~~Methodological approach to multi-hazard analysis: the case of~~ Development of a Natural Hazard Dataset: a Foundational Step Toward Multi-Hazard Risk Assessment. Application to the Garrotxa region (Catalonia, Spain)

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Abstract. Data-driven methodologies are increasingly being integrated into risk assessment, since they enable the identification of patterns and the treatment of uncertainties in multi-hazard scenarios. Thus, the construction of datasets constitutes the first step of the comprehensive multi-hazard risk assessment and management process. A dataset compiling natural geohazard and weather-related hazard events that occurred in the Garrotxa region (Catalonia, Spain) between 1900 and 2023 was done. Multiple sources were used: official inventories; written records (historical press and scientific literature); and oral information gathered through a citizen science workshop and close collaboration with local experts and regional risk management stakeholders. Data were processed and cross-validated to avoid duplication, resulting in a total of 1,049 events, with wildfires (264) and earthquakes (246) being the most frequent. Although the dataset follows a single-layer multi-hazard approach, it is conceived as a first step toward a multi-hazard risk assessment, for which a proposed methodology is also outlined. The study also identifies key limitations and challenges, including the focus on only six hazard types (earthquakes, landslides, rockfalls, ground subsidences, floods and wildfires), the 123-year time span, and the lack of uncertainty quantification. However, this dataset provides valuable preliminary insights for regional risk management, and the methodology developed for its construction is scalable to other regions. ~~Amidst the escalating impacts of climate change and the growing frequency of natural disasters, the urgent need for robust multi-risk assessment and proactive mitigation strategies has become increasingly apparent. The Garrotxa region, characterized by its diverse array of weather-related hazards (such as torrential rains, floods, debris flows, lahars, tornadoes) and geological hazards (including landslides, rockfalls, earthquakes, and volcanic eruptions), presents an example of the challenges faced by communities globally, necessitating a shift towards anticipatory disaster management. Departing from conventional simulation models, we recognize the fundamental role of past experiences in shaping future risk assessments and mitigation strategies. This paper~~

~~introduces a methodology for the creation of a multi-hazard database tailored to the Garrotxa region, serving as a foundational step towards subsequent multi-risk analysis. By meticulously documenting the region's historical hazards since 1900, our approach aims to equip stakeholders with a nuanced comprehension of multiple natural processes. This comprehensive strategy, which combines modern monitoring techniques with historical context, forms a synergistic approach crucial for effective, long-term disaster risk mitigation. Our work not only sheds light on the unique challenges faced by the Garrotxa region but also provides a scalable model for regions grappling with diverse natural phenomena worldwide. This contribution aims to enhance disaster resilience in regions confronting similar potential multi-hazard scenarios.~~

1 Introduction

The importance of a multi-hazard risk perspective has increased as it becomes evident that hazards rarely occur in isolation (Hewitt and Burton, 1971; Kappes et al., 2012; Gill and Malamud, 2014). Instead, they often interact amplifying their impacts and leading to increased losses (Tilloy et al., 2019; Zscheischler et al., 2020; Ward et al., 2022; Lee et al., 2024). A multi-hazard scenario refers to the occurrence of multiple hazards within a region, including situations where they manifest simultaneously, sequentially, or cumulatively, with potentially interrelated effects (United Nations Office for Disaster Risk Reduction [UNDRR], 2016; Gill et al., 2022). Accordingly, both the temporal and spatial interrelationships must be considered (Gill and Malamud, 2014; Tilloy et al., 2019; de Ruiter et al., 2020).

Multi-hazard risk is inherently dynamic, reflecting the evolving nature of hazards, exposure, vulnerability, and mitigation strategies (UNDRR, 2016). Therefore it can be expressed as a function of these components (Gill et al., 2020a). Driven by rapid urbanization and demographic growth, human settlements have increasingly expanded into high-risk areas ~~The increasing demographic expansion and rapid urban development are driving humanity to build in areas of escalating risk~~ (Pesaresi et al., 2017; Tellman et al., 2021; International Panel on Climate Change [IPCC], 2023). This trend is often exacerbated by a shortage of safe, suitable land and limited awareness or understanding of the specific hazards associated with particular regions ~~, often due to limited availability of safe spaces and a lack of knowledge about the hazards specific to a territory~~ (Cutter et al., 2001; Cutter and~~and~~ Finch, 2008). ~~This trend is further compounded by the effects of c~~Climate change further exarcebates this by ~~, which are not only~~ increasing hazard ~~the~~ magnitude and frequency, ~~of hazards but also creating risks in areas previously not considered at risk, or where a specific hazard had not posed significant risks before. Furthermore, climate change is~~ modifying hazard~~the~~ interactions, and creating risks in previously unaffected areas ~~between hazards, intensifying cascading effects, amplifying risks, and altering natural patterns~~ (IPCC, 2023). Moreover, ~~T~~these changes ~~phenomena~~ are also linked to ~~closely connected with~~ technological and global interconnectedness~~ivity~~, leading to transboundary disasters ~~whose impacts transcend borders~~ (Lee et al., 2012; Plag et al., 2013).

Although international frameworks advocate a multi-hazard approach (UNDRR, 2015), implementation at national, regional, and local scales remains limited. To address this gap, the scientific community are developing methodologies for both multi-hazard and multi-hazard risk assessments, which may improve the management of such situations in the future (Marzocchi et al., 2009; Zschau, 2017; Ciurean et al., 2018; López-Saavedra et al., 2023). The methodologies span from a qualitative (narrative descriptions, hazard wheels) to qualitative/semi-quantitative (hazard matrices, network diagrams, hazard maps, indices) and fully quantitative, data-driven approaches (physical modeling, probabilistic, and statistical methods) (Ciurean et al., 2018). Regardless of the strategy, two fundamental steps are required: 1) Identification of the individual hazards that affect a region, and 2) Characterization of their potential interrelationships. ~~In this context, scientific knowledge about the hazards that affect a region, both temporally and spatially, is crucial. Such knowledge enables the identification of vulnerable elements and the implementation of preventive and mitigative measures to minimize economic and social losses. A multi-hazard perspective is essential for this purpose, addressing the simultaneous or sequential occurrence of multiple natural and anthropogenic hazards and their potential interrelations (López-Saavedra and Martí, 2023). This approach surpasses the traditional single-hazard perspective, which fails to capture the complexity of real-world scenarios, where hazards interact in ways that may amplify, neutralize, or modify each other's impacts (Kappes et al., 2012; Petrini and Palmeri, 2012; Ward et al., 2022).~~

~~The Sendai Framework for Disaster Risk Reduction 2015–2030 has emphasized the importance of incorporating multirisk approaches across science, policy, and practice to better manage and reduce disaster risks (United Nations Office for Disaster Risk Reduction [UNDRR], 2015). Despite its introduction in the 1990s, the implementation of the multirisk perspective has been slow, leaving significant gaps in our understanding of hazard interrelations and their cumulative impacts (López-Saavedra and Martí, 2023).~~

~~Databases play a pivotal role in building this understanding, serving as foundational tools for compiling, centralizing, and standardizing hazard data. These repositories facilitate long-term hazard assessment and enable short-term evaluations during imminent emergencies.~~ Hazard databases are key to these assessments, enabling centralized, standardized data for long-term and emergency use. They can be applied across scales (international to local) depending on the study. Recent efforts have focused, on the one side, on compiling single events and their main characteristics (date, location, environmental and geological variables) for previously identified natural hazards affecting a region to support threshold-based network diagrams (Dunant et al., 2021; Dunant et al., 2025; Van Wyk de Vries et al., 2025). On the other side, on identifying all possible natural hazards and all potential interrelationships that may affect a region, to build regional/local multi-hazard matrices (Gill et al., 2020b; De Angeli et al., 2022; Šakić et al., 2024b; Thompson et al., 2025).

However, the current state of hazard data management is fragmented: data are often collected separately for each hazard type, by different institutions, in varying formats, and with inconsistent levels of accessibility and quality. This fragmentation hinders comprehensive risk analysis and preparation, often leaving authorities and communities unprepared for preventable disasters (Greiving, 2006; Bruneau et al., 2017; Šakić et al., 2024a). Moreover, the construction of such complex datasets imply consultation of multiple sources of evidence. Consequently, the process is time-consuming and not straightforward, particularly when capturing possible interrelationships, as this type of information is often absent from official records and/or is not collected in a uniform way (Šakić et al., 2024b).

The present study aims to contribute to the improvement of multi-hazard risk assessments by enabling future data-driven analyses. Therefore, a dataset of natural hazard events (including earthquakes, wildfires, floods, ground subsidences, landslides, and rockfalls) that occurred in the Garrotxa region (Catalonia, Spain) between 1900 and 2023 was compiled. The choice of the Garrotxa region for this study was motivated by several factors. First of all,

~~In the Garrotxa region of Catalonia, Spain,~~ the lack of an integrated natural hazard ~~multirisk~~ database in this zone is particularly concerning given ~~the region's~~ unique geographic and socio-economic characteristics of the region. The area is characterized by mountainous terrain, rural and urban zones, a significant industrial and agricultural presence, extensive forested areas, and ~~the presence of~~ the Natural Park of the Volcanic Zone of Garrotxa (Consorci de Medi Ambient i Salut Pública [SIGMA], 2024; Generalitat de Catalunya [Gencat], 2025;). These features make the region vulnerable to a variety of hazards, including intense easterly storms (*llevantades*, in Catalan local language) causing floods, generalized droughts, landslides due to steep slopes, and small earthquakes. While volcanic activity is infrequent, the ~~the region's~~ volcanic history at this region cannot be ignored (Bartolini et al, 2015; Martí et al., 2025). Moreover, the area has been the focus of the GarMultiRisk project, which promotes a science-for-policy approach to apply risk reduction strategies and which partially funded this research.

This dataset is intended to serve as a first step toward a multi-hazard risk assessment of the region. It provides relevant preliminary information to regional risk management stakeholders by presenting the first single-layer multi-hazard compilation for the Garrotxa region, where hazard-related data has traditionally been fragmented across different sources. The process followed to compile the current dataset is scalable to other regions globally, taking into account the challenges and limitations encountered during its construction, particularly those related to data availability and integration.

~~Existing data on these hazards in the Garrotxa region often fail to meet key criteria of accessibility, completeness, and standardization. For example, while some datasets are accessible, they may lack historical depth; others are incomplete or lack spatial and temporal precision. Additionally, data are scattered across inventories, historical records, and oral traditions, making it difficult to build a cohesive understanding of the risks of the region.~~

~~This study aims to establish the first multirisk database for the Garrotxa region, addressing these challenges by centralizing existing data and creating a standardized, interoperable repository. The proposed database will integrate intrinsic, extrinsic, and evolutionary variables for each hazard, allowing for comprehensive analyses of their interactions. This database is designed to support data science applications and facilitate long-term hazard assessments and short-term emergency evaluations, thereby enhancing the region's preparedness and resilience in the face of climate change and increasing hazard complexity.~~

~~The benefits of this initiative extend to a wide range of stakeholders, including policymakers, land-use planners, emergency response authorities, private enterprises, insurers, monitoring entities, and the local population. By providing a reliable source of information, the database will empower decision-makers, foster interdisciplinary collaboration, and promote a culture of risk awareness and prevention. Ultimately, it will contribute to the sustainable development of the Garrotxa region while safeguarding its unique ecological, economic, and cultural heritage.~~

2 Case study: the Garrotxa region

2.1 Geographical, geological and socio-economical setting

The Garrotxa region is located in the northeastern part of Catalonia, within the province of Girona, Spain (Fig. 1A~~a~~). It is characterized by a mountainous landscape and significant geological diversity, with the most distinctive feature being the Garrotxa Volcanic Zone Natural Park. This protected area~~ark~~ represents the most well-preserved volcanic landscape in the Iberian Peninsula, comprising over fifty~~orty~~ volcanic cones and extensive lava flows (Planagumà and~~and~~ Martí, 2018).

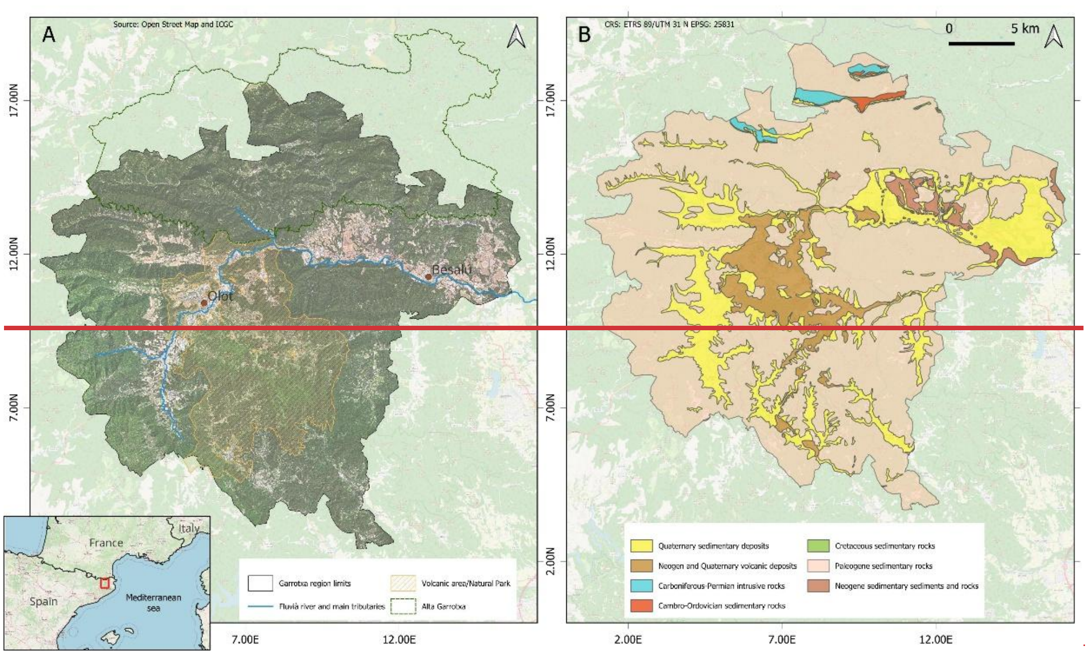
Two ~~The Garrotxa region can be distinguished into two~~ different relief units can be distinguished in the Garrotxa region (Fig. 1A~~a~~, 1B~~b~~) and t~~T~~he limit between the two sectors is marked by the Vallfogona thrust that runs from west to east (Martínez-Rius et al., 1990).~~:~~

~~The north: belongs to~~ T~~t~~he *Alta Garrotxa* ~~, which translates to Upper Garrotxa in English. It~~ is part of the pre-Pyrenees mountain range. It ~~and~~ covers the northern part of Garrotxa and extends beyond it. It is formed by cliffs and karstic relief originating from the east–west Alpine antiforms with Eocene limestones and Garumnian lutites. In the core of the folds, granites and schists outcrop the Paleozoic. In this area, the valleys are very closed and steep, with canyons produced by karstic erosion and mainly dominated by tectonic structures in the form of folds and thrusts in an east–west direction produced by the Alpine orogeny (65 Ma to 35 Ma).

The center~~re~~ and the south of the Garrotxa region are ~~(also known as *Baixa Garrotxa*, which translates to Lower Garrotxa in English): It is~~ part of the Transversal mountain range of Catalonia, here composed ~~. The main lithological~~

~~units are marls and sandstones~~ of ~~the~~ Eocene marls and sandstones. They are ~~,~~ faulted by the ~~tectonic structures of~~ Neogene ~~age~~ (20 Ma to ~~the~~ present) tectonic structures that form part of the European Rift. This area shows a ~~F~~flatter bottom and less abrupt reliefs as a result ~~predominate, a product~~ of the Quaternary volcanism and sedimentation (0.3 Ma to ~~the~~ present) (Martí et al., 2025). The different lava flows and sediments accumulated by the past volcanic eruptions have formed the valleys of Bas, Olot, Santa Pau and Brugent. T~~In this sector, the faults in a NW – SE direction generate a horst with the fault planes generating a steep relief in the Eocene sandstones of the Puigsacalm area or the slopes of La Salut and El Far (Martínez-Rius et al., 1990).~~

~~The limit between the two sectors is marked by the Vallfogona thrust that runs from west to east (Martínez-Rius et al., 1990).~~



~~Figure 1: Study area. a) Location and geographical map of the Garrotxa region. b) Lithological map of the Garrotxa region., under a CC BY 4.0 license.~~

~~T~~he Fluvià River traverses the region from west to east, playing a crucial role in shaping the local environment and hydrological dynamics. The ~~Garrotxa's~~ climate conditions of the Garrotxa region ~~is~~are classified as Mediterranean with montane influences, characterized by cold winters and mild summers. Precipitation levels are relatively high, which, together with the fertile volcanic soils, fosters the development of extensive forests, such as the beech forest of La Fageda d'en Jordà, ~~a beech forest growing on volcanic soil –~~ one of the most ecologically significant ecosystems in the region (Garrotxa Tourism, 2025).

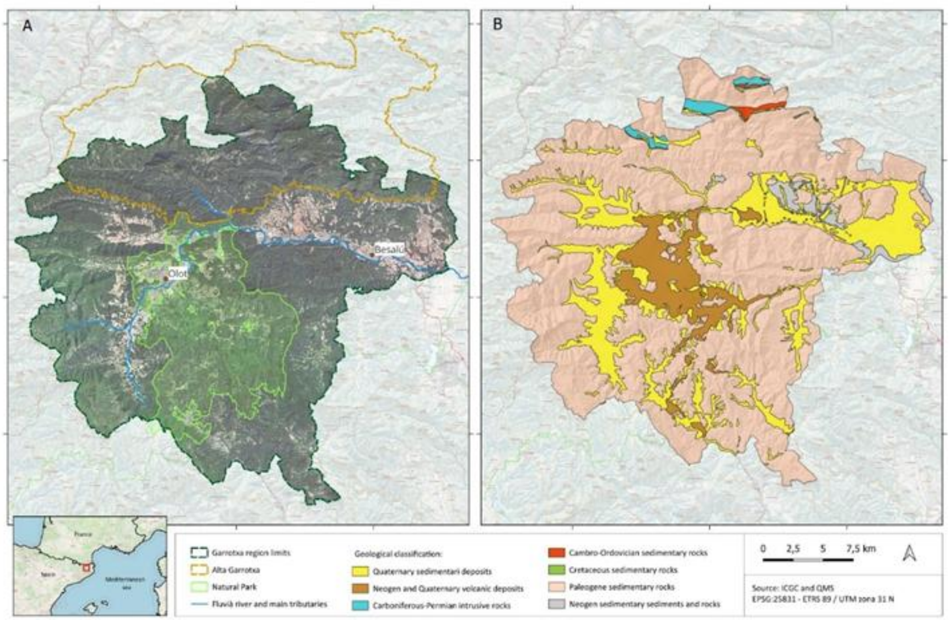


Figure 1: Study area. A) Location and geographical map of the Garrotxa region. B) Lithological map of the Garrotxa region. Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

Beyond its geological and geographical characteristics, the Garrotxa region also possesses distinct socio-economic features that make it particularly suitable for a study like this.

First of all, Garrotxa is the only mountainous administrative region of Catalonia with more than 20.000 inhabitants (GarrotxaDigital, 2022). ~~This makes it a suitable setting for studying the effects of climate change in mountain areas, particularly through the impact of natural hazards primarily related to meteorological phenomena.~~ Additionally, with a total area of 734.5 km², the region is highly accessible, and numerous scientific work has been conducted there, providing valuable knowledge of the zone (Bartolini et al., 2015; Varga et al., 2018; Revelles et al., 2023~~; Varga et al., 2018~~).

~~Another important aspect is the population distribution in the Garrotxa region, where~~ 91 % of the residents of the Garrotxa region live in urban settlements (~~Consorci de Medi Ambient i Salut Pública [~~SIGMA~~]~~, 2023). Olot, the regional capital, is home to 38.836 people (Institut d'Estadística de Catalunya [Idescat], 2025a), accounting for more than half of the~~Garrotxa's~~ total population of Garrotxa. The second most populated municipality, La Vall d'en Bas, has only 3,221 inhabitants (Idescat, 2025b). Therefore, although Olot is a small to mid-sized city, it functions as a metropolitan hub for the region.

The remaining 9 % of the population resides in dispersed settlements (SIGMA, 2023). ~~Recently, a new system was implemented to assign identification numbers to isolated houses, enabling first responders to locate them efficiently during natural hazard emergencies (SIGMA, 2024).~~

This population distribution reflects a broader trend in Catalonia, where only the province of Barcelona accounts for almost 73 % of the total population (~~Generalitat de Catalunya [~~Gencat~~]~~, 2023). Thus, Garrotxa serves as a valuable study area, representing a larger demographic pattern.

Additionally, Garrotxa has a~~'s population is increasing, driven by the region's~~ strong economic activity. Despite being a mountainous area, 42 % of the workforce is employed in industry, making it the second-largest ~~Garrotxa's~~ economic sector of the region (SIGMA, 2023). As a result, the unemployment rate remains below 10 %, slightly lower than the Catalonian average (SIGMA, 2023).

Industrial growth has driven the development of major road infrastructure in the region, creating strong connections to key destinations such as Barcelona, the French border, the high-speed train station in Figueres-Vilafant, and Girona-Costa Brava Airport.

Both industrial and transport infrastructure in ~~the~~ Garrotxa can be treated as vulnerable elements, which have to be included in risk assessment and management studies.~~ Therefore it is important to have them mapped and include them in risk management strategies.~~ Moreover, tourism is another important income for Garrotxa, which is attracted by its great natural beauty. In 2023,

~~The high natural and ecological value of the Garrotxa is also an important characteristic when linked to the touristic economic activity: in 2023,~~ Garrotxa welcomed 192.109 tourists (overnight stays), while 559.515 people visited the Garrotxa Volcanic Zone Natural Park (Turisme Garrotxa, 2023). However, the growing number of visitors has raised concerns about overcrowding in natural areas of the Garrotxa, especially in water ponds during summer and in La Fageda d'En Jordà during autumn.

~~Social movements like Save the Valleys (Salvem les Valls) have played a major role in preserving the landscape. Other notable stakeholders include the Consortium for Environmental and Public Health (SIGMA) and the Regional Council (Consell Comarcal). Both organizations contribute to the annual report Observatory for Sustainability of the Garrotxa, which compiles key information on topics such as population, territory, and economy. They have also collaborated on the 2020-2030 Participatory Strategic Plan, which outlines future actions for Garrotxa's development based on the Sustainable Development Goals and the 2030 Agenda, incorporating feedback from local residents.~~

2.2~~3~~ Natural hazards in the Garrotxa region

The Garrotxa region, characterized by its volcanic geomorphology, mountainous terrain, and Mediterranean climate, is exposed to multiple natural hazards. Although the volcanic activity in the region remains dormant (Martí et al., 2025), other geological~~geophysical~~ and hydrometeorological threats, including seismicity~~ disturbances~~, landslides, flooding, and wildfires, present ongoing risks to both the environment and local communities (Vilaplana et al., 2008; Ajuntament d' Olot, 2022).

Seismic activity, while generally moderate, is influenced by the proximity to the Pyrenean tectonic boundary and the presence of Neogene-Quaternary active normal faults (Institut Cartogràfic i Geològic de Catalunya [ICGC], 2006; Bolós et al., 2015). Despite large-magnitude~~Though~~ earthquakes in the region are relatively infrequent, moderate and low seismicity located along the main Neogene faults that cross the study area are common (Secanell et al., 2004; Ajuntament d'Olot, 2006; Jiménez and García, 2008; Departament d'Interior i Seguretat Pública, 2021). ~~existing fault systems indicate the potential for low-magnitude seismic events.~~ This ~~ese~~ seismicity~~tremors~~, while rarely destructive, highlight the underlying geodynamic instability of the region (Instituto Geográfico Nacional [IGN], 2017; ICGC, 2020).

The steep topography, combined with intense seasonal precipitation and soil saturation, contributes significantly to landslide susceptibility (Palau et al., 2023). The many~~region's~~ slopes, composed of weathered volcanic materials and unconsolidated sediments, are particularly prone to mass-wasting events following prolonged rainfall or seismic activity (ICGC, n.d.; Copons, 2008a). Landslides can disrupt transportation infrastructure, alter river courses, and threaten residential areas in both the highlands and foothill zones. Additionally, rockfall hazard is well-established at Castellfollit de la Roca. This municipality is characterized by a prominent, columnar-jointed basalt cliff standing above less cohesive alluvial and pyroclastic layers, whose differential erosion and fractures contribute to frequent rockfall hazards (Abellán et al., 2011; Bassols and Calm, 2018; Janeras et al., 2023).

Hydrometeorological hazards, particularly flooding, represent another major concern. The Fluvià River and its tributaries frequently experience episodes of rapid water level rise, particularly during extreme precipitation events (Escuer, 2008; Departament d'Interior i Seguretat Pública, 2015; SIGMA, 2017). The combination of steep catchments and variable rainfall patterns promotes flash flooding, which can impact urban areas such as Olot and pose significant threats to agricultural productivity (Agència Catalana de l'Aigua [ACA], n.d.). The increasing incidence of extreme weather events, attributed to ongoing climatic shifts, has further exacerbated flood risks in recent decades (Barriendos et al., 2019; Llasat, 2021; Sharma et al., 2021).

Soil erosion, closely linked to hydrological instability, is particularly pronounced in ~~Garrotxa's~~ the volcanic soils of Garrotxa, which are highly susceptible to weathering and displacement (Palou et al, 2010; Planagumà-Guàrdia et al., 2022). Factors such as deforestation, changes in land-use practices, and overgrazing have intensified soil degradation, especially on inclined terrain, leading to loss of arable land and increased sedimentation in river systems.

~~Although less frequent than other hazards,~~ W~~w~~ildfires remain a persistent risk, particularly in densely forested areas dominated by Mediterranean oak and beech woodlands (Consell Comarcal de la Garrotxa, 2021; Consorci de l'Alta Garrotxa, 2024; Departament d'Interior i Seguretat Pública, 2024). The dry summer season, coupled with increased temperatures and periodic droughts, creates favorable conditions for fire ignition and rapid spread (Pausas and Fernández-Muñoz, 2012; Turco et al., 2019; Duane et al., 2021). The expansion of forested areas due to rural depopulation has further increased fuel availability, heightening wildfire risks (Vila-Subirós et al., 2014).

Ground subsidences are concentrated in the eastern part of the study area, particularly in the municipality of Besalú. This trend has been documented by previous investigations on the evaporite karst system developed within the geological complex of the Fluvià Valley (Copons, 2008b; Gutiérrez et al., 2016).

Regarding volcanic hazard in the Garrotxa volcanic field, the area is considered active, with the most recent period of volcanic activity covering the last 250 ka (Martí et al., 2025). The most recent eruption in this zone has traditionally been dated to the early Holocene (11–13 ka), although recent studies suggest it may have occurred as recently as ~8 ka (Revelles et al., 2023; Martí et al., 2025). Volcanic activity in Garrotxa has ranged from effusive Hawaiian-style eruptions to more explosive Strombolian episodes, with numerous phases of phreatomagmatic activity (Martí et al., 2011). This volcanism is structurally controlled by the main regional normal faults formed during the Neogene extensional phase that affected the area (Bolós et al., 2015). Bartolini et al. (2015) identified five distinct hazard levels in the Garrotxa volcanic field, based on simulations of lava flows, pyroclastic density currents (PDCs), and fallout scenarios.

In recent years, climate change has played a significant role in amplifying the frequency and intensity of extreme weather phenomena in the region, including heatwaves, droughts, strong wind events, and intense rainfall episodes while at the same time contributing to a marked decline in snowfall events (Observatori Pirinenc del Canvi Climàtic [OPCC] and Comunitat de Treball dels Pirineus [CTP], 2018; Cortès et al., 2019; Servei Meteorològic de Catalunya [METEOCAT], 2024). These changes have compounded existing hazards, necessitating a more comprehensive approach to risk assessment and mitigation strategies in the Garrotxa region.

34 Methodology

3.1 Data identification

The first step to~~o~~ construct ~~a comprehensive historical database of natural hazard events~~the dataset was to define a temporal framework (1 January 1900–21 December 2023). It was established based on two primary criteria: 1) A sufficient time span to enable predictive modeling of future hazard occurrences, assuming a 100-year as the minimum period, and 2) the availability of reliable documentary sources.

The second step was to define which types of natural hazards would be included. These were: earthquakes, landslides, rockfalls, ground subsidences, floods, and wildfires. The following criteria was used for the selection: 1) High relevance from a risk assessment and management perspective, given the potential impacts of these natural hazards on the environmental, societal, and economic systems of the region. This prioritization was carried out in close collaboration with environmental technicians from the Garrotxa Environmental and Public Health Consortium (SIGMA), as well as local geoscientists, within the framework of the GarMultiRisk project. 2) Comparable recurrence intervals and compatible with the temporal framework of the study. For this reason, volcanic hazards, although significant from a long-term risk assessment perspective, were excluded from the dataset, as the last eruption in the region occurred approximately 8,000 years ago. 3) Sufficient data availability over the studied period. The preliminary literature review revealed that snow avalanches, snowstorms, tornadoes, and downbursts have been extremely rare in the Garrotxa region, with only isolated events recorded. Due to this lack of data, these phenomena were excluded from the main dataset. 4) Importance from a multi-hazard perspective. To address this, relevant scientific literature was reviewed (Gill et al., 2014; Zscheischler et al., 2020; López-Saavedra, 2023; Lee et al., 2024) in order to identify the main interrelationships patterns that could occur in a region with the characteristics of Garrotxa. Examples may be: earthquake-induced landslides, rainfall-triggered landslides, or landslide-induced flooding caused by the formation of natural dams that lead to overbank flow.

The third step aimed to identify the main variables that influence each natural hazard considered. This was done in order to guide the data collection strategy. The following approaches were performed (see Table 1): 1) Review of natural hazard models to identify the key input variables. When possible, interviews were conducted with the developers of the models. 2) Scientific literature review and additional expert interviews. 3) Knowledge from the previous experience of the authors of this study.

Table 1: Summary of the different information sources (models, interviews and scientific literature) used to develop a theoretical understanding of the main variables driving the initiation and development of the natural hazard events considered in this study.

Natural hazard	**Main models reviewed**	**Interviews conducted with the developers of the models reviewed (yes/no)**	**Additional scientific literature and/or interviews**
Earthquakes	Peak Ground Acceleration QGIS plugin (Núñez-Murillo, 2017)	No	Information provided by geoscientists specialized in seismic events and volcanic unrest of the National Geographical Institute of Spain (López et al., 2012)
Landslides	FSLAM: QGIS plugin for fast regional susceptibility assessment of rainfall-induced landslides (Guo et al., 2022; Medina et al., 2021)	No	
	Smoothed Particle Hydrodynamics (SPH) framework for slow and fast landslides (Pastor et al., 2024a; Pastor et al., 2024b)	Yes	
Rockfalls	RockGIS: GIS-based model for the analysis of fragmentation in rockfalls (Matas et al., 2017)	Yes	Interview conducted with geoscientists from Université Savoie-Mont Blanc specialized in rockfall simulations in mountain regions such as the Alps (Bourrier et al., 2009)
Ground subsidences		No	Information from caldera collapse models, which may reflect some of the processes involved in ground subsidence (Martí et al., 2008)
			Prior experience of the authors
Floods	IBER: numerical tool for flood simulation (Bladé et al., 2014)	Yes	

Wildfires	Cell2Fire: A cell based forest fire growth model (Pais et al., 2019)	Yes	Interview with Catalonian firefighters specialized in sixth-generation fire events (Duane et al., 2021)
			Review of fuel models, fire spread models and fire growth simulators (e.g. Tymstra et al., 2010; Rothermel, 1972; Scott and Burgan, 2005; Papadopoulos and Pavlidou, 2011)

Table S1 summarizes the main variables found in this search. Additionally, these variables can be classified into four types, according to their role and influence on the natural hazard, although a single variable may belong to more than one category: 1) Not influential: they do not have a significant impact on the occurrence or development of a phenomenon. 2) Internal or constitutive: intrinsic characteristics of a system or phenomenon that define its nature, structure, or composition. 3) External or environmental: factors originating from the surrounding environment that influence the behavior, intensity, or effects of a phenomenon. 4) Process development: they determine the evolution, dynamics, or progression of a phenomenon over time.

~~**affecting the Garrotxa region (Catalonia, Spain) since 1900, a systematical compilation of all existing records pertaining to geological and meteorological hazards was done. This process involved reviewing and integrating all available documentation for the following hazard types:**~~

- ~~**Earthquakes**~~
- ~~**Landslides**~~
- ~~**Rockfalls**~~
- ~~**Ground subsidences**~~
- ~~**Floods**~~
- ~~**Wildfires**~~

~~**Although the Garrotxa region has a volcanic history, no eruptions have been recorded within the selected study period. Consequently, volcanic activity was excluded from the database, although it remains a relevant factor for potential future analyses.**~~

~~**Among the identified hazards, earthquakes, landslides, and rockfalls were already known to occur frequently and in a spatially distributed manner. Ground subsidences, particularly in the eastern part of the study area (Besalú region), were also considered due to the presence of collapses and sinkholes. Floods and wildfires were included in the analysis due to their significant socio-environmental impact.**~~

~~**4.1 Selection of the study period**~~

~~**The temporal framework (1900–2023) was established based on two primary criteria:**~~

~~1. **A sufficient time span to enable predictive modeling of future hazard occurrences: according to the frequency of the different hazards considered, a 100-year minimum period was assumed as representative for analyzing hazard processes and their potential interrelationships.**~~

~~2. **The availability of reliable documentary sources: digitized newspapers (the oldest available sources), provided records dating back to the late 19th century. However, data from this initial period were scarce, leading to set 1 January 1900 to 31 December 2023, as the final study range.**~~

3~~4~~.2 Data ~~sources and~~ collection strategy

To structure data collection, three ~~wo~~ main types of sources (inventoried, written and oral) were categorized and reviewed. ~~:~~

~~1. Inventoried sources: Pre-existing databases, official records, and hazard inventories.~~

~~2. Written sources: Scientific publications, historical documents, and press archives.~~

First of all, inventoried datasets from official records were analyzed, as summarized in Table 2. ~~For inventoried sources, data were available for earthquakes, floods, wildfires, and some gravitational processes (landslides and rockfalls). These datasets were obtained from various public institutions:~~

- ~~Earthquakes: Data were requested from the Cartographic and Geological Institute of Catalonia (Institut Cartogràfic i Geològic de Catalunya [ICGC]). The dataset included events with epicenters both within and outside the Garrotxa region.~~
- ~~Landslides and rockfalls: Requested from the ICGC. Although the dataset was limited, it included valuable metadata such as event volume, precise coordinates, and verification status.~~
- ~~Floods: Data were retrieved from Portal Àgora (Llasat et al., 2022), an online platform managed by the Analysis of Adverse Meteorological Situations Group (Grupo de Análisis de situaciones Meteorológicas Adversas [GAMA]) of Barcelona University (Universitat de Barcelona [UB]).~~
- ~~Wildfires: The Catalan Government's Wildfire Prevention Department provided records of forest fires (1995–present) but excluded those affecting croplands or urban areas. Additional wildfire data for Alta Garrotxa (1975–present) were obtained from the same institution. All wildfire events were georeferenced according to their ignition points.~~
- ~~Ground subsidences: Georeferenced data were acquired through direct contact with researchers who had previously studied the phenomenon in the Garrotxa region.~~

~~Regarding wildfire records from Alta Garrotxa, some fires had originated outside the Garrotxa region. To account for these, a buffer analysis was applied:~~

1. ~~Wildfires originating more than 5 km beyond the regional boundary were excluded.~~
2. ~~Wildfires within the 5 km buffer were analyzed individually. Those affecting <10 hectares were disregarded.~~
3. ~~A second buffer (1 km) was applied to further refine the dataset. Wildfires affecting >0.5 hectares within this zone were retained.~~

~~Meteorological records were obtained from the State Meteorological Agency (Agencia Estatal de Meteorología [AEMET]), and the Catalan Meteorological Service (Servei Meteorològic de Catalunya [METEOCAT]) (Fig. 2). These datasets covered temperature trends, rainfall patterns, and wind conditions. Additionally, unofficial rain gauge data from Sant Feliu de Pallerols and Les Planes d'Hostoles were incorporated via oral source contacts of the ESBART group. For hydrological assessments, Fluvià and Llierca River flow records were retrieved from hydrometric stations, and groundwater levels from regional piezometers. These datasets were instrumental in analyzing flood dynamics and their relationship to broader hazard patterns.~~

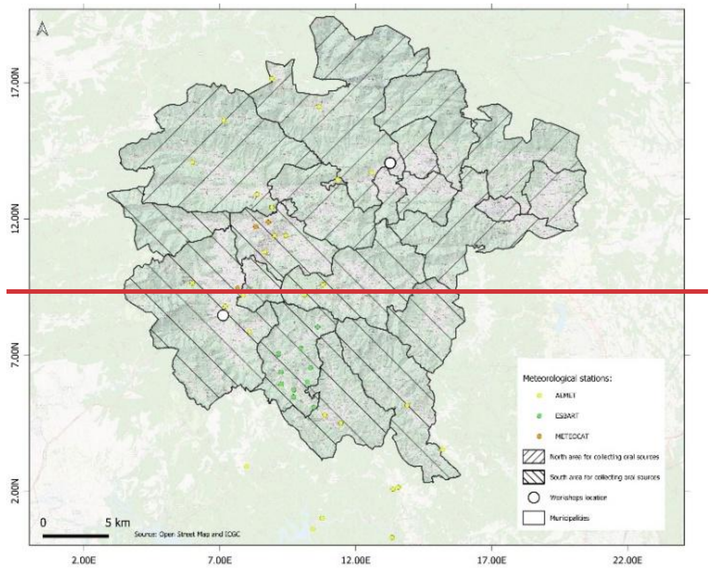


Table 2: Summary of the different inventory sources and methodologies used to collect the natural hazard events occurred in the Garrotxa region (1900-2023). ~~**Figure 2: Map displaying meteorological stations from various sources (AEMET, ESBART, METEOCAT) used for data collection and the locations of workshops conducted for gathering oral sources, one in the northern area and one in the southern area. © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.**~~

Natural hazard	**Inventory source**	**Methods and Actions**
Earthquakes	Cartographic and Geological Institute of Catalonia (ICGC): public institution responsible for geodesy, cartography and the spatial data infrastructure of Catalonia.	Data were obtained through a formal online request: https://www.icgc.cat/ca/LICGC/Contacte/Bustia-de-contacte. Two different datasets were provided: 1) Earthquakes felt in the Garrotxa region, with epicenters both inside and outside the region. 2) Earthquakes with epicenters located within the Garrotxa region.
Landslides and Rockfalls	ICGC	Data were obtained through a formal online request: https://www.icgc.cat/ca/LICGC/Contacte/Bustia-de-contacte. A dataset with 15 records was provided.
Floods	Portal Àgora, managed by: 1) the Analysis of Adverse Meteorological Situations Group (GAMA), a research group of Barcelona University (UB) in charge of studying adverse meteorological situations and their associated natural risks; and 2) the Catalan Water Agency (ACA), a public institution in charge of water resource management and flood risk planning in Catalonia.	Data were retrieved from the online software Portal Àgora (Llasat et al., 2022), which is publicly available and free.
	Garrotxa Environmental and Public Health	Data were obtained through a personal petition. A list was

	Consortium (SIGMA): public institution in charge of the environmental and public health management in the Garrotxa region.	provided based on the flood risk management plan for the Garrotxa region (SIGMA, 2017).
Wildfires	Catalan Government's Wildfire Prevention Service: public institution which forms part of the Catalan Agriculture, Livestock, Fisheries and Food Department, and is in charge of wildfire prevention and risk management in Catalonia.	Data were directly retrieved from the online records (Dades Obertes Catalunya, 2023). Data ranged from 2011 to the present and excluded wildfires affecting croplands or urban areas.
	SIGMA	Data were obtained through a personal petition. Two datasets were provided: 1) *Alta Garrotxa* wildfire records: 1975 to present and 2) Garrotxa wildfire records: 1991 to present
Meteorological data	State Meteorological Agency (Aemet) and Catalan Meteorological Service (Meteocat): both are public institutions responsible for collecting meteorological data and producing weather forecasts in Spain and Catalonia, respectively.	Data were retrieved using their Application Programming Interface (API) (AEMET, n.d.; METEOCAT, n.d.).

For natural hazards lacking information in the previously inventoried sources, a search of written sources such as historical press archives and scientific literature was carried out, as summarized in Table 3.~~For hazards not covered in inventoried sources, historical press archives were the primary data source. The Girona's Municipal Archive and Marià Vayreda Library (Olot) provided digitized newspaper collections. These archives were useful to:~~

~~1. Identify missing records for floods, landslides, rockfalls, and ground subsidences.~~

~~2. Verify and supplement existing inventoried datasets.~~

~~Search strategies varied depending on the archive structure:~~

- ~~In Marià Vayreda Library, local media archives were searched using event-specific terms in Catalan and Spanish.~~
- ~~In Girona's Municipal Archive, where data spanned the entire province, queries combined natural hazard nouns with "Garrotxa". A second search phase cross-referenced natural hazard terms with individual municipality names to ensure comprehensive retrieval.~~

~~All searches were conducted in both Catalan and Spanish to maximize data recovery.~~

~~Beyond press archives, additional information was obtained from scientific publications and specialized books (Maya and Bendinelli, 2005; Nierga et al., 2022; Fabregat et al., 2019; Linares et al., 2017; Gutiérrez et al., 2016; Vilar, 2019). Notably:~~

- ~~Historical flood data were retrieved from *Les Garrotxes* magazine (Nierga et al., 2022).~~
- ~~Sinkhole inventories were accessed through academic collaborations (Fabregat et al., 2019; Linares et al., 2017; Gutiérrez et al., 2016).~~
    - ~~Ground subsidence records for Alta Garrotxa were referenced from the Vilar monograph (Vilar, 2019).~~

Table 3: Summary of the different written sources and methodologies used to collect the natural hazard events occurred in the Garrotxa region (1900-2023).

Written source category	**Natural hazard**	**Written source**	**Methods and Actions**
Press archives, through digitized newspaper collections	Landslides, Rockfalls, Floods, Wildfires, Ground subsidences	Municipal Archive of Girona: preserves historical documents essential for studying the history of Girona province, an administrative division to which Garrotxa belongs.	Press archives were retrieved and are free and publicly available online (Ajuntament de Girona, n.d.; ReGira, n.d.). Search strategies included using natural-hazard specific terms, the term *Garrotxa*, the name of specific municipalities, and using both Catalan and Spanish languages.
		Marià Vayreda Library: main library of the Garrotxa region, located in its capital, Olot.	
Scientific literature	Landslides and Rockfalls	Vilar, 2022; Nierga, 2022	Data were consulted manually. The ground subsidence dataset of Fábregat (2020) was provided through a personal petition.
	Floods	Nierga, 2022	
	Wildfires	Maya & Bendinelli, 2005; Nierga, 2022.	
	Ground subsidences	Fábregat et al., 2019; Linares et al., 2017; Gutiérrez et al., 2016; Fábregat, 2020	

To supplement documentary sources, information was also retrieved from oral sources. ~~t~~Two citizen science workshops were conducted as shown in Table 4. In addition to the citizen science workshops, regular meetings were held with the Regional County Council, SIGMA, and local geologists. The information exchanged was useful for cross-validating some of the collected data. ~~in distinct subregions: Pre-Pyrenees (north) and Transversal Range (south) (Fig. 2). These workshops engaged local communities, rural officers, and amateur meteorologists.~~

Table 4: Summary of the basic information of the citizen science workshops performed.

Details	**Date**	16 and 17 January 2024
	Place	Montagut townhall (municipality in northern Garrotxa) and civic center of La Vall d'en Bas (southern Garrotxa). See Fig. 2A and Fig. 3.
	Participants	Ten. Different backgrounds: community members, rural officers, politicians, geologists, and meteorologists.
Outreach activities and channels used	1) Poster distributed via WhatsApp, official municipal channels, and the social media and website of the Center for Territorial Sustainability (leading entity of the GarMultiRisk project); 2) Interviews in local television; 3) Direct invitations to local individuals with expertise in geology, meteorology and wildfire management.	
Methodology	Participants were encouraged to mark on a printed map the locations where they recalled natural hazard impacts occurring in the Garrotxa region during the period 1900–2023. Notes were also taken on site to collect additional relevant information.	
Type of data collected	1) Map of the Garrotxa region with natural hazard events marked (see Fig. 2B); 2) Personal memories, particularly regarding the 1940 flood and hazard interactions between rainfall, river swelling, blockages, flooding, and ground movements (Oix municipality, 1970s); 3) Recommendations of written sources for additional data retrieval, such as Vilar (2022); 4) An observational record of landslides and rockfalls; 5) Precipitation data for Sant Feliu de Pallerols and Les Planes d'Hostoles (two municipalities in Garrotxa) provided by the local meteorological group named ESBART.	

Figure 2: A) Participants in the workshop held in Montagut on 16 January 2024. B) Printed map of the Garrotxa region used during the citizen science workshops.

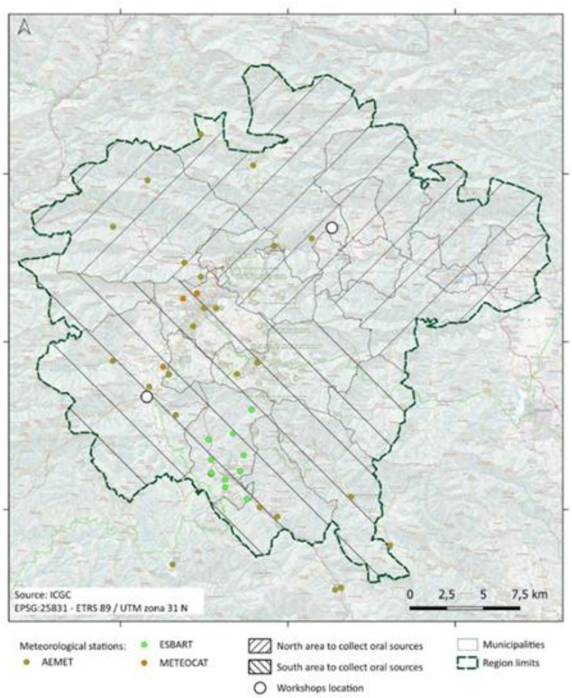


Figure 3: Map showing the meteorological stations from various sources (Aemet, Meteocat, and ESBART) used for data collection, along with the locations of the citizen science workshops held. Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

~~**Promotion strategies included social media campaigns, municipal outreach, and direct invitations to knowledgeable residents. Workshops had an average of 12 participants per session.**~~

~~**These workshops provided unrecorded hazard events missing from historical archives, as well as enhanced accuracy for known events (e.g., exact locations).**~~

3~~4~~.3 Data processing~~structuring and validation~~

This section explains how data from the different sources were incorporated into the final dataset for each natural hazard. To remove duplicate values, a script was run on all collected data.

Regarding earthquakes, both datasets obtained from the ICGC were merged into a single Excel table. The date was standardized into a day/month/year format and geographical coordinates were converted to UTM. Duplicate records were identified and removed when necessary. Finally, the earthquakes were sorted by date and incorporated into the final dataset.

In the case of landslides and rockfalls, two additional fields were created (*Non-precise initial date* and *Non-precise final date*) when lacking exact dates in the written and oral sources consulted. Also, due to lack of data, a volume classification in cubic meters (m^3) was established: Small (0–10), Medium (10–100), Large (100–1,000), and Very large (>1,000). Aerial photographs or descriptions provided in the news articles were consulted in order to infer the information. The field was left blank if not enough reference could be gathered. In some cases, local experts helped identify the exact geographical coordinates of the rockfall or landslide occurrence. Seismic amplification and lithology values were added to each recorded event. The seismic amplification map was developed separately, and each value was then assigned to the corresponding events using QGIS. Landslide and rockfall events triggered by tunnel construction or mining operations were excluded. Landslides occurring on roadside slopes were retained due to their relevance in the Garrotxa region as active hazards.

As for wildfires, the *Alta Garrotxa* dataset provided by SIGMA included wildfire events that had originated outside the study area. A buffer analysis was performed to decide which should be included in the final dataset. The following criteria was used: 1) Wildfires originating more than 5 km beyond the regional boundary were excluded. 2) Wildfires within the 5 km buffer were analyzed individually. Those affecting less than 10 hectares were disregarded. 3) A second buffer (1 km) was applied to further refine the dataset. Wildfires affecting more than 0.5 hectares within this zone were included. For wildfires known to have burned less than 1 hectare but without exact data available, the value *-1* was used in the *Magnitude* variable. Local experts assisted in identifying specific locations of the ignition points when data was missing. When coordinates could not be established, the event was included in the dataset with only the affected municipality specified. Maximum air temperature and maximum recorded wind speed were added to each wildfire record. These values were obtained for the specific day of each event and from the nearest available meteorological station. A script was developed to standardize and harmonize all meterological data as they were provided in different formats by Aemet and Meteocat. Regarding anthropogenic influence on wildfire occurrence in the region, the majority of wildfires are human-induced. Nevertheless, all events affecting forested areas were included, as their environmental impact was considered significant. In the case of the information gathered during the oral citizen science workshop, the recorded events were collected separately in an Excel table, validated using ortophotos and included if not duplicated.

In relation to ground subsidences, the *Non-precise initial date* and *Non-precise final date* fields were also applied when specific event dates were unavailable. These temporal ranges were determined by consulting aerial images of the area. For collapses identified on the earliest available imagery (1945 and 1956), the initial date of occurrence was left blank. Each sinkhole location was individually reviewed by local geologists to ensure that the assigned coordinates were as accurate as possible.

Concerning floods, in the dataset obtained from Llasat et al. (2022), each flood record included all the municipalities affected by that event in a single field. A script was executed to split each flood record into individual entries by municipality. A unique flood identifier (*flood_id field*) was assigned to each event to ensure that these entries were not counted as separate flood events. Finally, the dataset was filtered to retain only records referring to municipalities within Garrotxa. If georeferenced information lacked, insights from the citizen science workshop and close collaboration with regional experts were used to identify probable flood locations within each municipality. A QGIS point layer was created to represent the most probable overflow locations. For each flood event, rainfall on the day of the flood from the nearest meteorological station was added. In cases where heavy rainfall was continuous throughout the month, the variable *Duration* was marked as *Monthly*. All flood events potentially exacerbated by human negligence or land-use changes were fully included in the dataset.

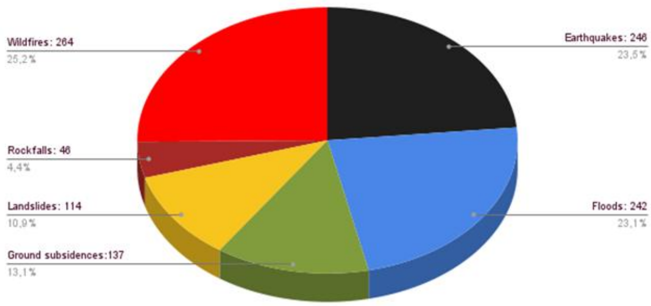
~~To ensure methodological rigor, all possible data were initially included, with subsequent filtering to determine relevance. The database structure followed a standardized template:~~

- ~~Tabs for each hazard type~~
- ~~Key data fields:~~
  - ~~Date of occurrence~~
  - ~~Geographic coordinates~~
  - ~~Affected area~~
  - ~~Event characteristics~~
  - ~~Source of information~~

~~A second validation phase cross-checked data against original sources before integration into the permanent dataset.~~

4~~5~~. Results

The dataset was completed and is publicly available at https://digital.csic.es/handle/10261/394924 (Lagresa et al., 2025). All recorded events were gathered in an Excel table, resulting in seven sheets. The first sheet *Metadata* contains the necessary information to comprehend the variables and codes used in the rest of the tabs. As for the next six tabs, each one refers to a specific natural hazard and they are sorted following this order: *Earthquakes*, *Landslides*, *Floods*, *Rockfalls*, *Wildfires*, and *Ground subsidences*. The final table has a total of 45 categorized variables and 1049 rows (i.e., records of different events). Each row is associated with a specific natural hazard event, giving in total the following distribution (Fig. 4): Earthquakes, 246. Landslides, 114. Floods, 242. Rockfalls, 46. Wildfires, 264. Ground subsidences, 137.



~~Once the database was fully established, a total of 1.050 records of natural hazard events occurring in the Garrotxa region between 1900 and 2023 were obtained (Fig. 3). Among these, wildfires accounted for the largest number of records, with 274 documented events. Earthquakes followed closely, with 254 recorded occurrences, while floods ranked third, with 218 events. Below this threshold, ground collapses and landslides were also well-represented, albeit in slightly lower numbers. Rockfalls, however, were the least frequently recorded hazards in the database.~~

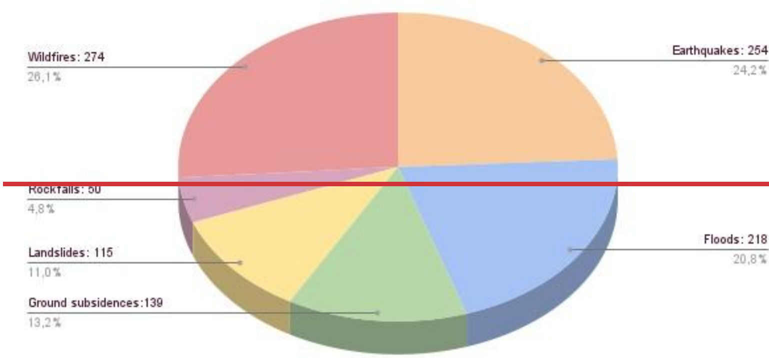


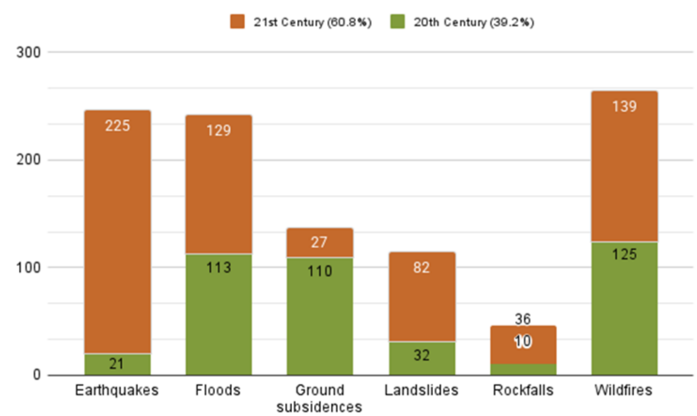
Figure 4~~3~~: Total recorded events in the Garrotxa region (1900–2023), distributed by type of natural hazard (wildfires, rockfalls, landslides, ground subsidences, earthquakes and ~~,~~ floods).

Table S2 provides information on the coordinate reference system used for geolocating the different natural hazard events, as well as the codes, descriptions, units (where applicable) or examples for each variable collected across the various natural hazards.

~~A particular consideration was given to flood events, as their initial classification required specific adjustments. Although the Portal Àgora database originally contained 90 flood records, these were documented with multiple affected municipalities listed within a single entry. This format posed challenges for subsequent data processing, as having multiple locations in the same record complicated the spatial analysis. To address this, the floods were disaggregated, assigning~~

~~separate records for each affected municipality while maintaining a unique identifier for each flood event. This methodological adjustment resulted in more than twice the original number of flood records, though many of these entries corresponded to the same flood event but affecting different locations. This refinement also allowed for a more precise geospatial representation of flood impacts across different municipalities.~~

In Fig. 5 data records by natural hazards are shown according to their temporal distribution (20th or 21st century). ~~Regarding the temporal distribution of records, 63 % of all events corresponded to the 21st century, while the remaining 37 % were documented during the 20th century (Fig. 4).~~ Despite covering only 23 years of the present century, the number of recorded hazard events from this period significantly exceeded those from the preceding 100 years (20th century). ~~This discrepancy is likely attributable to improvements in data collection, increased reporting capacity, and the digitization of historical records in recent decades.~~



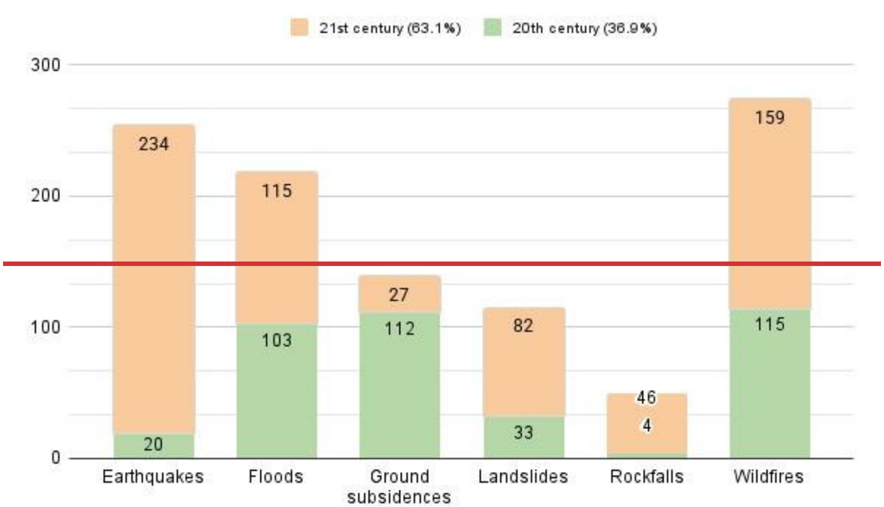
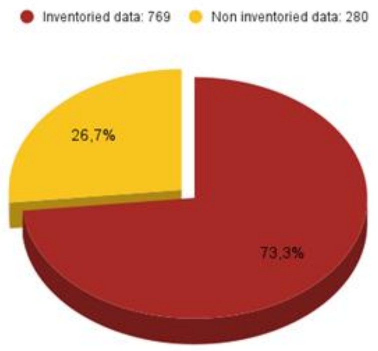


Figure 54: Total recorded events for each natural hazard in the Garrotxa region (1900–2023), distributed by century (20th and 21st).

~~Wildfires (115), ground subsidences (112) and floods (103) have been the most well-documented natural hazards of the 20th century in the Garrotxa region, accounting for 30 % of the total recorded data. In contrast, data on rockfalls (4), landslides (33), and earthquakes (20) in this period (20th century) only represent 5 % of the total collected data.~~

~~As for the 21st century, earthquakes (234), wildfires (159) and floods (115) are the natural hazards from which more events have been collected, followed by landslides (82), rockfalls (46) and ground subsidences (27). Overall, more data have been collected for natural hazards occurring in the 21st century, except for ground subsidences, which decreased from 112 recorded events in the 20th century to 27 in the 21st century.~~

According to the type of source (inventoried or not) hazard events are distributed as shown in Fig. 6. The natural hazard events collected from previously inventoried sources are mainly earthquakes, floods, and ground subsidences.~~Regarding data provenance, 76.9 % of the records have come from pre-existing inventoried datasets, while the remaining 23.1 % were gathered from other sources (Fig. 5). Data on earthquakes, floods, and ground subsidences primarily originated from inventoried datasets, requiring only validation and minor supplementation from additional sources. On the other hand, inventoried data on rockfalls were scarce and non-existent for landslides. As a result, the landslide dataset presented in this study had to be created from scratch.~~



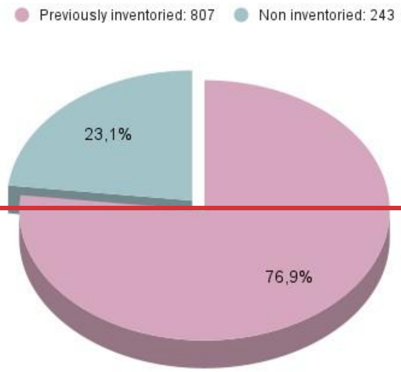
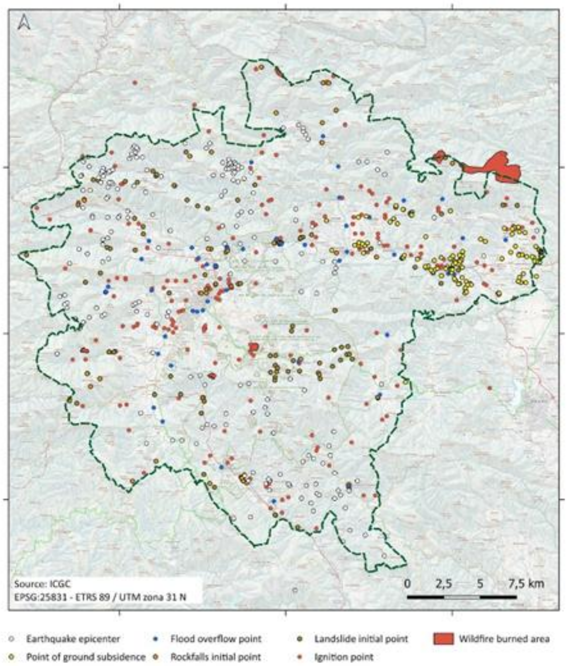


Figure 6~~5~~: Percentage of recorded natural hazard events in the Garrotxa region (1900–2023) by data source (previously inventoried and non-inventoried).

Since almost all events ~~all the data~~ were georeferenced, it was possible to visualize the results on a map using QGIS ~~the Quantum Geographic Information System (QGIS) software~~ (Fig. ~~6~~7). ~~Although events are distributed across the territory, certain areas show a higher concentration of hazards, particularly near human populations. This may be because hazards in easily accessible locations are more likely to be recorded, whereas those in remote areas may go undocumented.~~



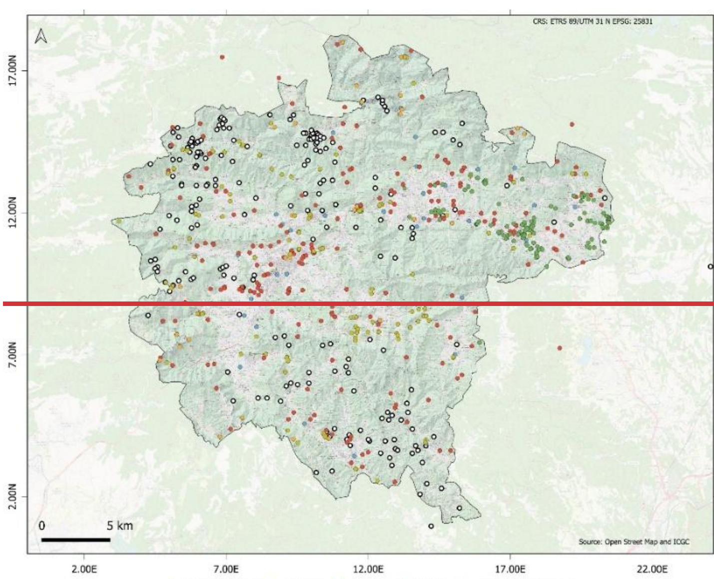


Figure 7~~6~~: Geographical distribution of the total recorded natural hazard events occurred in the Garrotxa (1900–2023). Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license. ~~Geographical distribution of the total recorded natural hazard events occurred in the Garrotxa (1900–2023). © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.~~

5 Discussion

5.1 Multi-hazard risk assessment framework

The dataset developed in this study is intended to serve as a first step toward a comprehensive multi-hazard risk assessment. Hereby we present an outline of how the data collected in this study can serve for this purpose. First of all, susceptibility maps can be obtained using QGIS, in order to identify areas prone to start or propagate each hazard. This information can then be combined with data on hazard recurrence to produce hazard maps for each natural phenomenon. Weighting techniques accounting for interactions between hazards may be applied to generate a final multi-hazard map (Ciurean et al., 2018). Graph theory can be employed to explore spatial and temporal patterns among the identified hazard events and other relevant meteorological conditions (Dunant et al, 2021; Dunant et al., 2025). This would require setting specific thresholds (e.g. spatial distance, event magnitude, and time span) informed by both local knowledge and data analysis. Also, Bayesian event trees or network models may be applied to analyze sequences of hazard events over time (Aquaro et al., 2010; Sobradelo and Martí, 2010; Gehl and D'Ayala, 2016). Moving on to risk assessment, the main exposure elements in the Garrotxa region could be identified and visualized through GIS-based approaches. Subsequently, a vulnerability assessment could be carried out, which would require access to extensive datasets in order to estimate economical potential losses for specific hazard scenarios (Scaini et al., 2014). Finally, a cost-benefit analysis would be of high value for supporting regional stakeholders in their decision-making processes (Sobradelo et al., 2015; Woo, 2015). It must be noted that the non-numerical data gathered in this study can be valuable for defining threshold parameters in graph networks or Bayesian event trees, thereby enhancing the robustness and contextual relevance of future analyses.

5.2 Implications for regional risk management strategies

The results presented in this study offer valuable insights for regional risk management for the Regional County Council and SIGMA as this is the first study of its kind conducted in the region. Until now, as revealed during the data collection process, there was significant disparity in the available data, scattered across various sources. This fragmentation made it difficult to obtain a comprehensive and integrated view of how the Garrotxa region is affected by different natural hazards. The present study addresses this gap by offering a unified and systematic overview of the single-layer multi-hazard context of the region. Moreover, Fig. 7 displays the spatial distribution of all documented natural hazard events included in this study, highlighting areas where these events tend to concentrate.

As mentioned in the Introduction, this study has been conducted under the umbrella of the GarMultiRisk project, which has enabled close collaboration with the Regional County Council and SIGMA. One of the key outputs of the project is the development of a Natural Risk Reduction and Management Plan tailored to the Garrotxa region. Thanks to the work performed in this study, recommendations will be made and included in the plan, structured around four thematic areas: (1) future research directions in the region; (2) enhancement of monitoring techniques; (3) actions to improve natural risk perception among the Garrotxa population; and (4) improvements to interventions across the four phases of the risk management cycle (prevention, preparedness, emergency response, and post-emergency recovery).

A major limitation in terms of risk management applicability is that the dataset presented in this study will no longer be updated once the project concludes. Therefore, it would be highly advisable to synchronize such datasets with existing monitoring stations in the region. Additionally, automated data transformation that enables the continuous and standardized integration of new data should be developed.

5.3 Scalability

We believe that the dataset developed in this study could be adapted to regions with characteristics similar to Garrotxa and also to other geographical contexts. It is important that the relevant hazards are carefully selected and collaboration with local stakeholders is established where possible. Nevertheless, issues such as limited data availability and the disparity in sources and formats can pose greater challenges. Indeed, a significant gap has been identified in how natural hazard data are collected gobally. The lack of standardized formats makes it difficult to compare datasets across regions and conduct consistent multi-hazard analyses. A major advancement would be the establishment, at national or even supranational levels, of standardized data formats for key variables associated with each natural hazard. These should ideally be linked to enhanced monitoring systems capable of collecting the necessary data in an automated and consistent manner. This would greatly improve the efficiency (less time-consuming) and comparability of multi-hazard risk assessment efforts.

5.4 Challenges of the data collection and processing

One of the primary challenges was the scarcity of pre-inventoried data from official records, particularly for geological hazards such as landslides, rockfalls, and ground subsidences. As a result, it was necessary to consult alternative sources, such as historical newspapers and input from local experts. The only natural hazard for which all relevant information could be retrieved from inventoried data were earthquakes, thanks to the seismic monitoring network in the area.

The search for information beyond official inventories was highly time-consuming, yet ultimately successful. It led to the identification of new events and helped improve data reliability. Special care was taken to avoid duplicating events and to ensure the trustworthiness of the data.

Methodological adjustments were required when processing the data provided by inventoried datasets, as different institutions responsible for similar types of data (e.g., meteorological agencies) often used varying formats. These had to be standardized in order to merge the data and include it properly in the corresponding sheets of the Excel table.

Inventoried datasets generally contained more structured and precise parameters, whereas written and oral sources often provided more subjective or incomplete information. As a result, additional effort was required to extract the most accurate data possible for the variables of interest by consulting aerial images or local experts.

Another key decision involved how to address the anthropogenic influence on certain natural hazards. Ultimately, a tailored approach was applied to each hazard type where human activity may have played a role, namely wildfires, floods, rockfalls, and landslides. This points out the importance of considering human–environment interactions and highlights the inherently dynamic nature of risk. To address this, it would be advisable to collect data on historical land-use changes, enabling a more comprehensive analysis of anthropogenic influences on natural hazard dynamics.

Automation of data collection is identified as a crucial need for future projects as a considerable effort was required to manually retrieve and process the data. Automating parts of this process would significantly reduce the time and resources involved. For instance, it may be necessary to train models capable of extracting structured information from digitized newspaper articles or other semi-structured sources.

5.5 Main limitations of this study

First, the scope of this paper is limited to the presentation of the natural hazard dataset, which is intended as a foundational step toward a broader multi-hazard risk assessment. We considered it important to present the dataset, as it already offers valuable guidance for constructing similar datasets and provides useful information for regional hazard analysis and risk management strategies.

Second, the dataset includes events related to only six types of natural hazards. This may limit the scope of future multi-hazard risk assessments, as other hazards are not represented. However, the decision to focus on these six was based on multiple factors: the potential to conduct more quantitative, data-driven analyses; the working capacity of the research group; and the social, economic, and environmental relevance of these hazards as identified by the Regional County Council and SIGMA.

The dataset has been constructed using a single-layer multi-hazard approach. Therefore, no direct interrelationships between hazards have been captured. Nevertheless, evidence of such interactions emerged during citizen science workshops and through close collaboration with local experts and the Regional County Council.

The time span covered, 123 years, also presents limitations. Some significant events, or even entire hazard types, may have been left out, especially those with longer recurrence intervals, such as volcanic hazards. Moreover, for statistical analyses, this time frame may be insufficient to identify meaningful patterns or trends, particularly for rare but high-impact events. This must be taken into account, as it may lead to an incomplete picture of hazard dynamics in the region.

The replicability of this methodology in other regions will depend on data availability and the types of natural hazards present in each context. Therefore, an initial assessment of local conditions and data infrastructure will be essential for adapting the approach elsewhere.

Finally, no quantification of uncertainty or statistical analysis has yet been conducted to assess the quality of the resulting dataset, especially accounting for trustworthiness principles: reliability, validity and provenience/provenance (Koedel et al., 2022).

~~One of the primary challenges encountered in the construction of this database was the scarcity of pre-processed data, particularly concerning geological hazards in the Garrotxa region. Few existing inventories documented such events, necessitating an extensive historical press review, from which 243 records were extracted. However, historical press sources~~

~~are inherently less comprehensive than structured inventories, and most crucially, they lack georeferenced data. While certain hazards were well-represented within available datasets, others required independent investigation using multiple sources. Earthquakes, floods, wildfires, and ground collapses had relatively robust documentation, with earthquakes being the only hazard type that did not require supplementation with additional data. Conversely, hazards such as landslides and rockfalls were significantly underrepresented in pre-existing inventories, necessitating a more labor-intensive data collection process, predominantly relying on historical press archives.~~

~~Another major limitation was the extensive cross-referencing required to ensure data reliability. Multiple historical sources had to be consulted, often containing variant nomenclature for locations and events. This verification process was conducted twice, through the Girona's Municipal Archive and the Olot's Library, which, although time-intensive, significantly enhanced the reliability of the dataset. This dual approach allowed for independent validation of many records, as well as the enrichment of data with additional contextual details. The Girona Archive primarily provided broader provincial-level data, particularly from newspapers such as *El Punt* and *Diari de Girona*. Meanwhile, the Olot Library's archive yielded more localized, detailed records, capturing events that were absent from provincial publications.~~

~~A significant methodological challenge was the geolocation of hazard events. Both inventoried and historical press sources frequently lacked precise spatial information, often only specifying the municipality where an event occurred. In some instances, vague toponyms were provided, but precise geographic coordinates were rarely available. Only in the cases of earthquakes, wildfires, and sinkholes were coordinates consistently found. For other hazards, spatial interpolation was necessary. Landslides and rockfalls could be reasonably approximated with a single point location, though a more detailed impact area-based dataset would have been preferable. However, for hazards such as floods and wildfires, which exhibit wider spatial distributions, the lack of precise geolocation posed a greater limitation.~~

~~To improve spatial accuracy, georeferencing efforts were undertaken in collaboration with geology experts and local specialists familiar with the region. Each gravitational hazard was reviewed individually, ensuring that the assigned coordinates were as accurate as possible. Different approaches were used for wildfires and floods. For wildfires, experts assisted in identifying specific events where possible. However, when neither the source (ignition point) nor the affected area (burned polygon) could be determined, the event was included in the database without coordinates. Floods were addressed through a different strategy: an existing inventory of affected municipalities was refined by consulting regional experts to define probable flood locations within each municipality. Given that the Fluvià River is the principal hydrological feature in the region, specialists identified likely flooding points along its course, allowing a systematic association between each flood event, a specific river segment, and the corresponding municipality. This methodological approach improved spatial resolution, but some degree of uncertainty remains, particularly for widespread hazards such as floods and wildfires. Despite these limitations, ensuring the highest possible spatial accuracy was essential for subsequent geographic analyses using GIS techniques.~~

~~Another challenge was the heterogeneous format of the data, both in terms of meteorological variables and hazard records. Data originated from different administrative sources, each employing distinct formats and reporting structures.~~

~~Meteorological data, for instance, were obtained from both AEMET and METEOCAT, but these agencies provided different variables in incompatible formats. AEMET supplied wind, rainfall, and temperature data spanning the operational periods of each station, whereas METEOCAT included only rainfall and wind data, structured in an entirely different format. Similarly, hazard records from diverse sources exhibited significant inconsistencies in structure and content. The process of data standardization and homogenization was particularly time-consuming, especially given the incomplete nature of some hazard records, where certain variables were missing for specific events.~~

~~An additional methodological challenge was the definition of anthropogenic influence in hazard classification. Unlike earthquakes, which are purely natural phenomena, other hazards often exhibit some degree of human influence. A case-by-case approach was adopted to determine whether an event could be considered a natural hazard or if it should be excluded due to a predominantly anthropogenic origin. In the case of wildfires, a substantial proportion were human-induced, yet all instances affecting forested areas were included, as their impact was considered environmentally significant. Similarly, floods, which may be exacerbated by human negligence or land-use changes, were fully included. However, for landslides and rockfalls, cases where human activity was the primary trigger were excluded. For instance, rockfalls associated with tunnel construction or mining operations were removed, as these were deemed industrial incidents rather than natural hazards. Similarly, events occurring in areas now fully urbanized, where future hazard recurrence is unlikely, were excluded. However, landslides occurring on roadside slopes, despite their potential anthropogenic component, were retained in the database due to their ongoing relevance as active hazards.~~

~~This database provides a critical resource for the analysis of geological multi-hazard interactions in the Garrotxa region. Beyond its academic contributions, it offers valuable insights for disaster risk reduction strategies and mitigation planning. The spatial and temporal trends observed in the dataset highlight the influence of socio-economic and land-use changes on hazard frequency and distribution. Factors such as urban expansion, population growth, deforestation, and shifts in economic sectors (e.g., the decline of traditional agriculture) have likely altered both hazard exposure and vulnerability patterns over time. The increasing prevalence of recorded hazards in the 21st century, despite covering a shorter time span, may also reflect improved hazard reporting and documentation practices, as well as greater awareness of environmental risks.~~

~~Future research should focus on enhancing the completeness and precision of geospatial data, particularly for floods and wildfires, where exact impact areas remain partially uncertain. Additionally, further efforts could be made to integrate meteorological data with hazard records to identify correlations between extreme weather events and hazard occurrences. The database could also be expanded to include historical land-use changes, allowing for a more comprehensive analysis of anthropogenic influences on natural hazard dynamics. In the context of climate change, where the frequency and intensity of extreme weather events are expected to increase, this database serves as a foundation for predictive modeling and risk assessment frameworks aimed at improving regional disaster resilience.~~

~~7 Challenges and future steps~~

~~The creation of the multi-hazard database for the Garrotxa region has enabled the systematic collection and organization of key information on natural events since 1900. However, to maximize its applicability in research and decision-making, further structuring and analysis using more advanced computational tools is necessary.~~

~~The next steps will focus on optimizing the database to enhance its accessibility, interoperability, and analytical capabilities. Efforts will be made to standardize the data, ensuring compatibility with other information sources and facilitating its integration into risk studies. Additionally, advanced spatial analysis and modeling techniques will be explored to identify patterns and trends in hazard occurrence, improving risk assessment and the development of more accurate hazard scenarios.~~

~~In parallel, interactive tools will be implemented to enable intuitive visualization and analysis of the data. The development of platforms based on GIS and simulation environments will facilitate the exploration of risk scenarios and the evaluation of mitigation strategies. Furthermore, the integration of real-time data sources, such as sensor networks and climate data, will be considered to enhance monitoring and response capabilities for extreme events.~~

~~Lastly, particular emphasis will be placed on data quality and reliability by establishing validation mechanisms to ensure that the information used for decision-making is accurate and up-to-date. These efforts will contribute to strengthening the region's resilience to natural hazards, providing evidence-based tools for risk planning and management.~~

6~~8~~ Concluding remarks

A single-layer multi-hazard compilation of natural hazard events, specifically earthquakes, landslides, wildfires, rockfalls, floods, and ground subsidences, was conducted for the Garrotxa region (Catalonia, Spain) covering the period from 1900 to 2023. Various sources of information were consulted, including inventoried datasets, written records (historical press and scientific literature), and oral testimonies (citizen science workshops, local experts and risk management stakeholders). Careful attention was paid to the integration and validation of all the data within the final dataset.

As a result, a total of 1,049 events were documented, being distributed as follows: wildfires (264), earthquakes (246), floods (242), ground subsidences (137), landslides (114), and rockfalls (46). 60.8 % of the events occurred in the 21st century, while 39.2 % belong to the 20th century. 73.3 % of the events were retrieved from previously inventoried datasets. The results presented already offer valuable preliminary insights for regional risk management, particularly in the field of territorial planning. Moreover, the dataset is conceived as a first step toward a broader multi-hazard risk assessment and a proposed methodology has been outlined in this study. The proposed dataset construction is scalable to other regions of the world, although success will largely depend on data availability and collaboration with local stakeholders.

Several challenges were encountered and should be considered in future applications. The most significant were related to data availability and the disparity of data formats across sources. These factors made the process time-consuming, requiring the consultation and cross-referencing of multiple types of sources to ensure reliability and avoid duplication. In this regard, the study highlights important gaps in data standardization and automation at both regional and broader levels.

Addressing these gaps would significantly improve the efficiency of future multi-hazard risk assessments, particularly in the data collection phase, which proves to be one of the most labor-intensive.

The limitations of the study are also acknowledged. Only six hazard types were considered, potentially limiting the scope of future assessments. The 123-year time span, while extensive, may exclude low-frequency, high-impact events such as volcanic eruptions, which are relevant in the region. Additionally, no uncertainty quantification was conducted to assess the reliability or confidence levels of the final dataset.

In summary, the completion of this dataset is seen as a powerful tool which aims to: 1) Support regional risk management stakeholders with a first visual overview of single-layer multi-hazard exposure in the Garrotxa region, 2) Provide a methodological framework for constructing similar datasets in other parts of the world, adapted to local characteristics and data contexts, and 3) Enable the application of data-driven multi-hazard risk assessments, contributing to the scientific community working in this field.

~~The development of a multi-hazard database for the Garrotxa region has provided crucial insights into the natural risks of the region over the past century, addressing the challenges of limited pre-existing inventories and the lack of georeferenced data. By integrating historical press records, institutional data, and expert input, this study has produced a robust dataset suitable for future research and risk assessment.~~

~~Wildfires, earthquakes, and floods emerged as the most frequently recorded hazards, though variations in reporting practices and data availability suggest that historical trends must be interpreted in the context of evolving monitoring capabilities and societal awareness. The marked increase in recorded events in the 21st century reflects improved documentation rather than necessarily an absolute rise in hazard frequency.~~

~~Georeferencing posed a significant challenge, particularly for hazards with widespread impact such as floods and wildfires. While expert consultation improved spatial accuracy, uncertainties remain in cases where precise coordinates were unavailable. Ensuring the highest possible spatial precision was essential, as the database is designed for GIS-based risk assessments.~~

~~This study also highlights the influence of anthropogenic factors on hazard occurrence and impact. While earthquakes are purely natural, hazards such as landslides, wildfires, and floods are often shaped by human activities. The exclusion of events with predominantly anthropogenic origins, such as construction-related rockfalls, ensures the database remains focused on natural risks while still considering human-environment interactions. Land-use changes, urban expansion, and demographic growth have contributed to shifting hazard vulnerabilities, reinforcing the need for integrated risk management strategies.~~

~~The database serves as a valuable tool for disaster risk reduction, informing mitigation measures, early warning systems, and resilience planning. It also offers potential applications in climate change research, hazard modeling, and policy-making. Future work should refine geospatial accuracy, integrate meteorological and land-use data, and analyze long-term trends to enhance understanding of regional risk dynamics.~~

~~By combining historical documentation, geospatial analysis, and expert validation, this study provides a comprehensive foundation for assessing multi-hazard risks in the Garrotxa region. Despite challenges in data standardization, the database represents a significant step forward in risk management and scientific research, supporting ongoing efforts to mitigate natural hazards and enhance regional resilience.~~

Data availability

The historical record of natural hazard events occurred in the Garrotxa region (Catalonia, Spain) from 1900 until 2023 is publicly available at: https://digital.csic.es/handle/10261/394924 (Lagresa et al., 2025). ~~Data will be made available on request.~~

Author contribution

AL: Formal analysis, Investigation, Methodology, Visualization, Writing–original draft, Writing–review&editing. **MLS:** Conceptualization, Investigation, Methodology, Supervision, Writing–original draft, Writing–review&editing. **MJL:** Funding acquisition, Project administration, Supervision. **JM:** Conceptualization, Resources, Supervision, Writing–review&editing. **MMS:** Data curation, Formal analysis, Investigation, Methodology, Software, Writing–original draft. **AO:** Resources, Supervision. **LP:** Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Writing–original draft. **ISP:** Project administration, Writing–original draft, Writing–review&editing.

Competing interests

The authors declare that they have no conflict of interest.

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