Natural Hazard Event Dataset for the Garrotxa Region (Catalonia, Spain): A Foundational Step Toward Multi-Hazard Risk Assessment

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Abstract. Data-driven approaches are increasingly essential for understanding complex, interacting natural hazards. We present a natural hazard event dataset compiling all documented occurrences of earthquakes, landslides, rockfalls, floods, wildfires, and ground subsidences in the Garrotxa region (Catalonia, Spain) between 1900 and 2023. The dataset integrates inventoried, written, and oral sources, including official inventories, historical press, scientific literature, and citizen-science contributions, cross-validated to remove duplication and inconsistencies. A total of 1049 events were compiled. A synthetic exploratory analysis illustrates the potential of the dataset for multi-hazard interaction and hazard–meteorological association studies. Comparison with national and international repositories (e.g., EM-DAT, SHELDUS, Risk Data Hub) shows that this dataset provides higher spatial resolution and includes locally validated records absent elsewhere. The work establishes both a data resource and a methodological framework for future susceptibility and multi-hazard risk analyses applicable to other regions.

1 Introduction

Understanding natural-hazard risk requires consistent knowledge of where and when past hazard events have occurred. While risk represents the potential for losses arising from the interaction of hazards, exposure, and vulnerability, hazard events are the observable manifestations, such as earthquakes, floods, wildfires, etc, that underpin quantitative and qualitative risk analyses. Global frameworks such as the United Nations Office for Disaster Risk Reduction (UNDRR) Sendai Framework (2015) emphasize multi-hazard perspectives, yet implementation at local scales remains limited by the scarcity of harmonized event data (e.g., Hewitt and Burton, 1971; Kappes et al., 2012; Gill and Malamud, 2014; United Nations Office for Disaster Risk Reduction [UNDRR], 2016; Tilloy et al., 2019; de Ruiter et al., 2020; Gill et al., 2022).

In regions like Garrotxa (Catalonia, Spain), environmental, geological, and climatic diversity leads to the occurrence of multiple hazards that may interact temporally or spatially. However, the available information is typically fragmented among institutions, stored in incompatible formats, and rarely cross-validated. This fragmentation hinders both single-hazard and multi-hazard risk assessments.

The present study aims to contribute to the improvement of multi-hazard risk assessments by enabling future data-driven analyses. For this, it addresses three main questions: 1) What is the historical record of natural-hazard events that have affected the Garrotxa region between 1900 and 2023? 2) How do these events relate spatially and temporally, indicating potential interactions (e.g., rainfall-induced landslides or earthquake-triggered rockfalls)? 3) How does the resulting dataset compare with existing national and international repositories, and what added value does it offer for future multi-hazard risk assessment? By answering these questions, the work provides a bridge between data compilation and applied risk-analysis frameworks.

This paper introduces a hazard event dataset, instead of a probabilistic hazard model. A hazard map quantifies the probability of an event of given magnitude within a specific period (e.g., Calder et al., 2015; Lindell, 2020; MacPherson-Krutsky et al., 2020), whereas a hazard event dataset records the actual, observed occurrences over time (e.g., St. Denis et al., 2023; Bisquert et al., 2025). Both are complementary: the latter supplies empirical evidence necessary to calibrate, validate, and contextualize the former.

Existing open datasets such as EM-DAT (Centre for Research on the Epidemiology of Disasters [CRED], n.d.), SHELDUS (Center for Emergency Management and Homeland Security [CEMHS], n.d.), or Risk Data Hub (Disaster Risk Management Knowledge Centre [DRMKC], n.d.) operate at national or continental scales but often lack spatial precision or local validation. At the regional scale of the Garrotxa region, no integrated, multi-hazard event repository previously existed. The dataset presented here therefore fills a critical resolution gap, enabling finer-scale analyses of hazard frequency, clustering, and potential interrelationships. In this sense, the present study contributes methodologically by integrating heterogeneous data sources (official, historical, and citizen-science), defining a reproducible workflow for data validation, and outlining how such data can inform susceptibility and multi-hazard risk modeling.

The following sections describe the study area, data-identification and processing methods, the resulting dataset structure, and a preliminary exploration of hazard interrelationships in the Garrotxa region.

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 (Martí et al., 2016). 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) (Fig. 1).

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 early Holocene) (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).

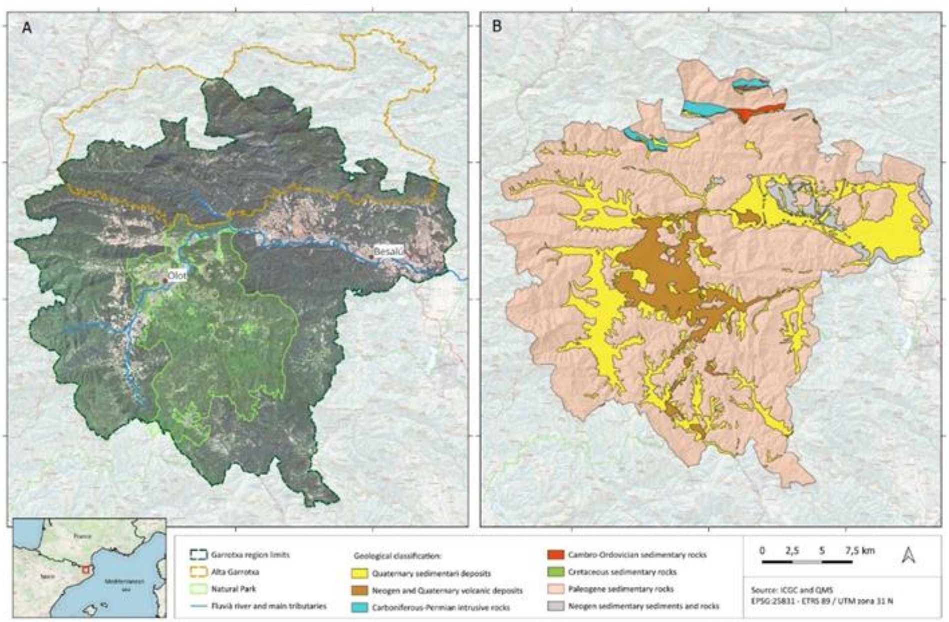

Figure 1: Study area. A) Location and geographical map of the Garrotxa region. B) Lithological map of the Garrotxa region. Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

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 (e.g., Bartolini et al., 2015; Varga et al., 2018; Revelles et al., 2023). 91 % of the residents of the Garrotxa region live in urban settlements (Garrotxa Environment and Public Health Consortium [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 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 dataset spans 1 January 1900–31 December 2023, chosen to ensure a century-scale temporal window suitable for trend and recurrence analysis while maintaining reliable documentation. Six hazard types were included: earthquakes, landslides, rockfalls, floods, wildfires, and ground subsidences. Selection was guided by (1) their risk relevance in Garrotxa, (2) data availability within the study period, and (3) their potential interactions in a multi-hazard framework (e.g., Gill et al., 2014; Zscheischler et al., 2020; López-Saavedra and Martí, 2023; Lee et al., 2024). Volcanic activity, though geologically important, was excluded because its most recent eruption (~8 ka BP, Revelles et al., 2023) falls outside the historical timeframe. Rather than deriving descriptive variables solely from historical records, we first reviewed existing hazard models (e.g., IBER for floods [Bladé et al., 2014], RockGIS for rockfalls [Matas et al., 2017], Cell2Fire for wildfires [Pais et al., 2019], FSLAM for landslides [Medina et al., 2021; Guo et al., 2022], Peak Ground Acceleration QGIS plugin [Núñez-Murillo, 2017]).

This model-first approach ensured that our variables list would be compatible with future numerical modeling, allowing seamless integration of our event data into susceptibility or hazard simulations. During data collection we observed discrepancies between model-defined variables and historical documentation: for example, early-century press articles rarely reported quantitative rainfall totals or precise coordinates, so surrogate variables (e.g., “affected_municipality”, “np_ini_date”, “np_fin_date”) were introduced.

3.2 Variable classification

Each variable was assigned to one of four analytical categories (Table 1) to structure subsequent statistical or network analyses. This typology links observational data to process understanding and helps prioritize which parameters can inform susceptibility or inter-hazard modeling.

Table 1. Illustrative classification of analytical categories applied to dataset variables.

Categories	Definition / Role	Example variables from the dataset	Utility for analysis
Internal (constitutive)	Intrinsic physical or geological properties influencing event generation	Lithology class, slope angle, soil type	Used in susceptibility modelling (e.g., landslide potential)
External (environmental)	External conditions triggering or modulating events	Daily rainfall, maximum wind speed, temperature anomaly	Supports correlation or co-occurrence analysis (e.g., rainfall-triggered failures)
Process-development	Variables describing temporal or dynamic evolution	Duration of rainfall episode, propagation direction of fire	Inputs for dynamic modelling or hazard-cascade simulations
Non-influential (meta)	Descriptive or administrative attributes	Data source, event ID, reporter type	Used for traceability, quality assessment, bias evaluation

This classification provides a conceptual bridge between raw observations and modeling frameworks, clarifying which variables act as drivers versus descriptors.

3.3 Data collection

Data were collected from three complementary source categories (Tables 2 to 4): 1) Inventoried datasets from official institutions (e.g., ICGC seismic catalogues, ACA flood inventories, and the wildfire database of the Catalan Government), obtained via formal data-sharing requests; 2) Written sources, including historical newspapers and scientific literature, retrieved through digital archives (e.g., Arxiu Municipal de Girona, ReGira) using bilingual keyword searches (Catalan / Spanish); and 3) Oral and citizen-science sources, gathered through two workshops (Montagut and La Vall d'en Bas) involving several participants with local and technical knowledge. Participants annotated printed maps and provided recollections, particularly regarding major floods and slope instabilities.

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	Data were retrieved from the online software Portal Àgora (Llasat et al., 2022), which is publicly available and free.

	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.	
	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.).

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	Nierga et al., 2022; Vilar, 2022;	Data were consulted manually. The ground subsidence dataset of Fábregat (2020) was provided through a personal petition.
	Floods	Nierga et al., 2022	
	Wildfires	Maya and Bendinelli, 2005; Nierga et al., 2022	
	Ground subsidences	Gutiérrez et al., 2016; Fábregat et al., 2019; Fábregat, 2020	

Table 4: Summary 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; 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.

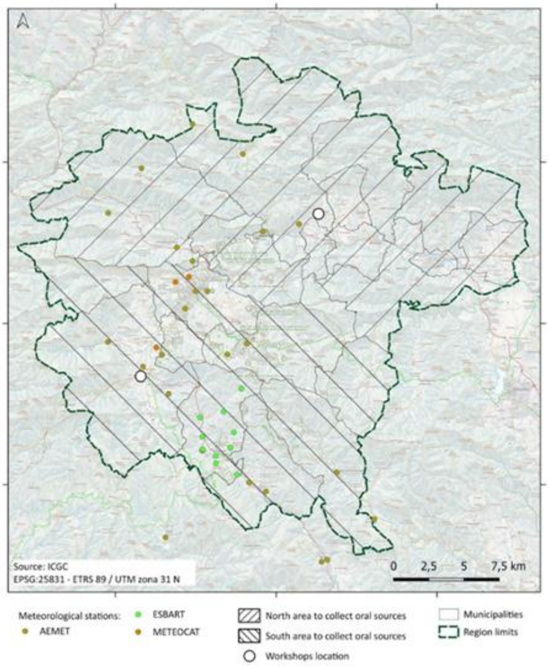

Figure 3: Map showing the meteorological stations from various sources (Aemet, Meteocat, and ESBART) used for data collection, along with the locations of the citizen science workshops held. Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

All sources were georeferenced, standardized, and entered into a unified relational structure. Each record includes metadata on provenance and reliability.

3.4 Data processing

Raw data were processed in two stages: 1) Standardization and merging: Temporal data reformatted to DD-MM-YYYY, and spatial coordinates converted to UTM Zone 31 N (EPSG:25831); 2) Duplicate detection and cross-validation: Automated string and coordinate matching in Python identified potential duplicates (e.g., two reports of the same flood). All candidates were manually checked against source texts. Discrepancies between institutions (e.g., AEMET vs METEOCAT rainfall units) were resolved through conversion scripts. A more detailed description of the data processing is provided in Supplementary Information S1.

3.5 Cross-validation and quality assurance

We applied three methods to conduct cross-validation and quality assurance: 1) Spatial verification: events plotted in QGIS and visually checked against topographic basemaps; 2) Expert review: geologists from SIGMA and the Natural Risks Assessment and Management Service (NRAMS) verified 100 randomly selected entries for plausibility; and 3) Uncertainty documentation: the fields "*np_ini_date*" (non-precise initial date) and "*np_fin_date*" (non-precise final date) are used to record uncertainty arising from the absence of exact dates in the written and oral sources consulted. This multi-layer validation ensures that even heterogeneous, century-spanning information attains consistent standards for subsequent analysis.

4 Results

4.1 Dataset overview

The finalized Garrotxa natural hazard event dataset contains 1,049 records covering six hazard types: Earthquakes (246), Landslides (114), Floods (242), Rockfalls (46), Wildfires (264), and Ground subsidences (137) (Fig. 4). The final table has a total of 45 categorized variables spanning location, timing, physical descriptors, triggering factors, and metadata fields for quality control. About 73 % of events derive from inventoried sources and 27 % from non-inventoried written or oral materials (Fig. 5). Temporal coverage is uneven, with a clear increase in reporting after 1980, reflecting improved monitoring and media documentation. This bias does not necessarily indicate higher hazard frequency but improved detectability and institutional recording capacity.

The dataset is publicly available at https://digital.csic.es/handle/10261/394924 (Lagresa et al., 2025). 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.

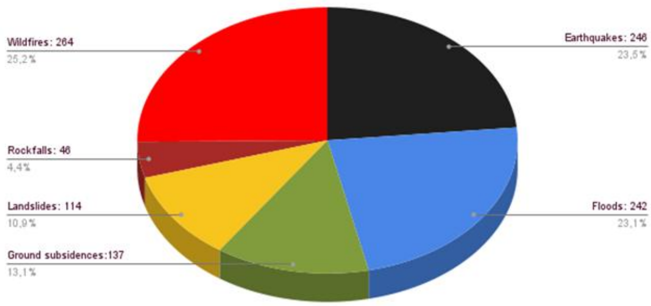

Figure 4: Total recorded events in the Garrotxa region (1900–2023), distributed by type of natural hazard (wildfires, rockfalls, landslides, ground subsidences, earthquakes and floods).

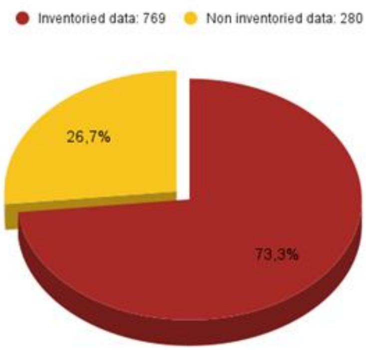

Figure 5: Percentage of recorded natural hazard events in the Garrotxa region (1900–2023) by data source (previously inventoried and non-inventoried).

4.2 Preliminary analysis of hazard interrelationships

Although the primary purpose of the dataset is descriptive, a simple exploratory analysis was performed to illustrate its potential for multi-hazard investigation. We examined temporal and spatial co-occurrence among hazard events using a synthetic yet realistic procedure, intended solely for demonstration purposes.

First, heuristic assumptions regarding potential temporal and spatial relationships between triggering hazards and subsequently triggered hazards were defined. These assumptions were informed by a preliminary inspection of the dataset and by prior geological knowledge of the study area. The assumed trigger–response relationships, along with the corresponding temporal and spatial windows, are summarized in Table 5. Wildfire and ground subsidence were not considered as triggering hazards for other events in this exploratory analysis. Ground subsidences were only evaluated as potentially triggered hazards. Wildfires were excluded from the interrelationship analysis due to their predominantly anthropogenic origin in La Garrotxa, which limits the interpretability of temporal and spatial associations within the adopted analytical framework. Therefore, a total of 912 events out of the total of 1049 were finally considered for this analysis.

Table 5. Assumed temporal and spatial windows for trigger–hazard co-occurrence used in the exploratory analysis. These temporal and spatial thresholds do not represent definitive physical limits but were selected to provide a plausible framework for illustrating how the dataset can be used to explore multi-hazard interactions.

Trigger hazard	Potentially triggered hazards	Temporal window	Spatial window
Flood	Landslide, rockfall, ground subsidence	Within 7 days	Within 2 km
Earthquake	Landslide, rockfall, ground subsidence	Within 7 days	Within 25 km
Landslide	Flood, rockfall	Within 7 days	Within 1 km
Rockfall	Flood, landslide	Within 7 days	Within 1 km

Out of the 912 events considered, 79 (approximately 8.4%) participated in at least one potential interrelated occurrence. Table 6 presents a sample of the observed relative frequencies of these interrelations. Percentages are calculated with respect to the total number of events of each potentially triggered hazard type and indicate the proportion of those events that were temporally and spatially associated with a given trigger hazard, according to the adopted criteria. For example, 28.6 % of landslide events were temporally and spatially associated with flood occurrences within a 7-day window and a 2-km distance threshold.

Table 6. Relative frequencies (expressed as percentages) of potentially triggered hazard events (columns) that were temporally and spatially associated with a given trigger hazard (rows), according to the assumed criteria. "–" indicates that no interrelated occurrences were identified for the corresponding hazard combination under the adopted criteria.

Trigger hazard	Relative frequencies of potentially triggered hazards		
	Landslide events (%)	Rockfall events (%)	Ground subsidence events (%)
Flood	28.6 %	5 %	-
Earthquake	5.5 %	22.5 %	27.8 %

In addition to hazard–hazard interrelations, a complementary exploratory analysis was conducted to examine associations between selected natural hazards and meteorological conditions. For this purpose, a set of simple meteorological thresholds was defined, and hazard occurrences were evaluated with respect to whether they coincided with these conditions within the relevant temporal context.

Table 7 summarizes the most characteristic hazard–meteorological associations identified. Percentages represent the proportion of events of each hazard type that occurred under the specified meteorological conditions. These associations are intended to illustrate potential links between hazards and meteorological drivers, rather than to establish causal relationships.

Table 7. Relative frequencies (expressed as percentages) of hazard events occurring under selected meteorological conditions. Percentages are calculated relative to the total number of events of each hazard type. "–" indicates that no associations were identified under the adopted criteria.

Meteorological condition	**Wildfire events (%)**	**Flood events (%)**	**Landslide events (%)**
Maximum temperature ≥ 30 ºC	28.7 %	-	-
Wind ≥ 20 km/h	4.9 %	-	-
Precipitation < 50 mm in the previous 2 weeks	87.2 %	-	-
Rainfall ≥ 100 mm	-	96 %	71.1 %

Patterns observed in Tables 6 and 7 are broadly consistent with commonly reported multi-hazard sequences and hazard-meteorology in Mediterranean mountain regions (e.g., Guzzetti et al., 2007; Turco et al., 2018; Rodríguez-Peces et al., 2020). In particular, rainfall-driven processes appear to dominate, with intense precipitation episodes frequently associated with flood occurrences and slope instabilities (Table 7). Seismic activity is occasionally followed by localized rockfalls or minor ground subsidence, although associated magnitudes are generally low (ML < 4) (Table 6). In addition, wildfire occurrences tend to coincide with periods characterized by limited precipitation over several consecutive days and elevated temperatures, as reflected in the adopted meteorological thresholds (Table 7). These associations are consistent with the regional climatic setting but should be interpreted cautiously, as they do not imply direct causality.

The temporal distribution of identified interrelations reflects a recency bias, with approximately 66% of associations occurring after 2011. This pattern likely results from both an increased reporting of hazard events and a substantial improvement in detection and documentation capabilities in recent decades.

A key limitation of the present analysis remains the uneven quantity of available data across events. Interrelationships are more readily identified for well-documented episodes, such as major storms (e.g., the Gloria event in January 2020), highlighting the importance of data completeness for robust multi-hazard analysis.

Although preliminary and based on synthetic aggregation, these findings demonstrate the capacity of the dataset to support exploratory multi-hazard association and causal-chain analyses once more complete and probabilistic information becomes available.

4.3 Spatial and temporal distribution

Spatial visualization in QGIS (Fig. 6) reveals several multi-hazard clusters, including: 1) the Fluvià River valley, where flood and landslide events overlap; 2) the Bas and Santa Pau valleys, combining volcanic substrates and steep slopes conducive to slope instability; and 3) the Alta Garrotxa range, showing numerous wildfire and rockfall events. Such clustering supports the identification of priority areas for integrated risk mitigation rather than single-hazard interventions.

Concerning temporal distribution, Fig. 7 shows an apparent rise in hazard occurrence after 2000. While partly due to improved reporting, this trend coincides with observed regional increases in extreme rainfall frequency and summer heatwave duration, aligning with findings from the Catalan Meteorological Service (Meteocat, 2024). The dataset therefore also offers an empirical basis for studying climate-hazard linkages at the regional scale.

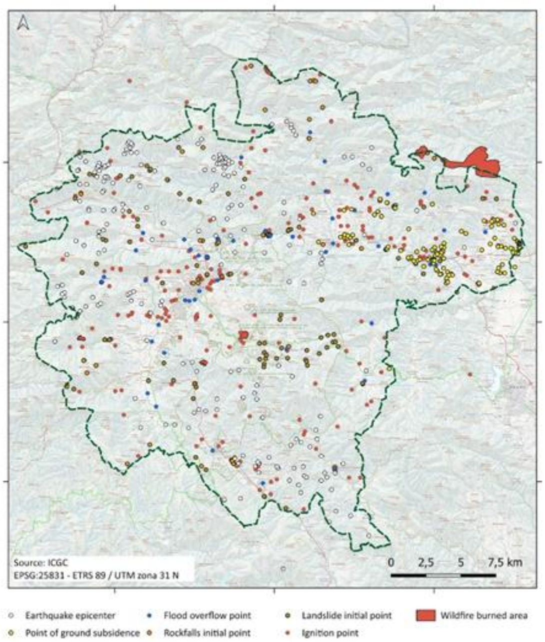

Figure 6: Geographical distribution of the total recorded natural hazard events occurred in the Garrotxa (1900–2023). Base map service of the Cartographic and Geological Institute of Catalonia (ICGC), under a CC BY 4.0 license.

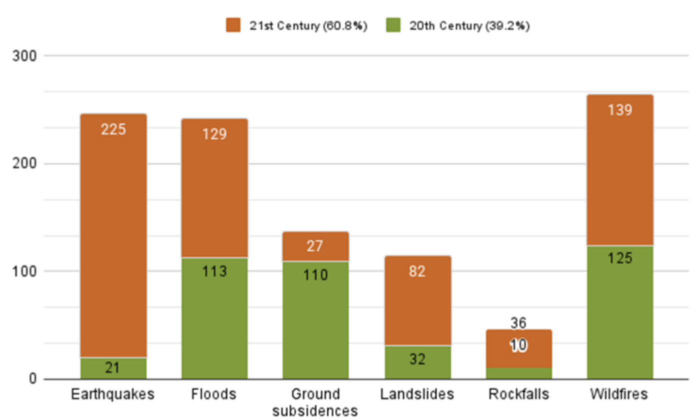

Figure 7: Total recorded events for each natural hazard in the Garrotxa region (1900–2023), distributed by century (20th and 21st).

5 Discussion

5.1 Dataset value and comparison with existing repositories

The Garrotxa natural hazard event dataset fills a unique spatial and thematic gap between global/national repositories (e.g., EM-DAT, SHELDUS, Risk Data Hub) and local administrative records. Compared with EM-DAT, which lists only disasters causing major economic losses or fatalities, our dataset captures all scales of events, including minor but frequent slope movements and small wildfires that shape local vulnerability. In contrast to SHELDUS (county-level U.S. data) or the Copernicus Emergency Management Service (European-scale), the Garrotxa dataset reaches municipality-level geospatial resolution (< 250 m). Moreover, it integrates non-institutional information such as historical newspapers and citizen-science memories, rarely present in official inventories.

From a scientific perspective, these differences translate into three clear contributions: 1) Enhanced resolution and completeness, supporting validation of susceptibility models that require fine-scale inputs; 2) Inclusion of cultural memory, linking physical events with community perception, crucial for risk-communication studies; and 3) Interoperable structure, as variables follow common vocabularies (e.g., INSPIRE, UNDRR Hazard Glossary), facilitating cross-dataset integration at European scale. Thus, the dataset moves beyond a purely archival purpose and becomes an enabling infrastructure for multi-hazard data-driven research.

5.2 Workflow toward multi-hazard risk assessment

The dataset forms the first step in a chain leading to a comprehensive multi-hazard risk analysis. Figure 8 (described below) outlines the sequential steps and data requirements in this process. Step 1, Hazard Event Dataset (Observed Data), uses an empirical record of past events, as detailed in this study. Step 2, Susceptibility Mapping, identifies the relative likelihood (low to high classes) of a hazard occurring at a specific location, based on intrinsic and environmental factors such as slope, lithology, and rainfall. Step 3, Hazard Mapping, integrates susceptibility data with the probability of an event occurring within a given time frame, such as flood inundation probability for 50- or 100-year return periods. Step 4, Exposure Assessment, overlays spatial data to identify exposed elements like people, buildings, infrastructure, and ecosystems. Step 5, Vulnerability Analysis, quantifies potential damage or loss for each exposed element. Step 6, Multi-Hazard Integration and Risk Mapping, combines hazard layers using weighting or network models to represent cascading or compound effects. Finally, Step 7, Decision Support and Policy Feedback, produces outputs that inform risk management plans, emergency preparedness, and climate adaptation strategies.

A susceptibility map expresses the relative predisposition of a location to event initiation, while a hazard map quantifies the probability of a given event magnitude occurring within a specified period. Not all hazard types have both products routinely: landslides, for example, often have susceptibility maps but rarely fully probabilistic hazard maps.

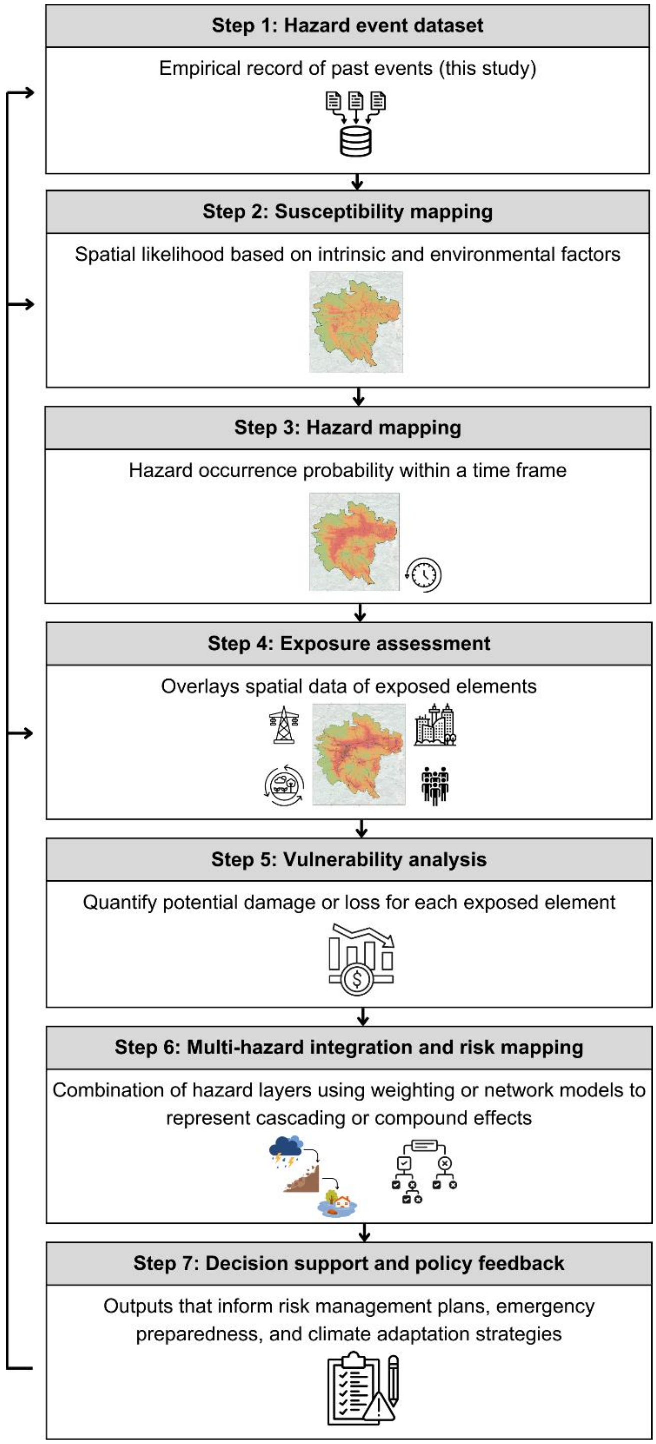

Figure 8: General workflow for an integrated multi-hazard risk assessment. Each step is represented by rectangular boxes linked by arrows. Icons in the chart symbolize datasets, GIS analyses, and feedback loops to policy actors.

5.3 Implications for regional risk management

For the Regional County Council and SIGMA, the dataset provides the first integrated evidence base of all recorded natural-hazard events in Garrotxa. Previously, disparate archives hindered coordinated action. Now, cross-hazard visualization reveals which municipalities face overlapping threats. For example, the overlap of flood and landslide records along the Fluvià River underscores the need for joint hydraulic–geotechnical planning, while patterns linking wildfire records to periods of limited precipitation and elevated temperatures inform vegetation-management priorities..

To maximize long-term utility, the dataset should be synchronized with existing real-time monitoring networks (meteorological and seismic) so that new events feed automatically into the database. Developing an open-data API would further enable public transparency and early-warning integration.

Beyond Garrotxa, this initiative demonstrates a replicable governance model: a partnership between research institutions and local administrations that aligns with the National Plan for Adaptation to Climate Change (2021–2030) in Spain.

5.4 Challenges and limitations

Despite its contributions, several limitations remain. Data heterogeneity exists, as different institutions record events with varying precision, with early-century entries relying on qualitative descriptions. Temporal bias is present, as record density increases after 1980, reflecting monitoring improvements rather than actual hazard escalation. Uncertainty quantification is lacking, as statistical confidence measures for location and magnitude are not yet formalized (e.g., Koedel et al., 2022), though a forthcoming phase will apply Bayesian updating to estimate data reliability. The scope is limited to six hazard types, and expanding to include windstorms or snow hazards will require additional data sources. Additionally, the dataset is currently single-layer, with inter-hazard relationships explored preliminarily but not explicitly modeled probabilistically. Future research should focus on (1) implementing automated web scraping of new events from press feeds, (2) developing multi-hazard network models using this dataset as training input, and (3) standardizing data formats across other regions for national integration.

6 Conclusions

This work presents the first integrated natural hazard event dataset for the Garrotxa region (Catalonia, Spain), documenting 1049 events from 1900 to 2023. By merging official inventories, historical sources, and citizen-science inputs, it transforms scattered information into a coherent, quality-controlled resource.

Beyond data compilation, the study illustrates how such a dataset can support the identification of preliminary hazard interrelationships as well as hazard–meteorological associations, and outlines a workflow toward comprehensive multi-hazard risk assessment. Comparative analysis shows that it complements and enhances broader databases by adding fine-scale, locally validated records.

In practical terms, the dataset equips regional authorities with a foundation for evidence-based risk planning and establishes a replicable model for other territories. Future extensions should quantify uncertainties and integrate probabilistic modeling, enabling transition from descriptive catalogues to predictive, data-driven multi-hazard risk maps.

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

Competing interests

The authors declare that they have no conflict of interest.

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