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.

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 (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 (Cutter et al., 2001; Cutter and Finch, 2008). Climate change further exarcebates this by increasing hazard magnitude and frequency, modifying hazard interactions, and creating risks in previously unaffected areas (IPCC, 2023). Moreover, these changes are also linked to technological and global interconnectedness, leading to transboundary disasters (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.

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, the lack of an integrated natural hazard database in this zone is particularly concerning given 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 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 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.

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). 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 represents the most well-preserved volcanic landscape in the Iberian Peninsula, comprising over fifty volcanic cones and extensive lava flows (Planagumà and Martí, 2018). Two different relief units can be distinguished in the Garrotxa region (Fig. 1A, 1B) and the limit between the two sectors is marked by the Vallfogona thrust that runs from west to east (Martínez-Rius et al., 1990). The *Alta Garrotxa* is part of the pre-Pyrenees mountain range. It 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 and the south of the Garrotxa region are part of the Transversal mountain range of Catalonia, here composed of Eocene marls and sandstones. They are faulted by the Neogene

(20 Ma to present) tectonic structures that form part of the European Rift. This area shows a flatter bottom and less abrupt reliefs as a result of the Quaternary volcanism and sedimentation (0.3 Ma to 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. The Fluvià River traverses the region from west to east, playing a crucial role in shaping the local environment and hydrological dynamics. The climate conditions of the Garrotxa region 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, one of the most ecologically significant ecosystems in the region (Garrotxa Tourism, 2025).

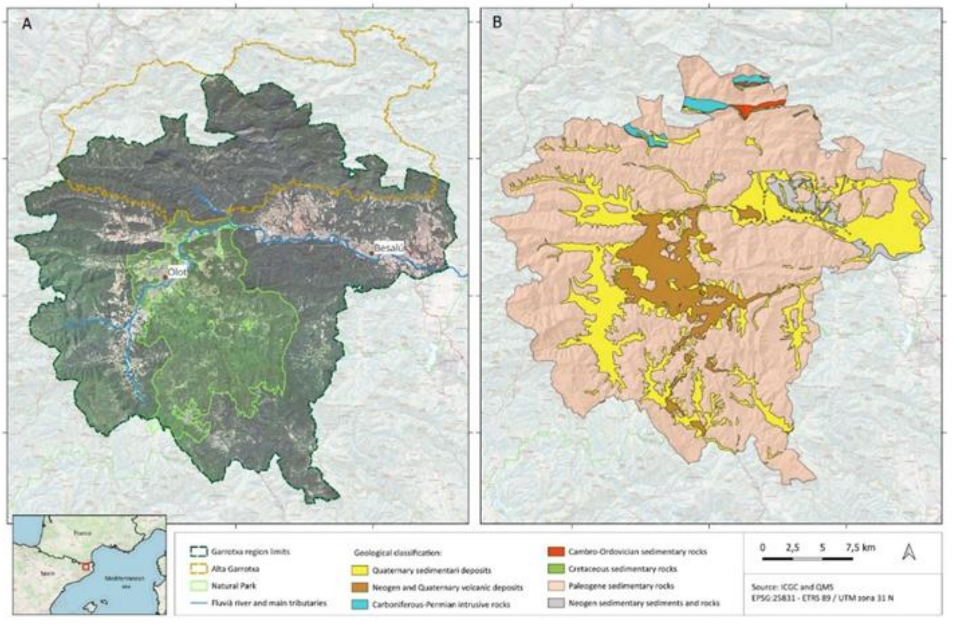

Figure 1: Study area. A) Location and geographical map of the Garrotxa region. B) Lithological map of the Garrotxa region. Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

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). 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). 91 % of the residents of the Garrotxa region live in urban settlements (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 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). This population distribution reflects a broader trend in Catalonia, where only the province of Barcelona accounts for almost 73 % of the total population (Gencat, 2023). Thus, Garrotxa serves as a valuable study area, representing a larger demographic pattern. Additionally, Garrotxa has a strong economic activity. Despite being a mountainous area, 42 % of the workforce is employed in industry, making it the second-largest 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 Garrotxa can be treated as vulnerable elements, which have to be included in risk assessment and management studies. Moreover, tourism is another important income for Garrotxa, which is attracted by its great natural beauty. 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.

2.2 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 and hydrometeorological threats, including seismicity, 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 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). This seismicity, 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 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 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.

Wildfires 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.

3 Methodology

3.1 Data identification

The first step to construct 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.

3.2 Data collection strategy

To structure data collection, three main types of sources (inventoried, written and oral) were categorized and reviewed. First of all, inventoried datasets from official records were analyzed, as summarized in Table 2.

Table 2: Summary of the different inventory sources and methodologies used to collect the natural hazard events occurred in the Garrotxa region (1900-2023).

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 Consortium (SIGMA): public institution in charge of the environmental and public health management in the Garrotxa region.	Data were obtained through a personal petition. A list was 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.

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. 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.

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.

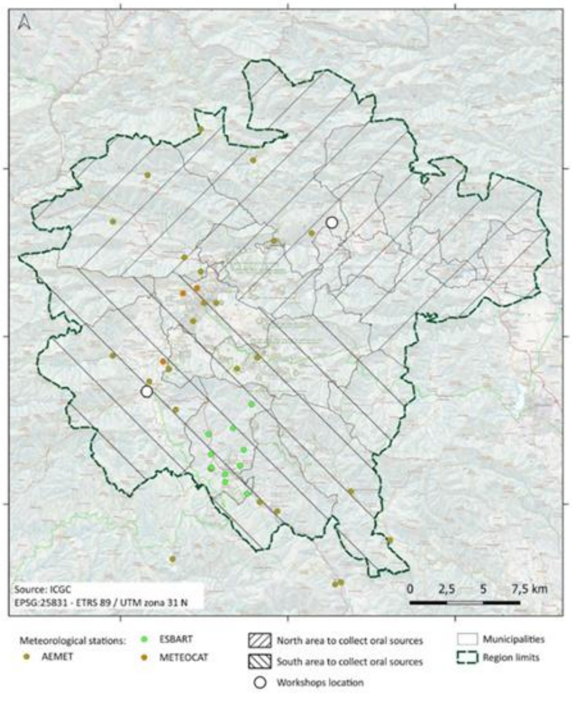

Figure 3: Map showing the meteorological stations from various sources (Aemet, Meteocat, and ESBART) used for data collection, along with the locations of the citizen science workshops held. Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

3.3 Data processing

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.

4 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.

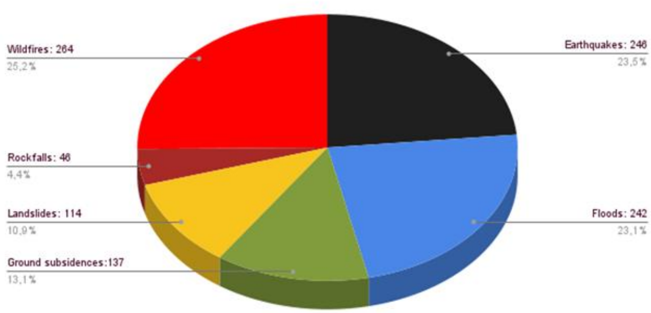

Figure 4: Total recorded events in the Garrotxa region (1900–2023), distributed by type of natural hazard (wildfires, rockfalls, landslides, ground subsidences, earthquakes and floods).

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. In Fig. 5 data records by natural hazards are shown according to their temporal distribution (20th or 21st century). 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).

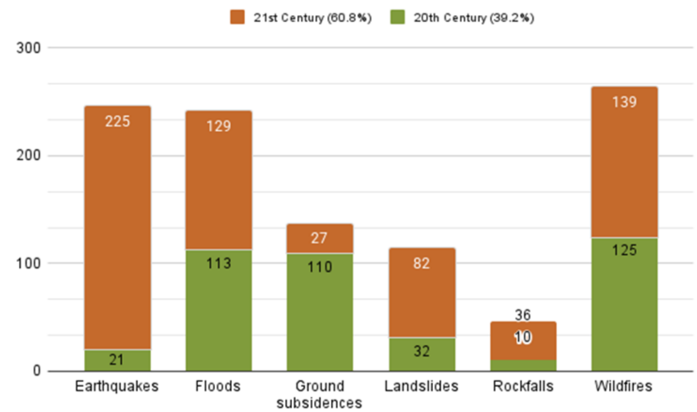

Figure 5: Total recorded events for each natural hazard in the Garrotxa region (1900–2023), distributed by century (20th and 21st).

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.

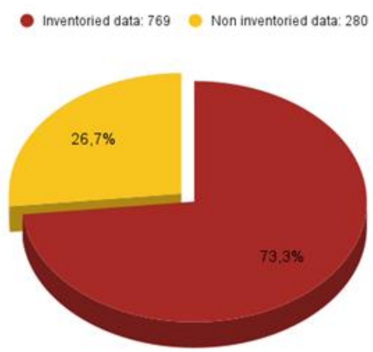

Figure 6: Percentage of recorded natural hazard events in the Garrotxa region (1900–2023) by data source (previously inventoried and non-inventoried).

Since almost all events were georeferenced, it was possible to visualize the results on a map using QGIS (Fig. 7).

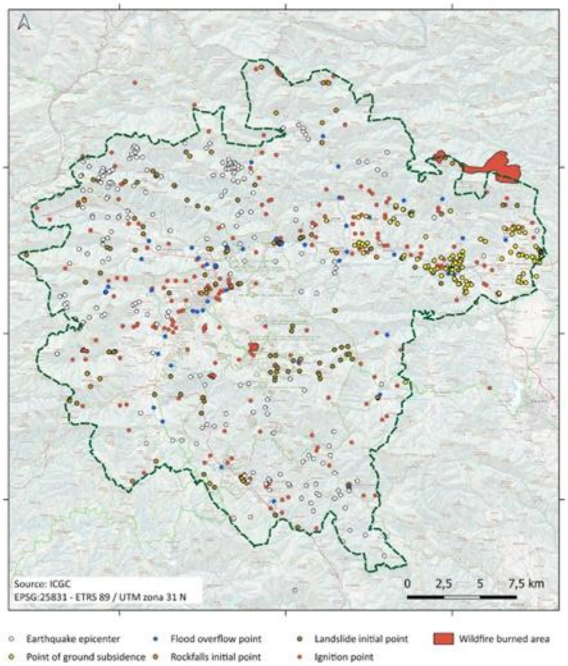

Figure 7: Geographical distribution of the total recorded natural hazard events occurred in the Garrotxa (1900–2023). Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

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).

6 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.

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).

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.

Financial support

This work is part of the GarMultiRisk project [grant number 670489], funded by the Biodiversity Foundation of Spanish Ministry for the Ecological Transition and the Demographic Challenge, through the Grants call in competition regime for the execution of projects that contribute to implementing the National Plan for Adaptation to Climate Change (2021–2030).

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