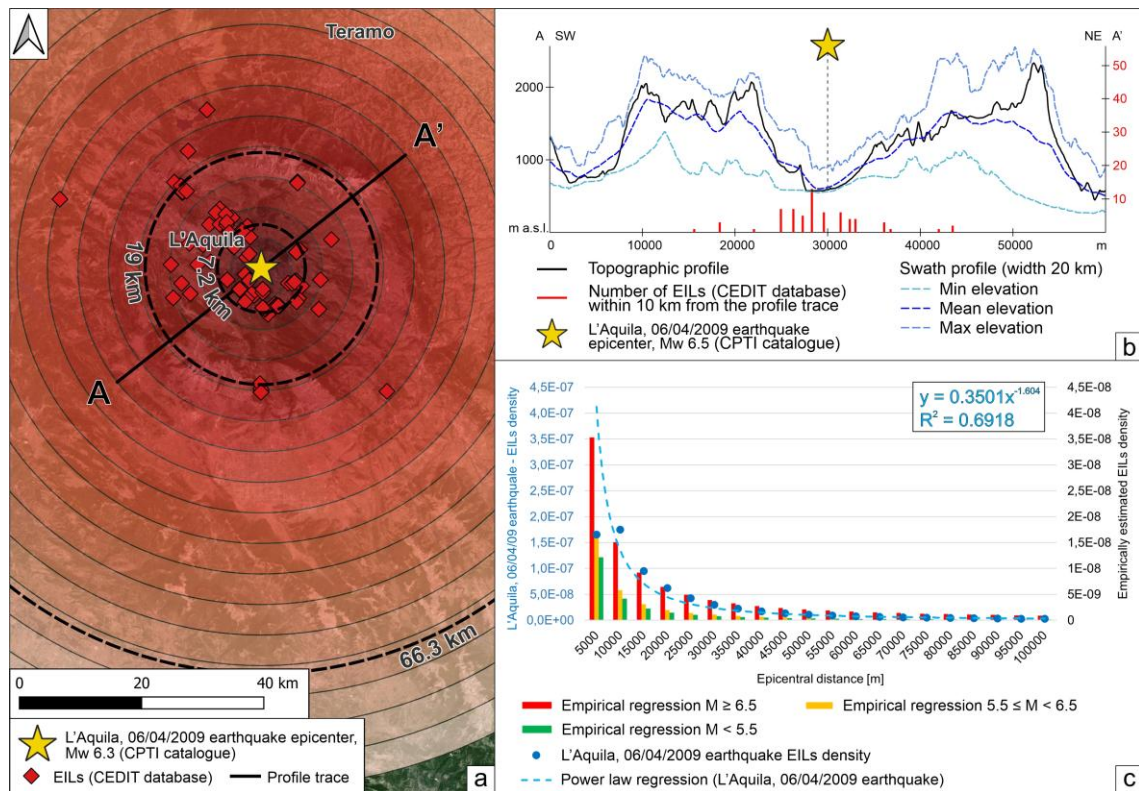


Figure 2.9. Analysis of EILs associated with the 2009 L'Aquila seismic sequence. a) Map of EILs distribution from the CEDIT database (Caprari et al., 2018; Martino et al., 2020b), showing the circular search areas with radii values progressively increasing of 5 km; dashed circles indicate the distances at which 33, 66, and 95% of EILs are expected to occur according to regressions computed for earthquakes with $5.5 \leq M < 6.5$; b) SW-NE oriented topographic and swath profiles (swath width of 20 km, trace in fig. a) showing the number and distribution of EILs occurred within 10 km from the profile trace; c) density of EILs occurred during the April 6th, 2009 L'Aquila earthquake, compared with expected values empirically derived for all classes of magnitude considered in this study.

Table 2.4. Comparison between empirical regressions computed based on historical events and equations derived for the 2009 L'Aquila seismic sequence.

	Empirical regressions			Case study	
	$M < 5.5$	$5.5 \leq M < 6.5$	$M \geq 6.5$	06/04/2009 earthquake Mw 6.3	L'Aquila
Equation	$y = 0.0059x^{-1.537}$	$y = 0.0071x^{-1.522}$	$y = 0.0012x^{-1.255}$	$y = 0.3501x^{-1.604}$	
$y = \alpha x^\beta$					
R^2	0.9973	0.9856	0.9073	0.6918	

Regarding the relationship between EILs and PGA values, they tend to distribute along NW-SE-directed patches, further underlining their link (Figure 2.10).

The highest PGA values are detected about 15 km NW of the epicenter, in a sector where no EILs were found according to available catalogs. Most landslides fall within the

0.2001-0.3000 and the 0.3001-0.4000 g classes. Compared to density values computed for historical earthquakes, higher values are obtained due to the higher available data for recent events (Figure 2.10c). Concerning the “shape” of the distribution, no relevant conclusions can be drawn given the shortage of PGA classes for the case study.

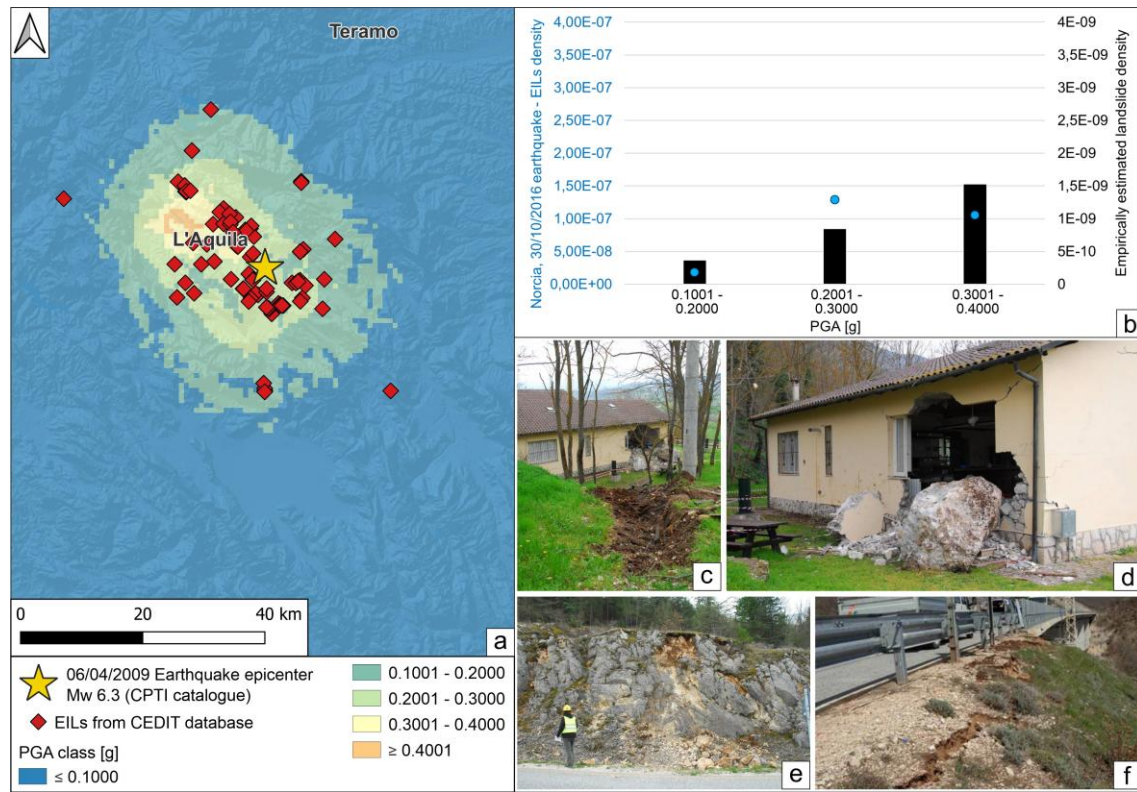


Figure 2.10. Analysis of EILs associated with the 2009 L'Aquila seismic sequence. a) Map of EILs distribution from the CEDIT database (Caprari et al., 2018; Martino et al., 2020b) against PGA values classified into 0.1 g intervals, b) density of EILs for each PGA class, compared with expected values empirically derived in this study. Photo documentation: c) Rockfall at the Caves of Stiffe with d) detail of the impact against a building, e) Shallow raveling-type failure of weathered limestone blocks along SP38 approximately 9.5 km south of L'Aquila, and f) Gravitational movement affecting an anthropic deposit along the Highway A24, between L'Aquila Est and Assergi), Photographic documentation from Blumetti et al., (2009).

Concerning the 2016-2017 Central Italy seismic sequence, EILs densities were computed accounting for the distance from the epicenter and to PGA values for the main shock that occurred on October 30, 2016 (Norcia, Mw 6.5). In this case, 378 EILs were extracted from the CEDIT catalog (Caprari et al., 2018; Martino et al., 2020) and used for the analysis.

According to the EILs distribution shown in Figure 2.11a, with reference to limits derived for the $M \geq 6.5$ class (Table 2.2), the highest density is again found within the innermost circle (33rd percentile limit, r 12.9 km), while fewer EILs are found within the second circle (66th percentile, r 26.7 km); almost no events occurred beyond this limit.

This behavior can be explained by the magnitude of the Norcia 2016 earthquake, which represents the lower boundary of the reference magnitude class. Historical events considered for the analysis, in fact, mainly featured M values greater than 6.5, thus returning a wider spatial distribution of associated EILs compared to the case study. In any case, it should be noted that the mapped landslides show a higher density along the road network, likely due to the practical need for surveying and securing these sectors after the earthquake. Nevertheless, many other landslides could have occurred in remote areas and might not have been mapped.

From the analysis of density values, it turns out that the highest ones are obtained for the 0-10 km circle and not for the 0-5 km one, as it happens for historical earthquakes. According to swath profiles reported in Figure 2.11b, this distribution could be linked to local morphological features, with peaks in the distribution found in correspondence with transects with high elevation ranges. Regarding the empirical law derived for the case study, the proximity of β values indicates substantial consistency among presented results (Figure 2.11; Table 2.5). Also, in this, s case, α factors show a remarkable difference, again due to the higher number of EILs data available for recent earthquakes.

Table 2.5. Comparison between empirical regressions computed based on historical events and equations derived for the 2016 Norcia seismic sequence.

c	Empirical regressions			Case study
	$M < 5.5$	$5.5 \leq M < 6.5$	$M \geq 6.5$	30/10/2016 Norcia earthquake Mw 6.5
Equation	$y = 0.0059x^{-1.537}$	$y = 0.0071x^{-1.522}$	$y = 0.0012x^{-1.255}$	$y = 0.0394x^{-1.270}$
$y = \alpha x^\beta$				
R^2	0.9973	0.9856	0.9073	0.3452

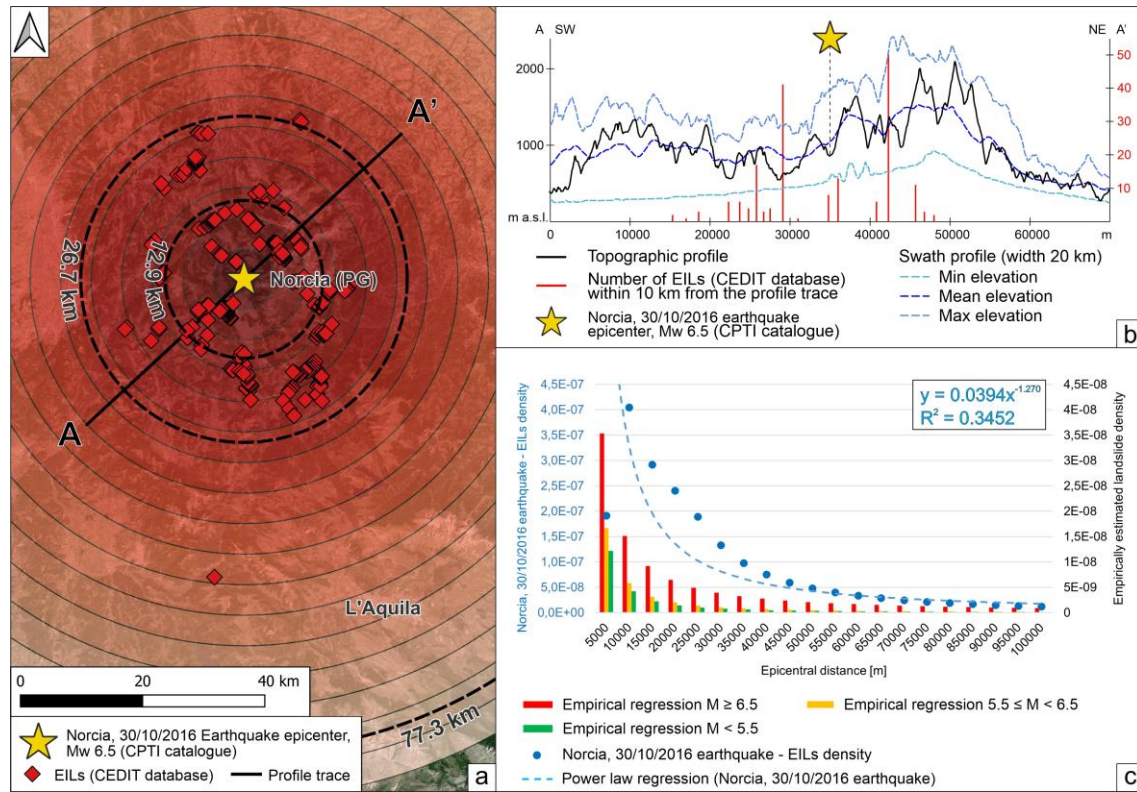


Figure 2.11. Analysis of EILs associated with the 2016-2017 Central Italy seismic sequence. a) Map of EILs distribution from CEDIT database (Caprari et al., 2018; Martino et al., 2020b), showing the circular search areas with radii values progressively increasing of 10 km; dashed circles indicate the distances at which 33, 66, and 95% of EILs are expected to occur according to regressions computed for earthquakes with $M \geq 6.5$; b) SW-NE oriented topographic and swath profiles (swath width of 20 km) showing the number and distribution of EILs occurred within 5 km from the profile trace; c) density of EILs occurred during the October 10th, 2016 Norcia earthquake, compared with expected values empirically derived for all classes of magnitude considered in this study.

EILs and PGA values tend to distribute along NW-SE directed patches (Figure 2.12). The highest PGA values are detected at about 10 km SSE in the epicentral area, and no EILs are detected in their correspondence due to the limited spatial extension of the related class. In this case study, a good consistency is observed between EILs distribution and results achieved by analyzing historical events. EILs density increases as PGA values increase; the difference in density values can be linked to the greater availability of data for recent events.

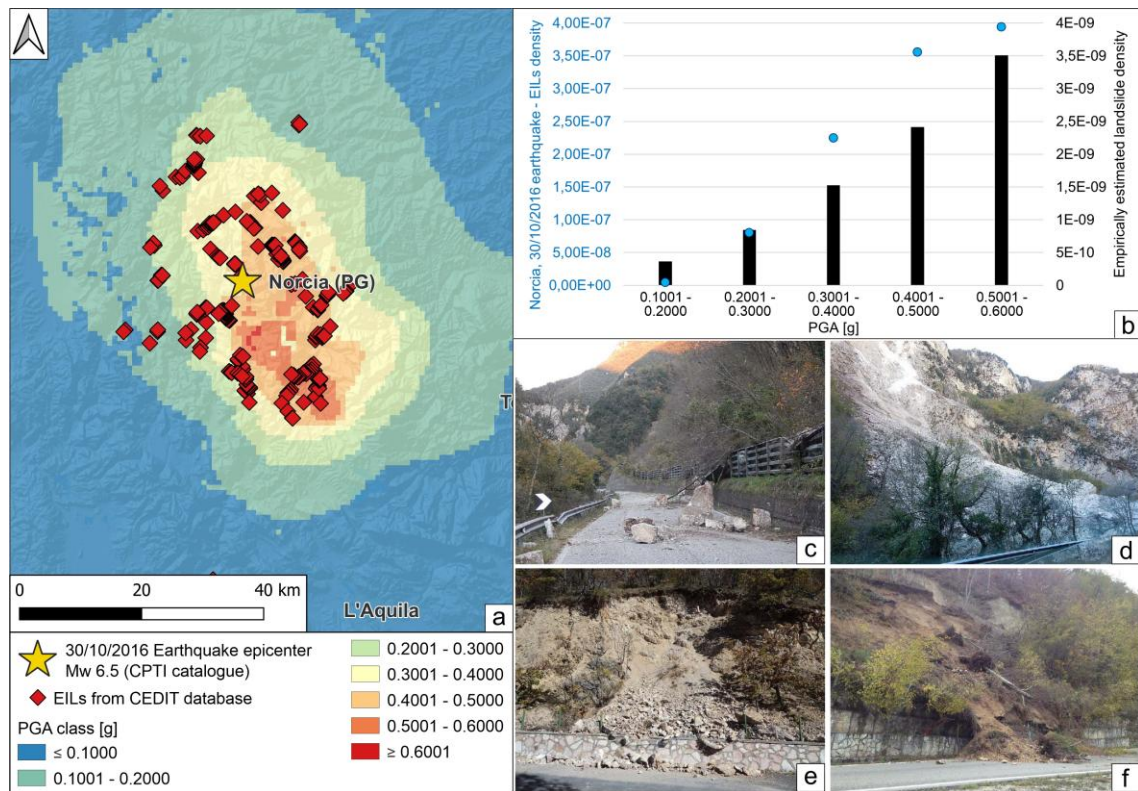


Figure 2.12. Analysis of EILs associated with the 2016-2017 Central Italy seismic sequence. a) Map of EILs distribution from the CEDIT database (Caprari et al., 2018; Martino et al., 2020b) against PGA values classified into 0.1 g intervals, b) density of EILs for each PGA class, compared with expected values empirically derived in this study. Photo documentation: c) rockfall event with metric blocks invading a road (Visso, MC), d) rock avalanche obstructing the course of the Nera River (Visso, MC), e) debris slide occurred along the SP 476 (Cascia, PG), and f) rock slump following the reactivation of a roto-translational landslide (Castelsantangelo sul Nera, MC), Photographic documentation from CEDIT database (Caprari et al., 2018; Martino et al., 2020).

2.5 Discussion and Conclusion

This study has significantly advanced the understanding of the relationships between earthquake-induced landslides (EILs) and seismological parameters. This was accomplished by developing robust, region-specific empirical models based on comprehensive historical datasets in the Italian context. The findings highlight the necessity of considering both earthquake magnitude and ground motion parameters (e.g., peak ground acceleration, PGA) to evaluate the spatial distribution of EILs, while also addressing critical methodological challenges and limitations inherent in such analyses. The two primary relationships established in this research, the density of EILs as a function of epicentral distance and earthquake magnitude, and the density of EILs relative to PGA, offer new insights into the interplay between seismic activity and slope instability. The attenuation curves derived for EIL density as a function of distance from the epicenter demonstrate high statistical reliability ($R^2 > 0.90$) and reflect consistent attenuation patterns across different magnitude classes. Conversely, the correlation between EIL density and PGA shows lower R^2 values

(~0.75). This lower value is likely due to the uncertainty in determining PGA values for historical earthquakes. Additionally, it suggests that local factors, such as topography and slope susceptibility, may significantly influence landslide occurrence. These findings align with previous studies but emphasize the need for further data and the refinement of models.

Nevertheless, the study also identifies significant limitations. The incompleteness of historical datasets presents a considerable challenge, making it unclear how missing data affects the resulting attenuation curves. It is still being determined whether the missing data shifts the curves downward, thereby underestimating landslide densities, or alters the slope of the curves, indicating different attenuation dynamics. Establishing a threshold of completeness and utilizing data that meets this standard may enhance the robustness of future models. Another limitation is the lack of differentiation based on landslide type (e.g., rockfalls, debris flows). This is primarily due to statistical constraints, as the dataset needs to contain sufficient information to enable reliable categorization.

Furthermore, the dataset used in this study does not differentiate between landslides triggered by seismic activity and those caused by climatic factors. While the CFTI landslides database focuses on events temporally linked to earthquakes, there remains a risk of misclassifying post-seismic, rainfall-induced landslides. Additionally, seasonal factors (e.g., winter *versus* summer conditions) and the cumulative impact of multiple seismic shocks within short time frames were not accounted for due to the limited number of events available for analysis. Similarly, the analysis should have included the focal mechanisms of earthquakes because estimating these parameters reliably for historical events is challenging. This could compromise the accuracy of ground motion characterizations and their relationship with landslide-triggering potential. Finally, historical EIL datasets need to be revised to establish strong statistical trends related to landslide size and volume, which hinders efforts to quantify the broader geomorphic and hazard impacts of EILs. The current insufficient number of historical EIL datasets further obstructs the establishment of robust statistical trends concerning landslide size and volume, limiting the ability to quantify the wider geomorphic and hazard impacts of EILs.

Despite these limitations, the findings of this study have direct implications for evaluating hazards associated with EILs and for developing risk mitigation strategies. The empirical relationships identified can inform the modeling of potential EILs scenarios, including the reactivation of inventoried landslides in the IFFI database. This methodology can be used to identify areas most susceptible to landslides, enabling the creation of hazard

maps tailored to specific seismogenic sources and scenarios. These tools are particularly valuable in pre-earthquake planning, including prioritizing vulnerable areas for detailed surveys and emergency response operations. To address the previously mentioned limitations, future research should focus on enhancing dataset completeness by updating historical catalogs with recent events and improving landslide inventories. Combining high-resolution landslide susceptibility maps with seismic hazard maps will help account for local geomorphological and geological variability, especially in regions where high peak ground acceleration values are recorded, yet no landslides are observed. Incorporating the cumulative effects of seismic sequences, distinguishing landslides by typology, and factoring in seasonal and focal mechanism elements could provide a more detailed and nuanced understanding of the spatiotemporal dynamics of EILs.

This study offers a solid framework for understanding the relationships between earthquake parameters and landslide occurrences, with important applications for seismic hazard assessment. However, the inherent complexity of earthquake-induced landslide dynamics necessitates ongoing research to refine models and incorporate additional parameters. By tackling these challenges, future efforts can improve predictive capabilities and support effective disaster risk reduction strategies in seismically active areas.

3 EARTHQUAKE-INDUCED LANDSLIDES SUSCEPTIBILITY EVALUATION: A CASE STUDY FROM THE ABRUZZO REGION (CENTRAL ITALY)

3.1 Introduction

Hazards and risks related to landslide events have become a major topic of interest in recent years, given the growing awareness of concomitant socio-economic implications, environmental degradation, climatic change, rapid population growth, and improper land use (Aleotti and Chowdhury, 1999; Konovalov et al., 2019; Nowicki Jessee et al., 2020; Salvati et al., 2010).

It is widely recognized that slope instability is linked to the combination of geological, geomorphological, and climatic factors with triggering mechanisms generally ascribable to extreme weather events, seismic inputs, and anthropic activities (Carabella et al., 2019; Esposito et al., 2021; Guzzetti et al., 2005; Livio and Ferrario, 2020). Among these, seismic shaking can induce relevant changes in the landscape, leading to coseismic and post-seismic phenomena such as landslide events. These can occur with sizes ranging from small, shallow failures in the soil to large, deep rock avalanches, along with phenomena responsible for extensive damages and many casualties, as shown by several historical and recent earthquakes (Livio and Ferrario, 2020; Martino et al., n.d.; Miccadei et al., 2010; Oswald et al., 2021; Pace et al., 2020). Furthermore, Earthquake-Induced Landslides (EILs) are generally responsible for severe damages and losses, as demonstrated by last decadal records when more than 50% of total worldwide losses due to landslides are associated with coseismic slope failures (Crescenti et al., 1984; Fan et al., 2019; Keefer, 2002, 1984; Martino et al., 2020a; Petley, 2012). Remarkably, over the past years, the use of Geographical Information Systems (GIS) and pioneering remote sensing techniques have considerably improved our ability to map earthquake-induced landslides and to schedule activities for land defense, protection, and management (Bozzano et al., 2010; Hasegawa et al., 2009; Marchesini et al., 2014).

Landslide susceptibility is identified as the propensity of landslide events to occur in a given area, regardless of whether such events have already taken place or not. In detail, it can be defined as the estimate of the likelihood that a landslide phenomenon happens in a specific area based on local geomorphological conditions without any statement about when it could happen (Guzzetti et al., 1999; van Westen et al., 2006; Varnes, 1984). A review of the existing literature regarding its evaluation criteria results in several approaches, depending on the final purpose and the scale of analysis, integrated with GIS techniques to

realize thematic data layers, compute, and integrate controlling factors and data, and assign weights. These various procedures can be generally classified into three main groups: heuristic, statistical, or deterministic methods (Fell et al., 2008; Marsala et al., 2019; Rapolla et al., 2012). Concerning statistical methods, in recent years, several approaches have been developed based on multivariate statistics or artificial neural networks, which are becoming increasingly important also in the analysis and prediction of earthquake-induced ground effects and represent a valuable tool since they can provide objective results (Amato et al., 2023; Martino et al., 2019). These studies have been conducted based on either detailed post-earthquake field investigations, aimed at producing comprehensive EILs inventories, or catalogs already available for the analysis, allowing a better evaluation of the role played by predisposing factors on EILs occurrence at different scales.

Within this general framework, landslide susceptibility maps exert an undeniable role since, in addition to containing relevant information on the current geomorphological instability condition of an area, depict its tendency to collapse in a probabilistic way (Cascini, 2008; Guzzetti et al., 2006). Areas of interest are usually divided into sectors sharing comparable susceptibility values and labelled according to them. Sometimes, the effort of making the understanding of the map quite immediate for the reader can lead to the identical classification of regions belonging to different areas while having different degrees of susceptibility - e.g., two or more regions can be labelled as "Highly susceptible" for having the highest susceptibility values detected in areas they belong to, regardless of whether or not their actual susceptibility degrees are comparable. Furthermore, for a given area available EILs inventories do not necessarily feature the completeness and the accuracy required for a good-quality statistical susceptibility evaluation.

Therefore, it is necessary to develop a repeatable methodology able to produce comparable results over different regions independently of the presence or absence of suitable landslide catalogs. Accordingly, in this chapter, a heuristic approach for the assessment of EILs susceptibility is proposed, with the aim of detecting landslide detachment prone sectors and categorizing them based on their susceptibility degree. Achieved results are then statistically analyzed to provide a meaningful data classification; an example of its application to the Abruzzo Region in Central Italy is therefore presented. The work could constitute an important methodological tool for the implementation of land planning and loss-reduction measures and contribute towards the determination of situations that could lead to hazards (such as landslides) following an earthquake. Finally, it shows that accurate

and multidisciplinary methodological approaches can provide important information, readily available for local administrations and decision-makers, for the implementation of sustainable land planning, emergency management, and buildings or structures design.

3.2 Study Area

3.2.1 Geological and Geomorphological Setting

The Abruzzo Region is located in the central-eastern part of the Italian peninsula. The landscape is characterized by three main orographic and morphostructural domains: the Apennine chain area, the piedmont area, and the coastal plain (D'Alessandro et al., 2003). The chain area is characterized by a series of mountainous ridges NW-SE aligned with elevations stretching from 1000 to 2900 m above mean sea level (a.m.s.l.); wide valleys and intermontane basins are often interposed (i.e., Fucino Plain, Sulmona Basin). The chain consists of pre-orogenic carbonate lithological sequences relating to different Mesozoic-Cenozoic structural domains comprising sequences with different thicknesses, rheology, and erodibility. The bedrock of the main ridges of the Abruzzo Apennines consists of carbonate shelf, slope, and pelagic basin facies, while pelagic sequences are widespread outcropping in the Molise Apennines consisting of a chaotic assemblage on clayey-marly-limestone units; locally Quaternary continental deposits, consisting of alluvial, marshy, detrital, and eluvial-colluvial deposits occur (D'Alessandro et al., 2008; Miccadei et al., 2017; Parotto et al., 2004; Piacentini and Miccadei, 2014). The chain sharply decreases down to the piedmont area (stretching from ~600 to ~300 m a.m.s.l.), which features a cuesta and mesa landscape gently sloping towards the Adriatic Sea and incised by SW-NE river valleys. It is mainly composed of sin- and late-orogenic deposits constituted by pelitic-arenaceous turbiditic foredeep sequences, which are often covered, with the presence of erosional surfaces, by clay, sand, and sandstone of hemipelagic sequences with conglomerate levels (Ascione et al., 2008; Bigi et al., 2013). The coastal area is characterized by a sub-horizontal clayey-arenaceous-conglomeratic sequence affected by regional uplift, with elevations ranging from 0 to 300 m a.m.s.l.; the landscape is constituted by shores (80%) and steep rocky sectors (20%), and is shaped by fluvial, slope, and coastal processes that have combined thus producing a plateau and mesa relief (Figure 3.1; Calista et al., 2019; Miccadei et al., 2019).

The major tectonic elements are represented by N-S to NW-SE-oriented thrusts, which influenced the chain morphostructural sector from the Late Miocene to the Early Pliocene. This tectonic phase caused the tectonic units' complex superimposition, one above the other and above the syn-orogenic turbiditic sequences. This tectonics phase was followed by

strike-slip tectonics characterized by NW-SE to NNW-SSE-oriented faults largely disguised by subsequent extensional tectonics. Subsequently, the orogen underwent regional uplifting since the Early Pleistocene that, in connection with local extensional tectonics affecting the chain area, caused the uplifting of the chain system, the formation of the intermontane basins, and the emersion of the Adriatic Piedmont (Figure 3.1; D'Agostino et al., 2001; D'Alessandro et al., 2003; Miccadei et al., 2012b; Parotto et al., 2004; Patacca et al., 2008; Sembroni et al., 2020).

In this context, the geological, structural, and geomorphological setting of the region is the consequence of a complex cyclical evolution that happened in subsequent phases with the leading role of morphostructural features related either to the conflicting tectonic movements and regional uplifting or to drainage network linear downcutting and slope instability processes (Bigi et al., 1995; Demangeot, 1965; Miccadei et al., 2017). In the inner sectors, processes and landforms mainly result from the slope gravity, surface water, karst activity, and litho-structural setting. Slope gravity processes involve the main slopes of ridges, with the formation of debris cones and talus slopes at their feet. Landslide events are widespread, with typologies influenced by the lithological and morphostructural settings: falls, topples, and debris flows along the carbonate ridges; slides and earthflows in areas where terrigenous successions outcrop (Calista et al., 2020; Carabella et al., 2019; D'Alessandro et al., 2003); also, karst landforms widely characterize the region, mainly affecting the chain area and its carbonate ridges (Miccadei et al., 2018). Structural landforms (structural surfaces and scarps, ridges alignments, cuestas, hogbacks, etc.), gravitational processes (i.e., rotational and translational slides, complex landslides), and fluvial landforms (alluvial fans and terraces, badlands, gully erosion) mainly characterize the piedmont area (Carabella et al., 2021; D'Alessandro et al., 2008; Della Seta et al., 2008; Esposito et al., 2021). In the coastal sector, marine landforms prevail with steep cliffs and wide shores interested by intense geomorphological processes controlled by the morphostructural setting. These processes are primarily represented by erosive processes, new landslides in correspondence of vertical rocky coasts, and local reactivations of ancient landslides (Calista et al., 2019; Miccadei et al., 2019).

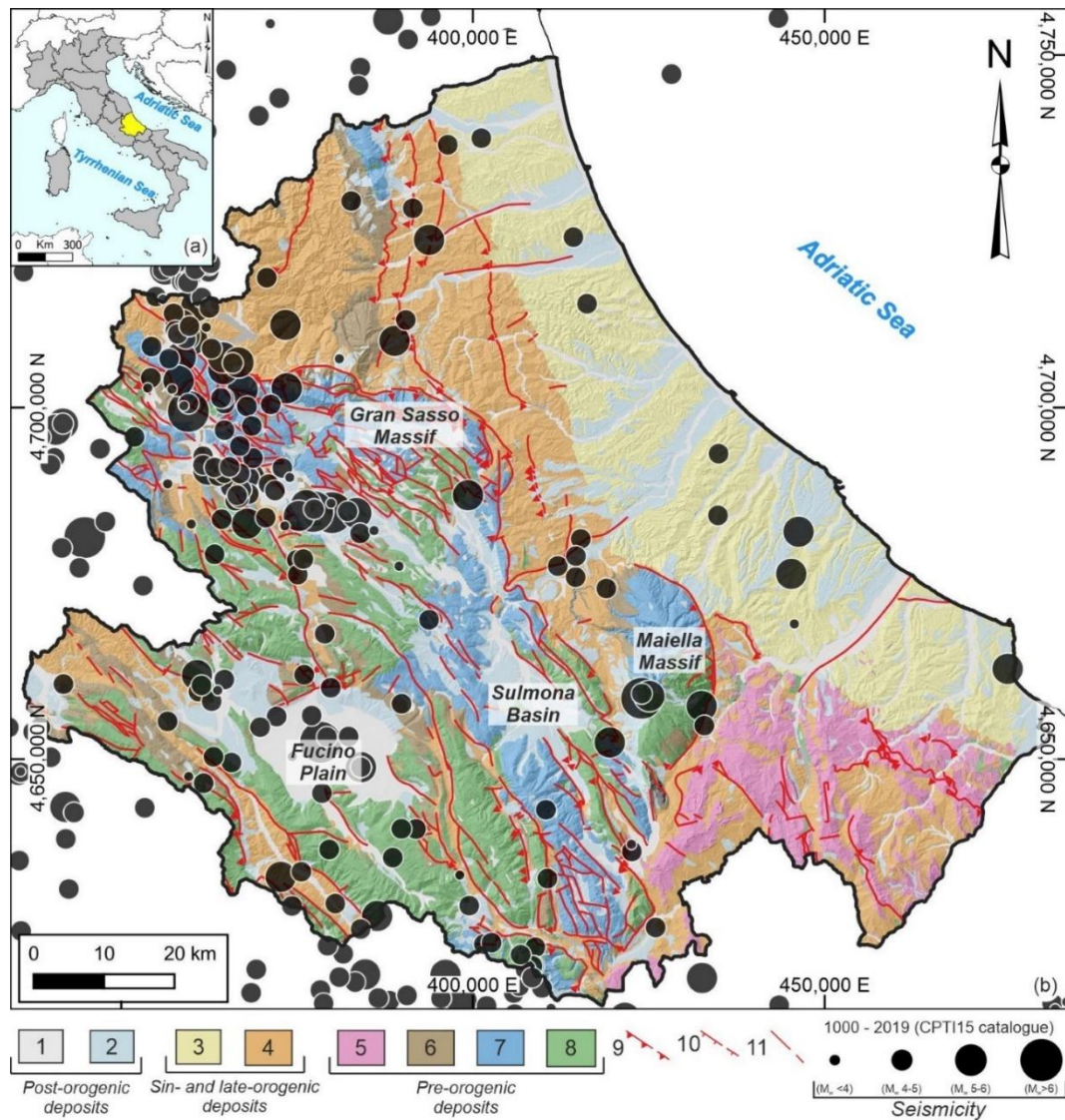


Figure 3.1. (a) Location of the Abruzzo Region in Central Italy; (b) Geological sketch of the Abruzzo Region. Legend: post-orogenic deposits - (1) actual fluvial deposits (Holocene), (2) old/terraced fluvial and alluvial fan terraced deposits (Middle-Late Pleistocene); sin- and late-orogenic deposits - (3) clay, sand, and sandstone of hemipelagic sequences with the presence of conglomerate levels (Late Pliocene-Early Pleistocene), (4) pelitic-arenaceous turbiditic foredeep sequences (Late Miocene-Early Pliocene); pre-orogenic deposits - (5) clay-marl-limestone of the Molise pelagic sequences (Oligocene-Miocene), (6) carbonate ramp limestones (Early Miocene- Early Pliocene), (7) slope and pelagic basin limestones and marls (Cretaceous-Miocene), (8) carbonate platform limestones (Jurassic-Miocene); (9) main thrust (dashed if buried); (10) main normal fault (dashed if buried); (11) main fault with strike-slip or reverse component (dashed if buried); seismicity -CPTI15 (Rovida et al., 2020) catalog (black circles).

3.2.1.1 Seismicity

The seismicity of the study area must be contextualized in the general framework of the Central Apennines, where several earthquakes are documented by historical sources since the beginning of the 19th century i.e., Baratta (1901) and, more recently, Valensise et al. (2020) and listed in the historical and instrumental catalogs (ISIDe Working Group, 2007; CFTI5Med, Guidoboni et al., 2019; CPTI15, Rovida et al., 2020). The seismic activity has been used for defining the seismotectonic framework of the area (i.e., Boncio et al., 2009;

Vannoli et al., 2012) while active tectonic studies on the different fault systems allow the identification of the related seismogenic sources (Basili et al., 2008; DISS Working Group, 2018). The present-day tectonic setting is dominated by extension, active in the axial part of the chain (e.g., Carafa et al., 2020), which is also the area characterized by the most intense seismicity and strongest historical earthquakes (up to M 7.0; e.g., Majella Massif, 1706; Fucino, 1915; L'Aquila, 2009; Central Italy 2016-2017). Conversely, the Adriatic piedmont and the offshore area are characterized by moderate seismicity in a compressional domain on the outer thrust fronts of the central Apennines belt and along E-W shear zone cutting through the Adriatic lower plate crust (Figure 3.1; Di Bucci and Angeloni, 2013b; DISS Working Group, 2018; Fracassi and Valensise, 2007; Kastelic et al., 2013).

According to this seismotectonic framework, the Abruzzo Region suffers mainly the shaking effects induced by strong earthquakes that enucleate along the axial zone of the Apennines and in neighboring areas of Central Apennines, as clearly observed during the 2016-2017 Central Italy seismic sequence (e.g., Luzi et al., 2017). However, in the Adriatic piedmont also lower magnitude and shallower earthquakes may locally induce high shakings (see, for example, the 2002 Molise earthquake; Gorini et al., 2004).

3.2.1.2 *Earthquake-Induced Landslides (EILs)*

In the last decades, detailed geomorphological analyses have shown that the Abruzzo Region is severely affected by EILs, linked to the extreme dynamics of the area. The distribution, mechanisms, and typology of mass movements are strictly related to the different physiographic and geological-structural settings. In detail, EILs in the chain area are mainly comprised of rockfalls, occurring especially on calcareous slopes, and minor earth slides, debris and earthflows, snow avalanches, and cavity collapses; in piedmont or coastal areas, on the other side, they are mainly comprised of rockfalls on scarps set on Quaternary clayey-sandy and conglomeratic deposits, by earth slides/flows, and by anthropogenic sinkholes collapse, occurring especially in urban areas (Blumetti et al., 2009; EMERGEIO Working group, 2016; Miccadei et al., 2010; Piacentini et al., 2020, 2013).

The analysis of available catalogs of earthquake-induced effects allowed the reconstruction of their spatial and temporal distribution in the Abruzzo Region; in particular, the CEDIT catalog (Italian catalog of earthquake-induced ground failures; Caprari et al., 2018; Fortunato et al., 2012) contains more than 150 earthquakes and about 2000 earthquake-induced effects, which affected almost 1100 locations; this catalog was recently updated with the Central Italy seismic sequence which occurred in 2016-2017. The catalog

is created on the basis of a detailed investigation of historical documents as well as on the analysis of numerous scientific papers. The analysis of documented earthquake-induced effects reveals that most of them concern landslides, being about half of the total incidents (44%). The EEE catalog (Earthquake Environmental Effects catalog; Guerrieri, 2015) aims to collect the wealth of information of geological and environmental effects caused by seismic events; it is composed of tables with information at site of each EEE, especially ground effects features. This database was updated with the 2016-2017 Central Italy seismic sequence, too. Finally, the landslide inventory map of the Abruzzo (Regione Abruzzo, 2011) includes the definition, recognition, and detailed cartography of different types of landslides. It contains several EILs, most of which consequent to the L'Aquila seismic event of April 6, 2009. A total of 446 EILs were extracted from the analysis of the catalogs and categorized according to the landslide kinematics (Figure 3.2).

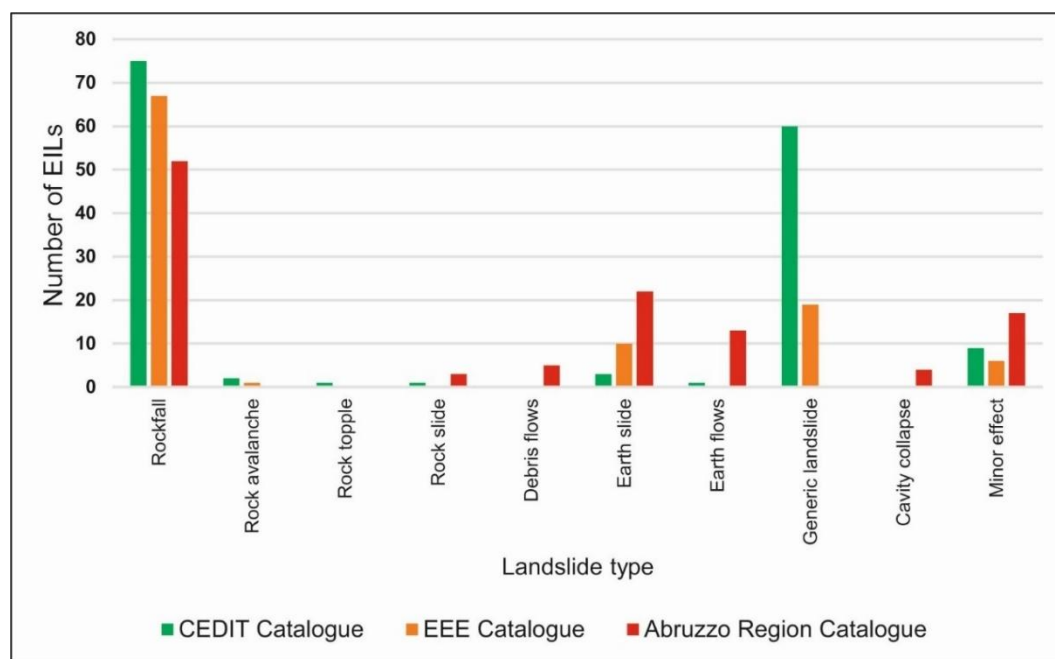


Figure 3.2. Bar chart showing the distribution of the type of EILs for each analyzed catalog ((Caprari et al., 2018; Fortunato et al., 2012; Guerrieri, 2015; Regione Abruzzo, 2011)) over the Abruzzo Region.

3.3 Materials and Methods

Earthquake-Induced Landslides (EILs) susceptibility analysis was performed through an integrated approach based on the combination of morphometric, geological, and geomorphological parameters derived from literature and field-based data, along with the critical evaluation of existing EILs catalogs, supported by multidisciplinary analyses and GIS-based techniques. In particular, a heuristic approach was applied in order to assess a

preliminary EILs susceptibility map with a cell size of 10 m; resulting values were then statistically analyzed to ensure a meaningful susceptibility classes definition.

3.3.1 Landslide-Triggering Parameters: Detection and Analysis

Statistical methods aimed at EILs susceptibility assessment require wide, complete, and temporally extended landslide inventories (Xu, 2015). Regretfully, with respect to the aim of this work, catalogs available for the study area feature substantial limitations, which make a statistical evaluation actually unfeasible. First and foremost, events localization is not accurate enough to distinguish sectors with different susceptibility degrees at this scale of analysis. Events such as rockfalls, though occurred and detected recently, are often mapped in correspondence of accumulation areas instead of detachment zones (Figure 3.3a). In the case of statistical analysis, this would result in a misleading sectors classification, with detachment and accumulation areas given, respectively, a lower and a higher susceptibility degree with respect to their actual one, in strict contrast with the purpose of this study. It should be stressed that smaller-scale studies, however, could be effectively conducted following this approach, since the spatial difference between detachment and accumulation zones would not affect the final result (Amato et al., 2023). Another aspect to consider is that different landslides are sometimes mapped as a single event when occurring in a small area, with a subsequent wrong susceptibility degree evaluation (Figure 3.3b). Finally, detailed data of non-recent events are definitively missing, with mapped EILs often featuring poor geographical and chronological constraints (Figure 3.3c).

For these reasons, given the available data, in this study a heuristic approach appears to be highly preferable to a statistical one. Heuristic methods require the combination of several parameters that contribute to slope instability. Each of these parameters and their spatial variability, represented through thematic maps, are, in turn, analyzed and subdivided into a suitable number of classes. Subsequently, each of these parameters is given a certain weight, based on expert judgment, and according to the influence exerted on landslide susceptibility derived by critically analyzing literature data and available EILs catalogs (Caprari et al., 2018; Guerrieri, 2015; Regione Abruzzo, 2011). From the algebraic sum of the weights associated with individual parameters, a final map is constructed wherein high/low numerical values correspond to a high/low propensity of the slope to fail (Magliulo et al., 2009; Pourghasemi et al., 2018; Reichenbach et al., 2018; Ruff and Czurda, 2008).

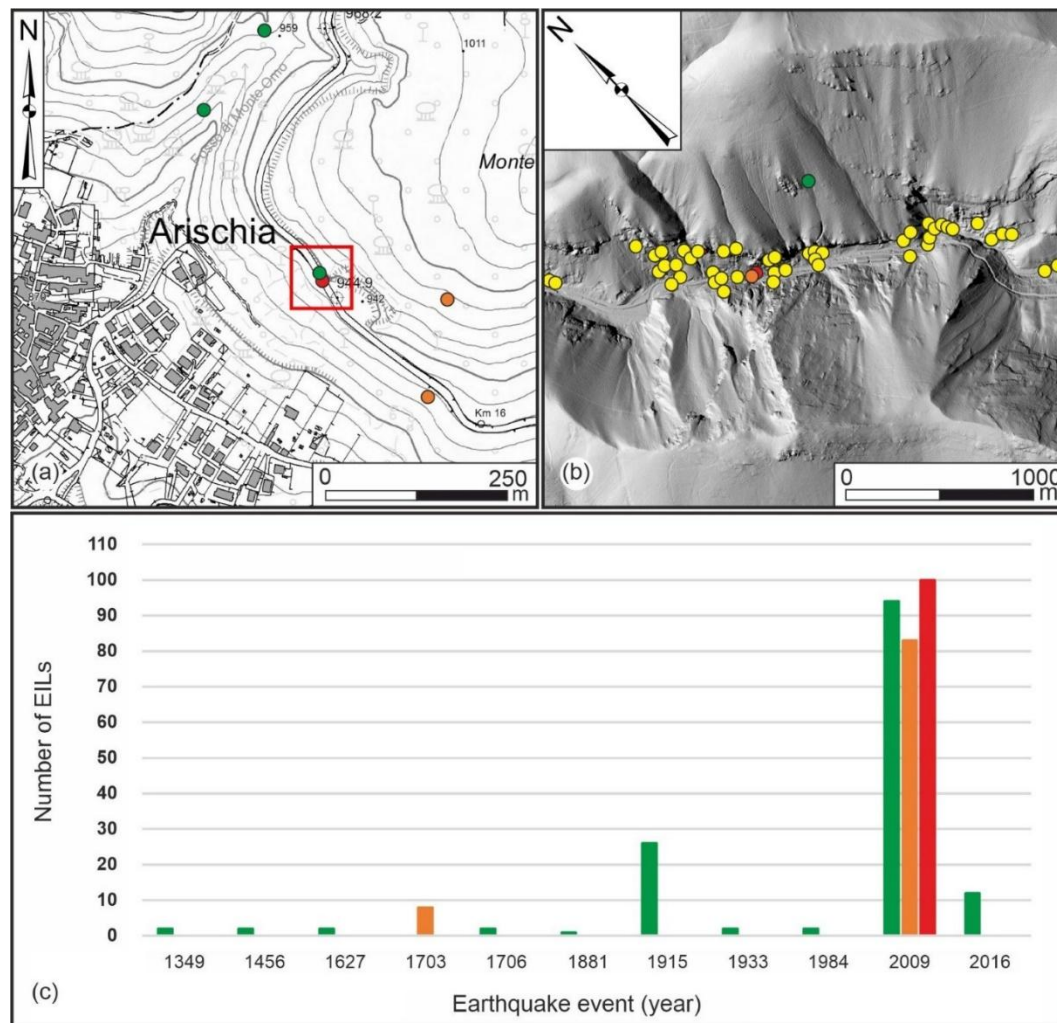


Figure 3.3. EILs events reported on CEDIT (green dots and bars; (Caprari et al., 2018)), EEE (orange dots and bars; (Guerrieri, 2015)), and Abruzzo Region (red dots and bars; (Regione Abruzzo, 2011)) catalogs. Yellow dots refer to earthquake-triggered rockfall blocks in the area of San Venanzio gorges (Raiano, AQ) according to (Piacentini et al., 2013). (a) Example of events mapped in correspondence of accumulation areas (roads) instead of detachment zones (red box); (b) example of multiple events mapped as a single event; (c) number of EILs per event showing a clear lack of available data for non-recent earthquakes.

The selection of factors strictly depends on available data concerning the object and the aims of the study. In this paper, each factor described in the following paragraphs was chosen to better match the variability of the data source and to outline its role in the landslide mechanism in the geological, structural, and geomorphological framework of the region. The nine different factors considered for the present landslide susceptibility analysis are: slope, aspect, topographic curvature, outcropping lithofacies, degree of rock fracturing, karst incidence, distance from active faults, distance from earthquake epicentres, and presence of anthropogenic sinkholes. The choice of these parameters was also dictated by the scale of analysis, since for studies of higher detail the integration of local-scale factors both of natural and anthropogenic origin is advisable e.g., slopes undercutting by erosion or artificial excavation (Chigira and Yagi, 2006; Martino et al., 2019). Finally, although Peak Ground

Acceleration (PGA) values are available for the study area through the MPS04 seismic hazard map of Italy (Stucchi et al., 2004), they were not considered to not overestimate the contribution of seismic parameters, already implemented by accounting for distances from active faults and earthquake epicentres.

Morphometric parameters, i.e., slope, aspect, and topographic curvature, are all derived from a 10 m resolution Digital Terrain Model (DTM) available at the opendata.regione.abruzzo.it web page, by means of ESRI ArcGIS™ 10.6 tools.

Slope, expressed as an angle [°] to the horizontal, is commonly used in landslide susceptibility analysis. An increase in its gradient usually corresponds to an increase in hillside instability (Çevik and Topal, 2003; Yalcin et al., 2011).

Topographic curvature, expressed in [m^{-1}], is computed along the direction of the maximum slope. The parameter is taken into account in terms of the control it exerts on ground shaking; in particular, a convex surface leads to a focusing of seismic waves, which increases acceleration; a concave surface induces the dispersion of waves and, consequently, an acceleration decrease (Maufroy et al., 2018; Pischiutta et al., 2017). In this work, topographic curvature (T_c) values are divided into three ranges, $T_c \leq -0.5$, $-0.5 < T_c \leq 0.5$, and $T_c > 0.5$, indicating, respectively, concave, planar, and convex surfaces (Pham et al., 2017).

Aspect, expressed as a cardinal direction, is considered less important compared to other parameters (Carrara et al., 1991; Çevik and Topal, 2003); nevertheless, it is generally taken into account due to its connection to the microclimate acting on slopes and the consequent weathering (Komac, 2006; Shahabi et al., 2014). According to many authors, it is assumed that such processes act more effectively on south-facing slopes due to pronounced temperature variations (Capitani et al., 2013; Pham et al., 2017).

Lithology has a great influence on landslide susceptibility (Carrara et al., 1991; Çevik and Topal, 2003; Esposito et al., 2021; Shahabi et al., 2014). A Lithofacies map of the Abruzzo Region was hence created through digitization of the 1:250.000 scale Lithofacies map of Latium-Abruzzo and neighboring areas (Accordi and Carbone, 1988). Missing sectors were included after analysis and re-adaptation of the 1:100.000 scale Geological map of Abruzzo (Vezzani and Ghisetti, 1998) and the 1:50.000 scale Geological sheets of the CARG Project available for the study area (ISPRA, 2017). Units resulting from this process were joined into 17 lithological units based on the sedimentation environment and the

lithological features of the outcrops. The impact on landslide susceptibility of each group is assessed by analyzing the distribution of the main landslides (APAT, 2007; Regione Abruzzo, 2019). It was also based on EILs density, which was computed for each lithological unit by accounting for inventoried events (Caprari et al., 2018; Guerrieri, 2015; Regione Abruzzo, 2011).

The **degree of rock fracturing** results from the interaction between the lithological features of outcrops and the regional tectonics (ISRM, 1979; Molnar et al., 2007; Sperrevik et al., 2002). This parameter exerts a clear influence on landslide susceptibility, and it is often used to detect failure mechanisms and define the landslide geometry, showing higher values linked to a greater slope instability (Barisone et al., 1992; ISRM, 1979).

Karst phenomena deeply affect rock mechanical properties by inducing the calcium carbonate dissolution and the subsequent formation of natural caves prone to collapse in response to seismic shaking (Pace et al., 2020; Santo et al., 2007). Different sectors were distinguished based on their lithological features, the presence of natural caves (Regione Abruzzo, 2011), and the karst state of activity. A higher karstification degree is associated with a greater landslide susceptibility.

The **distance from active faults** exerts a major control on earthquake-induced landslide susceptibility of a region, as empirically shown by the rapid decrease of EILs events moving away from the surface traces of faults connected to the attenuation of the seismic input (Shao et al., 2019; Xu and Xu, 2014). Detection and digitization of faults were based on the ITHACA catalog (ITaly HAZard from CAPable faults; ITHACA Working Group, 2019; Michetti et al., 2000) implemented with (Boncio et al., 2004). Areas located at different distances from faults traces are detected using the Buffer tool implemented in ArcGIS™ 10.6. Hanging walls and footwalls were differentiated, given the higher density of EILs usually occurring above the fault plane (Martino et al., 2014); consequently, two different rasters were created. In this Thesis, fault systems located in neighboring regions are also considered, given their contribution to the landslide instability of the Abruzzo Region (Villani et al., 2018).

By analyzing landslide movements in the first years after an earthquake, many authors detected a close correlation between the number of mass movements and the proximity to epicentral zones (Martino et al., 2014; Shao et al., 2019; W. Yang et al., 2017; Zhang et al., 2016). The **distance from epicentres** was therefore computed using the Euclidean distance

tool implemented in ArcGISTM 10.6. Only events with a $4.0 < M_w < 6$ were considered in the analysis since lower magnitudes rarely trigger landslides (Keefer, 1984), whereas higher magnitudes refer to infrequent events that are unrepresentative of the actual seismicity of the area (Rovida et al., 2020). It is widely recognized that an increase of the magnitude corresponds to an increase in the area prone to EILs (Keefer, 2002). For a correct assessment of landslide susceptibility related to the epicentral distance, seismic events were thus divided into four equally spaced classes based on related M_w ; consequently, four different thematic maps were created. Each class is also corrected by a factor stating the epicentres density using the Kernel density tool with a radius of 10 km. As for the distance from active faults, epicentres falling into neighboring regions are taken into consideration. Weights were then assigned based on literature-accepted relations between epicentral distances of landslides and earthquake magnitudes (Keefer, 2002, 1984).

Finally, **anthropogenic sinkholes** were considered. They have a consistent role in arising the EILs hazard, given their presence in areas often heavily urbanized (Fiore and Lanzini, 2007; Nisio et al., 2007). Their detection and digitization were based on the Geohydrological Plan (Regione Abruzzo, 2011), properly integrated with the ISPRA Sinkhole catalog (ISPRA, 2020). Areas of attention were defined by setting a buffer zone around mapped sinkholes with a radius of 500 m.

The above listed parameters were therefore classified following a heuristic approach and given proper weight, based on literature data as well as on the critical evaluation of available EILs inventories Table 3.1.

Table 3.1. Parameters analyzed in EILs susceptibility assessment and assigned weights.

Parameter #	Parameter	Source	Class	Weight
1	Slope [°]	DTM	0-20	0
			20-30	1
			30-35	2
			35-40	3
			40-45	5
			45-60	7
			60-70	9
			70-80	11
			80-90	12
2	Topographic curvature	DTM	Concave	0
			Planar	2
			Convex	7
3	Aspect [°]	DTM	Plain	0

Parameter #	Parameter	Source	Class	Weight
4	Outcropping lithofacies	Literature (Accordi and Carbone, 1988; Vezzani and Ghisetti, 1998)	337.5-22.5 - N	0
			22.5-67.5 - NE	0
			67.5-112.5 - E	1
			112.5-157.5 - SE	2
			157.5-202.5 - S	3
			202.5-247.5 - SW	2
			247.5-292.5 - W	1
			292.5-337.5 - NW	0
			Eluvial and colluvial deposits	2
			Sandy shore deposits	0
			Recent fluvial-lacustrine deposits	0
			Travertine deposits	7
			Moraine deposits	7
			Old fluvial-lacustrine deposits	2
			Conglomerate deposits	7
			Clay-sand deposits	3
			Sand turbidites	7
			Pelitic turbidites	3
			Limestone deposits in conglomeratic and calcarenitic facies	6
			Allochthonous pelagic deposits	3
			Limestones in carbonate ramp facies	10
			Limestones and marls in basin facies	7
			Limestones in slope facies	6
			Limestones in open carbonate shelf-edge facies	7
			Limestones and dolomites in carbonate shelf facies	8
			Not susceptible to fracturation	0
5	Degree of rock fracturing	Field data and literature (Pasculli et al., 2014)	Low	4
			Medium	5
			High	7
			Very high	12
			Null	0
6	Karst incidence	Field data and literature (Pasculli et al., 2014)	Inactive	1
			Low	2
			Medium	5
			High	10

Parameter #	Parameter	Source	Class	Weight
7	Distance from active faults [km] Hanging wall	Literature (Boncio et al., 2004; Michetti et al., 2000)	0 - 5	12
			5 - 10	9
			10 - 15	8
			15 - 20	7
			20 - 25	6
			25 - 35	5
			35 - 45	4
			45 - 60	3
			60 - 70	2
			0 - 5	9
			5 - 10	7
			10 - 15	5
	Distance from active faults [km] Footwall	Literature (Boncio et al., 2004; Michetti et al., 2000)	15 - 20	4
			20 - 25	3
			25 - 35	2
			35 - 45	1
			> 45	0
			0 - 3	9
	Distance from epicentres $4 \leq M_w < 4.5$	Literature (Rovida et al., 2020)	> 3	0
			0 - 3	64
			3 - 6	15
			6 - 10	6
			10 - 12	3
			> 12	0
8	Distance from epicentres $5 \leq M_w < 5.5$	Literature (Rovida et al., 2020)	0 - 3	291
			3 - 6	68
			6 - 10	27
			10 - 15	14
			15 - 20	8
			20 - 25	5
			25 - 30	4
			> 30	0
			0 - 3	1000
			3 - 6	232
			6 - 10	93
			10 - 15	47
	Distance from epicentres $5.5 \leq M_w < 6$	Literature (Rovida et al., 2020)	15 - 20	27
			20 - 25	19
			25 - 30	14
			30 - 40	11
			40 - 50	7
			50 - 60	6
			60 - 80	4

Parameter #	Parameter	Source	Class	Weight
			> 80	0
9	Anthropogenic sinkholes	Field data and literature (ISPRA, 2020; Regione Abruzzo, 2011)	Buffer zone (radius = 500 m)	5

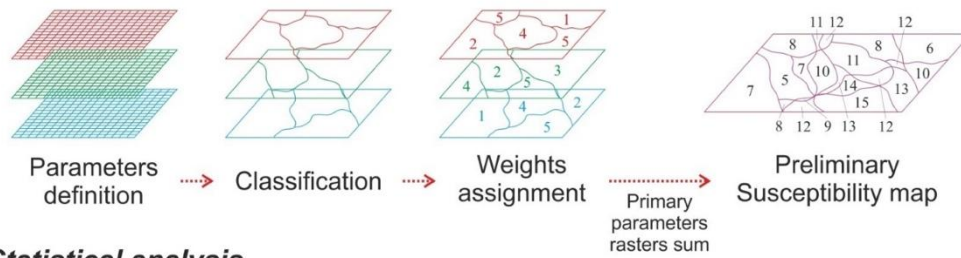
The listed parameters were then subdivided into primary and secondary, based on the extension of the area they affect. In this paper, only Anthropogenic sinkholes are categorised as the latter since they influence a percentage of the regional territory much less than other parameters.

Subsequently, using the Raster Calculator tool implemented in ArcGIS™ 10.6, thematic maps depicting the distance from the epicentres are all summed cell by cell, and resulting values are expressed on a scale from 1 to 10 to ensure comparability with other parameters; the resulting map is then summed cell by cell to weighted rasters of other primary parameters. A preliminary EILs susceptibility map is thus obtained using GIS technology (Figure 3.4).

3.3.2 Unsupervised Classification, Susceptibility Classes Definition, and Map Creation

Statistical analysis was performed after the preliminary landslide susceptibility analysis to divide the study area into an optimal number of susceptibility classes, a number that is actually beforehand unknown. In order to define it, an unsupervised classification is executed by means of kmeans R[®] routine (Forgy, 1965) on the preliminary map resulting from the heuristic analysis. The process groups together pixels sharing similar statistical properties into a user-specified number of distinct clusters. For each cluster, it also returns relevant statistics, including the central value, the number of cells, and the Within Cluster Sum of Squares and, for each group of clusters, the total Within Clusters Sum of Squares (WCSS) and the Between Clusters Sum of Squares (BCSS). The preliminary susceptibility raster is hence classified into a number of groups ranging from 2 up to 7. The optimal number is finally defined through the elbow method by plotting the WCSS/BCSS ratios against the number of clusters. A bend in the plot occurs indicating the minimum number of clusters such that the total intra-cluster variation is minimized, and the between-clusters variation is maximized (Mascioli et al., 2021; Tripathi et al., 2018; Figure 3.4a).

Heuristic analysis



Statistical analysis

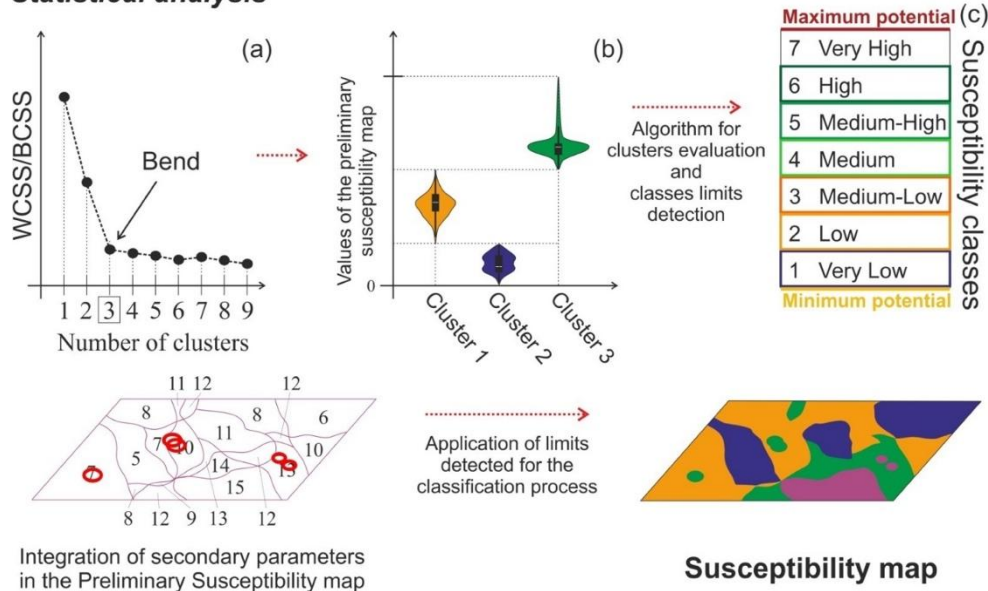


Figure 3.4. Workflow of the applied methodology. In the Heuristic analysis, the steps followed to get the Preliminary Susceptibility map from rasters of primary parameters are shown. In the Statistical analysis, the Elbow method, the analysis of cluster values by means of violin plot diagrams, and the detection of limits of susceptibility classes - with respect to an absolute scale and after application of the algorithm shown in Figure 3.5- are presented. Finally, the integration of secondary parameters in the Preliminary Susceptibility map and the creation of the final Susceptibility map are shown.

Statistics of clusters are analyzed by plotting values of each group on violin plot diagrams, which are a combination of a box plot and a probability density function plot. They explicitly show the median, the interquartile range, the upper and lower adjacent values, and the kernel probability density of the data at different values (Wei et al., 2012); (Figure 3.4b).

An absolute susceptibility scale is then introduced with values ranging from the minimum to the maximum potential values of the area, computed by summing the minimum and the maximum potential values of all primary parameters. By dividing the resulting range into a fixed number of equally spaced intervals, a series of meaningful classes are detected. This procedure ensures the comparability of results obtained in different areas when maximum and minimum potential values of parameters are used to build the scale (e.g., if slope values of a region range from 20° to 50°, upper and lower limits of the absolute scale should be computed by accounting also for weights associated to 0°-20 and 50°-90° slope

classes). The application of the algorithm presented in Figure 3.5, i.e. the critical comparison between clusters statistics and classes of the absolute susceptibility scale, allows the definition of proper numerical limits for the final classification (Figure 3.4c).

The last phase of the analysis is the creation of the final Susceptibility map. In this phase, secondary parameters - previously set aside - are taken into consideration. In this work, the raster depicting the Anthropogenic Sinkholes is summed cell by cell to the preliminary susceptibility map. The resulting raster is then classified based on limits detected through the statistical steps. Values eventually exceeding the absolute susceptibility scale are assigned to the highest-level susceptibility class.

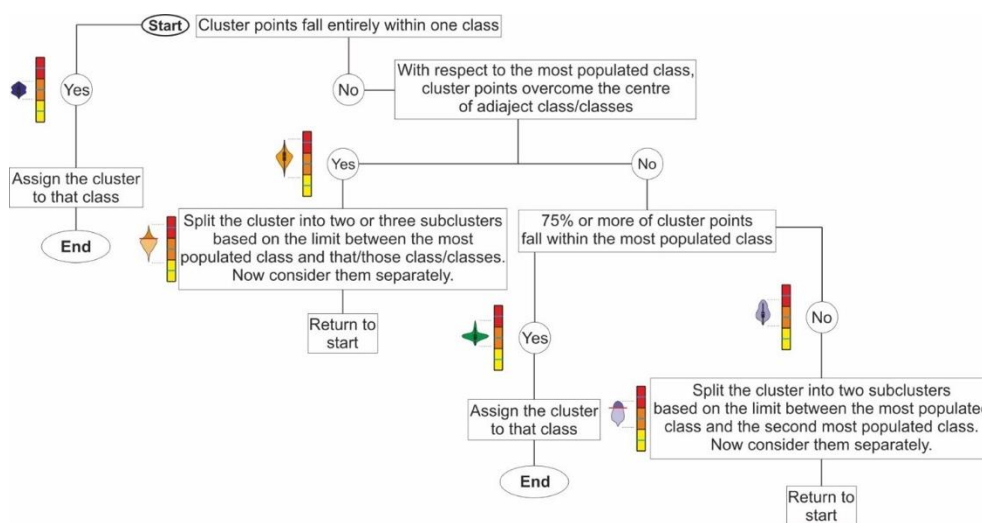


Figure 3.5. Flowchart showing the logical process for class detection. Steps are designed to achieve the best differentiation among classes and overcome limits intrinsic to the stand-alone unsupervised classification, such as the grouping of values representative of clearly different susceptibility degrees.

3.4 Results

3.4.1 Morphometric Maps

3.4.1.1 Slope map

The study area shows slope values ranging from 0 up to approximately 90° (Figure 3.6a). Values between 0 and 5° are detected in coastal areas, alluvial valleys of piedmont areas, and intermontane basins (such as Fucino Plain and Sulmona Basin), as well as basins with a minor areal extension. Low-to-medium values (ranging from 5 to 20°) are found in the whole piedmont area and along narrow sectors surrounding the intermontane basins. Finally, values ranging from 20 to 40° characterize the chain sector corresponding to the main ridges interrupted by longitudinal and transversal valleys; slope values above 50° are mostly detected on Maiella and Gran Sasso massifs, although narrow steep sectors are locally found in ridges, gorges, and minor valleys.

3.4.1.2 Topographic curvature map

The surface curvature of the study area is characterized by well-defined planar surfaces, characterizing coastal sectors, the main alluvial plains in the piedmont area, and the intermontane basins (i.e., Fucino Plain and Sulmona basin; Figure 3.6b). On the other hand, convex and concave surfaces alternate almost regularly across the study area, depicting a mountainous and hilly landscape dominated by ridges, isolated reliefs, and longitudinal and transversal river valleys.

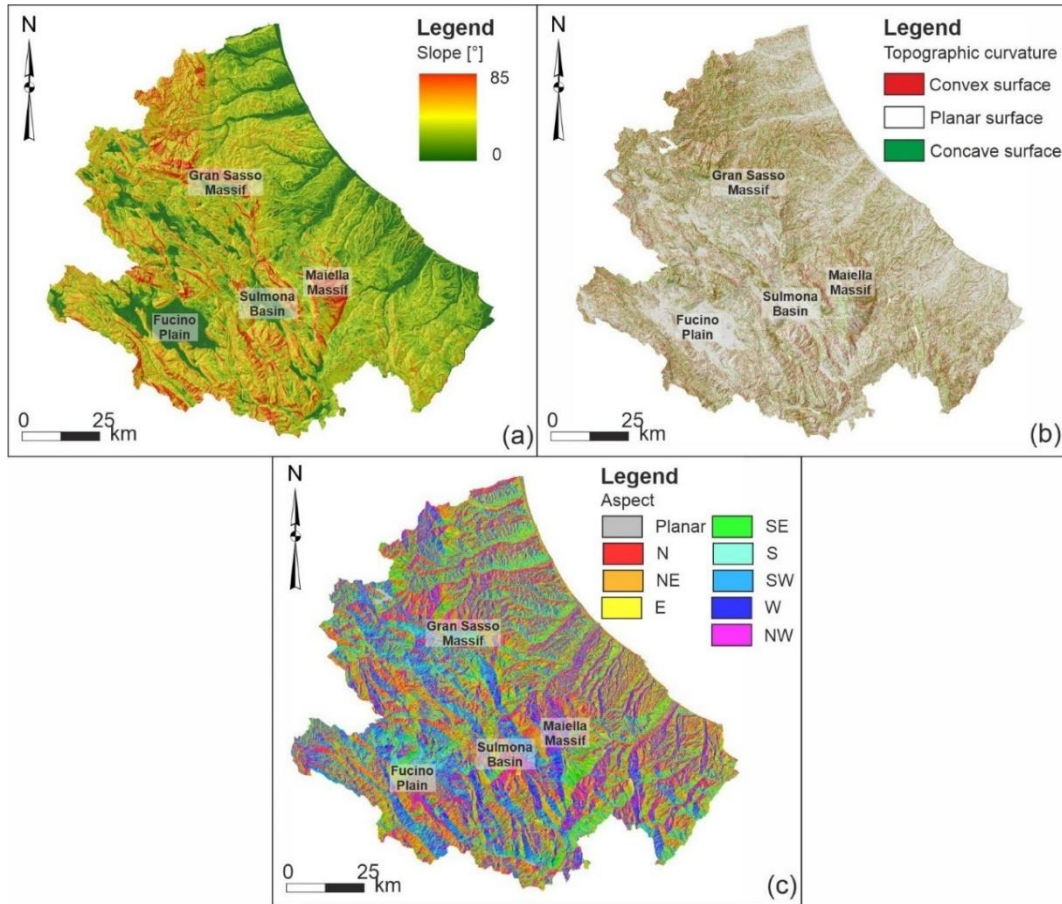


Figure 3.6. Morphometric maps of Abruzzo Region. (a) Slope map; (b) Topographic curvature map; (c) Aspect map.

3.4.1.3 Aspect map

The study area shows a clear differentiation between the chain and the piedmont/coastal sectors (Figure 3.6c). The former is characterized by mainly NW-SE oriented slopes, in accordance with the vergence of the Central Apennine chain. The latter shows an average SW-NE direction in close relationship with the development of the drainage network, characterized by main fluvial valleys and the small tributary catchments of main rivers and those incising the coastal slope.

3.4.2 Geothematic Maps

3.4.2.1 Lithofacies map

From a lithological standpoint, limestones in carbonate shelf facies, limestones in slope facies, limestone and marls in basin facies characterize the major ridges of the Abruzzo Apennines (i.e., Gran Sasso Massif and Maiella Massif). Allochthonous pelagic deposits are widely outcropping in the southern areas showing a chaotic assemblage on clayey-marly-limestone units. Bedrock lithologies in the piedmont sector pertain to sand-pelitic turbidites and marine clay-sand and conglomerate deposits (Figure 3.7). Quaternary continental deposits are extensively outcropping in the intermontane basins, alluvial valleys, and coastal sectors. They pertain to fluvial-lacustrine, travertine, sandy shore, and eluvial and colluvial deposits.

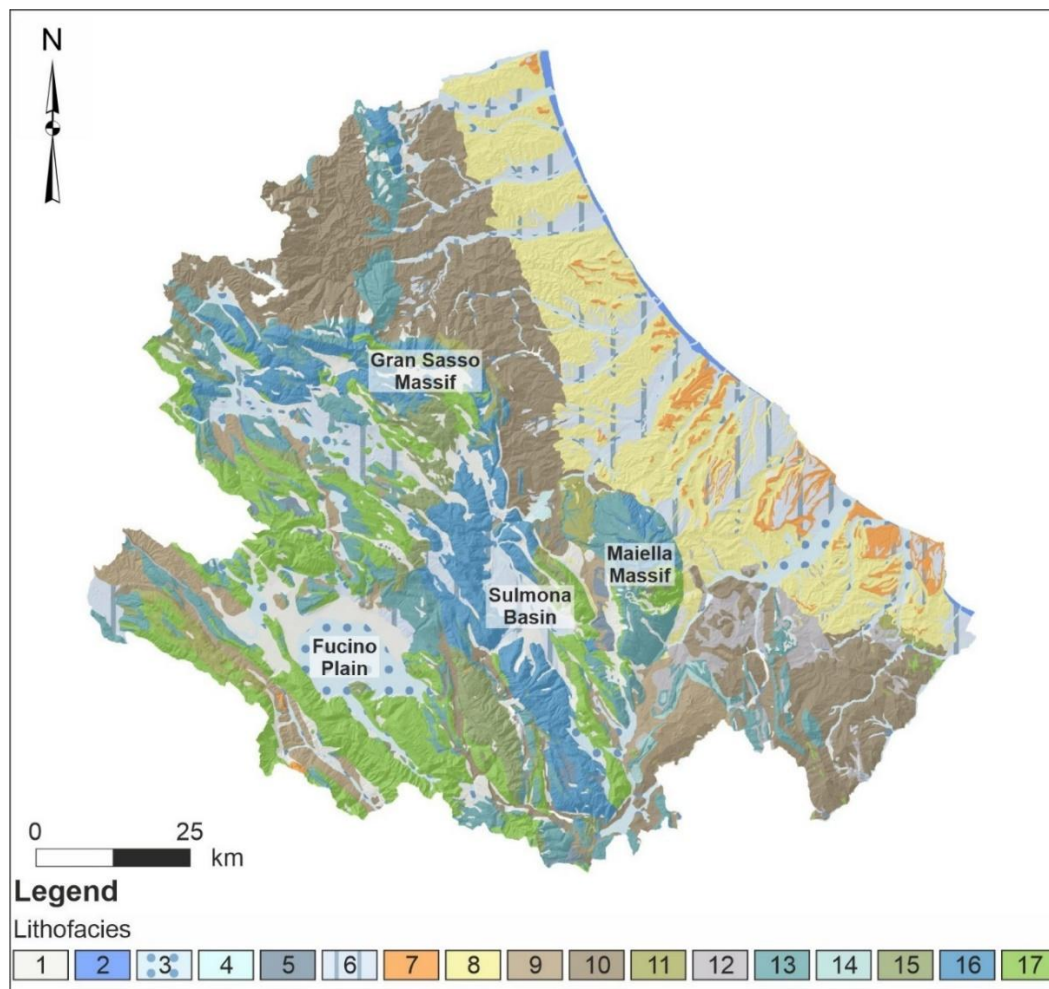


Figure 3.7. Lithofacies map of the Abruzzo Region (modified from (Accordi and Carbone, 1988; Esposito et al., 2021; ISPRA, 2017; Vezzani and Ghisetti, 1998)). 1) Eluvial and colluvial deposits; 2) Sandy shore deposits; 3) Recent fluvial-lacustrine deposits; 4) Travertine deposits; 5) Moraine deposits; 6) Old fluvial-lacustrine deposits; 7) Conglomerate deposits; 8) Clay-sand deposits; 9) Sand turbidites; 10) Pelitic turbidites; 11) Limestone deposits in conglomerate and calcarenite facies; 12) Allochthonous pelagic deposits; 13) Limestones in carbonate ramp facies; 14) Limestones and marls in basin facies; 15) Limestones in slope facies; 16) Limestones in open carbonate shelf-edge facies; 17) Limestones and dolomites in carbonate shelf facies.

3.4.2.2 Degree of rock fracturing map

Fractures, faults, and their patterns exert a fundamental influence on the mechanical and transport properties of rocks. According to its physiographic and geological-structural setting, the Abruzzo Region shows a heterogeneous spatial arrangement of fracture arrays. Piedmont and coastal sectors, as well as intermontane basins, are characterized by lithologies that do not have a large effect on fracture attribute distributions. Nevertheless, there are episodic and localized slope instability processes related to morphostructural setting in weak rock hills (e.g., hog-back relief, mesa relief affected by intersecting major joints) and cliff recession processes combined with wavecut and slope gravity processes widely controlled by main joints in the coastal area (Calista et al., 2019; Miccadei et al., 2019). In these areas, outcropping weak rocks are classified as not susceptible to fracturation (Figure 3.8a). In detail, areas showing a low degree of fracturation are detected towards NW and in narrow sectors of the piedmont. Medium values are found along the slopes of the Maiella Massif and the Gran Sasso ridge. High and very high values, finally, characterize the carbonate sectors of the westernmost sectors of the Abruzzo Region in accordance with a general NW-SE trend of tectonic lineaments.

3.4.2.3 Karst incidence map

According to the lithological framework, karst incidence is completely absent in the piedmont sector and in intermontane basins (Figure 8b). Karst morphogenesis widely affects carbonate rocks outcropping in the chain area, showing the highest values on carbonate shelf successions and low-to-medium values on limestones in carbonate ramp and basin facies. Finally, inactive karst processes characterize the limestones in open carbonate shelf-edge facies, locally widespread in central and southern sectors of the region.

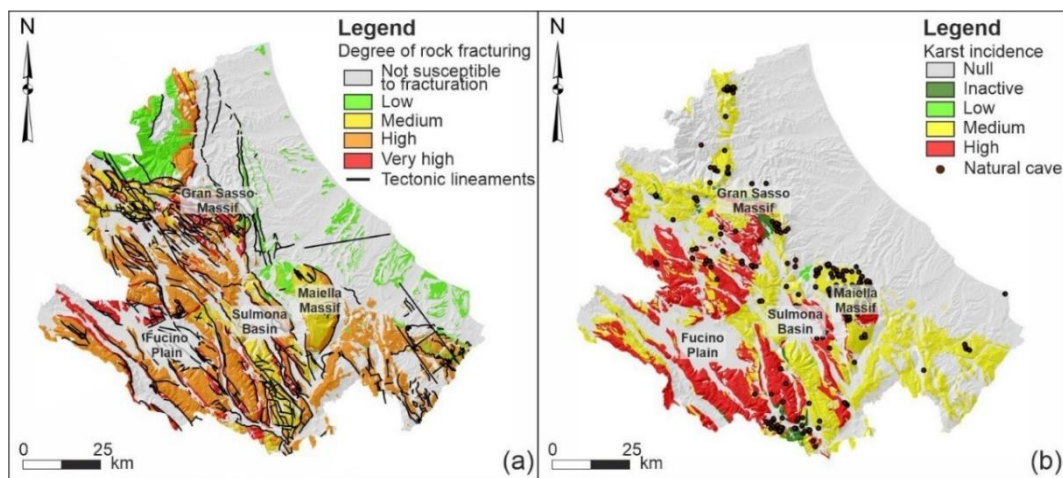


Figure 3.8. (a) Degree of rock fracturing and (b) Karst incidence maps (modified from (Pasculli et al., 2014)).

3.4.2.4 Distance from active faults maps

Thematic maps depicting the distance from active faults show values ranging from 0 up to approximately 60 km, with slight differences between hanging walls/footwalls-related maps (Figure 3.9). Minimum distances are detected in the chain sector according to the spatial arrangement of fault systems derived and implemented from Boncio et al. (2004) and the ITHACA Working Group (2019). Active fault systems located in neighboring regions are also considered, taking into account their contribution to landslide instability of the Abruzzo Region as clearly observed during the 2016-2017 Central Italy seismic sequence. Maximum values are found in the external piedmont sector and along the coastal one.

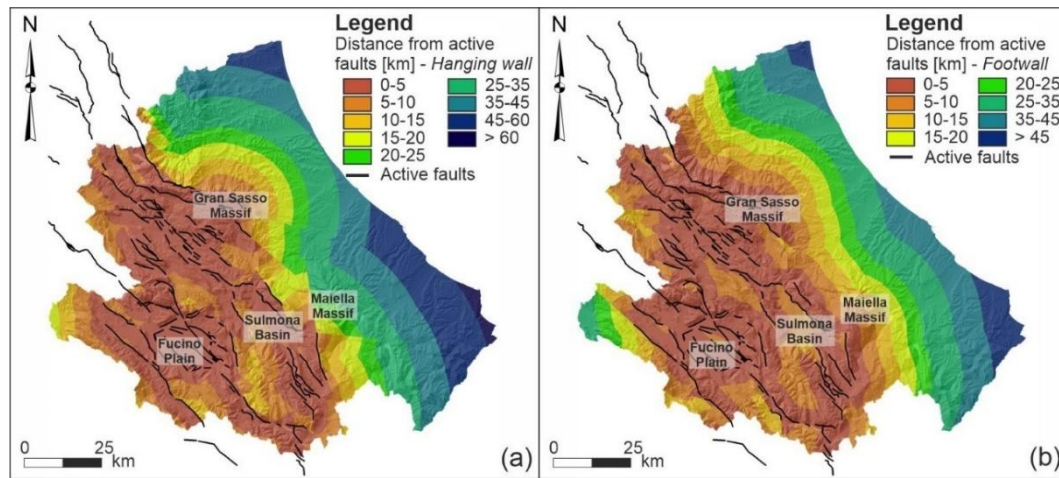


Figure 3.9. Distance from active faults maps: (a) hanging wall and (b) footwall.

3.4.2.5 Distance from epicentres and epicentres density maps

Maps depicting the distance from epicentres show values ranging from 0 to approximately 50 km, depending on the magnitude range (Figure 3.10, left column). The spatial distribution of epicentres reflects the tectonic setting of the Abruzzo Region, characterized by both historical and recent strong seismicity. The majority of epicentres related to events with $4 \leq M_w < 4.5$ falls into the chain sector, with rare events located in the central and northern piedmont/coastal area (Figure 3.10a, left column).

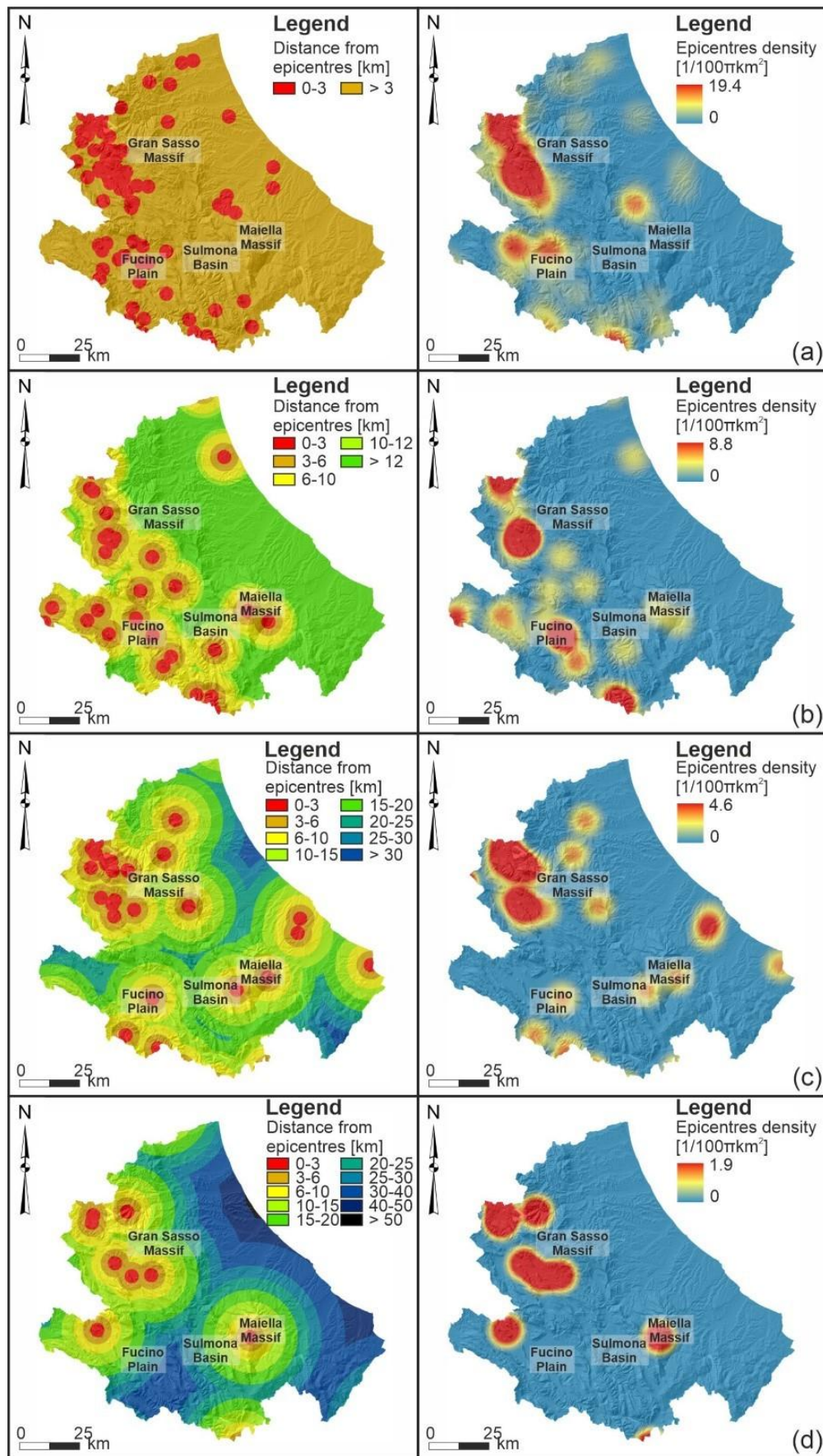


Figure 3.10. Thematic maps depicting distance from epicentres (left column) and epicentres density (right column) for earthquakes with a) $4 \leq M_w < 4.5$, b) $4.5 \leq M_w < 5$, c) $5 \leq M_w < 5.5$, and d) $5.5 \leq M_w < 6$.

Epicentres of earthquakes with $4.5 \leq M_w < 5$ are all located in the chain sector, except for sporadic events found in the northern piedmont/coastal area (Figure 3.10b, left column). Events with $5 \leq M_w < 5.5$, on the other hand, are concentrated in the north-western sector and, secondarily, in the Fucino plain and Maiella areas as well as in the central-southern piedmont/coastal sector (Figure 3.10c, left column). Finally, epicentres of earthquakes with $5.5 \leq M_w < 6$ are absent in the piedmont/coastal area, being mostly located in the north-western sector of the region (Figure 3.10d, left column). Epicentres density is graphically shown in thematic maps of Figure 3.10 (right column). This analysis was performed by dividing seismic events into four equally spaced classes based on related M_w , according to the georeferenced location of epicentres. Relevant values decrease as related magnitude increases; the highest values, however, are always detected in the chain sector.

3.4.2.6 Anthropogenic sinkholes map

Anthropogenic sinkholes present a high concentration in the external sector of the chain and the piedmont/coastal area, greater in major urban areas (Figure 3.11).

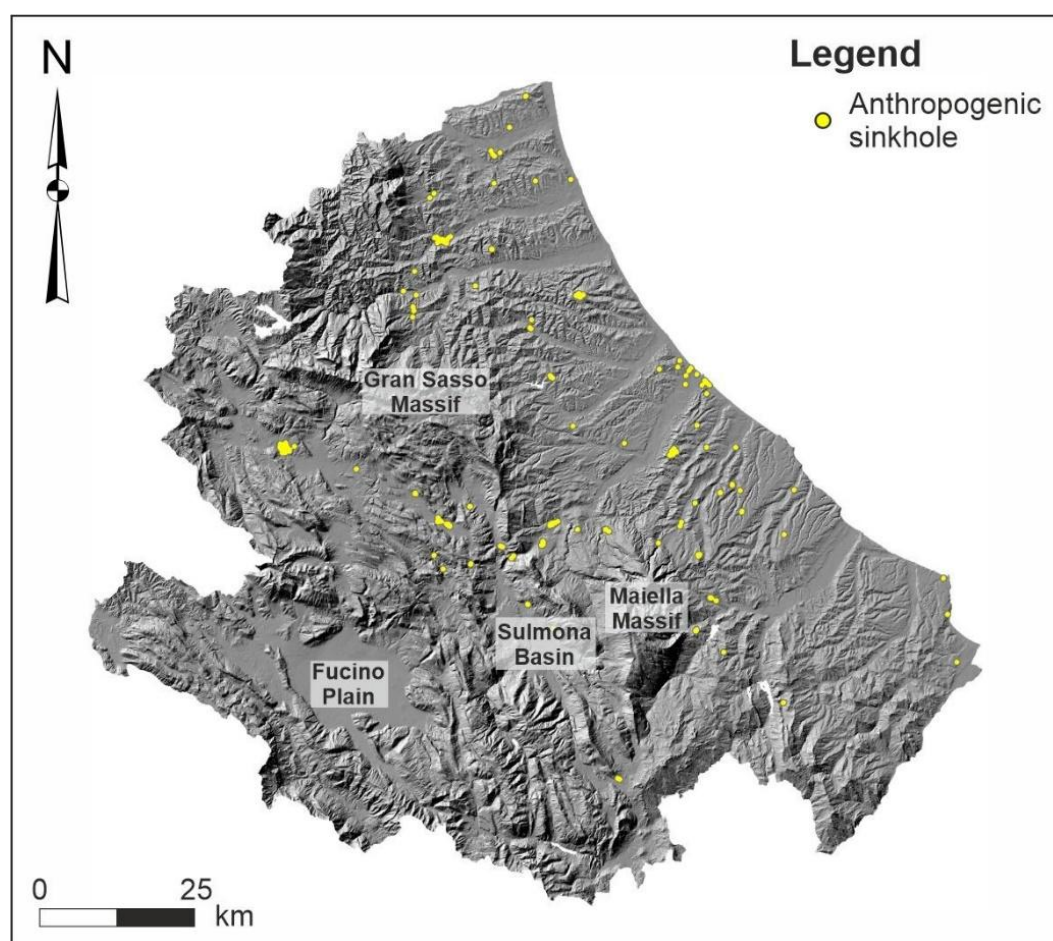


Figure 3.11. Anthropogenic sinkholes map.

3.4.3 Susceptibility Map

3.4.3.1 Preliminary susceptibility map

The Preliminary susceptibility map shows values generally increasing moving from the coastal sector towards the piedmont and the chain ones (Figure 3.12). In the current analysis, different regions featuring low, medium, and high landslide susceptibility were identified. More specifically, areas characterized by low values are located in the external portion of the piedmont sector and along the coastal area. Medium values are mainly detected in the inner piedmont and intermontane basins. The highest values are located in correspondence with reliefs in the inner chain sector and the incision of main rivers. Local areas without class values present no landslide susceptibility and mostly correspond to lake surfaces.

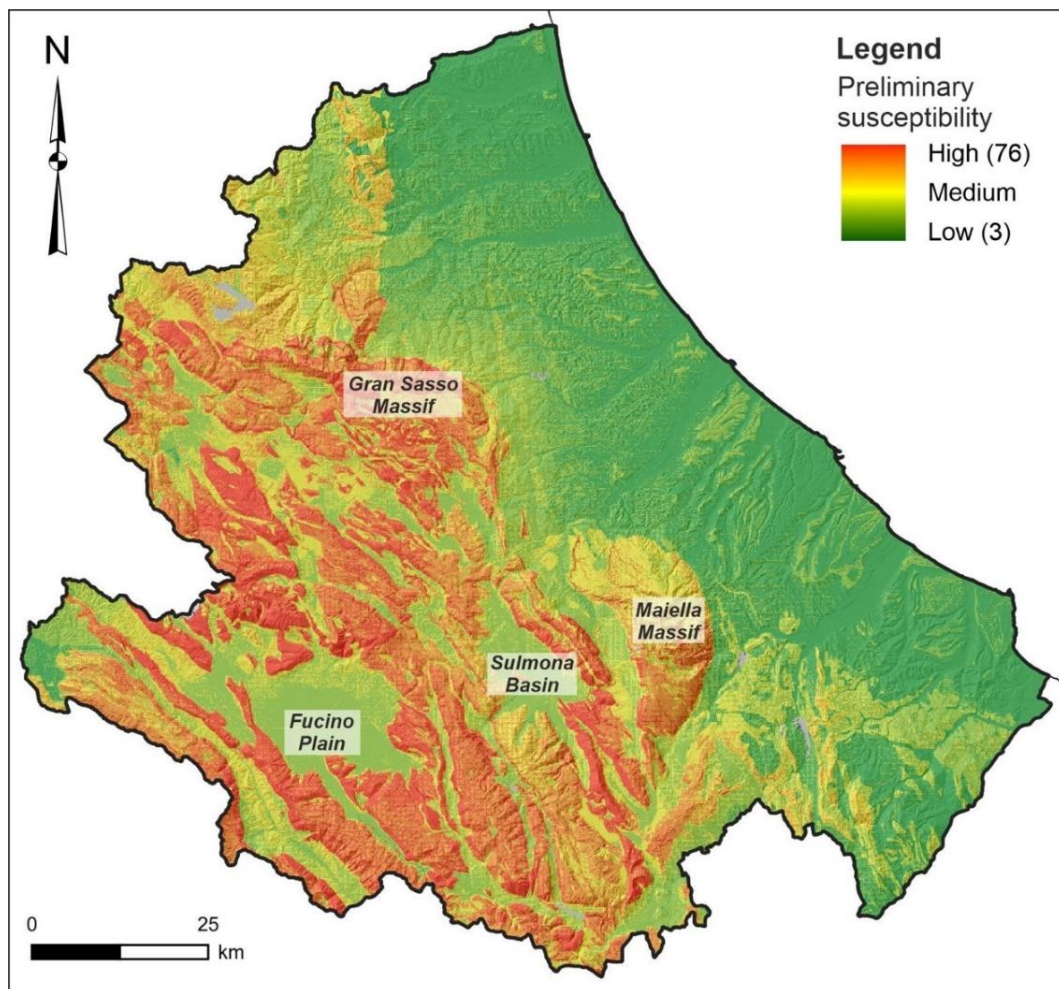


Figure 3.12. Preliminary susceptibility map.

3.4.3.2 Clusters determination, statistics, and susceptibility classes definition

The ratio between the total Within Clusters Sum of Squares (WCSS) and the Between Clusters Sum of Squares (BCSS) suddenly decreases, moving from 2 to 5 clusters and almost stabilizes after this number. Accordingly, the related curve nearly flattens after this value, with a slope gradient progressively closer to zero (Figure 3.13).

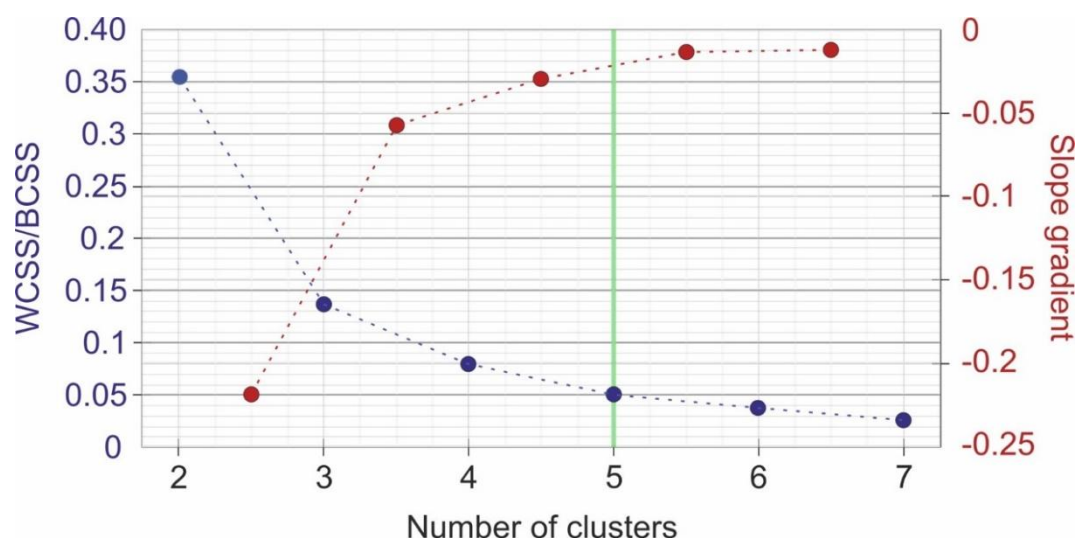


Figure 3.13. Plot of the WCSS/BCSS ratios (blue dotted line) against the number of clusters and related slope gradient (red dotted line). The solid green line indicates the optimal number of clusters identified through the elbow method.

From the above, five turns out to be the optimal number of clusters since an increase in this value does not result in a finer data clustering. Consequently, points of the Preliminary susceptibility raster are clustered into five groups.

From the analysis of values distribution within each cluster, it results that Cluster 3 contains the greatest volume of data, Cluster 5 the smallest one (Table 3.2); clusters 2 and 5 present, respectively, the narrowest and the widest extensions. Mean and median values are fairly near in each cluster; mode values slightly deviate from these. Cluster 2 shows the lowest standard deviation, while Cluster 5 the highest one. Finally, the InterQuartile Range (IQR) extensions of all clusters are rather comparable.

By comparing cluster statistics to classes of the absolute susceptibility scale of Figure 3.4 and by applying the workflow of Figure 5, six susceptibility classes result ranging from I to VI out of VII (Figure 3.14).

Table 3.2. Statistic of clusters.

Cluster #	Number of data-%	Values range	Mean-Median-Mode values	Standard deviation	IQR
1	22707492-21.2	3-16	12-12-12	2.64	10-14
2	23776539-22.1	17-25	21.1-21-24	2.62	19-24
3	25171384-23.4	26-36	30.4-30-26	3.15	28-33
4	20324367-18.9	37-47	42.2-42-47	3.16	39-45
5	15477554-14.4	48-76	52.6-52-48	3.83	49-55
Whole dataset	107457336-100	3-76	29.9-28-24	14.01	18-42

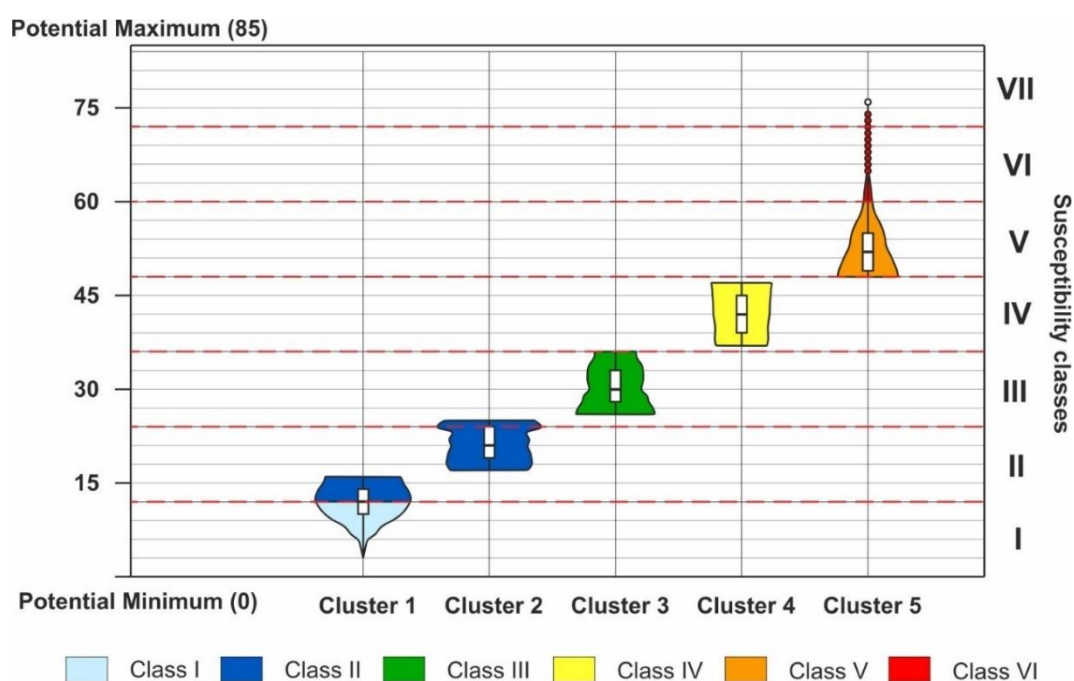


Figure 3.14. Violin plots of clusters data. Cluster 1 data greater than 12 constitute 35% of the group and are consequently assigned to Class II. Cluster 5 data mostly fall into Class V but partially overcome the central value of the adjacent higher class; consequently, values greater than 60 are assigned to Class VI. Concerning box-plots, lower and upper limits of boxes represent the first (Q1) and the third (Q3) quartile of clusters data, lines inside the boxes the median values, whiskers the values greater than $Q1 - 1.5 \cdot IQR$ and smaller than $Q1$ or greater than $Q3$ and smaller than $Q3 + 1.5 \cdot IQR$ with $IQR = Q3 - Q1$. Circles represent the outliers, i.e., values smaller than $Q1 - 1.5 \cdot IQR$ or greater than $Q3 + 1.5 \cdot IQR$.

3.4.3.3 Earthquake-induced landslides susceptibility map of the Abruzzo Region

The refinement of the susceptibility map results in the final detection of six susceptibility classes, ranging from I-*Very Low* to VI-*High* out of a maximum of VII (Figure 3.15).

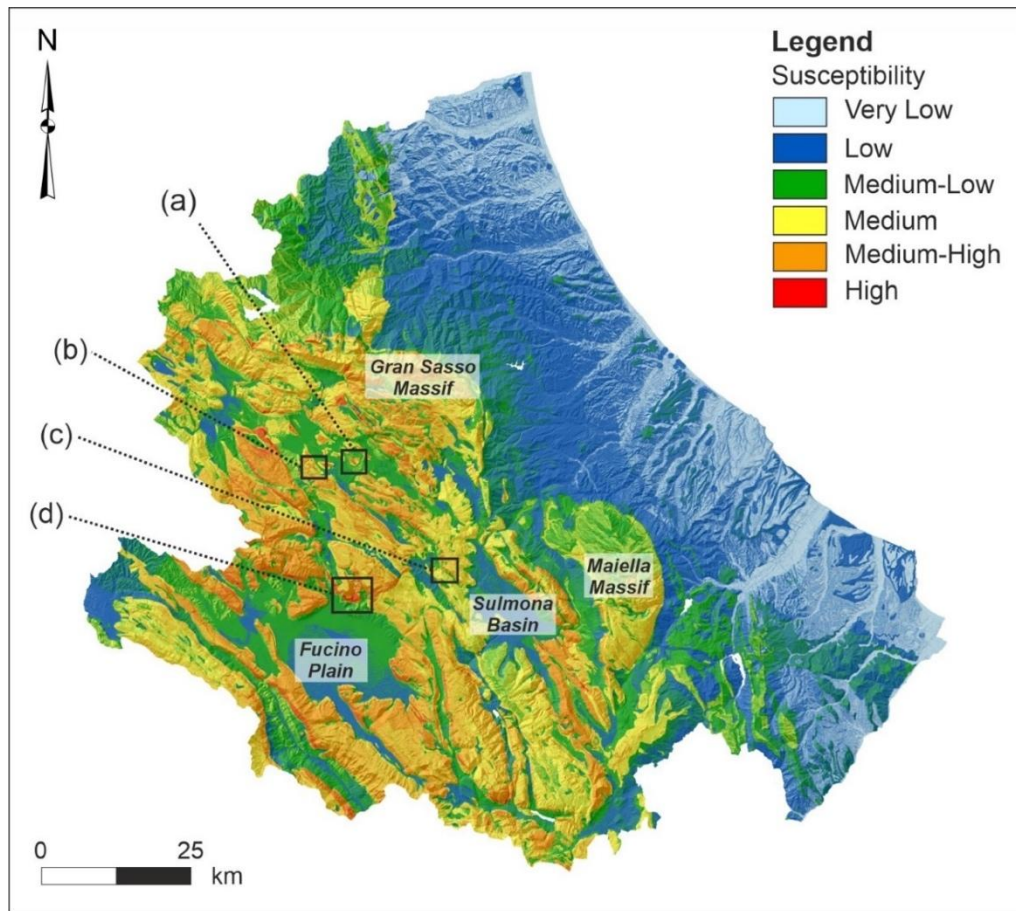


Figure 3.15. Earthquake-Induced Landslides (EILs) Susceptibility map of the Abruzzo Region. Black polygons indicate sectors presenting recorded EILs events; a detailed cartographic representation, supported by photo documentation, for each site is shown in Figure 3.16.

Coastal areas are mostly characterized by *Very Low* susceptibility values. *Low* values are locally spotted in correspondence with high coasts and areas featuring the presence of anthropogenic sinkholes. The piedmont area presents *Very Low* values, progressively increasing to *Medium* moving towards the chain sector. Fluvial plains are clearly distinguished from adjacent areas, having *Very Low* susceptibilities. The chain sector, finally, presents values ranging from *Medium-Low* to *High*. In detail, the major intermontane basins (i.e., Fucino Plain and Sulmona Basin) are well described by *Low* and *Medium-Low* values; these last also characterize the northern portion of the Maiella massif. *Medium* and *Medium-High* susceptibilities are detected in correspondence of reliefs, moving to *High* values in correspondence of steep slopes, mostly on south-western flanks of ridges.

3.5 Discussions and Conclusions

In this study, an expert-based approach followed by a statistical classification of resulting values is tested in order to evaluate the EILs susceptibility of the Abruzzo Region.

The comparison between sectors falling into different susceptibility classes and the geomorphological features of investigated areas highlight the quality of achieved results. The method, indeed, proves to be highly effective in distinguishing regions featuring different stability degrees, with well-known EILs detachments zones actually falling into *Medium-High* and *High* classes (Figure 3.16). *Very Low* to *Medium* values, on the other hand, mostly identify stable areas.

It is beyond question that the availability of good-quality data deeply affects the outcomes, and that the accuracy of results increases as the number and the suitability of parameters increases. In this work, their choice and classification/weighting is performed by expert judgment, based on the critical analysis of literature data as well as of inventoried landslide events; the combination of nine morphometric and geothematic features turns out to be highly proper.

In the case of parameters affecting limited sectors of the study area and here referred to as secondary ones, it is advisable not to consider their contribution in the definition of the minimum/maximum potential values in order to avoid the relative scale compaction with respect to the absolute one and the subsequent lowering of detected susceptibility degrees. Their impact is to be assessed in a second phase. The question is here managed by excluding the *Anthropogenic sinkholes* factor in the heuristic analysis to later sum their associated weight to the Susceptibility map right before the final classification step.

The analysis of variance performed on clusters resulting from Forgy's Kmeans algorithm allows the detection of the most suitable number of data groups actually present in the study area. Nevertheless, a statistical analysis of these data groups is required, given their variable extension, in order to assign them the appropriate susceptibility class. A correction of limits detected through the process is opportune and desirable in cases of clustered values encompassing too wide ranges or a relevant percentage of data falling into a class different from the most populated one. The workflow presented in this paper proves to be highly effective in this regard.

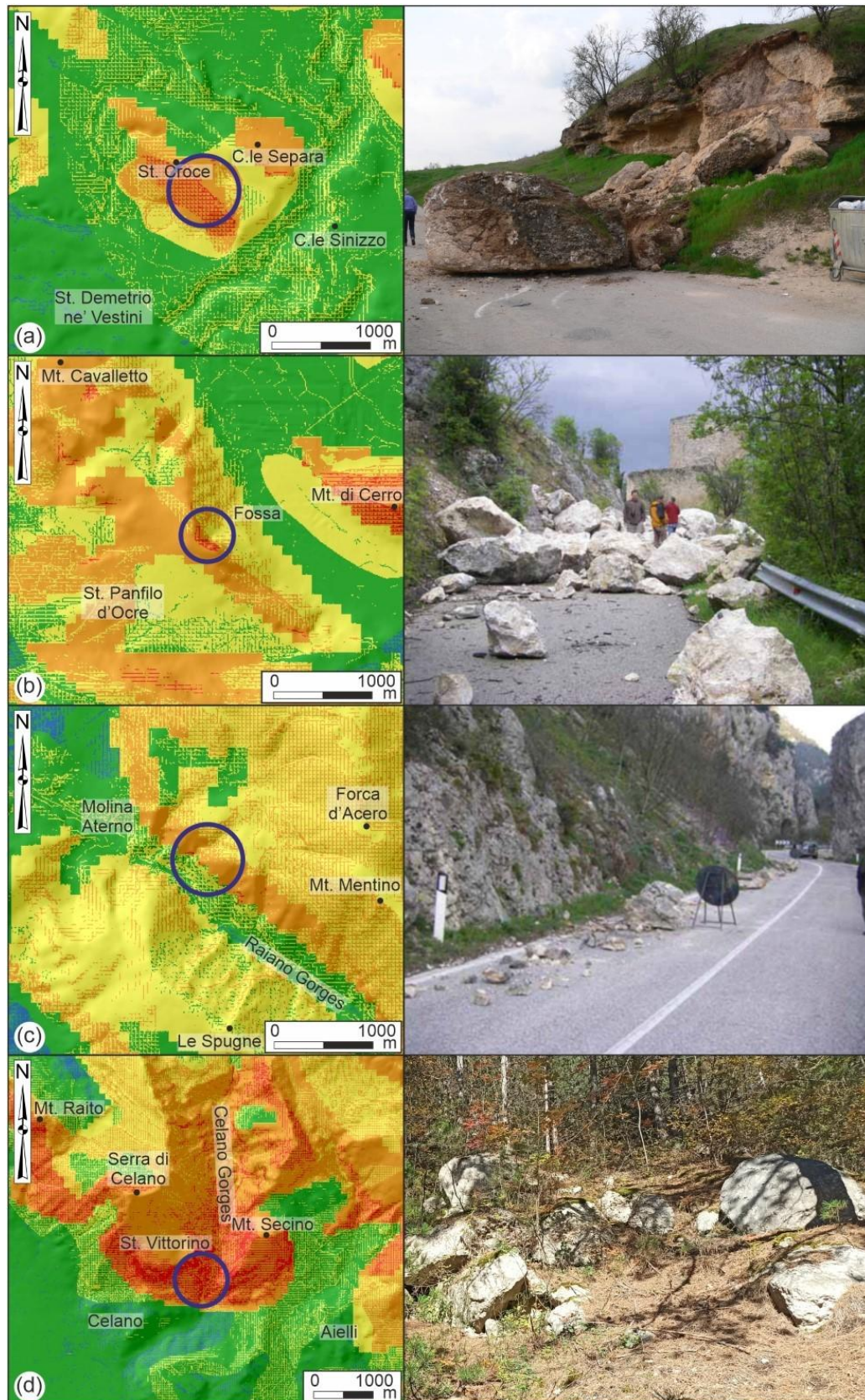


Figure 3.16. Photo documentation of recorded EILs events over the Abruzzo Region; for site locations and legend, see Figure 3.15. On the left, magnification of the resulting landslide susceptibility map (Figure 3.15) for each site: a) San Demetrio ne' Vestini (AQ), b) Fossa (AQ), c) Raiano (AQ), d) Celano (AQ); on the right, photo documentation of selected EILs events (Figure 3.16b and c are modified from (Blumetti et al., 2009)). Blue circles indicate detachment areas.

In conclusion, an accurate EILs susceptibility evaluation of the Abruzzo region is achieved by joining expert-based heuristic and statistical analyses. Results here presented highlight the robustness of the approach; remarkably, the applied methodology overcomes limits eventually intrinsic to catalogs, making the approach a valuable tool in the development of territorial planning, emergency management, and loss-reduction measures, readily applicable even in areas where fairly detailed EILs data are missing. The statistical analyses and the adoption of an absolute scale ranging from minimum to maximum potential values, finally, ensures the comparability of results among different study areas, if the same classification and weighting of parameters here used are applied.

4 DEBRIS FLOW ON ACTIVE FAULT ESCARPMENTS ON CARBONATE ROCKS: THE CASE OF THE MONTE MARINE RIDGE (PIZZOLI-BARETE AREA, L'AQUILA CENTRAL ITALY)

4.1 Introduction

Geomorphological mapping is a fundamental tool for understanding and assessing geological hazards, providing a comprehensive inventory of landscape features and a valuable resource for hazard management. Mapping techniques are essential for the systematic representation of landforms and landscape dynamics, which are crucial in a range of applications, including land-use planning and natural hazard assessment (Bocco et al., 2001; Chelli et al., 2021; Otto and Smith, 2013). The integration of Geographic Information Systems (GIS) and high-resolution Digital Terrain Models (DTMs) has enhanced the accuracy of geomorphological maps, enabling an accurate representation of geomorphological features (Xiong et al., 2022).

Debris flows are rapid, destructive movements of saturated debris along slopes. These flows are highly sensitive to both topographical configuration and the availability of loose material on slopes (Blahut et al., 2010; Guzzetti and Cardinali, 1991; Pasculli et al., 2021; Takahashi, 1981; Wilford et al., 2004). Although debris flows are triggered by heavy rains or the melting of large snow masses, earthquakes can be a major contributor to the predisposing conditions that lead to debris flows (Chen and Petley, 2005; Fan et al., 2019; Pierson et al., 1990). In this context, geomorphological mapping becomes particularly relevant, providing a detailed spatial understanding of slope gradients, drainage patterns, and sediment sources. Furthermore, geomorphological maps allow the identification of areas prone to debris flows, which can be crucial in designing effective mitigation strategies. As debris flows can have severe impacts on infrastructure, populations, and the environment, especially in mountainous regions, the mapping of areas most susceptible to debris flow is of paramount importance in the development of effective mitigation strategies (Baggio et al., 2024; Guzzetti et al., 2008), especially in seismically active areas that feature documented active fault (D. Yang et al., 2017; Yang et al., 2023).

The Apennine chain, composed of carbonate ridges crossed by longitudinal-transversal valleys and intermontane basins (D'Alessandro et al., 2003), reflects the interplay of Neogene compressional tectonics and Pleistocene high-rate uplift, which at the regional scale influenced the distribution and the main geomorphological features (Ambrosetti et al., 1982; D'Agostino et al., 2001; Demangeot, 1965; Dramis, 1992; Galadini et al., 2003).

Conversely, at the local scale, landscape evolution is driven by Pleistocene-Holocene extensional tectonics, mainly along NW-SE to NNW-SSE normal faults, resulting in different types of ridges (i.e., thrust, faulted homocline, and anticline ridges), valleys (i.e. tectonic and transversal valleys) and basins (i.e. tectonic basins) (D'Agostino et al., 2001; D'Alessandro et al., 2003; Miccadei et al., 2017; Piacentini and Miccadei, 2014; Roberts and Michetti, 2004).

These normal faults are affected by moderate seismicity, including significant events in recent decades (e.g., 2009 L'Aquila Mw 6.3 earthquake and 2016-2017 Central Italy Mw 6.5 earthquake, Rovida et al., 2020) and in historical times (e.g., 1703 Middle Aterno Valley Mw 6.7 earthquake, Rovida et al., 2020; Tertulliani and Graziani, 2022), and exhibit average slip rates of up to 1.0 mm/yr (e.g., Iezzi et al., 2023; Figure 1).

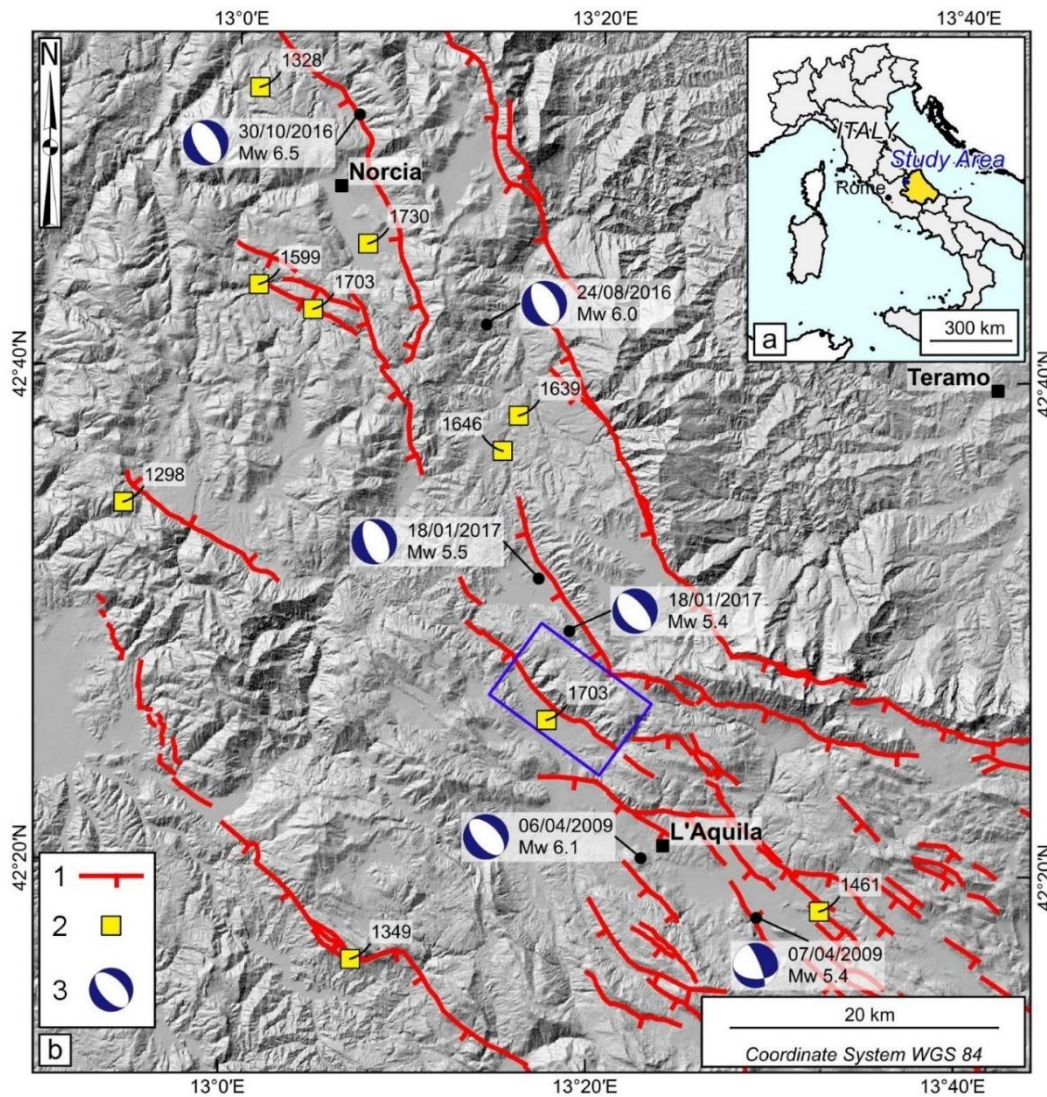


Figure 4.1. a) Location map of the study area. b) Seismotectonic framework of the Central Apennines Fault System, the blue rectangle highlights the study area. 1: Main active normal faults of the Central Apennines Fault System (Boncio et al., 2004; ITHACA Working Group, 2019); 2: Epicentres of historical earthquakes with macroseismic intensity > 9 (CPTI15; Rovida et al., 2022); 3: Focal mechanisms refer to the 2009 L'Aquila and 2016 Central Italy seismic sequences.

These elements induced substantial morphotectonic landscape evolution (e.g., fault scarps and escarpments) and dismantling by erosional-depositional processes, both over long-term (e.g., drainage network evolution, valley incision) and short-term (e.g., landslides, debris flows) timescales (Bagnaia et al., 1996; Blumetti et al., 1993; Bull, 2008; Burbank and Anderson, 2012; Civico et al., 2015; Miccadei et al., 2004; Piacentini and Miccadei, 2014).

Geomorphological mapping along these fault escarpments is crucial to identify the morphogenetic processes at work and to assess the geological (location and expected coseismic slip) and geomorphological (landslides and debris flows) hazards.

This study focuses on the Mount Marine ridge fault escarpment (on the western side of the Gran Sasso chain, Pizzoli-Bartee area, L'Aquila, Central Italy), which consists of a faulted homocline crossed by NW-SE and SW-NE faults inducing strong cataclasis of the carbonate rocks. It borders to the NE the intermontane tectonic basin of the Pizzoli area along the Upper Aterno Valley normal fault system (e.g., Galadini and Galli, 2000; Moro et al., 2016) and plays an essential role in the geomorphologic activity of the region; in fact, historical surface faulting (Guidoboni et al., 2019) and debris flows (ISPRA, 2007a; Regione Abruzzo, 2019, 2011) at its base highlight the ongoing morphogenetic processes.

In addition, anthropogenic factors, such as urbanization (e.g., buildings, roads) and land management practices (e.g., reforestation, embankments, and dams), further alter the landscape. Coupled with occasional wildfires (Cannon and Michael, 2011; Carabella et al., 2019; Debell et al., 2015; Jackson and Roering, 2009; Parise and Cannon, 2012), these factors influence the rates of geomorphological processes and often mask the original landforms.

The geomorphological mapping undertaken in this study integrates various techniques, including (i) multitemporal photogeological investigations, (ii) LiDAR data analysis, and (iii) geomorphological field mapping, supported by geophysical and paleo seismological investigations. This comprehensive approach has resulted in (i) a detailed (1:5,000 scale) geomorphological map (Figure 4.15), (ii) the mapping of debris flow (accumulation, transfer, and source area), and (iii) the mapping of the main fault scarps and active capable fault traces. These results are essential application tools for correct land-urban management strategies in mitigating earthquake and debris flow effects, particularly in areas where the two phenomena overlap.

4.2 Study Area

The Mount Marine ridge, located along the northeastern edge of the Upper Aterno River Valley in the northernmost sector of the Abruzzo Central Apennines (Italy), provides an excellent example of the complex interactions between tectonic, geomorphological, and sedimentary processes. This region constitutes part of the Miocene-Pliocene fold-and-thrust belt, which was formed by the convergence of the European and African tectonic plates. The structural framework of the area is defined by the thrusting of Meso-Cenozoic limestones over Miocene turbiditic deposits, driven by southwest-to-northeast-oriented shortening (Anderson and Jackson, 1987; Doglioni, 1991). Subsequently, extensional tectonics, which started 2-3 million years ago, led to the formation of normal fault systems within the fold-

and-thrust belt. This resulted in the formation of intermontane basins filled with continental deposits (Cavinato and De Celles, 1999; Cosentino et al., 2017; Piacentini and Miccadei, 2014).

These normal faults are typically oriented in a NW-SE direction, with lengths ranging from 20 to 40 km. They commonly occur in an array of dip-slip fault systems and often display both en-echelon and end-on arrangements (Boncio et al., 2004; Pizzi and Scisciani, 2000; Roberts and Michetti, 2004). These faults are associated with medium to large magnitude earthquakes (6.5-7.0) with recurrence intervals spanning from hundreds to thousands of years and slip rates that can exceed 1 mm/yr, as evidenced by historical seismicity records (Catalogo Parametrico dei Terremoti Italiani, CPTI15; Fig. 1; Rovida et al., 2022, 2020), along with paleoseismological investigations results (e.g., Galli et al., 2008; Cinti et al., 2021).

The area is situated within an active seismotectonic context, where the interplay between seismic activity, the topographic features of the terrain, and the underlying geological and geomorphological conditions has resulted in several earthquake-induced landslides. These phenomena have been extensively documented in the scientific literature and available databases (Caprari et al., 2018; Carabella et al., 2022; Guerrieri, 2015; Miccadei et al., 2010; Zei et al., 2024a).

Into detail, Mount. Marine Fault is a NW-SE striking normal fault stretching about 15 km within the northern segment of the Aterno Valley Fault System, west of the Gran Sasso area (Blumetti and Guerrieri, 2007; Galli et al., 2011; Iezzi et al., 2019). The fault activity led to the formation of a hanging wall basin, filled with hundreds of meters of quaternary continental deposits, alongside a limestone faulted homocline ridge at the footwall (Blumetti and Guerrieri, 2007; Bosi et al., 2003; Messina et al., 2001; Figure 4.2).

This fault is located in the epicentral regions of the 2009 Mw 6.3 L'Aquila earthquake and the 2016-2017 Mw max 6.5 Central Italy seismic sequence, as well as in the epicentral region of the historical Mw 6.7 earthquake of 2 February 1703 (Figure 4.1).

From a geomorphological point of view, the area is characterized by a complex interaction between tectonic movements that affected the region and the subsequent development of morpho-structural elements, as well as the action of erosional processes that led to the formation of morpho-sculptural and depositional elements. The recent activity and the geomorphological characteristics of the Mount. Marine fault were investigated in several

studies, including morphotectonic and paleoseismological investigations (Bosi et al., 2003; Galadini and Galli, 2000; Galli et al., 2011; Iezzi et al., 2019; Moro et al., 2016; Papanikolaou et al., 2005; Roberts and Michetti, 2004); Fig. 2). These studies highlighted the occurrence of numerous surface ruptures along multiple fault splays associated with the Mt. Marine main fault, which shows an average slip rate of 0.5-0.7 mm/y slip rates during Late Pleistocene-Holocene (F. Iezzi et al., 2023). About the morpho-sculptural and depositional process, these landforms are primarily the result of selective erosion and the influence of surface-running water and slope landforms. These last are represented by a wide variety of slope geomorphological features that are widespread across the southwestern flank of Mount Marine ridge, as proved by the main official catalogs (ISPRA, 2007a; Regione Abruzzo, 2019, 2011). Earthquake-induced landslides have been observed in the area following both the 6 April 2009 L'Aquila earthquake and the 18 January 2017 earthquake of the 2016-2017 Central Italy earthquake sequence, as reported in the CEDIT catalog (Caprari et al., 2018; Fortunato et al., 2012). However, these studies need more systematic mapping of landforms arising from the combination of tectonic, water and slope-related processes within this active geomorphological landscape.

The study area has been historically and extensively affected by debris flow phenomena. The orographic setting exerts a strong influence on the rainfall distribution, which in turn affects the triggering of phenomena and the distribution of damage. Notable examples include the events near Barete (AQ) in 1954 and 1998, and the Arischia (AQ) debris flow in 2020. Despite their importance in shaping geomorphology and posing significant risks to infrastructure and communities, such phenomena remain underrepresented in the scientific literature. The availability of information on major events is drastically reduced as one moves back in time, which is related to the occurrence of damage to public infrastructure, which is not widespread throughout the territory.

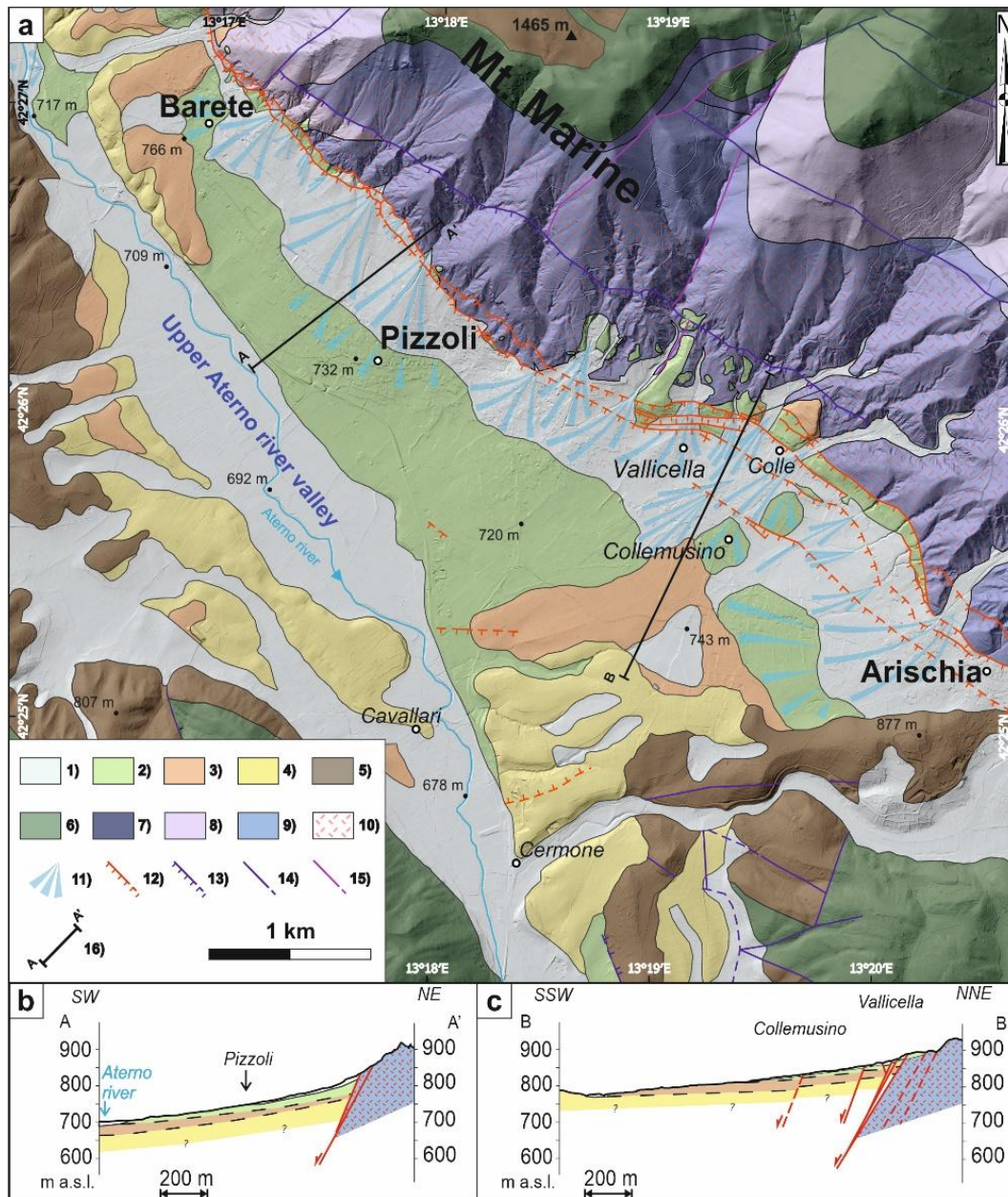


Figure 4.2. Geological setting of the studied area (modified from Iezzi et al., 2023). a) Geological scheme of the Mount Marine area, modified from CARG geological sheet “348 Antrodoto” (SGI, 2022). The map highlights the extensive presence of fan deposits along the base of the slope. Legend: Quaternary continental deposits - 1) Holocene alluvial plain, alluvial fan and eluvial-colluvial deposits. 2) Late Pleistocene alluvial fan, slope and eluvial-colluvial deposits. 3) Middle Pleistocene alluvial fan and eluvial-colluvial deposits. 4) Early Pleistocene alluvial fan, slope, and lacustrine deposits. Bedrock - 5) Paleocene-Miocene marls and calcareous marls of slope to carbonate ramp facies. 6) Upper Jurassic - Cretaceous limestones of slope to basin facies. 7) Jurassic limestones and marly limestones of condensed basin facies. 8) Jurassic limestones of slope to basin sequence facies. 9) Lower Jurassic dolostones and dolomitized limestones of inner carbonate platform facies. Other symbols - 10) Cataclastic belt on bedrock. 11) Fan deposits. 12) Active and capable normal fault (dashed when uncertain). 13) Normal fault on bedrock (dashed when uncertain). 14) Fault on bedrock (dashed when uncertain). 15) Jurassic sinistral fault (dashed when uncertain). 16) Trace of geological cross-section. b) Fault map showing the linkage zone between the main Pizzoli and Arischia segments. c) A-A' geological cross section (Location in fig. a). d) B-B' geological cross section (Location in fig. a).

4.3 Material and Methods

An integrated approach combining morphometric, geological, and geomorphological analyses, including both remote sensing and field data, was used to achieve a comprehensive geomorphological characterization of the study area. These analyses resulted in a geomorphologic map of the southwestern slope of Mount Marine, focusing on features and landforms related to slope phenomena, those shaped by running waters and the morphotectonic features mainly related to the fault escarpment. The workflow (Figure 4.3) was structured in three main phases: pre-field, field, and post-field.

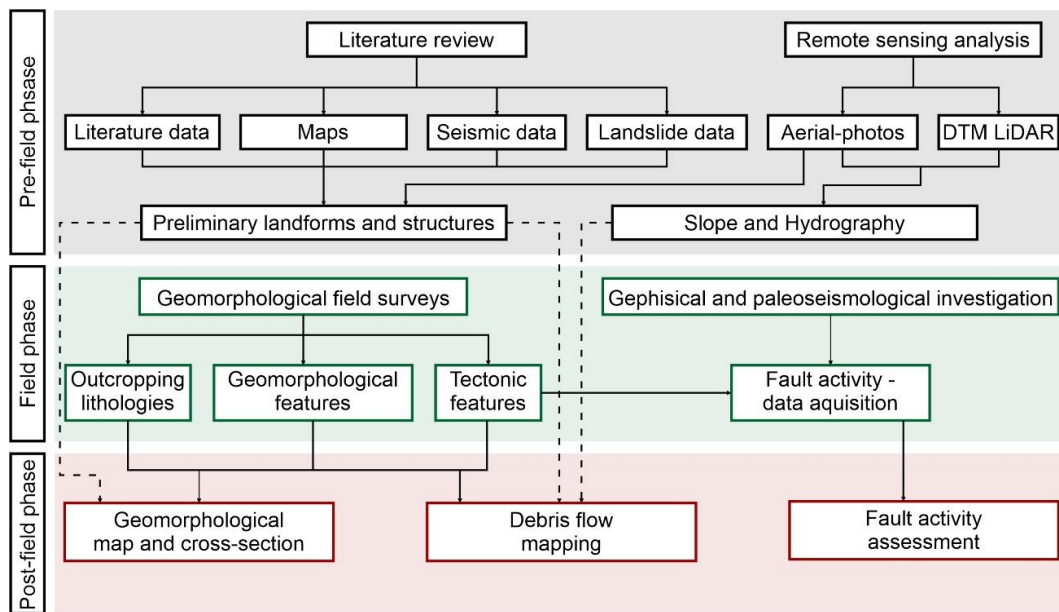


Figure 4.3. Flowchart of the three phases of the applied methodology. Black boxes indicate pre-field phase activity and related preliminary results, green boxes field phase data acquisition, and red boxes post-field phase results.

In the pre-field phase, literature data were collected and critically analyzed to provide a general geological and geomorphological framework for the area. Into detail, a large dataset of previous studies (e.g., Chiaradonna et al., 2021; Cortinovis et al., 2024; Geurts et al., 2020; Moro et al., 2002) and maps (Bosi et al., 2024; Santo et al., 2014; SGI, 2022, 2010; Vezzani and Ghisetti, 1998); as well as of technical reports, such as seismic microzonation studies (GLMS, 2018, 2017) and active and capable faults studies (GLR, 2021), and investigations on tectonic (Boncio et al., 2004; ITHACA Working Group, 2019; Michetti et al., 2000), seismic (Locati et al., 2022; Rovida et al., 2022) morphotectonic features (Bagnaia et al., 1996; Blumetti, 1995; Blumetti and Guerrieri, 2007) and landslides and debris-flows catalogs (Caprari et al., 2018; Guerrieri, 2015, 2012; ISPRA, 2007a; Martino et al., 2020b; Regione Abruzzo, 2019, 2011; Trigila et al., 2007; Zei et al., 2024b)

Remote data analyses were conducted using high-resolution aerial images, satellite imagery and digital terrain models (Abruzzo Region, National Civil Protection, Ministry of the Environment and Protection of Land and Sea, Italian Military Geographic Institute, Google satellite; Table 1). The aerial photos acquired spanned from 1954 to 2007 (pre-L'Aquila earthquake) and from 2009 to 2019 (post-earthquake), and Google satellite imagery time span is from 2003 to 2024

An analysis of the topography with a focus on morphological scarps and features related to debris flows was performed by a high-resolution (1m/pixel) Digital Terrain Model (DTM) derived from LiDAR data acquired by the Civil Protection of the Friuli-Venezia Giulia Region after the L'Aquila earthquake in 2009 via an Optech ALTM 3100 EA Airborne Laser Terrain Mapper System. In areas not covered by the high-resolution DEM, the 10 m/pixel resolution DTM from the Abruzzo Region (2007) was used.

Multitemporal photogeological analysis allowed to preliminary outline the main landforms with specific reference on tectonic and structural landforms, gravity and water related ones. In particular, in the highly urbanized areas, the use of aerial photo from 1945 to present, combined to DTM analysis, supported the field analysis in the discernment of the anthropic scarps from tectonic ones as well as in the infer of the state of activity or most recent activation of the debris flows.

The most recent debris flows can be mapped from the LiDAR data based on the roughness of the topography if compared to the surrounding areas (Figure 4a), while the recent activity is evidenced by the comparison of multitemporal aerial photo and satellite imagery (Figure 4b, c, d).

Table 4.1. Details of the data used in this work, including type of data, scale/resolution, year of acquisition and source.

Type of data	Scale/resolution	Year of acquisition	Source
DTM LiDAR	1 m/pixel	2009	Civil Protection of the Friuli-Venezia Giulia Region
Aerial Photos	1:55.000	1945	IGMI
Aerial Photos	1:33.000	1954	IGMI
Aerial Photos	1:25.000	1985-1986	IGM
Aerial Photos	1:13.000	2001-2005	Abruzzo Region
Aerial Photos	1:30.000	2007	IGMI
Aerial Photos	1:5000	2019	AGEA
Satellite imagery	<1m/pixel	2003-2024	Google satellite

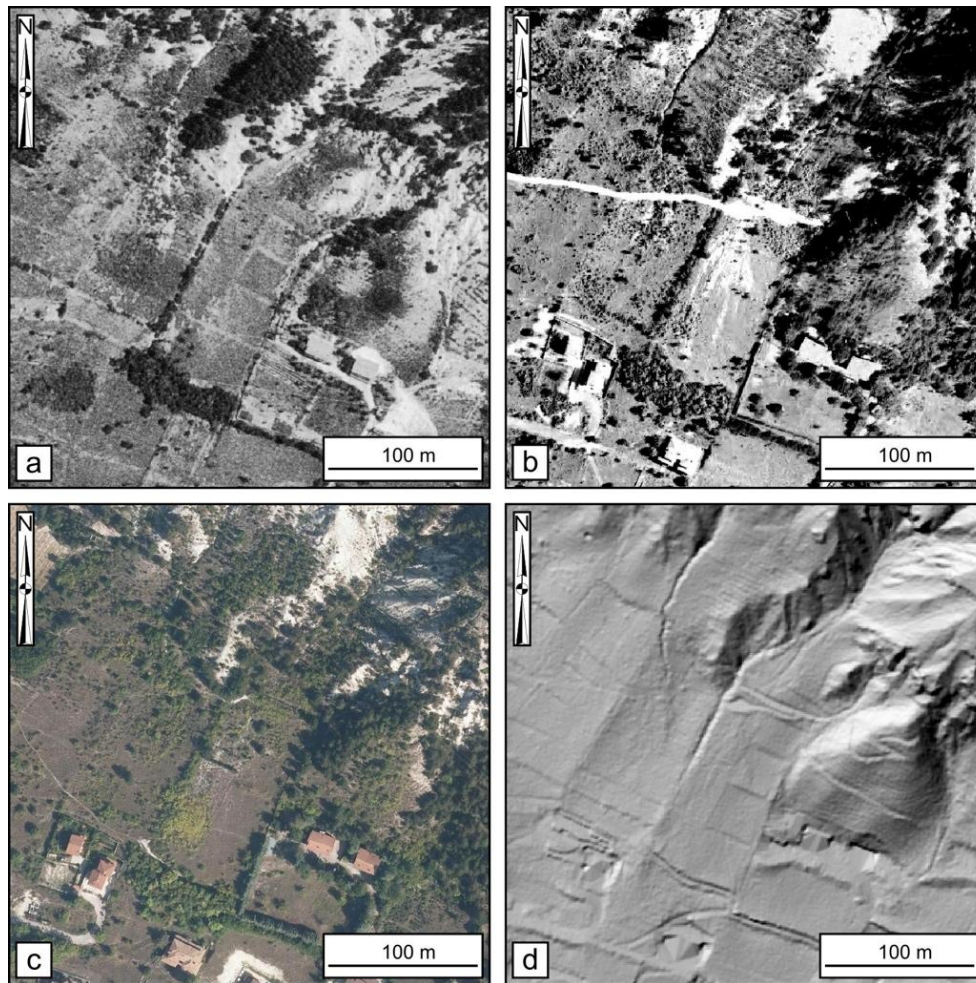


Figure 4.4. Multitemporal photogeological analysis of debris flow activity within the study area. The 1986 aerial photo (a) shows no evidence of recent debris flow deposits; the 2001 photo (b) shows clear evidence of the debris flow phenomenon that occurred between 1986 and 2001; the 2019 orthophoto (c) still shows traces of the event, but much of the deposit is covered by vegetation; the 2009 LiDAR hillshade image (d) shows a roughness that can be associated with the debris flow deposit.

In the field phase data resulted from geomorphological surveys, landslides/debris flows inventory and mapping, and paleoseismological trench investigations, supported by geophysical investigations (i.e., georadar, geoelectrical).

Geological and geomorphological survey was conducted at 1:5,000 scale. The geological mapping is based on the lithologies depicted in the Geological Map of Italy (SGI, 2022, 2010) integrated according to the scale of the present work following the guidelines of the Geological Survey of Italy (ISPRA, 2022). Geomorphological mapping was carried out following the guidelines of the Geological Survey of Italy and the Italian Association of Physical Geography and Geomorphology (ISPRA and AIGEO, 2022). Using a standardized legend (GNGFG, 1994), landform classification and symbology were customized to fit the specific scale and objectives of this research

The mapped features include: i) Quaternary continental deposits (i.e., Pleistocene-Holocene deposits mainly related to slope, fluvial, and colluvial geomorphologic environments); ii) bedrock lithology (i.e., Meso-Cenozoic carbonate rocks, locally turned into fault rocks); iii) main tectonic features; and geomorphological landforms (i.e., tectonic, litho-structural, slope fluvial and running water, krastic, polygenic anthropic landforms).

A specific field activity was focused on the check and inventory of the alluvial fan and debris flow preliminary mapped from remote data analysis performed in the previous step.

Geophysical and paleoseismological trenches investigations were focused specifically on the verification of the main scarps of tectonic and/or polygenic origin and the location of the tectonic coseismic slip. The results of the paleoseismological investigations are presented in a dedicated paper integrating geomorphological, geophysical and trench investigations (Iezzi et al., 2023).

In the post-field phase, data collected from remote analysis and validated with field survey results provided a more accurate comprehension and classification of the processes and related landforms acting in different sectors of the slope. The integration of field and remote data resulted in the production of a comprehensive geomorphological map of the study area at a scale of 1:5,000. This map delineated the extent of debris flow-related features, their current activity status at specific sites, and also mapped the primary scarps at the base of the fault escarpment. This escarpment separates tectonic, anthropogenic, and other scarps whose origin requires further investigation. Moreover, specific areas of debris flow accumulation, transfer, and source were identified through dedicated mapping.

After a severe wildfire that occurred in August 2020 in the southeastern sector of the study area, a debris flow was triggered. The degree of burn severity in the affected area was evaluated using satellite data from the Landsat 2 program. The occurrence of fires can lead to a significant deterioration in the geomorphological and pedological stability of slopes. This is due to the removal of vegetation and the alteration of soil properties, which in turn increases the probability of slope phenomena such as debris flows. Such changes have also served to heighten the hydrogeological risks for areas situated in the downstream direction.

The degree of organic matter loss or decomposition is typically used to quantify burn severity, which is defined as the immediate impact of fire on aboveground vegetation and belowground soils (Keeley, 2009). In this study, fire severity was quantified using the Delta Normalized Burn Ratio (dNBR), which was calculated as the difference between pre- and

post-wildfire values of the Normalized Burn Ratio (NBR). The NBR was derived using the following equation:

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \quad [4.1]$$

The resulting dNBR values were then classified into severity categories based on the thresholds defined by Key and Benson (2006). This method allows to archive an objective assessment of the impact of the wildfire on slope stability.

4.4 Results

4.4.1 Geomorphological Map

Figure 4.15 map shows the main geological and geomorphological features of the south-western flank of the Monte Marine ridge, as shown in the following paragraph.

4.4.1.1 Orographic and hydrographic features

Morphometric analyses were performed to derive the main landscape features of the study area, as part of geomorphological mapping preliminary activities.

The southwestern flank of Monte Marine stretch for about 10 km in NW-SE direction. The elevation ranges from 1591 m a.s.l., found at Colle delle Macchie in the easternmost sector, to about 675 m a.s.l., in correspondence of the Aterno river in the southernmost sector of the study area.

Based on morphometric features, the entire area can be divided into three main sectors, roughly parallel to the slope direction. The first is represented by a low-slope sector located in the upper part of the slope, characterized by a gentle morphology with slopes generally less than 25°. Here, the hydrographic network is characterized by valleys with concave or flat bottoms that alternate with less common V-shaped incisions that are arranged in a loosely organized network. The second sector is the higher part of the slope, characterized by slopes generally between 25° and 45°, but locally exceeding 60°. This sector is characterized by deep V-shaped with an average NE-SW direction valley arranged in a dendritic to parallel drainage pattern. The last sector is that of the floodplain of the Aterno river, characterized by an almost tabular geometry and slopes generally less than 10°, but which can reach up to 25° in the slope connecting area.

4.4.1.2 *Lithological features*

The Mt. Marine ridge is mainly constituted of Mesozoic to Cenozoic calcareous and dolomitic lithotypes referable to transitional platform-to-basin succession of the *Latium-Abruzzi* domain (SGI, 2022). They have been merged in three units (from 9 to 11 in the main map), described below from the oldest to the youngest. The oldest unit (11) is composed by massive to poorly stratified dolostone and dolomitized limestone of carbonate platform to slope facies referred to the Lower Jurassic. These units outcrop in the southern sector of the map. The intermediate unit (10) is composed by well stratified limestones, marly limestones, and calcareous marls of distal scarp to proximal basin facies referred to the Lower Cretaceous, which upwards change to limestones and calcareous marls of slope to carbonate ramp facies ranging from the Upper Cretaceous to the Oligocene. These units outcrop in the northern sector of the map and on the summit area of the relief. The youngest unit (9) is composed by marls and calcareous marls of carbonate ramp facies referred to the Lower Miocene. These unit outcrops only on the summit of the relief.

The foot of the slope and the basin along the Aterno River valley host wide cover of continental Quaternary deposits, with a maximum thickness of over 200 meters (SGI, 2022), divided into units separated by unconform boundaries.

Alluvial fan deposits and scree slope debris (8) (Lower Pleistocene), these deposits consist of heterometric gravels and sandy gravels with clasts ranging from sub-angular to rounded, along with breccias and intercalated paleosols. They are generally well-cemented and can reach a thickness of up to 30 meters (Figure 4.5). These deposits outcrop only in the northern and southern sector of the map respectively along the proximal and distal part of the slope down to the valley bottom.

Alluvial fan and eluvial colluvial deposits (7) (Middle Pleistocene), this unit features heterometric gravels with volcanic clasts and interbedded sands (Figure 4.6). It is found in the Barete (AQ) and Tarignano (Barete, AQ) area, with terrace surfaces where newer deposits are incised.

Alluvial fan deposits (6) (Middle Pleistocene), these deposits are made up of well-cemented calcareous gravels, interbedded with sands and clays (**Figure 4.7**) and are found near San Lorenzo and Collemusino (Pizzoli, AQ), particularly at the base of Holocene alluvial fans.



Figure 4.5. Heterometric, millimeter to decimeter, predominantly subrounded, matrix-supported, sandy gravels in a sandy-loam matrix, interbedded with moderately cemented to well-cemented sandy-loam levels and fine gravelly levels, in a slightly counter slope bedding. Outcrop in excavation at the Barete sports field. These are referable to the alluvial deposits of unit 8 in the main map.

Alluvial fan and eluvial-colluvial deposits (5) (Middle Pleistocene), this unit is made up of heterometric gravels with intercalations of volcanic materials. It is primarily located near the Colle area, at the main fault footwall.

The units 7, 6 and 5 outcrops mainly above the oldest unit or in isolated sectors of the slope and valley bottom.

Alluvial fan deposits (4) (Upper Pleistocene), these deposits include sandy gravels with volcanic reworked materials. It can be found between Pizzoli (AQ) and San Lorenzo.

Alluvial plain, alluvial fan and eluvial colluvial deposits (3) (Upper Pleistocene), it consists of sandy gravels with alluvial plain characteristics (Figure 4.8a), extending over terraced surfaces between Barete (AQ) and Scentella.



Figure 4.6. (a) Heterometric centimeter to decimeter breccias, with angular and subangular clasts, with sparse or absent matrix, well cemented. Outcrop in *Madonna della Valle* locality (Tarignano, AQ) is referable to alluvial deposits of unit 7 in the main map. b) Stratigraphic contact between the older gravelly unit (8 on the main map) at the base, and brown silty-sandy deposits with thin gravelly and silty stratified levels. Outcrop in the excavation of the sports field in Barete (AQ). The upper part is referable to the unit 7 in the main map.



Figure 4.7. Centimetric to decimeter heterometric gravels, with subrounded and subangular, clast-supported in a silty sandy matrix, with a chaotic structure. Outcrop in the fault bed at Colle (Pizzoli, AQ). These are referable to the alluvial fan deposits of unit 6 in the main map.

Scree slope debris, slope, and alluvial fan deposits (2) (Upper Pleistocene), this unit include alluvial fans and debris flows deposits, present throughout the Pizzoli-Barete area, along with colluvial deposits on the valley slopes (Figure 4.8b).

The units from 4 to 2 outcrop widely in the central sector along the distal part of the slope.

Scree slope debris, slope, alluvial fan, alluvial plain, mixed origin end eluvial colluvial deposits (1) (Holocene), the most recent deposits, consisting of slope debris, alluvial fan materials, and anthropogenic deposits (Figure 4.9). This unit is present widely throughout the map but mainly in the valley bottom and along the foot of the slope, covering each of the oldest units.



Figure 4.8. a) Stratified sandy gravels with heterometric clasts with millimeter to decimeter size, subrounded to subangular, in silty-sandy matrix, alternating with silty-sandy levels. Outcrop in a recent man-made excavation in the Frattale locality (Pizzoli, AQ) at one of the fault segments. These are referable to unit 3 of the main map. b) Heterometric angular breccias with millimeter to centimeter clast size, clast-supported, sandy-loam matrix, well cemented suspended in slope support at the fault bed east of the Villa Mazza quarry (Pizzoli, AQ). These are referable to unit 2 of the main map.



Figure 4.9. Holocene gravelly-sandy alluvial fan deposits covered by colluvium in Vallicella locality (Pizzoli, AQ). These are referable to unit 1 of the main map.

4.4.1.3 *Tectonic features*

The SW slope of Mt. Marine is bordered by an 8 km long westward dipping normal fault that puts in contact the Mesozoic units at the footwall and the Cenozoic units at the hanging wall. The fault, from the north to south, has NNW-SSE strike for about 5 km, then bends with a step-over striking E-W and ESE-WNW for about 800 metres, and finally returns to an NNW-SSE and locally N-S pattern for just over 2 km. This fault is considered active and capable as shown by existing morphostructural and paleoseismological studies and is considered part of the wider Upper Aterno Valley fault system (e.g., Blumetti, 1995; Galli et al., 2011; F. Iezzi et al., 2023; Moro et al., 2016, 2002).

At the footwall of the main fault other minor tectonic elements are present. The most evident is a NW-SE oriented normal fault about 4 km long that dislocates Jurassic and Cretaceous units (Figure 4.10a). Along with this are several Mesozoic faults with strike from NE-SW, NW-SE to E-W ranging from a few hundred of metres to 3.5 km long.

The main fault can be distinguished into two sectors: i) the northern one in which there are two splays a hundred metres apart with a well-defined trace at the base of the slope where the carbonate substrate and faulted Pleistocene deposits come into contact; ii) the central-southern one in which the structure branches out into numerous splays at the hanging wall

of the main fault, even antithetic ones, arranged in a band more than 500 metres wide within the extended cover of Quaternary deposits at the base of the slope.

The substrate outcropping at the footwall is strongly fractured and shattered, with a damaged area extension of about 200 m in the northern sector and more than 500 m in the central-southern sector. This is the result of the superposition of several deformation structures and events (i.e., Mesozoic thrust and normal Quaternary faults) and seismic rupture propagation during earthquakes (e.g., Cortinovia et al., 2024; Figure 4.10b).

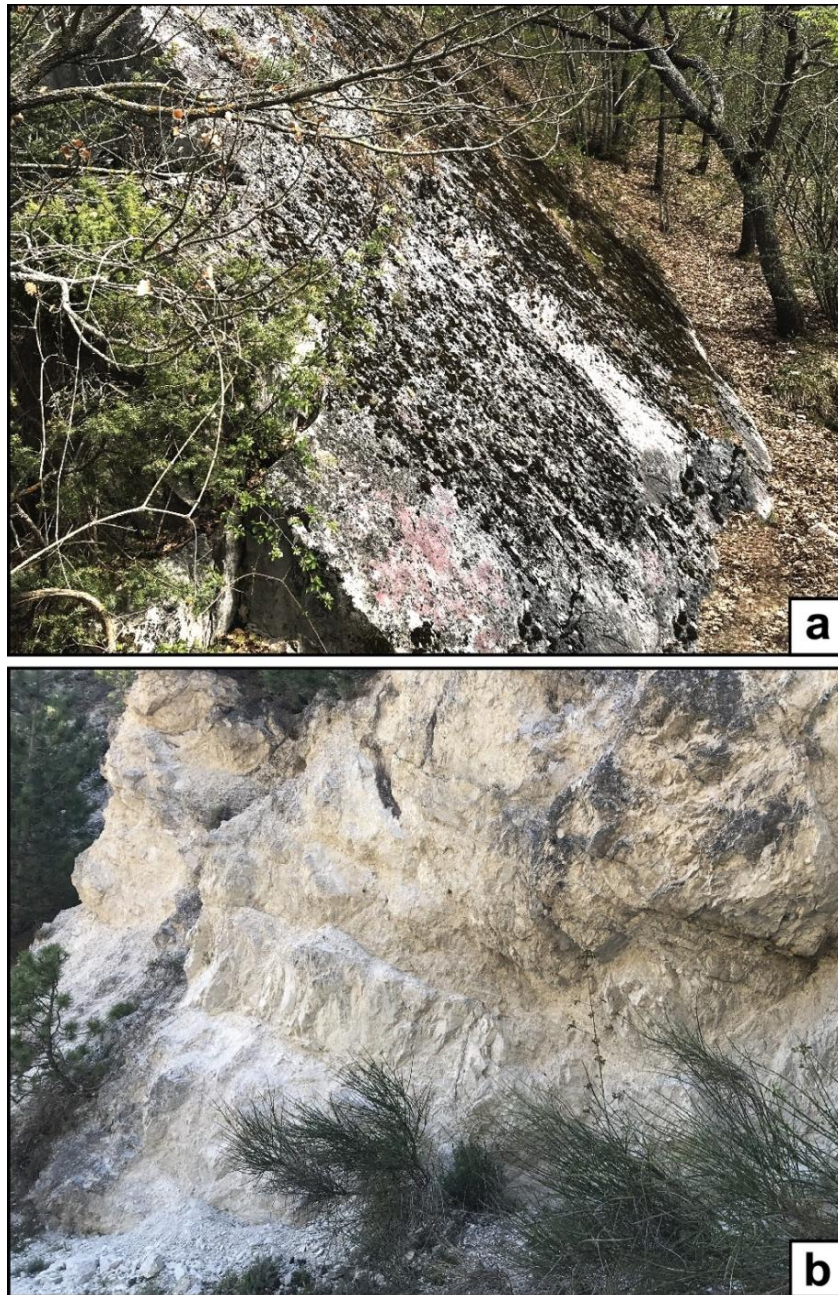


Figure 4.10. Example of main tectonic features detected in the study area. a) Fault plane of the NW-SE striking Mount Marine fault near Barete (AQ); b) outcrop of Cataclastic rocks on the flank above Pizzoli (AQ)

4.4.1.4 *Geomorphological features*

Monte Marine area feature tectonic, litho-structural, slope, fluvial and running water related, karstic, polygenic, or anthropic landforms depicted in the main map.

The tectonic landforms are mainly found on the steepest sector of the slope. Triangular or trapezoidal facets are distributed all over the slope. In the northern area, at Colle della Rete and Le Schiazze, two triangular facets extend from the base to a height of about 1300 meters above sea level. Along the rest of the slope, the triangular or trapezoidal facets have a more limited vertical extent, reaching about 200 meters in height. Normal fault scarps, with or without visible fault bands, have been identified at the base of the slope. These scarps run in a NW-SE direction and are continuous in the NW sector of the slope, but become more irregular towards SE.

The litho-structural features are settled on limestone and dolomitic rocks. Erosional scarps, caused by selective erosion, are mainly found in the NW sector where they affect most of the slope. These scarps extend in a NW-SE direction, parallel to the slope, and in a NE-SW direction, perpendicular to the slope, near the incisions. There are large areas of stepped rocky slopes, particularly developed above the settlements of Tarignano and Barete, in the lower part of the slope, and in the upper part above Pizzoli. Saddles in cataclastic dolomitic rocks and resulting from the presence of fault segments are present in the southern sector of the slope.

Slope landforms are well developed and widespread distributed along the slope. Erosional/landslide scarps, as well as the Rock avalanches main scarps, are mostly parallel to the base of the slope, while they develop perpendicularly along the many debris flow channels (Figure 4.12b) that cut the slope in a general NE-SW direction. These features are mainly found on the steepest parts of the slope. Accumulation landforms are dominant at the base of the slope and in the transition to flat sector. They consist mainly of debris flow deposits (Figure 4.12a) and debris cone found at the main transverse valley and, to talus slope deposits of a limited size distributed along the slope. These landforms are mainly located at the base of the slope, where degradation scarps affect the cataclastic rocks at the fault footwall. Only localized debris cones and slopes debris are identified at the base of the scarps on cataclastic material.



Figure 4.11. Example of main scarps detected in the study area. a) Structural scarp on Mesozoic carbonate rocks; b) Degradation scarp on highly fractured carbonate rocks.



Figure 4.12. Example of main debris flow related landforms detected in the study area. a) Apex of debris flow cone constituted by highly heterometric chaotic deposits with centimeter to decimeter angular clasts and a sandy-silt matrix; b) end section of debris flow channel showing evidence of recent activation.



Figure 4.13. Example of main fluvial and running water landforms detected in the study area. a) V-shaped valley transverses to the slope; b) pseudo-badlands landforms due to accelerate erosion process on cataclastic rocks.

Fluvial and running water landforms affect the entire slope. In the upper part of the slope, on cataclastic and carbonate bedrock, rills, and gullies - arranged in pseudo-badlands landforms - are present near the main fault and along the trace of other fault segments affecting the cataclastic bedrock. The slope is deeply incised by transverse V-shaped valleys and, extensively, by concave and flat-bottomed valleys. In the lower part of the slope, where the influence of fault activity is greater, hanging valleys can be identified, while just upstream there are numerous kink points of regressive erosion. At the base of the slope, the main depositional landforms are present, including large coalescing alluvial fans with small,

more recent lobes. Their origin is related to fluvial and debris flow processes fed by transverse valleys on the slope.

Karst landforms dominate the gently sloping upper slopes and are particularly well developed in the north-west. Here there are numerous flat-floored, U- and V-shaped fluvio-karstic valleys, which extend mainly in a NW-SE direction, parallel to the overall slope. Several depressions, associated with uvalas and dissolution dolines, are also present.

Polygenic features in the study area include NE-SW oriented crests and spurs shaped on limestone and dolomitic rocks, found along the entire slope, particularly in the southwestern sector. At the foot of the slope, in Madonna della Valle, polygenic scarps with a NW-SE orientation were reported. These landforms are mainly the result of the combined influence of tectonic activity, litho-structural conditions, and slope dynamics.

Anthropic landforms are widespread throughout the plain, marked by large urban centers, numerous roads, and other structures, as well as long-term agricultural practices. The slope is significantly affected by large quarries between the Pizzoli and Arischia areas, mainly in cataclastic material (Figure 4.14b). In almost all the debris flow channels, numerous check dams and artificial channels (Figure 4.14a) were built to control sediment transport and manage debris flow activity. At the foot of the slopes, the dominant features are excavation scarps, embankments, and road embankment.



Figure 4.14. Main anthropic landforms detected in the study area. a) Solid transport control system consisting of check dams and artificial channels; b) Cataclastic rock quarry located at the slope toe.

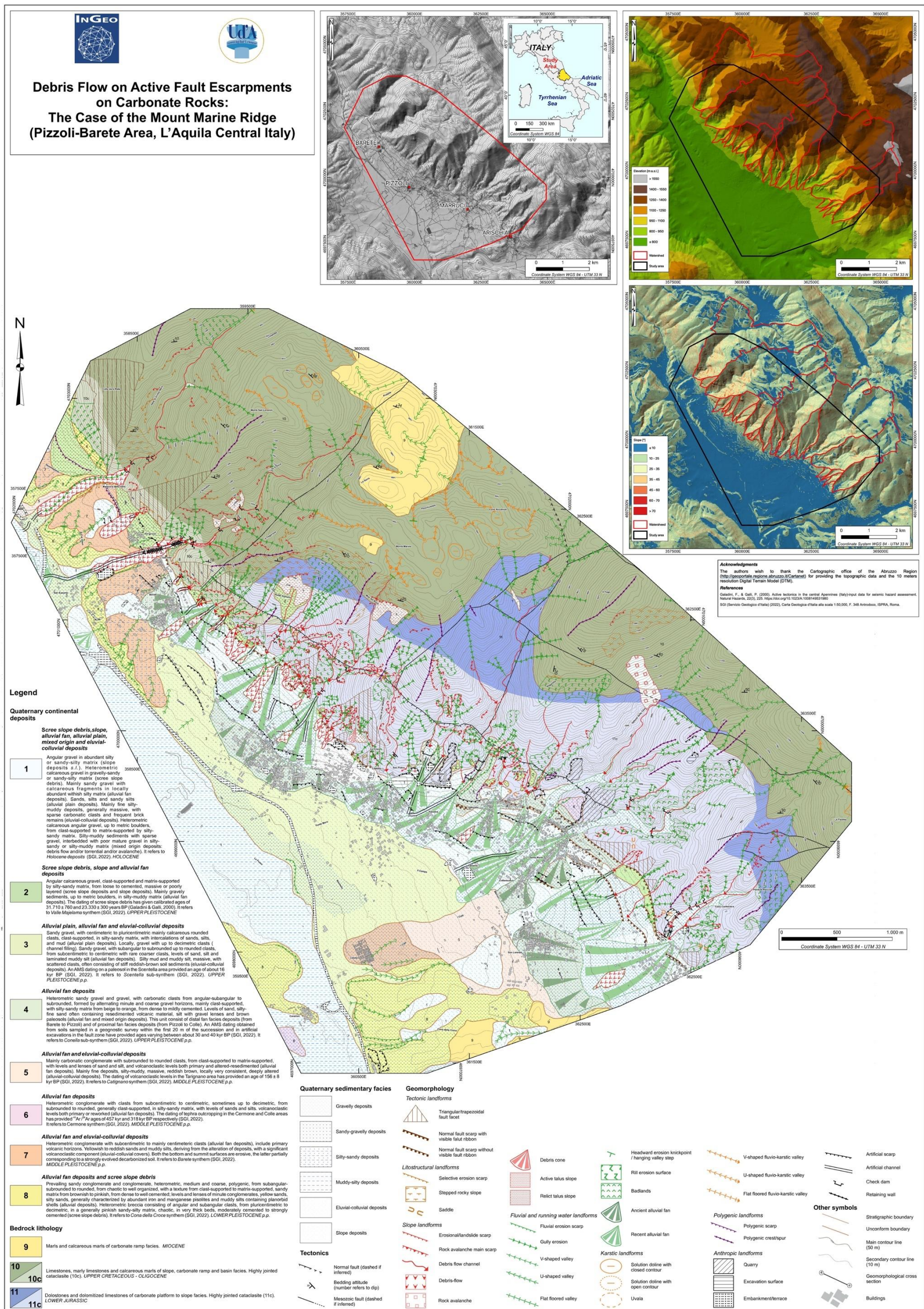


Figure 4.15. Geomorphological map of Mount Marine area.

4.4.2 Fault-related Morphotectonic Features

The south-western slope of Mount Marine is marked along its entire length by striking morphotectonic features that can be readily attributed to recent normal faulting, such as fault scarps, triangular facets, narrow valley floors, hanging valleys, almost straight mountain-piedmont junction, and locally aggrading alluvial fan deposits. (e.g., Bull, 2008).

As stated in the previous paragraph, the mountain front could be divided in two sectors: i) northern and ii) central-southern.

The first (i) presents well-preserved triangular facets, with heights of up to 400 m, separated by deeply incised narrow valley bottoms with high slope flanks. The mountain front is linear for about 4.5 km, with several hanging valleys on the fault footwall. In this sector the fault has the best outcropping planes on the bedrock with two closely spaced scarps running parallel to the slope. From north to south, the triangular facet decreases in height and is heavily eroded by degradational scarps and badlands, and the alluvial fan deposits show aggradational setting.

The second one shows only local and smaller triangular facets, mostly in the southern part with maximum height of 70 meters. The mountain front is less linear, due also to the step-over that the fault does in the central part (e.g., Iezzi et al., 2023) and no hanging valleys are recognized in this sector. The main fault generates fewer clear scarps on the bedrock, visible only in specific spots, and crosses mainly the aggraded alluvial and colluvial deposits on the hanging wall with several sub-parallel scarps ranging in a distance from 100 to 500 meters from the main scarp on the bedrock.

4.4.3 Debris Flows Mapping and Inventory.

The detailed geomorphological field survey, integrated with photogeological analysis and literature data, highlights that the primary active processes occurring in the area are attributable to slope and running water related phenomena. These processes are enhanced by the structural and lithological setting, as well as by the presence of thick cover of loose surficial deposits resulting from intense tectonic activity.

Debris flows represent the most significant landform on the southwestern slope of Mount Marine, characterized by a series of north-east to south-west-oriented channels and couloirs along the slope with debris discharge. At the transition between the slope and the Aterno River floodplain, extensive debris flow deposits are observed, which cover the base of the slope almost entirely.

These processes are extremely rapid, generated by the saturation of detrital masses by water and the associated deposits are characterized by the absence of stratification and a highly variable sediment texture, ranging from clay to pebbles to blocks.

The analysis of the oldest continental deposits in the area and the present morphological features allowed to define the period of activity for such debris flows phenomena as spanning from the Upper Pleistocene to the present. Many of these channels and deposits exhibit indications of recent reactivation well documented through multitemporal photogeological analysis as shown in Figure 4.4.

This study allowed for the delineation of the source, transit, and accumulation areas for each debris flow channel identified within the study area. Into detail, a total of 32 debris flows were identified along the southwestern slope of Monte Marine. Each one exhibited distinct characteristic in terms of the dimensions of the source area, the slope gradient, the extent of the accumulation area, and the configuration of the associated hydrographic network. The dimensions of the source areas span a considerable range, from approximately 1,600 m² to over 1,850,000 m². The greatest values are observed in the Valle di Grotta Nera, located northwest of Barete (AQ), and along the main channels between the Pizzoli and Arischia settlements. The average source areas exhibited slope gradients of between 25° and 35°, which is generally consistent with the data presented in the literature regarding the slope of debris flow-prone channels (Chau et al., 2000; Prochaska et al., 2008). However, it is notable that some smaller debris flow channels, with slope angles of approximately 20° and up to 45°, were also identified in this study. The depositional areas exhibited a range of dimensions, spanning a minimum of 850 m² and a maximum of 300,000 m². The highest values were observed for dormant deposits situated between Barete and Pizzoli settlements, in the central region of the study area. Conversely, the lowest values were noted for active deposits.

No statistically significant correlation was identified between the size of the source areas and their corresponding deposition areas. This discrepancy is likely attributable to the considerable human activity in the area at the base of the slope. Agricultural practices and urban development may have partially erased the accumulation areas of older debris flow events. Furthermore, the implementation of several sediment transport control structures, including check dams and artificial channels, particularly in the upstream sections in proximity to population centers, has likely reduced the volume of material reaching and being deposited at the base of the slope.

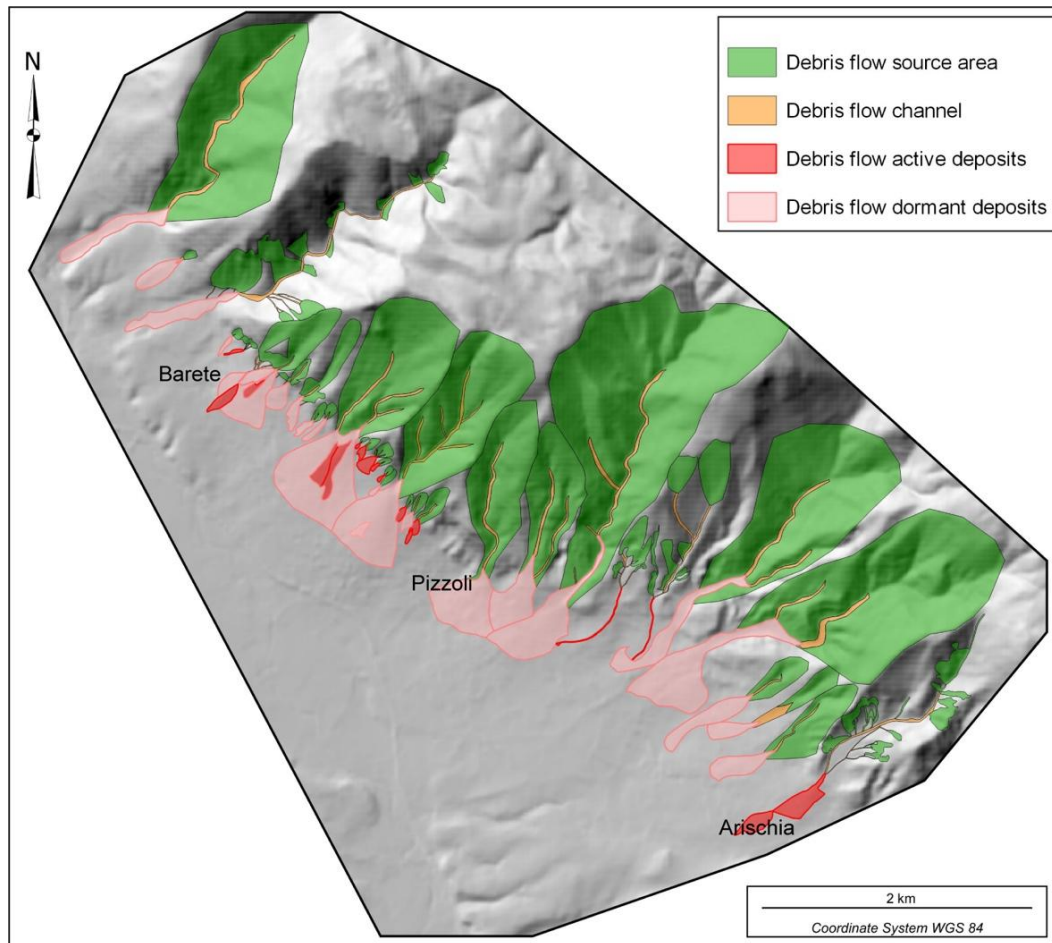


Figure 4.16. Debris flow source area, channel and deposits detected on the southwestern flank of Mount Marine. Black polygon depict the study area.

During the July-August 2020 period, the south-eastern sector of the study area in the municipality of Pizzoli (AQ) was affected by extensive forest fires. The pyrological phenomena worsening the geomorphological and pedological criticalities of the affected slopes, increasing the probability of triggering gravitational phenomena, particularly in the form of debris flows. This, in turn, heightened the risk of repercussions on the hydrogeological safety of the areas located at the base of the slope.

In this work burning severity was assessed for the area that was affected by wildfires by calculating the Delta Normalized Burn Ratio (dNBR) as the difference between NBR index pre- and post- wildfire (Equation [4.1]):

The resulting burning severity map (Figure 4.17) highlights that the wildfire only spread in the south-eastern sector of the study area in the surrounding area of the town of Arischia (AQ), resulting in severe damage to the source areas of some of the debris flow channels identified in this study. The degradation of soil characteristics and general slope stability conditions as a consequence of the fire was substantiated by the emergence of debris flows

in the channels affected by the fires following the occurrence of intense rainfall events in the days immediately following.

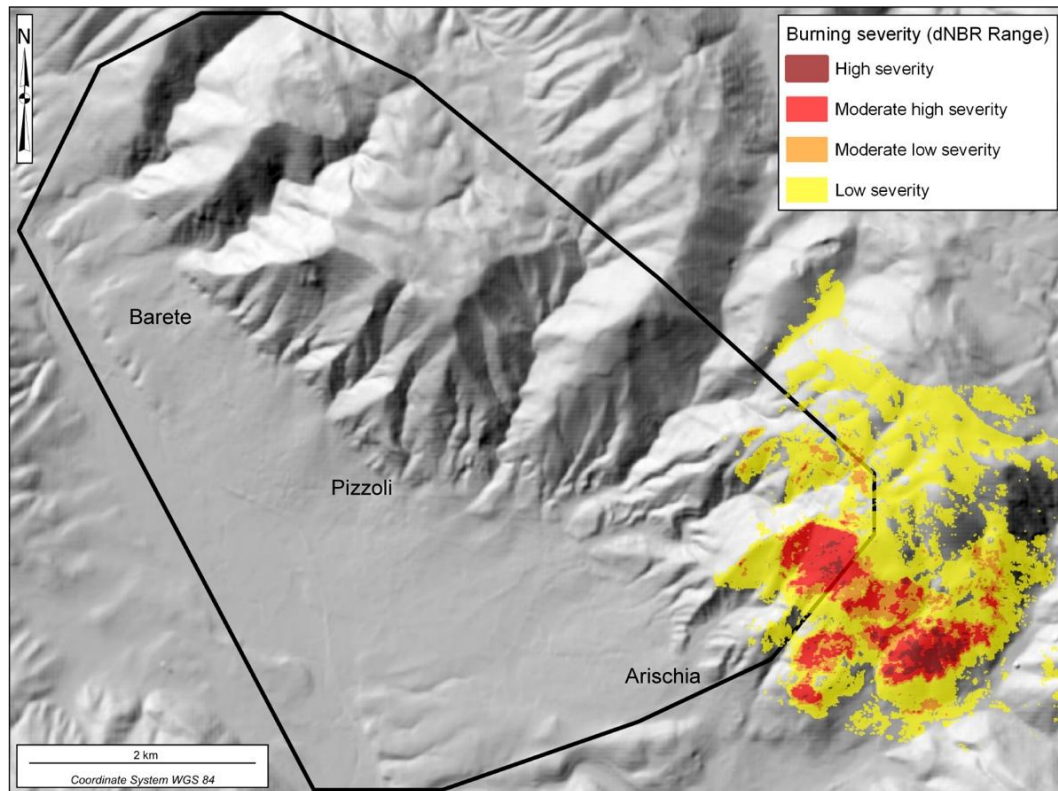


Figure 4.17. Burning severity levels from dNBR after wildfire occurred in August 2020 in the southeastern sector of the study area. The dNBR index is calculated based on Sentinel-2 satellite imagery from 29 July 2020 (pre-fire) and 28 August 2020 (post-fire) available for the area. Black polygon depict the study area.

4.5 Discussion and Conclusions

The geomorphological map is an essential tool for assessing susceptibility and hazard. This study focuses on mapping the geomorphological landforms of the southwestern slope of Mount Marine in the upper Aterno Valley (Central Italy). It follows an integrated approach that combines morphometric, geological, and geomorphological analyses, incorporating both remote sensing and field data, to achieve a comprehensive characterization of area.

The lithological framework of the study area consists of Mesozoic and Cenozoic carbonate rocks covered at the toe of the slope by extensive Quaternary deposits, which significantly influence the shaping of geomorphological features. The slope displays steep fault scarps, triangular facets, and a complex network of debris flow channels primarily oriented in the NE-SW direction. The carbonate lithologies are markedly affected by tectonic activity, particularly the presence of an active normal fault system intersecting the area. This

fault activity has led to the creation of structural discontinuities and the weakening of rock masses, which are the main sources of debris for the slope processes.

Debris flows, recognized as the most significant geomorphic processes, are closely related to the tectonic and lithological setting. A total of 32 debris flow systems were mapped, showing a variety of differences in source area size, slope gradients (averaging between 25° and 35°), and accumulation zones. The interaction between fault-induced steep slopes and loose Quaternary deposits plays a crucial role in the frequent occurrence of debris flows, which can be exacerbated by wildfires. The 2020 wildfire in the southeastern part of the study area illustrated how vegetation loss and soil degradation heighten slope instability, thereby triggering debris flows during subsequent intense rainfall events.

The integration of lithological, structural, and morphometric analyses with field data highlights the crucial role of the Mount Marine fault in influencing debris flow susceptibility. By modifying slope gradients, enhancing sediment availability, and altering drainage patterns, the fault system serves as a primary control on the geomorphological evolution of the area.

In conclusion, the geomorphological map produced in this study serves as a critical tool for land-use planning and hazard mitigation. By identifying areas highly susceptible to debris flows and delineating their geomorphic controls, the map provides a comprehensive framework for evaluating debris flow hazards. This information is crucial for implementing effective management strategies aimed at reducing risks to infrastructure and communities in this tectonically active region.

5 ROCKFALL SUSCEPTIBILITY ASSESSMENT AND LANDSCAPE EVOLUTION OF SAN NICOLA ISLAND (TREMITI ISLANDS, SOUTHERN ADRIATIC SEA, ITALY)

5.1 Introduction

The Tremiti Islands (Puglia Region, Italy) are located in the Southern Adriatic Sea, within a complex geological–geomorphological framework. Representing the emerged part of the main structural high within the Adriatic basin and being situated in an intermediate position between the central–southern Apennines and the Dinaric chain, the archipelago has been the subject of several scientific studies focusing on the Quaternary Adriatic basin evolution, mostly driven by eustatism and tectonics (Festa et al., 2014; Teofilo et al., 2016). The present-day landscape, indeed, is the result of a complex interaction among climate, tectonics, and sea-level changes with geomorphological landforms featuring slope, marine, fluvial, and karst origins (Mastronuzzi and Sansò, 2002).

Within the Tremiti Archipelago, San Nicola Island, with a surface of only 0.42 km², is of paramount historical and natural value, as shown by the large number of studies carried out in the area (Baldacci, 1953; Ceva-Grimaldi F, 1852; Checchia Rispoli, 1926; Cocarella B, 1606; Dell’Aquila, 1908; Fumo, 1980; Lollino and Pagliarulo, 2008; Radicchio, 1993; Squinabol, 1908; Tellini, 1890; Zorzi, 1958). Historically, several populations inhabited the area, of which the major remnants are a Roman domus (II century B.C.) and the Benedictine abbey of Santa Maria a Mare, in addition to a whole host of ancient lithic artifacts. Nowadays, the island’s wealth comes from its monumental heritage as well as from its valuable landscaping, which every year attracts thousands of travelers from all over the world. This represents a highly favorable circumstance for the local economy, tourism, and cultural activities; on the other hand, it poses the question of how to protect people and the historical heritage from hazard and risk linked to the local geological and geomorphological settings. In fact, San Nicola Island, like other highly frequented coastal areas, is frequently subject to instability processes which can lead to sudden and hazardous landscape modifications, such as rockfalls and mass movements (Iadanza et al., 2009; Lollino and Pagliarulo, 2008).

Rockfalls are classified as a type of landslide consisting of the detachment and the following rapid down-slope motion of one or more rock blocks from a steep cliff and are often responsible for major accidents and sudden fatalities (Varnes, 1984). From a general perspective, landslide susceptibility can be seen as a relative indication of the spatial probability of landslides to occur in a specific region, linked to local geo-environmental

conditions and without any reference to past phenomena occurrence; its evaluation, furthermore, does not account for the timing or magnitude of expected phenomena (Guzzetti et al., 1999; van Westen et al., 2006). Various methods for landslide susceptibility assessments can be encountered in the scientific literature, based on available data as well as on the scale of analysis. Applied models can be grouped into four categories: physical, heuristic, statistical, and machine learning (Merghadi et al., 2020). Physical models require accurate site characterization and are more suitable for slope-scale analysis and mapping (Dong et al., 2023). Heuristic methods mostly rely on expert knowledge and expertise, focusing on the importance of the field survey to prevent statistic bias, and can be used in areas where detailed geotechnical information and/or reliable, accurate, and complete landslide inventories are missing (Carabella et al., 2022; Leoni et al., 2015; Ruff and Czurda, 2008). Statistical models are based on the analysis of the functional relationships between slope instability factors and landslide distribution and require wide, complete, and temporally extended landslide inventories (Reichenbach et al., 2018; Xu, 2015). Machine learning techniques, finally, are becoming more popular given their ability to deal with large datasets and derive complex non-linear patterns (Frattini et al., 2008). In the specific case of rockfalls, research has shown rapid growth in recent years, with a clear increasing trend of annual publications on the topic, and several works based on different datasets and techniques have recently been published (Alvioli et al., 2021; Bajni et al., 2023; Briones-Bitar et al., 2020; Cignetti et al., 2021; Frattini et al., 2008; Toševski et al., 2021; Wen et al., 2022).

Starting from this standpoint, this study is aimed at providing a useful tool for rockfall susceptibility assessment through the evaluation of main contributing factors, which has been poorly known in the previous thematic studies, and to individuate the main critical areas all over the San Nicola Island. The preliminary analysis of available geomorphological data pointed out that the study area lacks complete and accurate regional and national landslide inventories. In detail, the IFFI (*Inventario dei Fenomeni Franosi in Italia* (APAT, 2007)), the CEDIT (*Italian Catalog of Earthquake-Induced Ground Failures* (Caprari et al., 2018; Fortunato et al., 2012)), and the EEE (*Earthquake Environmental Effects Catalog* (Audemard et al., 2015)) catalogs report no event for the study area, even though many landslides have actually been present. Since inventories represent the necessary base for meaningful statistical model calibration and susceptibility assessments, a heuristic method was applied in San Nicola Island to detect and classify areas most prone to collapse. The

following activities were consequently carried out: (i) main photo-lineaments were detected by multitemporal stereoscopic aerial photo interpretations; (ii) morphometric features of the island were derived based on a high-resolution Digital Terrain Model (DTM); (iii) detailed field surveys were carried out to derive lithological and geomorphological features of the area, along with geomechanical investigations performed on rock masses through scan line surveys; and (iv) acquired data were synthesized in a GIS environment to produce a rockfall susceptibility map, accounting for different morphometric and geothematic parameters (i.e., slope, slope aspect, outcropping lithologies, structural discontinuities density, distance from landslide scarps, and presence of anthropic caves). After combining and comparing the achieved results with field and historical data, it was possible to uncover some clues related to the extant relationships between landscape evolution and litho-structural/tectonic factors.

In conclusion, this work provides a scientific and methodological approach that could effectively be applied for landslide susceptibility assessments in any other small insular areas, such as San Nicola Island, showing similar geological–geomorphological features and landscape values, to develop sustainable territorial planning and loss-reduction measures.

5.2 Study Area

The Tremiti Islands constitute an archipelago in the southern Adriatic Sea, offshore of the Gargano coast, and were designated as a Marine Protected Area (MPA) in 1989 for their great scientific and cultural value. They consist of four islands, namely San Domino, San Nicola, Capraia, and Cretaccio (Figure 5.1), while a fifth island, Pianosa, is located about 20 km far from the others towards the northeast.

The islands rise from gentle underwater slopes reaching a depth of 80 m b.s.l.; their morphology is overall tabular, with summit surfaces usually bounded by very steep or vertical cliffs; and the maximum altitude is 116 m a.s.l. and is detected in the southern sector of San Domino Island (Buccolini et al., 2020; Miccadei et al., 2012a; Piattelli et al., 2023).

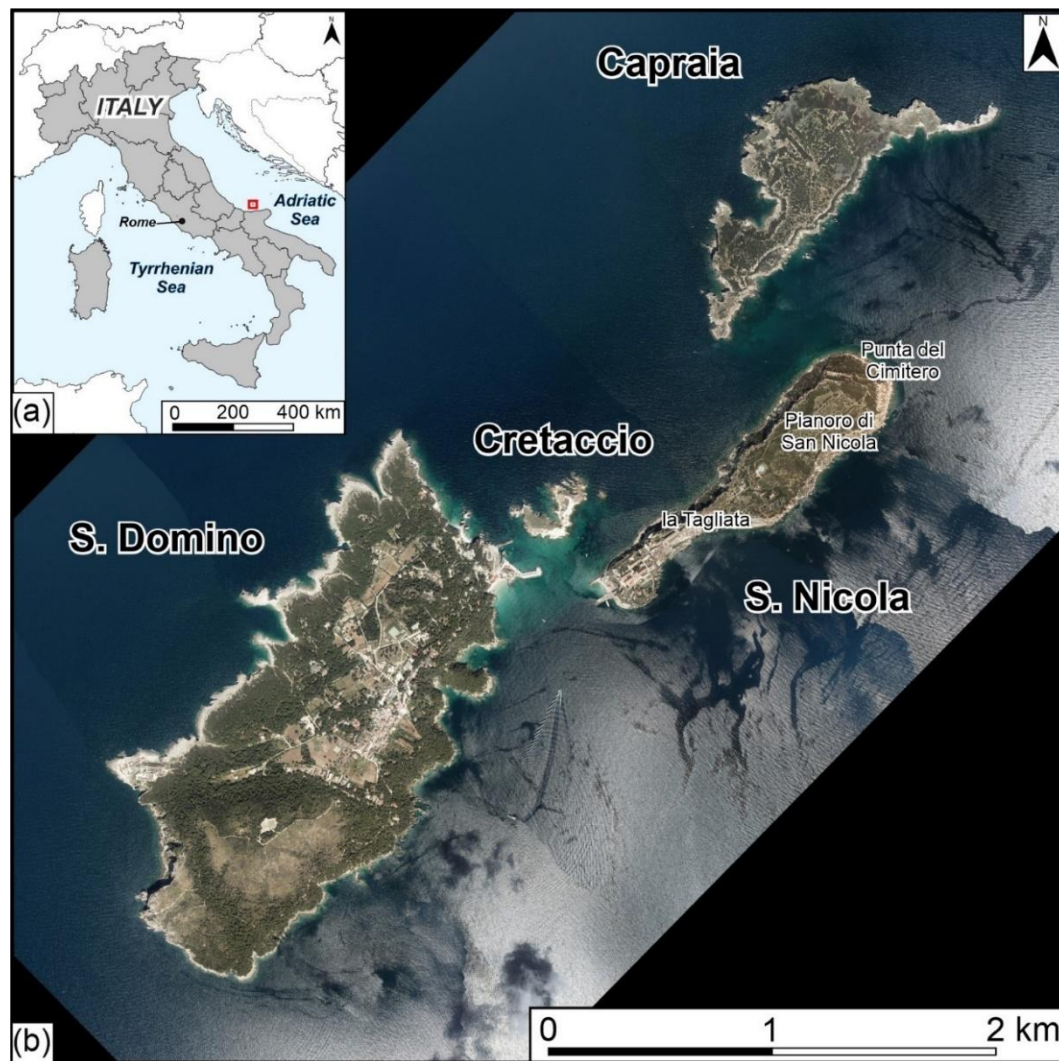


Figure 5.1. (a) Location map of Tremiti Islands in the Southern Adriatic Sea (Italy)—the red box identifies the location of Tremiti Islands; (b) 2019 orthophoto image of San Domino, San Nicola, Capraia, and Cretaccio Islands (Puglia Region, <http://www.sit.puglia.it>, accessed on 12 June 2023).

With reference to the tectonic framework, marine successions feature a general SE-dipping homocline setting consistent with a limb of a regional NE–SW anticline and are characterized by main discontinuities that are E–W, WSW–ENE, and NE–SW directed, with strike-slip kinematics; secondary systems are present with strike-slip and dip-slip kinematics and directions ranging from NW–SE to N–S (Miccadei et al., 2011). Seismic activity is well documented by earthquakes that occurred in the neighboring areas. In historical times, the Tremiti Islands experienced strong seismic events, severely affecting both the Gargano and Periadriatic areas. More recently, events with magnitudes greater than 4 have enucleated in the nearby Adriatic sector (Del Gaudio et al., 2007; Di Bucci et al., 2007; Favali et al., 1993; Miccadei et al., 2021; Rovida et al., 2022).

From a geomorphological point of view, the islands present a wide variety of landforms mainly of marine, slope, karst, and fluvial origin which are linked to long-term evolutionary processes such as Quaternary tectonics, regional uplift, and eustatic sea-level changes (Andriani and Guerricchio Romano, 1996; Miccadei et al., 2012; Parlagreco et al., 2011; Ridente and Trincardi, 2002; Romano et al., 2023). In this context, San Nicola Island is characterized by widespread instability processes, affecting the cliff and the coastal sectors for almost their whole length and featuring complex failure mechanisms. Landslide typologies range from rockfalls, topples, and lateral spreads with retrogressive evolution (Cotecchia et al., 1996; Lollino and Pagliarulo, 2008).

5.3 Materials and Methods

To achieve a comprehensive characterization of the geomorphological processes affecting San Nicola Island, with a special focus on the typology, geometry, and triggering mechanisms of landslide movements, and to derive the role played by the main litho-structural and tectonic features, integrated and multidisciplinary analyses were carried out. In detail, the present work focuses on rockfalls affecting the cliff and the coastal sectors of the island. A stepwise approach, based on either direct (geomorphological field mapping) or indirect (photogeology and GIS data processing) analyses, consequently followed to better investigate the geological–geomorphological features influencing this type of mass movements. The followed methodological approach is graphically synthesized in Figure 5.2.

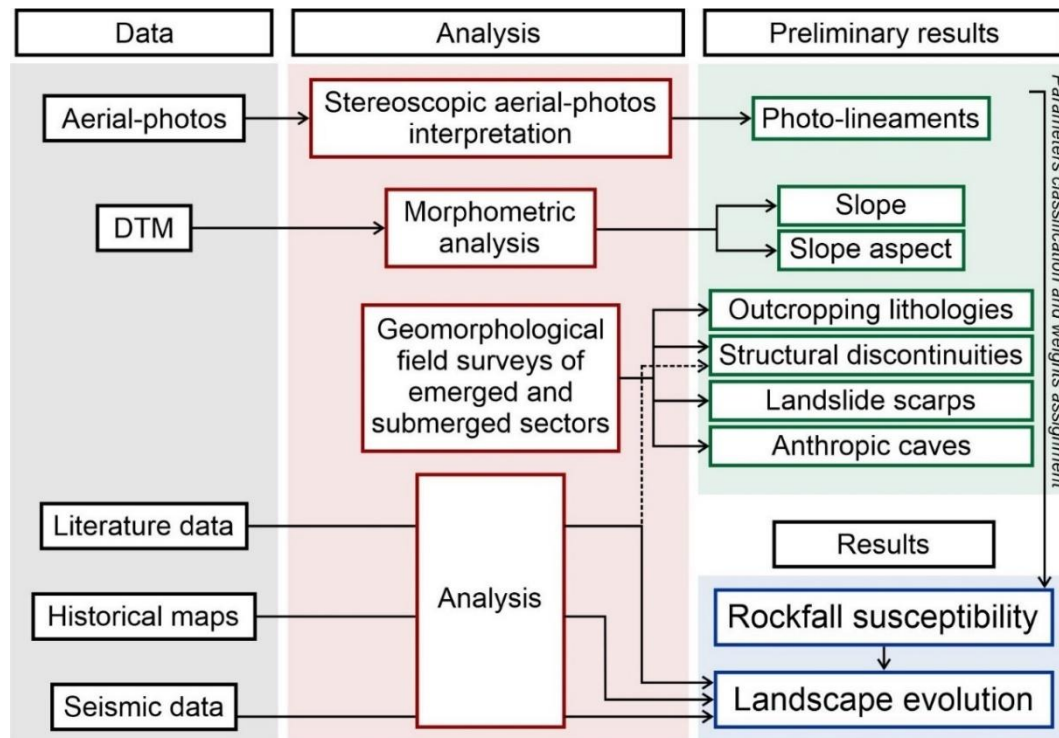


Figure 5.2. Flowchart of the applied methodology. Black boxes indicate used data, red boxes performed analyses, green boxes preliminary results used for rockfall susceptibility assessment, blue boxes final results.

5.3.1 Geothematic and Literature Data

At first, a multitemporal stereoscopic aerial photo interpretation was performed to detect main photo-lineaments, which can be a valuable indicator of past and/or ongoing tectonic processes. It was achieved using 1:33,000 to 1:5000 scale stereo image pairs covering a time span from 1955 to 2019 (1955, 1977, and 1996 IGM Flights; 2019 AGEA Flight), supported and integrated by Google Earth® imagery.

Digital Terrain Model (DTM) data (raster elevation model at 2 m spatial resolution) of Laser imaging Detection And Ranging (LiDAR) technology were provided by the Italian Ministero dell'Ambiente e della Sicurezza Energetica (MASE) and were used to outline the main orographic features of the study area. In detail, morphometric analyses were carried out, starting from using ESRI ArcGIS 10.6™ tools, to produce maps of the slope and slope aspect, which are widely used in landslide mapping and modeling given the linkage between slope geometry and potential landslide movements (Coco and Buccolini, 2015).

Detailed field surveys were then conducted to derive lithological features along with the spatial distribution of tectonic and geomorphological elements, in accordance with official Italian geomorphological guidelines and the thematic literature (Ciccacci et al., 1999; ISPRA, 2007b; Seijmonsbergen, 2013; Smith et al., 2011). Submerged rockfall deposits along island coastal sectors were also mapped through underwater geomorphological

surveys, carried out up to 30 m b.s.l. Moreover, a comprehensive characterization of the study area was completed with geomechanical investigations, performed on rock masses through scan line surveys. These analyses allowed us to define the bedding, spacing, and persistence of discontinuity systems and to outline the dimension of blocks potentially involved in rockfalls. Joints and open fissures were portrayed on stereographic projections to highlight structural features of different sectors of the island. During field activities, a drone survey was also performed to acquire high-resolution images with a cell size of about 3 cm in the NE area of la Tagliata; these were then compared with AGEA 2019 orthophotos to detect landslide movements that occurred in the period 2019–2022 through the detection of recent detachment sectors, as well as run-out and deposition zones. A 1:2500 geomorphological map was, finally, produced along with geomorphological cross-sections. In addition, field survey activities were supported by the analysis of Permanent Scatterers (PSs) data, both provided by *Ministero dell'Ambiente e della Sicurezza Energetica* and retrieved from the European Ground Motion Service, which is openly available at <https://egms.land.copernicus.eu/> (accessed on 29 August 2023). A PSs analysis was used for a prior definition of the general geomorphological dynamics and the potential slope deformations phenomena (Mantovani et al., 2016), with a special focus on areas historically affected by mass movements; points located in vegetated and innermost flat areas or in isolated blocks located within rockfall deposits were not considered for this evaluation.

Data on the seismic features of San Nicola Island, retrieved and gathered from available catalogs and literature data, were analyzed according to the role played by earthquakes in triggering rockfalls and inducing landscape evolution over a long period. In detail, seismic data were extracted from the Italian Macroseismic Database (DBMI15 v4.0, (Locati et al., 2022)), which is openly available at <https://emidius.mi.ingv.it/CPTI15-DBMI15/> (accessed on 1 September 2023), and macroseismic intensity (I) data for Italian earthquakes with $I_{max} \geq 5$ for the period 1000–2020. Data regarding more recent earthquakes were derived from the Italian Seismological Instrumental and parametric Database (ISIDe Working Group, 2007), reporting earthquake parameters of events recorded by the Italian Seismic Network from 1985 to the present day. Data-gathering was also focused on cartographic and historical information. Hence, historical maps reporting morphological features of the island dating back to the XVI century were also retrieved and analyzed.

Specific morphometric and geothematic parameters were considered as landslide-predisposing or triggering factors based on the influence exerted in slope instability and the role played in the mechanism of rockfall occurrence. The factors considered for the susceptibility analysis were slope, slope aspect, outcropping lithologies, structural discontinuities density, distance from landslide scarps, and presence of anthropic caves. The slope gradient was used since higher values are commonly linked to a higher rockfall susceptibility (Çevik and Topal, 2003; Gupta et al., 1999; Marsala et al., 2019; Yalcin et al., 2011). The aspect of slopes bordering the island was considered to account for the effect produced by their exposure to wave erosion and undercutting processes; the approaching direction of dominant waves, indeed, is of great importance in coastal vulnerability assessments (Anfuso et al., 2021; Montoya-Montes et al., 2012). The wind and wave data used in this study were directly retrieved from (Katalinić and Parunov, 2021), focusing on information about the approaching direction of dominant waves. Concerning outcropping lithologies, they exert a significant influence on rockfall susceptibility and slope instability, according to their nature, degree of cementation, and behavior towards degradation processes, as also supported by literature data (Carrara et al., 1991; Esposito et al., 2021). The structural discontinuities density, here meant as the number of faults, joints, open fissures, and trenches per unit of surface, is directly linked to the degree of rock fracturing, which in turn affects slope firmness, with higher values associated with a higher instability (Vanneschi et al., 2022); it was computed by means of the “Line Density” tool implemented in QGIS 3.22 Białowieża, setting a search radius of 10 m, after the digitization of elements derived from literature data, especially the work by (Cotecchia et al., 1996), and geomechanical investigations. Moreover, the spacing and persistence of the discontinuity sets were analyzed together with their relationship with the bedding attitude and slope orientation to preliminarily define the size of blocks susceptible to fall, as well as their fall mechanism (Piacentini et al., 2013). The distance from landslide scarps was also considered since they represent main rockfall and topple source areas; with this in mind, a buffer zone of 10 m downward and 2 m landward was set, accounting for the presence and persistence of rock discontinuities as derived through geomechanical field surveys (Piacentini et al., 2015). The presence of anthropic caves, finally, was considered since they reduce rock mass stability, inducing overlying layer deformation and collapse (Liguori et al., 2006). Since the detected elements were only partially accessible, they were mapped as points at their entrance or their central part. Consequently, to account for their actual extension as well as

for the presence of unexplored sectors possibly affecting slope stability, a buffer zone of 15 m was considered around mapped detected caves for the susceptibility assessment.

5.3.2 Rockfall Susceptibility Assessment

Morphometric and geothematic parameters were subdivided into a suitable number of classes, encompassing the whole variability of each parameter in the wider geological–geomorphological context of the island. Each class was then assigned a weight following an expert-based approach, considering the influence exerted by selected parameters in rockfall occurrence, based on the critical evaluation of literature data and field survey results (Chalkias et al., 2016; Khatun et al., 2023). More in detail, classes were assigned values ranging from 0 to 12, with higher values indicating a higher influence exerted on rockfall susceptibility, according to methodological approaches proposed by (Carabella et al., 2022). This procedure led us to rate each individual class, providing an immediate measure of the role played by each factor and related classes on the rockfall susceptibility, as shown in Table 1. Concerning outcropping lithologies, eluvium–colluvium, rockfalls, and anthropic deposits were given the value of the inferred underlying lithology, except for sectors along the coastline. Concerning the structural discontinuities density parameter, its values were divided into 5 equal interval classes labelled from *Very Low* to *Very High*.

Table 5.1. Analyzed parameters and related assigned weights based on field surveys and literature data following a heuristic approach.

Parameter	Source	Class	Weight
Slope [°] (Çevik and Topal, 2003; Gupta et al., 1999; Marsala et al., 2019; Yalcin et al., 2011)	DTM	0–20	0
		20–30	1
		30–35	2
		35–40	3
		40–45	5
		45–60	7
		60–70	9
		70–80	11
		80–90	12
Slope aspect (Anfuso et al., 2021; Montoya-Montes et al., 2012)	DTM	Plain	0
		North	2
		Northeast	2
		East	1
		Southeast	3
		South	1
		Southwest	0

Outcropping lithologies (Carrara et al., 1991; Esposito et al., 2021)	Field surveys	West	0
		Northwest	0
		Dolomitic limestones	10
		Marls	7
		Breccias and conglomerates	7
		Anthropic deposits	0
		Sandy shore deposits	0
		Rockfall deposits	0
		Very low	0
		Low	3
Structural discontinuities density (Vanneschi et al., 2022)	Field surveys; geomechanical investigations and data from [Cotecchia]	Medium	5
		High	8
		Very high	12
Distance from landslide scarps (Piacentini et al., 2015)	Stereoscopic aerial-photos interpretation; field surveys	Buffer zone (radius: 10 m downward, 2 m landward)	5
Presence of anthropic caves (Liguori et al., 2006)	Field surveys	Buffer zone (radius: 15 m)	3

After this step, all the collected data were portrayed in thematic maps. Rasters of weighted parameters were overlain and summed cell by cell using the “Raster Calculator” tool implemented in ESRI ArcGIS™ 10.6, through the equation:

$$R_s = \sum_{i=1}^n w_n \quad [5.1]$$

where R_s is the rockfall susceptibility and w_n is the weight assigned to the class of the n -factor. The final thematic map was built classifying the resulting raster map into 5 equal interval classes using the “Equal interval” classification tool implemented in ESRI ArcGIS™ 10.6. By applying this cartographic and weighted overlay process, the interactions between the assigned parameters’ weights resulted in the assessment of the rockfall susceptibility, labelled in five classes (*Very Low*, *Low*, *Medium*, *High*, and *Very High*).

Then, the spatial distribution of rockfall susceptibility was compared with information derived from GIS analyses, field surveys, seismic data, and historical map analyses to provide an assessment of its reliability, depicting the main critical areas all over the San Nicola Island, and to offer clues about possible relationships between landscape evolution and the litho-structural and tectonic setting of the area.

5.4 Results

5.4.1 Geothematic Parameters

5.4.1.1 Photo-lineaments

The multitemporal stereoscopic analysis of available aerial photos covering the period 1955–2019 allowed us to detect the main photo-lineaments of the area, which served as a basis for the subsequent field surveying. The island presents an overall tabular morphology, with high flat sectors bordered by almost continuous sub-vertical cliffs (not portrayed in Figure 5.3 for the sake of image clarity). Detected and mapped features are represented by inner scarps and trenches. Concerning the former, a steep NW–SE-oriented scarp is clearly visible SW of la Tagliata. Other scarps visible in all aerial acquisitions are found in Punta del Cimitero, with W–E direction and demarcating sub-horizontal surfaces set at progressively lower elevations moving towards north.

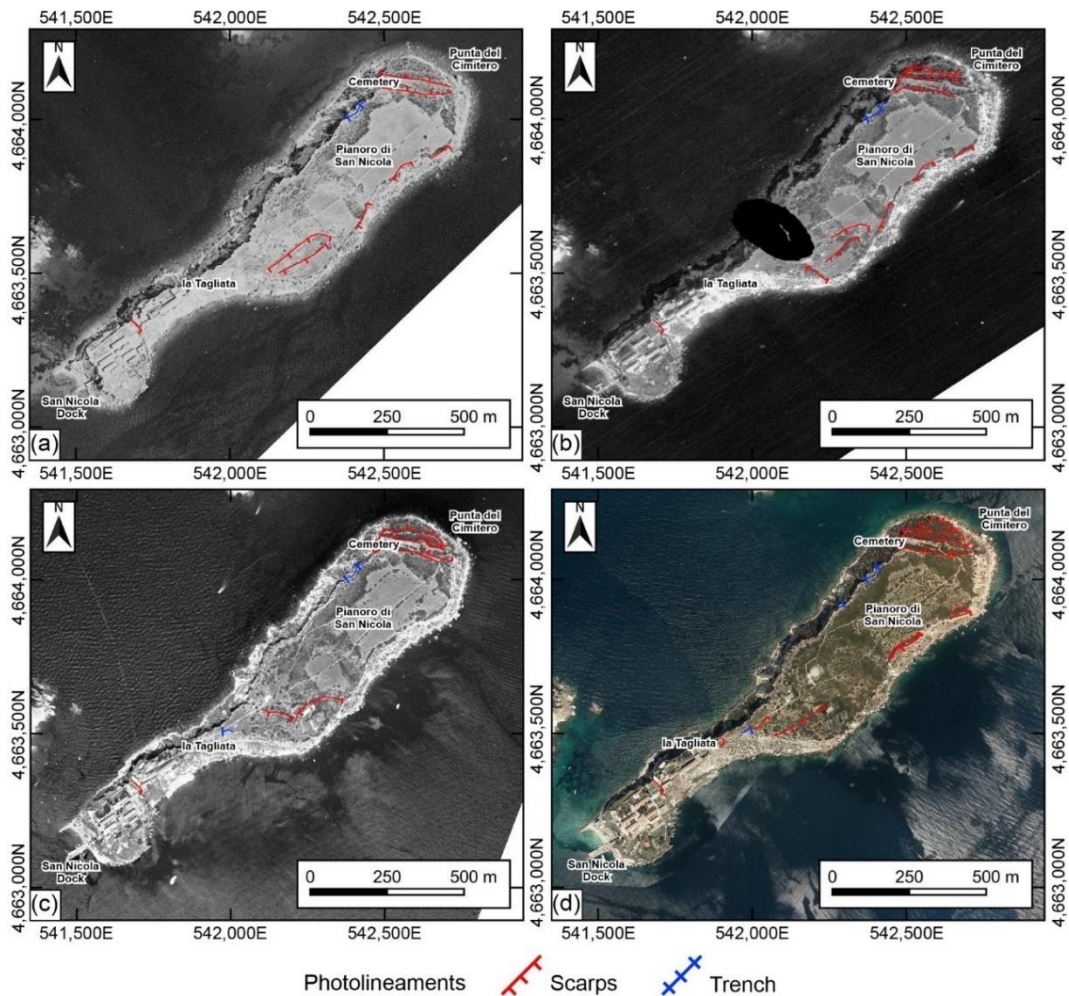


Figure 5.3. Photo-lineaments derived through the multitemporal stereoscopic analysis of aerial photos of San Nicola Island referring to (a) 1955, (b) 1977, (c) 1996, and (d) 2019 flights. Coordinate system: WGS84 UTM Zone 33N.

Other elements are, finally, visible in the eastern sector of Pianoro di San Nicola a few meters inland, with respect to the main cliffs of the island. Concerning trenches, they show a main SW–NE direction and are found in the northwestern sector of Pianoro di San Nicola and NE of la Tagliata, along the southern border of the summit tabular surface.

Finally, urbanized sectors are mostly found in the southwestern sector of the island and do not display significant variations over the analyzed period.

5.4.1.2 Morphometric Features

From a morphometric perspective, the island features an elongated shape with a SW–NE directed major axis of about 1600 m and a width ranging approximately between 130 and 420 m, respectively, measured in relation to la Tagliata and the northern portion of Pianoro di San Nicola. The coast extends for a total length of 3700 m and the maximum elevation is around 76 m a.s.l.

Two main flat sectors constitute its summit surface, mainly set at 43 (the southwestern one) and 75 (the northeastern one) m a.s.l., with slope values generally lower than 10°; they are separated by the NW–SE-oriented scarp already detected in the aerial photo interpretation and located SW of la Tagliata. This element features slope values greater than 60°, as do cliffs bordering the high sectors as well as the W–E-directed scarps found in Punta del Cimitero. Sectors with slope gradients ranging between 20° and 60°, finally, connect summit surfaces to the coastal areas (Figure 5.4a).

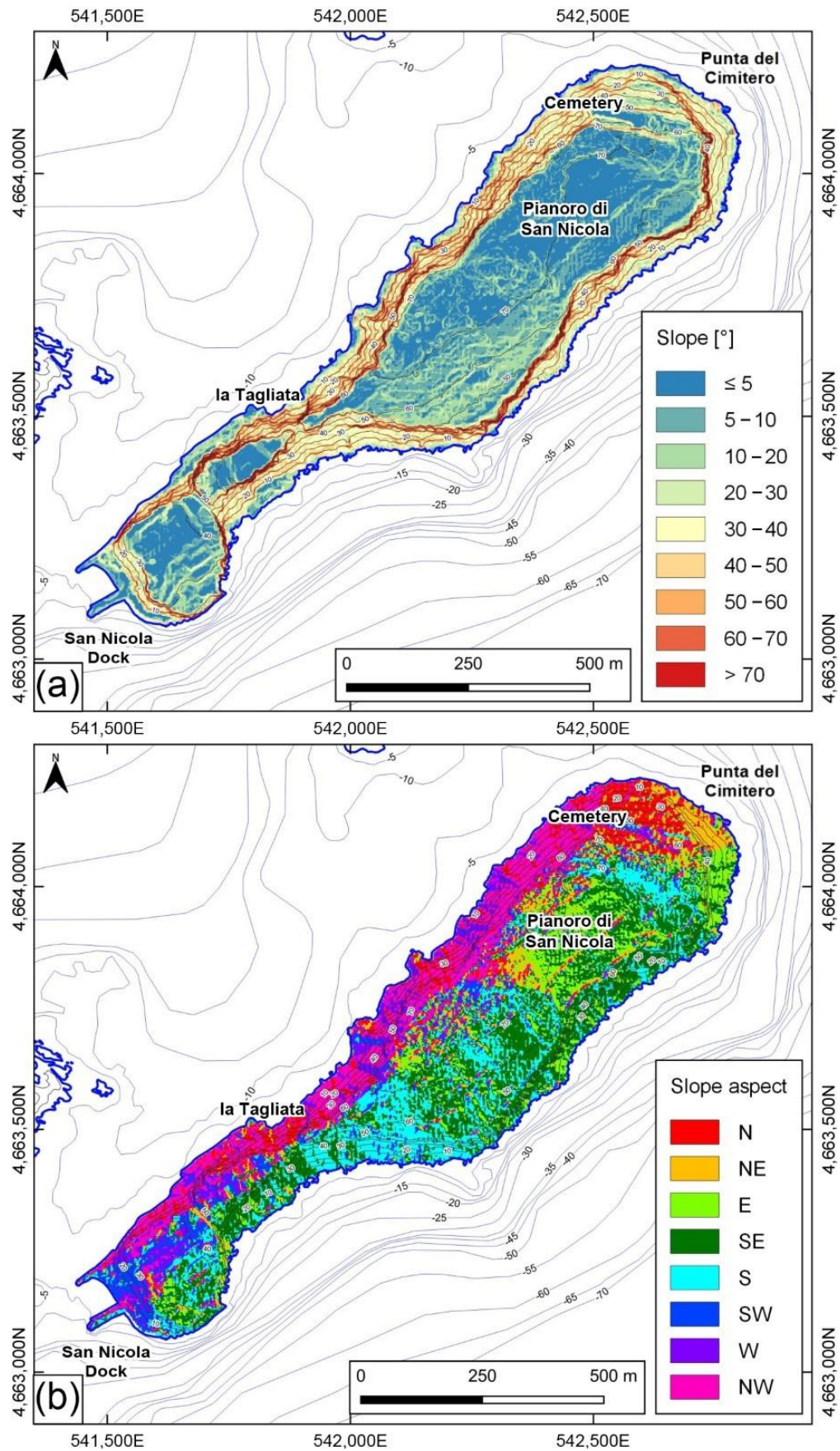


Figure 5.4. Maps of the (a) slope and (b) slope aspect of San Nicola Island. The blue line indicates the coastline. Coordinate system: WGS84 UTM Zone 33N.

Concerning slope aspect values, they appear organized in SW–NE directed patches. The northwestern slopes mainly feature NW dipping; southwestern ones a dipping mostly varying between S and SE. The Punta del Cimitero area, on the other hand, shows an average N slope aspect, although S- or SW-dipping narrow sectors are present, which develop parallel to the main and continuous scarps. Within Pianoro di San Nicola, the slope aspect values feature a high variability, even if small SW–NE-directed sectors with N, NW, or W dipping are visible (Figure 5.4b).

5.4.1.3 Geomorphological Features

From a lithological point of view, the island is composed by a Cenozoic succession of marine origin, consisting of gently SE-dipping marls with local high fossiliferous content which are unconformably overlain by dolomitic limestones (Figure 5.5). Superficial deposits consist of reddish breccias and conglomerates organized in 0.25 m thick layers, outcropping on the southwestern slope of the island and lying on the marly deposits with erosive contact (Figure 5.5a); eluvial colluvial deposits, found on flat or gently dipping summit sectors; sandy shore deposits, present only in the surrounding areas of the San Nicola Dock; rockfall deposits, made up of decimeter- to meter-sized blocks of marly or dolomitic limestone lithology, broadly found along island coastal sectors and often covering sloping marly sectors (Figure 5.5b); and anthropic deposits.

Tectonic features are represented by several faults which are mainly NW–SE directed, cutting both marly and dolomitic limestone deposits. The main element is constituted by a normal fault detected in the southern sector, of which past activity resulted in a difference of elevations between the southwestern and northeastern high topographic sectors. Other faults are visible in the same area, cutting marly units overlain by breccias and conglomerate deposits and mostly featuring NE dipping, and along the slopes bordering Pianoro di San Nicola.

From a geomorphological viewpoint, detected and mapped elements mainly refer to slope, structural, and anthropic features (Figure 5.5). Slope elements consist of emerged and submerged landslide bodies and related scarps, landslide terraces, trenches, counter slopes, and isolated blocks. Landslide bodies, referring to rockfall and topples, widely cover the Pianoro di San Nicola slopes, often burying underlying marly deposits, especially in the southeastern sector. The Punta del Cimitero area, on the other hand, presents a wide and complex gravitational phenomenon, with E–W-directed landslide terraces bordered by steep scarps and featuring elevations which get progressively lower moving towards the north,

with a constant difference of about 15 m (Figure 5.6a). Unstable blocks of dolomitic limestone lithology are often found along terrace borders (Figure 5.6b). Other slope scarps border the southwestern summit surface, with heights greater than 10 m. Two main trenches are detected in the Pianoro di San Nicola area (Figure 5.6c, d), of which the former is found east of la Tagliata, along the southern cliff. It develops in the SW–NE direction, with depth values ranging from 6 to 9 m and an opening of about 2 m. Different sub-vertical fracture systems affect the rocky mass, with SW–NE or E–W directions and openings up to 15–25 cm. Several counter slopes, finally, are present in the southeastern sector of the Pianoro di San Nicola.

Structural landforms are mainly represented by scarps, among which the NW–SE-directed ones separate the summit flat surfaces and those partially bordering the urbanized sectors. Anthropic elements, finally, are represented by landslide and coastal defense works and by anthropic caves located under the northeastern inhabited sector and along the southern slope immediately east of la Tagliata (Figure 5.6e).

From a geomechanical viewpoint, rock discontinuities feature different densities and distributions in the area, with variable directions and openings from null to tens of centimeters. N60W- and N60E-oriented systems are the most present, widely affecting dolomitic limestones nearby island cliffs and, to a lesser extent, the inner sectors of Pianoro di San Nicola. W-E-directed fractures are mainly detected south of the Punta del Cimitero area. A N–S oriented system, finally, is present but much less represented compared to the others (Figure 5.7a).

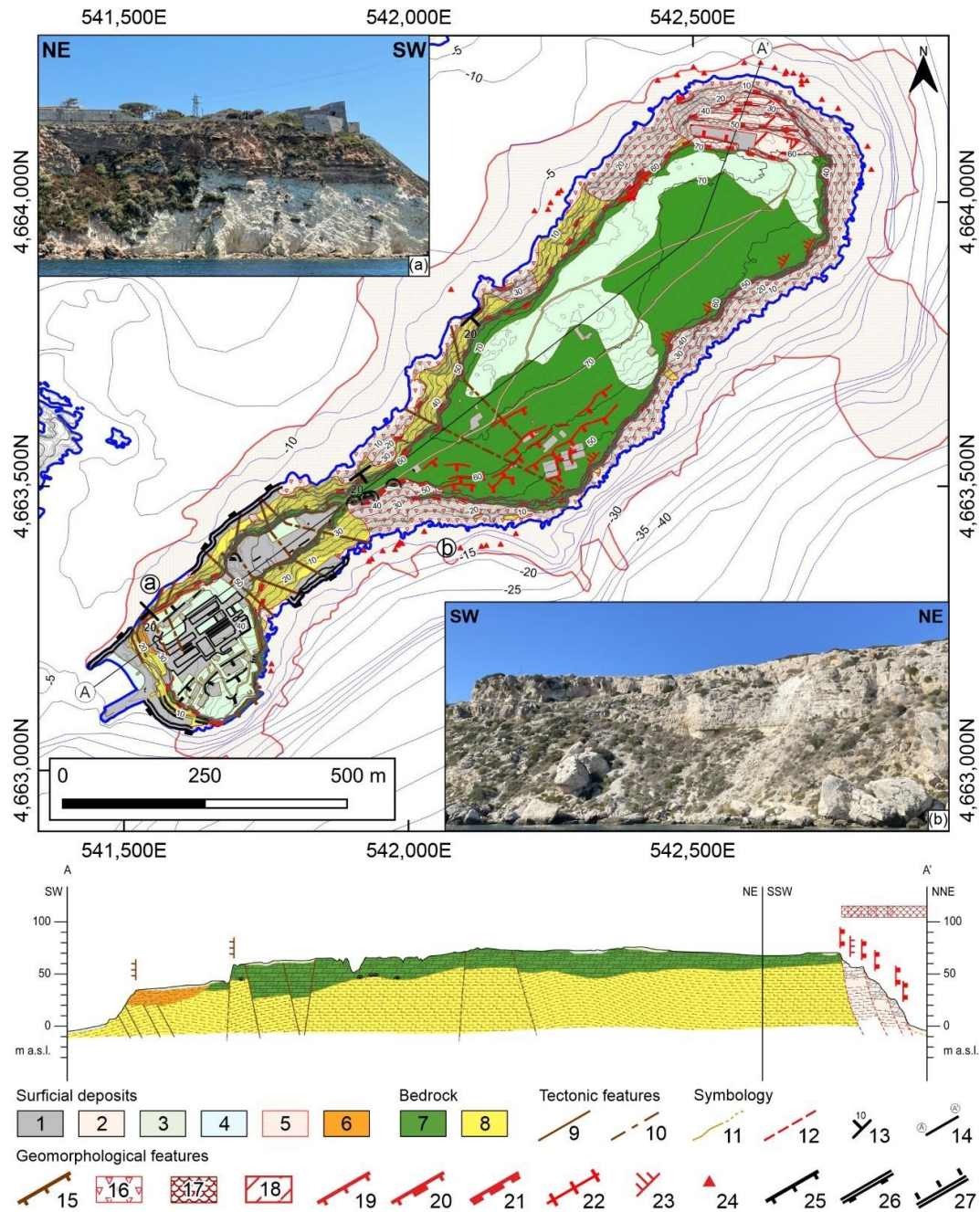


Figure 5.5. Geomorphological map and cross-section of San Nicola Island. Legend: (1) anthropic deposits, (2) landslide deposits, (3) eluvial–colluvial deposits, (4) sandy shore deposits, (5) submerged landslide deposits, (6) breccias and conglomerate levels, (7) dolomitic limestone deposits, (8) marls deposits, (9) fault, (10) inferred fault, (11) lithological boundary, dashed if inferred, (12) landslide surface, (13) bedding, (14) cross-section trace, (15) photo acquisition point, (16) structural scarp, (17) rockfall deposits, (18) rotational landslide, (19) landslide terraces, (20) slope scarp, height < 5 m, (21) slope scarp, 5 m < height < 10, (22) slope scarp, height > 10 m, (23) trench, (24) counter slope, (25) isolated block, (26) anthropic scarp, (27) coastal defense work, (28) landslide defense work. Photo documentation: (a) marly deposits unconformably overlain by reddish breccias and conglomerate layers in the southwestern sector of San Nicola Island; (b) example of rockfall deposits made of decimeter- to meter-sized rockfall deposits of dolomitic limestone lithology. The blue line indicates the coastline. Coordinate system: WGS84 UTM Zone 33N.



Figure 5.6. Photo documentation of geomorphological features of San Nicola Island: (a) landslide scarps, inferred sliding surfaces, and meter-sized fallen block detected in correspondence of Punta del Cimitero; (b) unstable meter-sized block of dolomitic limestone lithology detected in the Cemetery area—the position is indicated by the violet polygon in Figure (a); (c,d) deep trenches and rockfall deposits along the southern flank, east of la Tagliata, and the northwestern one of Pianoro di San Nicola; (e) anthropic cave carved into marly deposits. Legend: (1) structural scarp, (2) isolated block, (3) slope scarp, (4) trench.

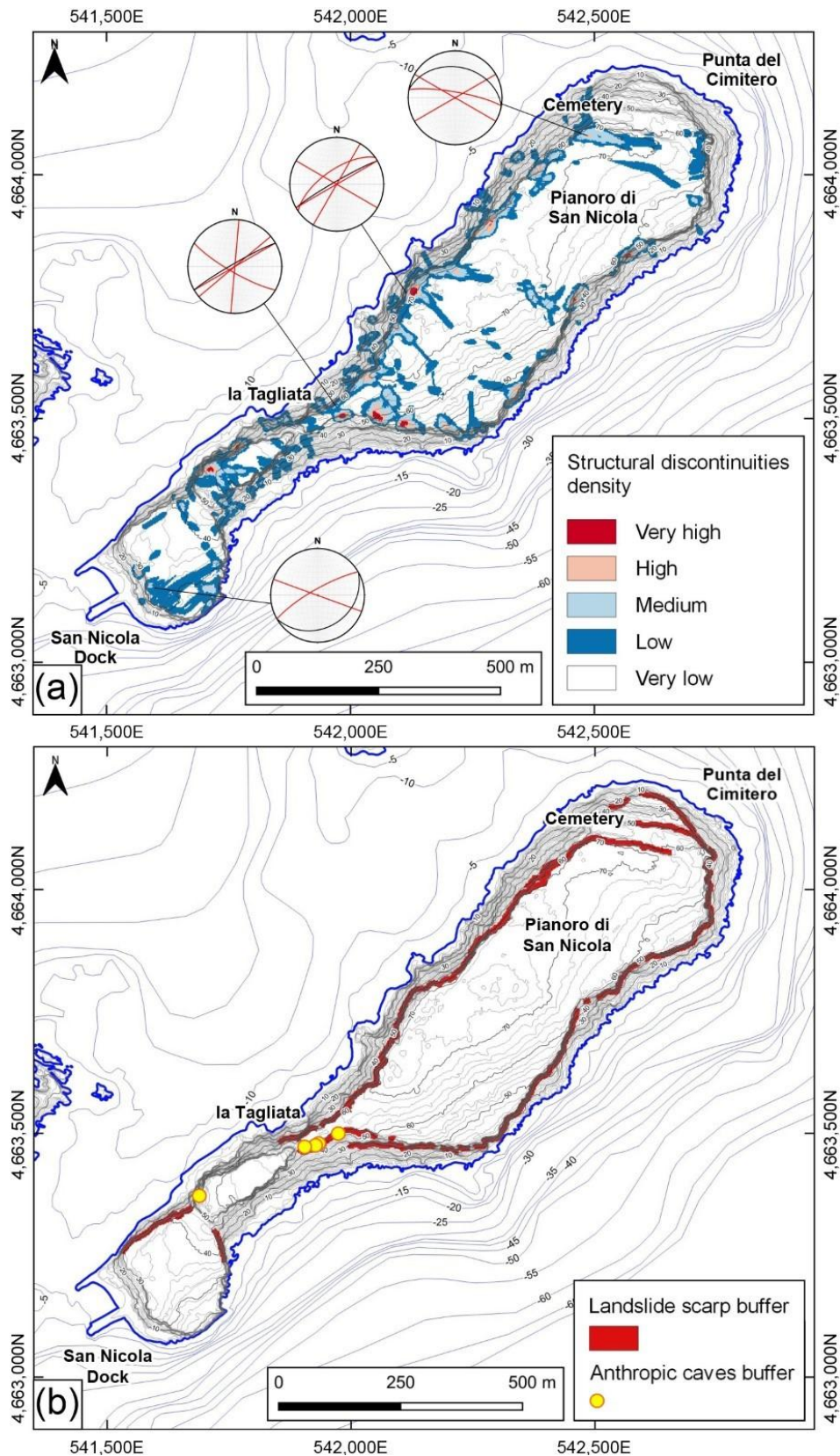


Figure 5.7. Maps of (a) structural discontinuities density and (b) landslide scarps buffer (buffer zone of 10 m downward and 2 m landward) and anthropic caves buffer (buffer zone of 15 m around detected elements) of San Nicola Island. Stereographic projections in (a) depict fracture systems detected through geomechanical investigations or literature data analysis (red lines) and slope geometry (black line). The blue line indicates the coastline. Coordinate system: WGS84 UTM Zone 33N.

Concerning density values, the inner Pianoro di San Nicola shows meanly *Very Low* values, as does the southwestern inhabited sector. *Low* to *Medium* values, on the other hand, are mainly found near high tabular sector edges, secondarily in NW–SE elongated patches set in tectonic lineaments. *High* and *Very High* classes, finally, are spotted in the southern sector of Pianoro di San Nicola, east of la Tagliata, and in small sectors along its eastern and western borders and on the northwestern side of the urbanized sector (Figure 5.7a).

Concerning landslide scarps and anthropic caves (Figure 5.7b), the former border almost the whole Pianoro di San Nicola and partially the northwestern and northeastern sectors of the southern urbanized area, while the latter show the distribution already depicted in Figure 5.5.

5.4.2 Rockfall Susceptibility Map

The distribution of rockfall susceptibility classes derived using morphometric and geothematic parameters, reported in Table 5.1, is shown in Figure 5.8.

The *Very Low* class accounts for about 3% of the territory and is well represented in flat sectors distributed all along the coastline, where mostly rockfall deposits outcrop, and in the western part of the urbanized sector. *Low* values are the most present ones, characterizing around the 67% of the whole area, and are mainly found in flat areas, including the terraced ones in the Punta del Cimitero area; low-susceptibility sectors are also widely present in sloping sectors bordering the island, where marly deposits locally covered by fallen limestone blocks outcrop. Medium values are spotted in island sloping flanks, near the edge of summit tabular areas and along E–W-oriented scarps found in the Punta del Cimitero area and bordering the terraced sectors; they constitute up to the 20% of analyzed sectors. *High* values tend to match with landslide scarps bordering high flat surfaces almost continuously; they represent about 10% of the island surface. *Very High* susceptibility sectors, finally, account only for 0.5% of the total; they feature the highest potential instability within the study area and are mainly identified in dolomitic outcrops with a high fracturing density. In detail, *Very High* susceptibility sectors are detected east of la Tagliata, where stereoscopic aerial photo analyses and field surveys pointed out the presence of wide trenches, extensive and pervasive fracture systems, along with anthropic caves carved in the marly deposits. Other *Very High* susceptibility sectors are located along the southeastern border of Pianoro di San Nicola, which are also characterized by counter-slopes and diffuse fracturing. The northwestern flank of the island, on the other hand, features *Very High* values only in small sectors north of la Tagliata and of the northwestern inhabited sector.

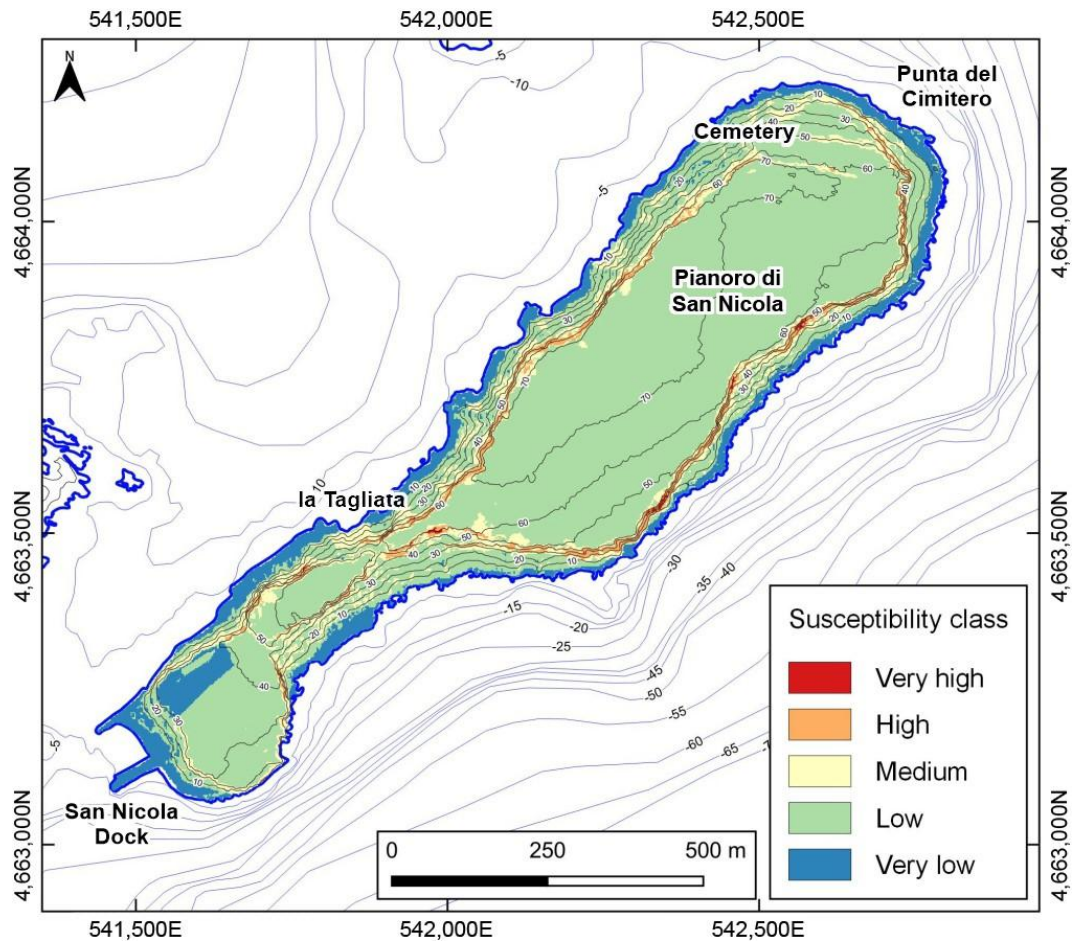


Figure 5.8. Rockfall susceptibility map of San Nicola Island. The blue line indicates the coastline. Coordinate system: WGS84 UTM Zone 33N.

5.5 Discussions

In this work, different geothematic data were collected and analyzed to discover a new zonation of rockfall susceptibility for San Nicola Island, identifying five classes (*Very low*, *Low*, *Medium*, *High*, and *Very high*). The spatial distribution of rockfall susceptibility was carried out in a GIS environment following a stepwise approach, based on either direct (geomorphological field mapping) or indirect (photogeology and GIS data processing) analyses.

The performed investigations also allowed us to derive a comprehensive overview of geological and geomorphological features of the study area, which is severely affected by cliff retreat and gravitational phenomena, as shown by Cotecchia et al., 1996; Lollino and Pagliarulo, 2008; Miccadei et al., 2012a; Piattelli et al., 2023. In detail, by combining multitemporal stereoscopic aerial photo interpretations, geomorphological field surveys, and geomechanical characterization of rock masses, it was possible to discriminate the main critical areas all over the island, in good accordance with historical data available from the

literature for the study area. Some sectors characterized by *Medium-to-High* values of rockfall susceptibility correspond to those where a major retreat of the coastal cliff has occurred historically, such as the area east of la Tagliata. This instability condition could be confirmed by damage to landscape features; here, in recent times, landslide movements have led to the destruction of the road network which connected the human settlement with the northeastern portion of the island, as shown in Figure 5.9a–c (Cocarella B, 1606; Cotecchia et al., 1996; Radicchio, 1993). The same sector, along with most of the southeastern portion of Pianoro di San Nicola, features slope landforms such as trenches, scarps systems, and counter slopes, which testify to ongoing geomorphological processes (Figure 5.5); these are also pointed out by the spatial distribution of rockfall susceptibility, with values ranging from *Medium* to *Very High* along the main slope scarps.

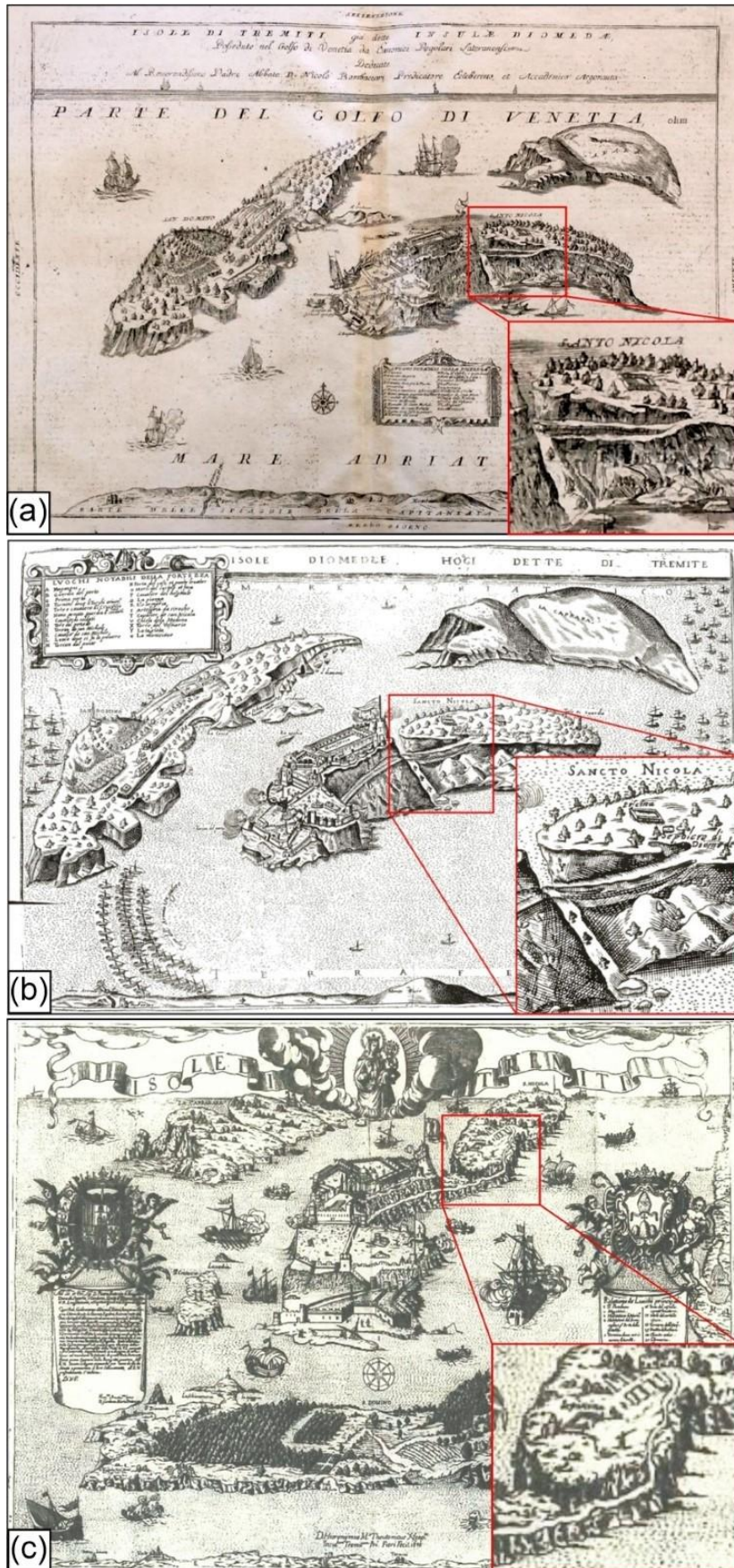


Figure 5.9. Historical maps of Tremiti Islands attributed to: (a) Bonifacio Natale, 1567 (Cotecchia et al., 1996); (b) Cocarella Benedetto, 1606 (Cocarella B, 1606); (c) D. Bonifacius Ticin. S Mortar, 1670 (Radicchio, 1993).

Generally, the island features an active and dynamic landscape marked by significant sudden and localized slope instability processes (mainly rockfalls), as confirmed by geomorphological field surveys (Figure 5.6) and achieved rockfall susceptibility zonation (Figure 5.8). In this context, the analysis performed on Permanent Scatterers (PSs) data revealed an overall stability condition all along the island, without suggesting the presence of areas affected by slow-moving slope deformations. Only a few points, indicative of potential mass movements, were found in areas with a high/very high structural discontinuities density or along island edges in proximity of landslide scarps and anthropic caves. Consequently, these data were not used in the computation of susceptibility values to not overestimate a slopes' tendency to fail, avoiding redundancies and overlapping effects which would be difficult to discriminate. From a geomorphological point of view, the landslide phenomena detected through field surveys present failure mechanisms ranging from lateral spreading, rockfall/topple, to rotational sliding in close connection with the tectonic and litho-structural setting of the area. In fact, marly deposits tend to deform plastically, inducing the growth of shear or tensile fractures within the overlying dolomitic units, which distinctly exhibit brittle behavior as a consequence of the different rheology. Furthermore, they are affected by intense erosion phenomena due to wind or marine spray action, although fallen blocks locally form natural reefs which represent effective barriers against excavation processes acting at the base of slopes. In this context, slope phenomena are due to the detachment and sliding of dolomitic blocks, of meter to decameter size, isolated by intersecting fracture systems. Similar contexts are found in the insular environments of Malta (Colica et al., 2023; Magri et al., 2008; Soldati et al., 2019) and Mallorca (Mateos et al., 2018), where the landscape results from the interplay of tectonics, slope processes, and marine action. This situation is comparable with the geomorphological dynamics of San Nicola Island. It is clearly evident in the southern sector of the Pianoro di San Nicola, east of la Tagliata, where the slope evolution has produced a wide trench, as above described. In terms of susceptibility, the highest values are indeed detected in heavily fractured dolomitic limestone, which is mostly found near island edges where marly layer deformation occurs more easily due to lateral unconfinement.

To better discriminate the triggering mechanisms of some of the detected landslide movements and to derive the role played by the main litho-structural and tectonic features, seismic features of San Nicola Island were taken into account. According to the geological and tectonic context of the area, seismic loading can contribute to the general slope

instability, either by reducing the strength of rock masses by propagation and widening of present fractures, or by triggering rockfall and topple phenomena (Zhang et al., 2022). According to the DBMI15 v4.0 catalog (Locati et al., 2022), indeed, San Nicola Island has suffered shaking produced by several earthquakes, starting from the XVII century, and affecting both the Gargano and Southern Adriatic areas (Figure 5.10).

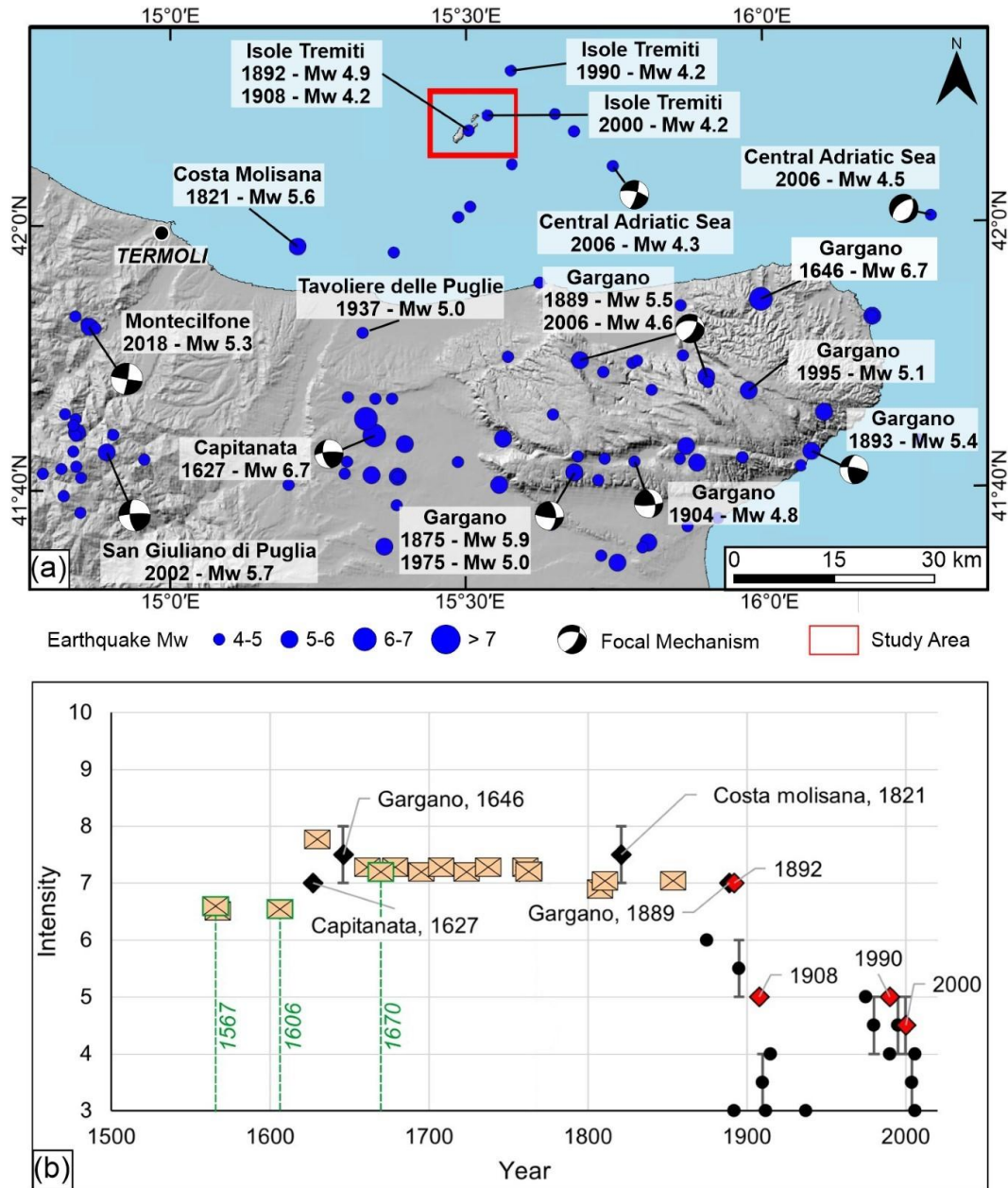


Figure 5.10. (a) Hillshade of the Gargano area with main earthquakes derived from the CPTI15 v4.0 catalog (Rovida et al., 2022)—for seismic events that most affected the study area (red box), focal mechanisms derived from DISS database (DISS Working Group, 2021) are shown when available; (b) seismic intensities inferred for San Nicola Island during earthquakes affecting the Gargano and the Southern Adriatic Sea areas (DBMI15 v4.0; (Locati et al., 2022))—red diamonds indicate earthquakes which enucleated at Tremiti Archipelago. Orange boxes indicate the year of production of historical maps of Tremiti Islands analyzed in this work. Green dashed lines refer to maps shown in Figure 9.

The first of them, the Capitanata event (30 July 1627 $M_w = 6.66$), enucleated in the Gargano area, producing damage assessed as VII–VIII degree on the MCS scale on San Nicola Island and also being responsible for a major tsunami event (Cotecchia et al., 1996). After this, the island underwent even greater seismic intensities due to the Gargano (31 May 1646, $M_w = 6.72$) and the Molise coast (22 November 1821, $M_w = 5.59$) events. More recently, the area suffered shaking produced by earthquakes which occurred in the Gargano promontory (e.g., the Gargano earthquake, 8 December 1889, $M_w = 5.47$) or at the archipelago, where low magnitudes can result into severe ground motion (e.g., the Isole Tremiti earthquake, 6 June 1892, $M_w = 4.88$). Finally, according to the ISIDe database, the area has recently been subject to seismic events occurring in neighboring areas with on-shore and off-shore epicenters (e.g., the Central Adriatic earthquake, 27 March 2021, $M_w = 5.2$). In this context, a comparison between the 2019 AGEA orthophotos of the southern sector of the Pianoro di San Nicola and a high-resolution drone image of the same area acquired in summer 2022 reveals the mobilization of some meter-sized blocks and their transit area from the detachment to the deposition zones (Figure 5.11a, b). As during the same time interval, the area suffered seismic shaking produced by the Central Adriatic earthquake, it is reasonable that this movement was induced by this event; although, an initiation due to heavy meteoric events cannot a priori be excluded. Furthermore, new rockfalls occurred after the earthquake which took place off the Tremiti Islands on 21 June 2023 ($M_w = 4.2$, Figure 5.11c).

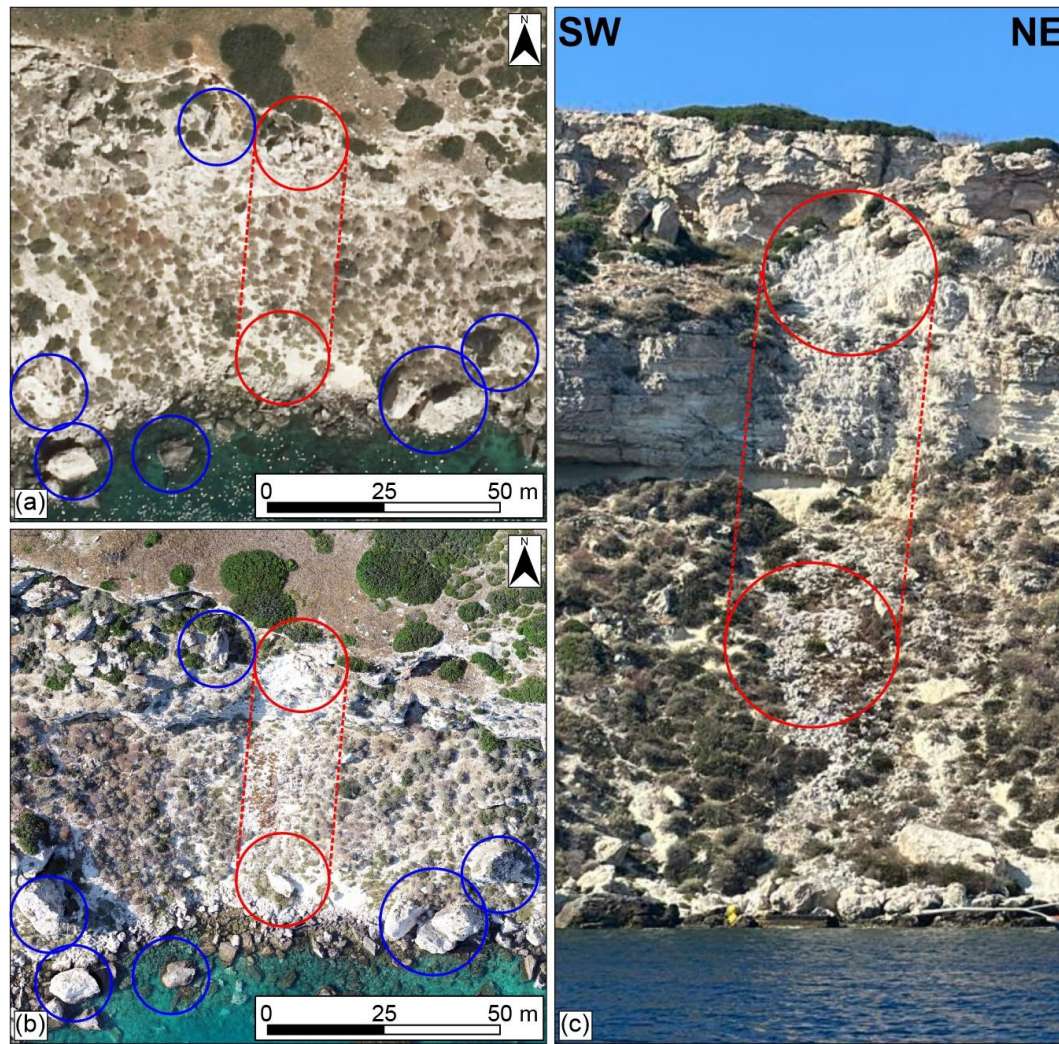


Figure 5.11. Comparison between (a) 2019 Orthophoto image and (b) 2023 high-resolution drone-acquired image of the area east of la Tagliata and (c) rockfall which occurred at the southeastern flank of San Nicola Island after the June 21st, 2023, earthquake. Red circles indicate areas affected by rockfall events occurring in the analyzed period; red dashed lines indicate the transit area. Blue circles indicate previously mobilized and potentially unstable blocks.

In addition, the synthesis of all collected data allowed us to reconstruct the geomorphological evolution of Punta del Cimitero. Starting from the results of field surveys, a schematic and qualitative representation of inferred evolutionary stages is reported in Figure 5.12, corresponding to the SSW–NNE portion of the geomorphological cross-section in Figure 5.5. The area appears to be affected by a slowly evolving complex landslide movement, which is characterized by the presence of at least three sub-parallel rotational sliding surfaces with approximately an E–W direction. At present, the sector not affected by slope deformations shows a sub-horizontal geometry, the slope terrace located at the highest elevation shows exposure partially towards the south, and terraces located at lower elevations show an exposure markedly towards the north. Given the rotational component of the landslide movement affecting the different blocks, it is possible to infer that originally

the outermost sector showed a greater northward dipping compared to the present, while the intermediate sector between the present landslide body and the stable area was sub-planar, perhaps weakly north dipping. These observations agree with those proposed by Cotecchia et al. (1996), according to which the structure of San Nicola Island can be approximated to an anticline, of which the Cemetery area represents a slightly sloping flank.

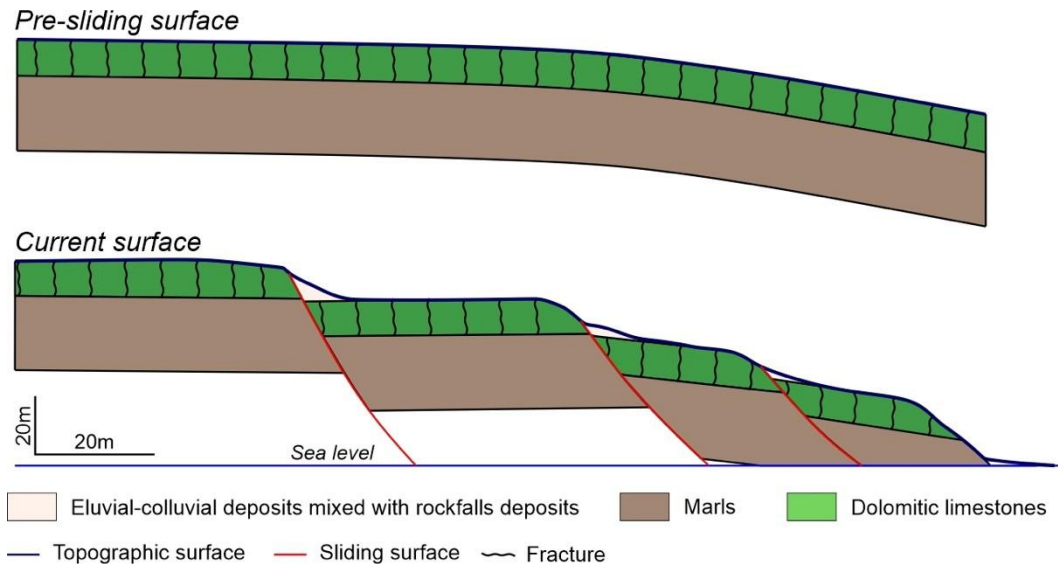


Figure 5.12. Schematic representation of the evolution of the Cemetery area showing the inferred pre-sliding and current topography.

Finally, the combination and overlapping of gathered data (geothematic parameters and spatial distribution of rockfall susceptibility) allowed us to preliminarily highlight the interplay between the litho-structural/geological framework and landslide dynamics of San Nicola Island. It is possible to infer that, sectors with a higher susceptibility are those in which the tectonic control prevails over the litho-structural one, so that the evolution of the landscape is driven by sudden gravitational phenomena such as rockfalls and topples. In this context, the shaking produced by earthquakes that enucleate in the area or in neighboring regions represents a triggering factor but also a strongly predisposing parameter, given the weakening action exerted on rock masses. In areas where the susceptibility is lower, on the other hand, the litho-structural control prevails, and the landscape evolution is markedly slower.

5.6 Conclusions

San Nicola Island features a dynamic landscape, where short- and long-term evolution is strictly connected to geomorphological processes mainly acting on its steep slopes and cliffs. In this work, the detection and classification of areas most prone to collapse was carried out following a multidisciplinary approach. It involved data gathered through

multitemporal stereoscopic aerial photo analyses (1:33,000 to 1:5000 scale), morphometric analyses (from 2 m resolution DTM), and geomorphological field mapping (1:2500 scale).

A rockfall susceptibility map was created combining morphometric and geothematic parameters (i.e., slope, slope aspect, outcropping lithologies, structural discontinuities density, distance from landslide scarps, and presence of anthropic caves) through a heuristic approach. The spatial distribution of rockfall susceptibility in the study area was then defined, identifying five classes marking *Very Low*, *Low*, *Medium*, *High*, and *Very High* rockfall susceptibility. The resulting data were integrated with seismic data and historical maps to highlight variations in natural and anthropic landscape features within the wider geomorphological and seismotectonic contexts.

In San Nicola Island, landscape modifications mainly occur suddenly through rockfalls and topples in response to impulsive triggering events such as strong earthquakes, as documented and testified by the recent seismicity. Moreover, a comparison between data reported in Cotecchia et al. (1996) and those derived through field surveys results in an increase of about 4% in landslide affected areas (from 20.8 to 25.1%), which is likely linked to seismic events which occurred between the late 90s and the present day. Remarkably, major increments are detected in those areas featuring the highest susceptibility values; areas with *Low* to *Medium* rockfall susceptibility, such as the Cemetery one, show no significant variations.

In conclusion, the presented results are meant as an overall representation of areas with different susceptibility levels to rockfalls at specific sites. In particular, it allowed us to produce a new zonation of rockfall susceptibility for San Nicola Island, together with defining and mapping critical areas all over the island. In this context, the outcomes of this research outline the importance of geomorphological field mapping in the rockfall susceptibility assessment of the island, as well as in the evaluation of the overall accuracy of results. In detail, field activities allowed us to produce an updated and detailed geomorphological map which is helpful for depicting the spatial distribution of rockfalls for proper parameter selection and weighting and for deriving insights about the geomorphological evolution.

For San Nicola Island, given the well-known seismicity of the area and accounting for climate change and the potential occurrence of extreme weather events, risk mitigation measures should ultimately be adopted to reduce rockfall-related hazards and risks. Sectors

showing a major propensity to fail should be the subject of consolidation and ongoing monitoring activities; the creation of buffer zones at their base with bathing prohibition would also be advisable for people's safety.

Finally, this work presents a scientific and methodological approach that could be effectively applied in any other small insular areas, showing comparable geological–geomorphological features and landscape values, to support landslide hazard assessments and proper territorial planning.

6 DISCUSSION AND CONCLUSION

This thesis presents a comprehensive multiscale framework for assessing earthquake-induced landslides (EILs) susceptibility across the Italian territory. The proposed approach integrates empirical models at the national scale with detailed geomorphological methods at regional and local scales. This approach contributes to the further understanding of EIL dynamics, but also supports risk reduction strategies and land management policies.

At the **national scale**, empirical models were developed based on historical landslide data (Zei et al., 2024a) to establish power-law relationships between EIL density and key seismic parameters, specifically, epicentral distance and peak ground acceleration (PGA). Models based on epicentral distance show high reliability (with R^2 values exceeding 0.9), confirming that seismic intensity is a predominant driver of landslide distribution; while the relationship between EIL density and PGA demonstrates moderate statistical strength ($R^2 \approx 0.75$). The applied empirical approach has proven to be robust when validated against recent earthquake events in the central Apennines. These findings underscore the potential and limitations of historical databases, emphasizing the necessity to enhance and update landslide inventories for improved national-scale assessments. The analysis also highlighted significant limitations in historical landslide inventories, particularly in terms of completeness, spatial accuracy, and homogeneity, due to a strong bias toward mapped events near road networks and accessible areas, with underrepresentation of remote regions. These gaps can critically affect the reliability of statistical and machine learning models, unless properly calibrated using geomorphological criteria.

At the **regional scale**, the incompleteness and inconsistency of available landslide inventories in the Abruzzo Region compelled to apply a fully geomorphological approach to develop EILs susceptibility maps. This case study demonstrates the effectiveness of combining expert-based heuristic methods with statistical classification techniques applied to morphometric and geothematic parameters. This methodological approach has proven to be reliable in differentiating between areas exhibiting varying degrees of stability, thereby corresponding well with known detachment zones and regional geomorphological features. The analysis demonstrates that even in the absence of comprehensive landslide inventories, a meticulous geomorphological assessment can offer valuable insights into the susceptibility to EILs and support the development of region-specific risk mitigation strategies.

Local scale investigations focused on detailed geomorphological methods to identify critical areas most prone to failure. In the Monte Marine Ridge study, an integrated approach,

combining morphometric, geological, and geomorphological analyses with remote sensing and field observations, proved effective in pinpointing zones where active fault systems and slope-valley interactions drive debris flows. A multidisciplinary geomorphological strategy was also employed on San Nicola Island, incorporating field mapping, stereoscopic aerial photo analysis, and GIS-based morphometric mapping to produce a refined rockfall susceptibility zoning. These local-scale studies highlight the importance of high-resolution geomorphological analysis in capturing the complexities of terrain dynamics, especially in areas where detailed landslide inventories are lacking.

A key strength of this research is its multiscale integration, which integrates national-scale empirical models that provide a broad context with regional and local geomorphological methods that offer the resolution necessary for effective site-specific risk evaluation. The research findings show that:

- **Data Quality Dependency:** The reliability of national-scale assessments is strongly linked to the completeness of historical landslide inventories. In contrast, the geomorphological approach at regional and local scales can mitigate these limitations by focusing on observable morphological, geological, and geomorphological features.
- **Methodological Synergy:** Although the empirical methods provide robust statistical relationships at the national scale, the exclusive use of geomorphological assessments at finer scales has proven invaluable for understanding local dynamics and provides a valuable tool to assist policy makers with risk mitigation measures.
- **Spatial Variability:** The results demonstrate significant spatial heterogeneity in EILs susceptibility. National models capture general trends driven by seismic parameters, while regional and local analyses reveal the critical influence of geomorphological controls in defining site-specific hazards.

Looking ahead, four main directions for further development are identified:

- **Enhanced Database Construction:** This involves enhancing the resolution and completeness of landslide databases through the use of modern remote sensing techniques and systematic field surveys.

- **Expanded Triggering Factors:** Integrating additional parameters, such as rainfall and season impacts, into national assessments to create more comprehensive susceptibility models.
- **Numerical Modeling:** Employing detailed numerical simulations at the local scale to further understand debris flow and rockfall dynamics, thereby refining hazard predictions.
- **Broader Applicability:** Testing the multiscale framework in regions with different geological and geomorphological settings to validate and extend its applicability.

In summary, his thesis has successfully achieved its main objectives by developing a multiscale framework that integrates national empirical models with geomorphological analyses at regional and local levels. This approach not only deepens our understanding of EILs processes but also provides practical tools for effective land management and hazard mitigation. The insights gained from this study lay a strong foundation for future research aimed at enhancing landslide susceptibility assessments and adapting strategies to related risk mitigation.

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