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Methodological approach to multi-hazard analysis: the case of the Garrotxa region (Catalonia, Spain)

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Abstract. Amidst the escalating impacts of climate change and the growing frequency of natural disasters, the urgent need for robust multi-risk assessment and proactive mitigation strategies has become increasingly apparent. The Garrotxa region, characterized by its diverse array of weather-related hazards (such as torrential rains, floods, debris flows, lahars, tornadoes) and geological hazards (including landslides, rockfalls, earthquakes, and volcanic eruptions), presents an example of the challenges faced by communities globally, necessitating a shift towards anticipatory disaster management. Departing from conventional simulation models, we recognize the fundamental role of past experiences in shaping future risk assessments and mitigation strategies. This paper introduces a methodology for the creation of a multi-hazard database tailored to the Garrotxa region, serving as a foundational step towards subsequent multi-risk analysis. By meticulously documenting the region's historical hazards since 1900, our approach aims to equip stakeholders with a nuanced comprehension of multiple natural processes. This comprehensive strategy, which combines modern monitoring techniques with historical context, forms a synergistic approach crucial for effective, long-term disaster risk mitigation. Our work not only sheds light on the unique challenges faced by the Garrotxa region but also provides a scalable model for regions grappling with diverse natural phenomena worldwide. This contribution aims to enhance disaster resilience in regions confronting similar potential multi-hazard scenarios.

1 Introduction

The increasing demographic expansion and rapid urban development are driving humanity to build in areas of escalating risk (Pesaresi et al., 2017; Tellman et al., 2021; International Panel on Climate Change [IPCC], 2023), often due to limited availability of safe spaces and a lack of knowledge about the hazards specific to a territory (Cutter et al., 2001; Cutter and Finch, 2008). This trend is further compounded by the effects of climate change, which are not only increasing the magnitude and frequency of hazards but also creating risks in areas previously not considered at risk, or where a specific hazard had not posed significant risks before. Furthermore, climate change is modifying the interactions between hazards,

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intensifying cascading effects, amplifying risks, and altering natural patterns (IPCC, 2023). These phenomena are closely connected with technological and global interconnectivity, leading to disasters whose impacts transcend borders (Lee et al., 2012; Plag et al., 2013).

In this context, scientific knowledge about the hazards that affect a region, both temporally and spatially, is crucial. Such knowledge enables the identification of vulnerable elements and the implementation of preventive and mitigative measures to minimize economic and social losses. A multi-hazard perspective is essential for this purpose, addressing the simultaneous or sequential occurrence of multiple natural and anthropogenic hazards and their potential interrelations (López-Saavedra and Martí, 2023). This approach surpasses the traditional single-hazard perspective, which fails to capture the complexity of real-world scenarios, where hazards interact in ways that may amplify, neutralize, or modify each other's impacts (Kappes et al., 2012; Petrini and Palmeri, 2012; Ward et al., 2022).

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

Databases play a pivotal role in building this understanding, serving as foundational tools for compiling, centralizing, and standardizing hazard data. These repositories facilitate long-term hazard assessment and enable short-term evaluations during imminent emergencies. 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., 2024).

In the Garrotxa region of Catalonia, Spain, the lack of an integrated multirisk database is particularly concerning given the region's unique geographic and socio-economic characteristics. The area is characterized by mountainous terrain, rural and urban zones, a significant industrial and agricultural presence, extensive forested areas, and the presence of the Natural Park of the Volcanic Zone of Garrotxa. 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 region's volcanic history cannot be ignored.

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

This study aims to establish the first multirisk database for the Garrotxa region, addressing these challenges by centralizing existing data and creating a standardized, interoperable repository. The proposed database will integrate intrinsic, extrinsic, and evolutionary variables for each hazard, allowing for comprehensive analyses of their interactions. This database is

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designed to support data science applications and facilitate long-term hazard assessments and short-term emergency evaluations, thereby enhancing the region's preparedness and resilience in the face of climate change and increasing hazard complexity.

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

2 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 park represents the most well-preserved volcanic landscape in the Iberian Peninsula, comprising over forty volcanic cones and extensive lava flows (Planagumà and Martí, 2018).

The Garrotxa region can be distinguished into two different relief units (Fig. 1a, 1b):

- The north: belongs to the *Alta Garrotxa*, which translates to Upper Garrotxa in English. It is part of the pre-Pyrenees mountain range and 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 centre and the south (also known as *Baixa Garrotxa*, which translates to Lower Garrotxa in English): It is part of the Transversal mountain range of Catalonia. The main lithological units are marls and sandstones of the Eocene, faulted by tectonic structures of Neogene age (20 Ma to the present) that form part of the European Rift. Flatter bottom and less abrupt reliefs predominate, a product of the Quaternary volcanism that exists in this area (0.3 Ma to the present) (Martí et al., 2025). The different lava flows and sediments accumulated by the past volcanic eruptions have formed the valleys of Bas, Olot, Santa Pau and Brugent. In this sector, the faults in a NW – SE direction generate a horst with the fault planes generating a steep relief in the Eocene sandstones of the Puigsacalm area or the slopes of La Salut and El Far (Martínez-Rius et al., 1990).

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

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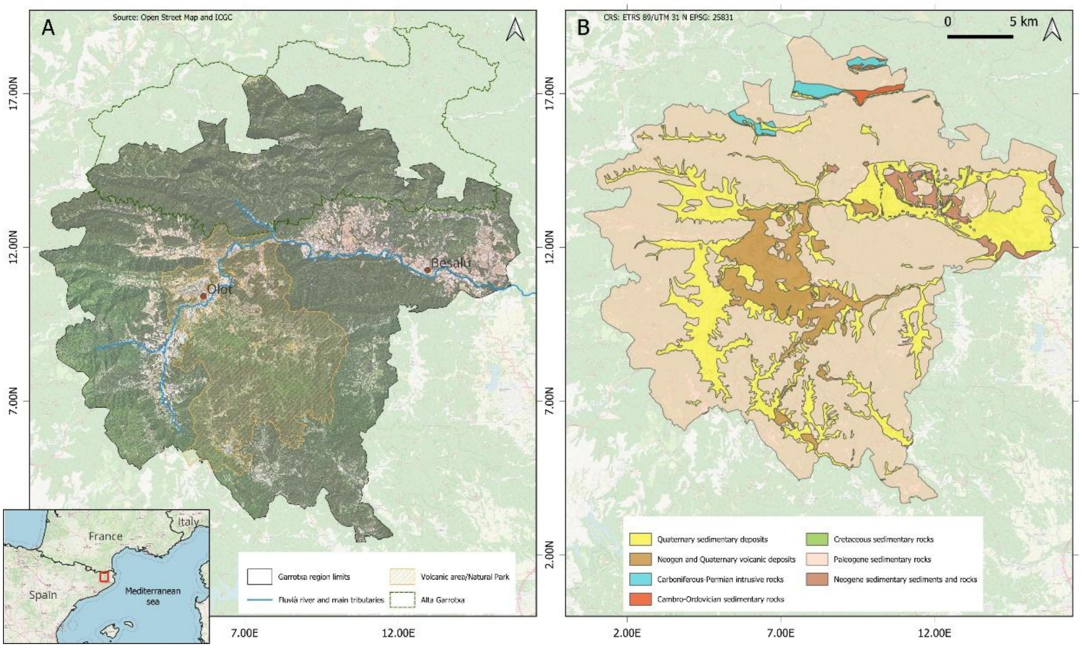

Figure 1: Study area. a) Location and geographical map of the Garrotxa region. b) Lithological map of the Garrotxa region. © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

The Fluvià River traverses the region from west to east, playing a crucial role in shaping the local environment and hydrological dynamics. Garrotxa's climate is classified as Mediterranean with montane influences, characterized by cold winters and mild summers. Precipitation levels are relatively high, which fosters the development of extensive forests, including the Fageda d'en Jordà, a beech forest growing on volcanic soil—one of the most ecologically significant ecosystems in the region.

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

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

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

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

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

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

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

Both industrial and transport infrastructure in the Garrotxa can be treated as vulnerable elements. Therefore it is important to have them mapped and include them in risk management strategies.

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

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

3 Natural hazards in the Garrotxa region

The Garrotxa region, characterized by its volcanic geomorphology, mountainous terrain, and Mediterranean climate, is exposed to multiple natural hazards. Although the volcanic activity in the region remains dormant, other geophysical and

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meteorological threats, including seismic disturbances, landslides, flooding, and wildfires, present ongoing risks to both the environment and local communities.

Seismic activity, while generally moderate, is influenced by the proximity to the Pyrenean tectonic boundary and the presence of Neogene-Quaternary normal faults. Though earthquakes in the region are relatively infrequent, existing fault systems indicate the potential for low-magnitude seismic events. These tremors, while rarely destructive, highlight the underlying geodynamic instability of the region.

The steep topography, combined with intense seasonal precipitation and soil saturation, contributes significantly to landslide susceptibility. The region's slopes, composed of weathered volcanic materials and unconsolidated sediments, are particularly prone to mass-wasting events following prolonged rainfall or seismic activity. Landslides can disrupt transportation infrastructure, alter river courses, and threaten residential areas in both the highlands and foothill zones.

Hydrological 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. 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. The increasing incidence of extreme weather events, attributed to ongoing climatic shifts, has further exacerbated flood risks in recent decades.

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

Although less frequent than other hazards, wildfires remain a persistent risk, particularly in densely forested areas dominated by Mediterranean oak and beech woodlands. The dry summer season, coupled with increased temperatures and periodic droughts, creates favorable conditions for fire ignition and rapid spread. The expansion of forested areas due to rural depopulation has further increased fuel availability, heightening wildfire risks.

In recent years, climate change has played a significant role in amplifying the frequency and intensity of extreme weather phenomena, including heatwaves, droughts, and intense rainfall episodes. These changes have compounded existing hazards, necessitating a more comprehensive approach to risk assessment and mitigation strategies in the Garrotxa region.

4 Methodology

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

- Earthquakes
- Landslides

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- Rockfalls
- Ground subsidences
- Floods
- Wildfires

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

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

4.1 Selection of the study period

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

1. A sufficient time span to enable predictive modeling of future hazard occurrences: according to the frequency of the different hazards considered, a 100-year minimum period was assumed as representative for analyzing hazard processes and their potential interrelationships.
2. The availability of reliable documentary sources: digitized newspapers (the oldest available sources), provided records dating back to the late 19th century. However, data from this initial period were scarce, leading to set 1 January 1900 to 31 December 2023, as the final study range.

4.2 Data sources and collection strategy

To structure data collection, two main types of sources were categorized:

1. Inventoried sources: Pre-existing databases, official records, and hazard inventories.
2. Written sources: Scientific publications, historical documents, and press archives.

For inventoried sources, data were available for earthquakes, floods, wildfires, and some gravitational processes (landslides and rockfalls). These datasets were obtained from various public institutions:

- Earthquakes: Data were requested from the Cartographic and Geological Institute of Catalonia (Institut Cartogràfic i Geològic de Catalunya [ICGC]). The dataset included events with epicenters both within and outside the Garrotxa region.
- Landslides and rockfalls: Requested from the ICGC. Although the dataset was limited, it included valuable metadata such as event volume, precise coordinates, and verification status.

- Floods: Data were retrieved from Portal Àgora (Llasat et al., 2022), an online platform managed by the Analysis of Adverse Meteorological Situations Group (Grupo de Análisis de situaciones Meteorológicas Adversas [GAMA]) of Barcelona University (Universitat de Barcelona [UB]).
- Wildfires: The Catalan Government's Wildfire Prevention Department provided records of forest fires (1995–present) but excluded those affecting croplands or urban areas. Additional wildfire data for Alta Garrotxa (1975–present) were obtained from the same institution. All wildfire events were georeferenced according to their ignition points.
- Ground subsidences: Georeferenced data were acquired through direct contact with researchers who had previously studied the phenomenon in the Garrotxa region.

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

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

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

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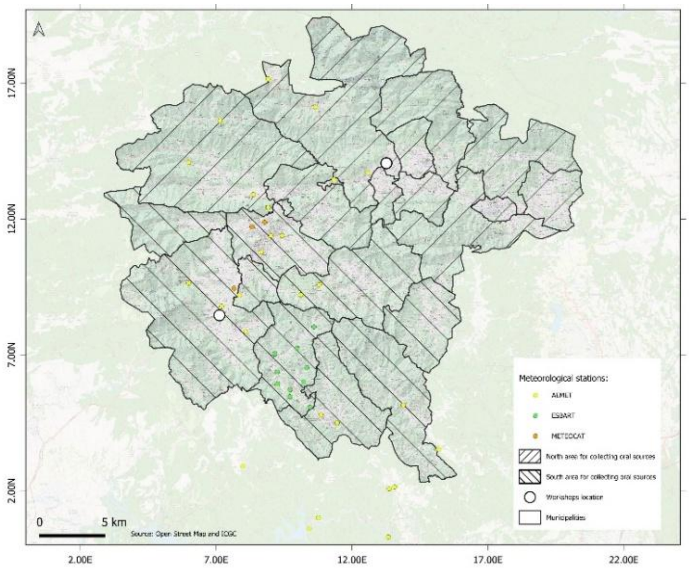

Figure 2: Map displaying meteorological stations from various sources (AEMET, ESBART, METEOCAT) used for data collection and the locations of workshops conducted for gathering oral sources, one in the northern area and one in the southern area. © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

For hazards not covered in inventoried sources, historical press archives were the primary data source. The Girona's Municipal Archive and Marià Vayreda Library (Olot) provided digitized newspaper collections. These archives were useful to:

1. Identify missing records for floods, landslides, rockfalls, and ground subsidences.
2. Verify and supplement existing inventoried datasets.

Search strategies varied depending on the archive structure:

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

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

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

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

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To supplement documentary sources, two citizen science workshops were conducted in distinct subregions: Pre-Pyrenees (north) and Transversal Range (south) (Fig. 2). These workshops engaged local communities, rural officers, and amateur meteorologists.

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

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

4.3 Data structuring and validation

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

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

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

5. Results

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

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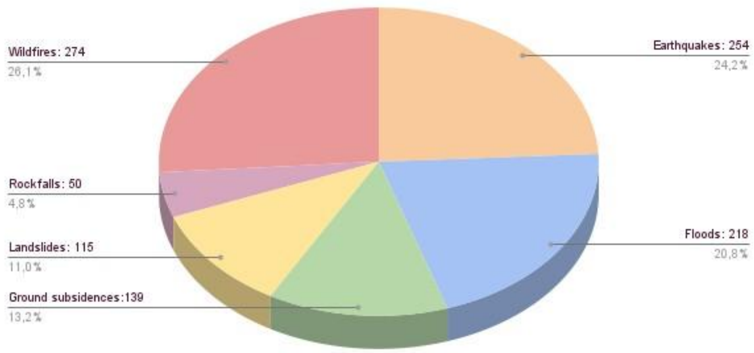

Figure 3: Total recorded events in the Garrotxa (1900–2023), distributed by type of natural hazard (wildfires, rockfalls, landslides, ground subsidences, earthquakes, floods).

A particular consideration was given to flood events, as their initial classification required specific adjustments. Although the Portal Àgora database originally contained 90 flood records, these were documented with multiple affected municipalities listed within a single entry. This format posed challenges for subsequent data processing, as having multiple locations in the same record complicated the spatial analysis. To address this, the floods were disaggregated, assigning separate records for each affected municipality while maintaining a unique identifier for each flood event. This methodological adjustment resulted in more than twice the original number of flood records, though many of these entries corresponded to the same flood event but affecting different locations. This refinement also allowed for a more precise geospatial representation of flood impacts across different municipalities.

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

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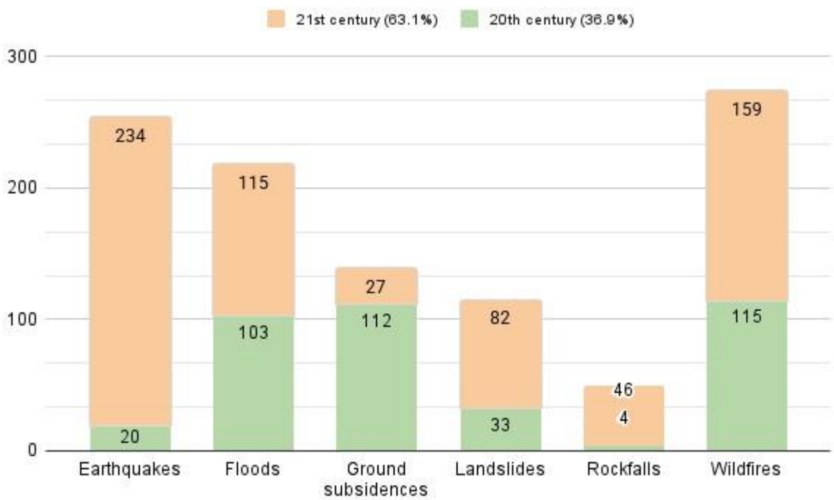

Figure 4: Total recorded events for each natural hazard in the Garrotxa (1900–2023), distributed by century (20th and 21st).

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

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

Regarding data provenance, 76.9 % of the records have come from pre-existing inventoried datasets, while the remaining 23.1 % were gathered from other sources (Fig. 5). Data on earthquakes, floods, and ground subsidences primarily originated from inventoried datasets, requiring only validation and minor supplementation from additional sources. On the other hand, inventoried data on rockfalls were scarce and non-existent for landslides. As a result, the landslide dataset presented in this study had to be created from scratch.

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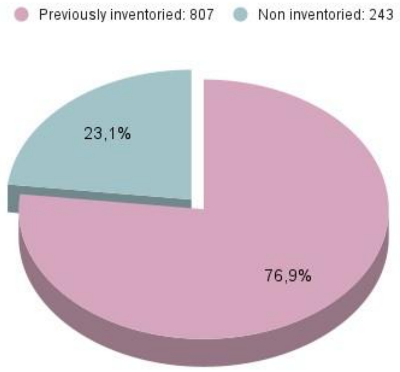

Figure 5: Percentage of recorded natural hazard events in the Garrotxa region (1900–2023) by data source (previously inventoried and non inventoried).

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

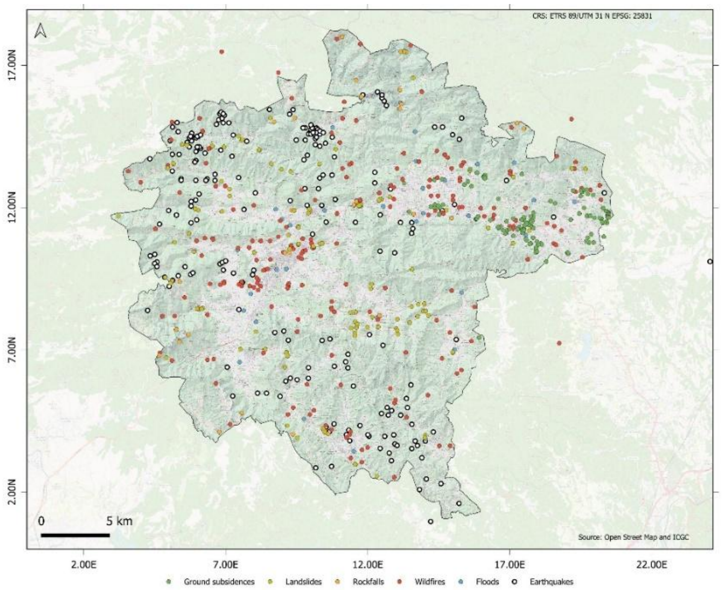

Figure 6: Geographical distribution of the total recorded natural hazard events occurred in the Garrotxa (1900–2023). © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

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6 Discussion

One of the primary challenges encountered in the construction of this database was the scarcity of pre-processed data, particularly concerning geological hazards in the Garrotxa region. Few existing inventories documented such events, necessitating an extensive historical press review, from which 243 records were extracted. However, historical press sources are inherently less comprehensive than structured inventories, and most crucially, they lack georeferenced data. While certain hazards were well-represented within available datasets, others required independent investigation using multiple sources. Earthquakes, floods, wildfires, and ground collapses had relatively robust documentation, with earthquakes being the only hazard type that did not require supplementation with additional data. Conversely, hazards such as landslides and rockfalls were significantly underrepresented in pre-existing inventories, necessitating a more labor-intensive data collection process, predominantly relying on historical press archives.

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

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

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

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resolution, but some degree of uncertainty remains, particularly for widespread hazards such as floods and wildfires. Despite these limitations, ensuring the highest possible spatial accuracy was essential for subsequent geographic analyses using GIS techniques.

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

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

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

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

7 Challenges and future steps

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

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

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

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

8 Concluding remarks

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

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

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

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

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

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

Data availability

Data will be made available on request.

Author contribution

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

Competing interests

The authors declare that they have no conflict of interest.

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