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► To cite this version:

Alix Bisquert, Robin Mainieri, Simon Carladous, Yannick Robert, Florie Giacona, et al.. The RTM Event Database for Understanding Natural Hazards in Mountainous Regions: The Example of the Isere Department (France). *Revue de Géographie Alpine / Journal of Alpine Research*, 2025, 113-4, 10.4000/137kg . hal-04934104

HAL Id: hal-04934104

<https://hal.science/hal-04934104v1>

Submitted on 7 Feb 2025

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Electronic version

URL: <https://journals.openedition.org/rga/13767>

DOI: 10.4000/137kg

ISSN: 1760-7426

This article is a translation of:

La base de données événementielles RTM pour la connaissance des risques naturels en montagne :
L'exemple du département de l'Isère (France) - URL : <https://journals.openedition.org/rga/13719> [fr]

Publisher:

UGA Éditions/Université Grenoble Alpes, Association pour la diffusion de la recherche alpine

Electronic reference

Alix Bisquert, Robin Mainieri, Simon Carladous, Yannick Robert, Florie Giacona, Pierre Verry and
Nicolas Eckert, "The RTM Event Database for Understanding Natural Hazards in Mountainous Regions:
The Example of the Isere Department (France)", *Journal of Alpine Research | Revue de géographie
alpine* [Online], 113-4 | 2025, Online since 15 January 2025, connection on 31 January 2025. URL:
<http://journals.openedition.org/rga/13767> ; DOI: <https://doi.org/10.4000/137kg>

This text was automatically generated on January 31, 2025.



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This work was carried out with financial support from MTEECPR and MASAF. The authors would like to thank all contributors to the BD-RTM, including the RTM technical personnel responsible for data input, administrator of the BD-RTM since the 2000s, and its maintenance contractor, and, more generally, all the people/services/institutions who contributed to data collection in the field, as well as to data archiving. The development of the BD-RTM and data input are financed by MASAF and MTEECPR. Currently, the BD-RTM is accessible to external users via the following link : <https://geo-onf.opendata.arcgis.com/maps/760c436f2736431fb0cae21c14c7414b/about>. This platform will continue to evolve, for more information, please contact : [admin.bdrtm\[at\]onf.fr](mailto:admin.bdrtm[at]onf.fr). The authors would also like to thank the reviewers for their constructive feedback, as well as Hannah Rowe for her valuable assistance with the English translation of the manuscript. F. Giacona and N. Eckert are members of the Grenoble Risk Institute (<https://risk.univ-grenoble-alpes.fr/en>). IGE is a member of OSUG.

Introduction

- 1 In mountainous regions, due to favourable topographic and climatic conditions, avalanches, landslides, torrential floods and rockfalls can cause significant material damage and, in some cases, human casualties (Ancy, 1998; Dussauge-Peisser *et al.*, 2002; Chambon *et al.*, 2013; Cerema, 2014). Implementing an effective and well-adapted risk management strategy requires a spatial and temporal characterization of (1) natural hazards, described through the analysis of the magnitude/intensity/frequency trio (Thouret and D'Ercole, 1996), and (2) vulnerability, which is characterized by the

potential damage to exposed elements which are at risk (Leone *et al.*, 2011; Favier *et al.*, 2014), along with an analysis of the complex spatio-temporal dynamics underlying the risk: representations, perceptions, etc. Documenting risks and their natural and social components of a studied territory over a sufficiently long period is therefore essential. For this purpose, the compilation of data series on observed hazards and their impacts, derived from geohistorical approaches, emerges as an indispensable tool (Giacona *et al.*, 2019a). These series are often the result of archival research of diverse origins (administrative, private, religious archives, etc.) and various forms (digital, written, photographic, etc.), which provide information on “events” understood as natural and/or climatic hazards that have been recorded and for which a trace has been preserved (Giacona *et al.*, 2019a).

- 2 In order to capitalize on these events, various databases have been developed to organise the data in a structured framework. For example, the global DesInventar database, initiated by the Disaster Information Network for Latin America and the Caribbean (LA RED), compiles information on natural hazards (floods, landslides, cyclones, tsunamis, etc.). This database records human and/or material losses caused by events across different countries (UNDRR, 2019). Similarly, the Italian database SICI (Information System on Hydrological and Geomorphological Catastrophes), created in 1999, contains various inventories, including AVI (Damaged Urban Areas), which documents landslides and flood events across the Italian territory from 1900 to this day (Guzzetti *et al.*, 1994; Guzzetti and Tonelli, 2004). The Yosemite National Park rockfall database in the United States, initiated by the USGS (U.S. Geological Survey) and NPS (National Park Service), provides a historical inventory of events occurring within the national park. This database results from a compilation of published and unpublished historical sources (archives, testimonies, photographs), observations and interviews documenting events from 1857 to nowadays (Guzzetti *et al.*, 2003; Stock *et al.*, 2013). The WISL (Würzburg Information System on Landslides) database records landslides across German areas subjected to this hazard (Damm and Klose, 2015; Kreuzer *et al.*, 2017; Jäger *et al.*, 2018). Other notable examples include the “Swiss Flood and Landslide Damage Database” managed by the Swiss Federal Institute for Forest, Snow and Landscape Research (Hilker *et al.*, 2009), the Austrian database “Austrian Service for Torrent and Avalanche Control” (Perzl *et al.*, 2019), or the “National Landslide Database of Great Britain” developed by the BGS (British Geological Survey) (Foster *et al.*, 2012; Pennington *et al.*, 2015). Many other similar databases exist whether they are continuously managed and maintained or they are the result of specific research projects conducted over a limited period.
- 3 In France, other inventories of potentially damaging natural hazards also exist. Among them, the BDHI database, created in 2013 and funded by the Ministry of the Environment, records major floods on a national, metropolitan and overseas scale (Lang *et al.*, 2016). The ORRION database is the result of a participatory observatory for flood risk in the Alsace region (Giacona *et al.*, 2019b). The HistRhône database, initiated in 2011, provides a historical inventory of hydrological events in the Rhône Valley (CEREGE-SIGéo, 2018). Hydrological risks are thus well-documented. However, this is mainly the case for large rivers, and much less for smaller mountain torrents, which are also often destructive, as demonstrated by the recent impacts of Storm Alex in the Nice hinterland (Liébault *et al.*, 2024). Avalanche events are catalogued within the Permanent Avalanche Survey (EPA-INRAE, assisted by RTM services) covering a set of

pre-identified and selected avalanche paths (Bourova *et al.*, 2016). Initiated at the end of the 19th century in Savoie by the Administration of Water and Forests with the general avalanche observation system, its extensive temporal series of observations, regular updates, and advanced digital infrastructure are significant strengths. For gravitational hazards, the Landslide Database (BDMvT-BRGM) aims to document hazards such as landslides, rockfalls, mudflows, collapses, subsidence, and bank erosions (Rivera *et al.*, 2021) on a national scale (including metropolitan and overseas territories). Finally, the C2ROP_INRAE database, developed in the context of the National C2ROP Project, compiles events related to rockfall hazards across the six departments of the French Alps (Eckert *et al.*, 2020). This inventory was created by compiling and homogenizing pre-existing inventories (Departmental Councils, SNCF, BD-RTM, BDMvT-BRGM, and other more specific sources), and it continues to rely on these sources.

- 4 Almost all of the above-mentioned databases are single hazards, which limits their potential for territorial risk management. Furthermore, most of them are not specific to mountainous areas. Finally, they can be described as “hazard-centred,” in the sense that they provide little detailed information on the impacts of the events and even less on the components of vulnerability and risk exposure and their underlying mechanisms. In response to these limitations, in the 1980s, the French government assigned the Restoration of Mountainous Areas Service of the French National Forestry Office (ONF-RTM) with a unique mission to inventory and make available information on natural events in mountainous areas. Through its history and its other missions in association with natural hazard prevention in the mountains, this service has been a key observer of the occurrences and evolution of natural hazards in these territories since the late 19th century. The BD-RTM is therefore a specialised database that is distinguished by the following key features:
 - A clear distinction between the occurrence zones of hazards (sites) and events;
 - The characterization of each event by date, location and a description of the impact;
 - Coverage of a time scale as long as possible through the “systematic” inventorying of new events and occasional historical research to document older ones;
 - Inclusion of all natural hazards potentially damaging to mountain areas: specifically avalanches, torrential floods, rockfalls, landslides, gullying, and subsidence.
- 5 Since the early 2000s, a formalized framework for recording this data has aimed to ensure the uniformity of information and its availability at a national level. In practice, natural hazards are inventoried by ONF-RTM agents for each department and described according to pre-structured qualitative and quantitative characteristics. However, the implementation of this inventory occurs within an evolving spatial and temporal context (a specific time, location, and an observer), leading to certain disparities in its content depending on the time period and territory. As a result, the updating of this database remains imperfect, and several limitations have already been identified, such as the limited temporal coverage of certain series or the uncertainty regarding the localization of certain events (Malet *et al.*, 2009; Fressard *et al.*, 2013; Malet *et al.*, 2013). These limitations should be taken into account when interpreting or using data. The analysis of geochronology, an integral part of geo-history, provides a rigorous analytical framework to make sense of the spatial and temporal distribution of events (Giacona *et al.*, 2019a).
- 6 The Isère department (38) currently records the highest number of events among the 12 departments covered by the BD-RTM. Using this example, the objective of this

article is to present the characteristics of this unique data source and to illustrate its strengths and limitations in relation to other existing inventories for documenting and understanding mountain hazards. The article first presents (1) the structure and the information contained in the BD-RTM, followed by (2) the historical context of event inventorying by the ONF-RTM service since its creation. (3) Examples of the information recorded in the BD-RTM are then presented for the Isère department. Finally, (4) the strengths and limitations of the BD-RTM as well as the results for the Isère department are discussed.

Data and Methods

The Isère Department: Presentation of the Study Area

- 7 The geographic scale of the department is considered here, as it corresponds to the administrative, historical and current scale, to which each ONF-RTM service is attached. This scale is also shared with other institutions and local authorities that have maintained stable geographical boundaries since the French Revolution, such as Departmental Councils and decentralized government services. Among the 12 departments of the Alps and Pyrenees concerned (Alps: 74, 73, 38, 05, 04, 06; Pyrenees: 66, 11, 09, 31, 65, 64), the Isère department (38) was selected because it has recorded the highest number of events to date. In this way, Isère provides a representative sample, accounting for 14% of the national event inventory, in which various types of hazards are represented.
- 8 The Isère department is located in the Auvergne-Rhône-Alpes region in southeastern France (Fig. 1). It includes 512 municipalities, with Grenoble as its prefecture. The department's topography is divided into two distinct zones. In the north, the peri-Alpine domain is characterized by modest altitudes (200 to 900 m a.s.l) geologically made up of Tertiary molasse (conglomerates, sandstones, sands, clays) and Jurassic limestones. In contrast, the southern Alpine zone is marked by high-altitude reliefs (500 to 4000 m a.s.l) consisting of crystalline massifs (Belledonne, Grandes Rousses, Écrins) and sedimentary ranges (Vercors, Chartreuse: limestones and marls). This topographic variation within the department generates a difference in the natural hazards observed (Fig. 8). The ONF-RTM service operates throughout the department, but its focus and approach adapt to the unique needs and challenges of each sector.

Figure 1. Geographical representation of the Isère department (38), showing mountain ranges in orange



Source: IGN

- 9 The Isère department is subject to a variety of climatic influences: predominantly oceanic (westerly flux) with Mediterranean incursions in the central-western part of the territory and mountain climates in the Alpine region, with a pronounced tendency to snow in the high massifs. Significant temperature variations are observed between seasons and locally due to the pronounced relief. The department is notably characterized by high average precipitations (1000 mm/year), including snowfall in mountainous areas over a significant part of the year. Its orography and climate create favorable conditions for the occurrence of natural hazards such as avalanches, rockfalls, torrential floods, landslides, and hillside runoff.

BD-RTM Structure

- 10 The BD-RTM is an event database. It has been developed in an open-source environment, under the “PostgreSQL” management system and is hosted on a server at the ONF Data Center in Toulouse. Within the BD-RTM, an event is defined as the manifestation of a natural hazard at a specific date and location, for which information has been recorded in the database. Each event is assigned a hazard code that determines the physical nature of the natural hazard. The BD-RTM catalogues six primary types of natural hazards: avalanches (A), gullying (E), subsidence (F), landslides (G), rockfalls (P), and torrential floods (T). However, the database can also be used to record other types of events, such as earthquakes, wildfires and floods.
- 11 An event must be linked to a site, which is a geographic entity freely chosen by the relevant ONF-RTM operator. Each site is identified by a name, an identifier, and a

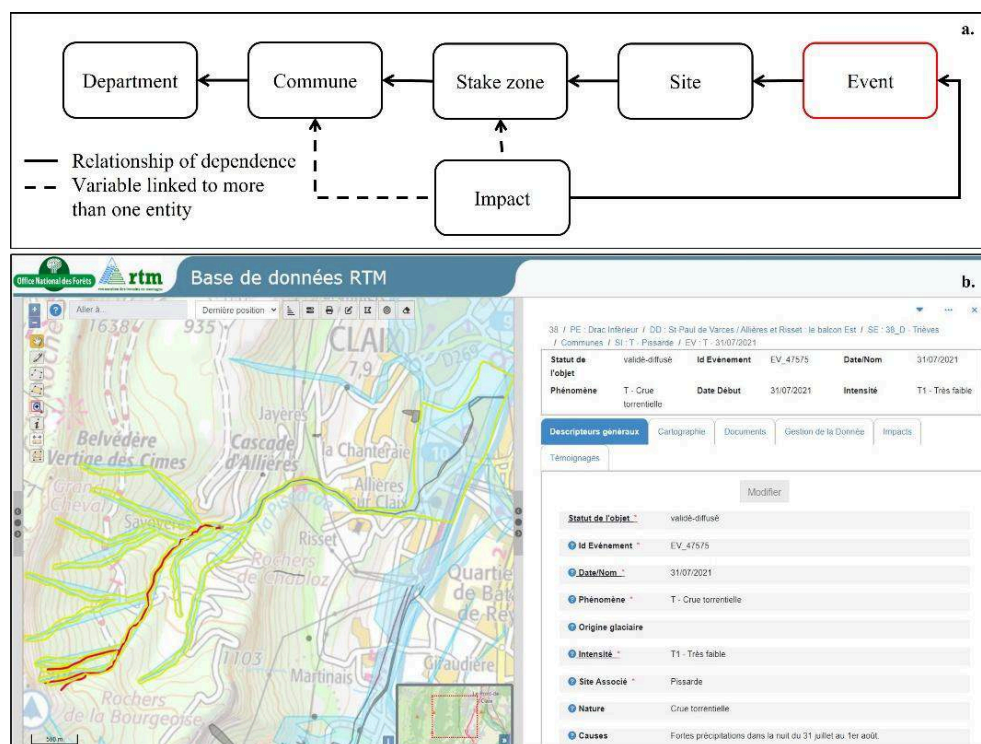
hazard code. Each site is characterized by a specific type of natural hazard. Each event is linked to a single site, as well as a municipality and a department (Fig. 2). For each event, impacts are systematically recorded using various indicators for their description such as casualties (number of deaths and/or injured), damages (direct impacts on material assets such as buildings, roads, bridges, vegetation, etc.), and disruptions (indirect impacts such as network outages, temporary and/or permanent closures of economic, educational, or recreational establishments, etc.). Within the structure of the BD-RTM, impacts are linked to an event, to a municipality and to the impacted zones. Therefore, there is no direct link between impacts and sites, except through the impact zones (Fig. 2).

- 12 Today, the inputting and recording of events is the responsibility of ONF-RTM agents as well as a network of departmental and national administrators. In each service, a database manager and an event thematic coordinator are appointed to ensure data consistency and dissemination (Tab. 1).
- 13 Specifically, within the ONF-RTM service of Isère, events can be reported by any agent working in the field or responsible for a specific sector. Events are then submitted for validation by the departmental thematic coordinator, who is responsible for changing their status to “validated and disseminated” in the database.

Table 1. Distribution of roles related to the management and access rights of the BD-RTM within the RTM departmental services, grouped into three agencies: the Northern Alps Agency for departments 73, 74 et 38; the Southern Alps Agency for departments 04, 05, 06 and the Pyrenees Agency for departments 09, 11, 31, 64, 65 et 66

Status	Associated Missions
National Administrator	<ul style="list-style-type: none"> • Manages the creation of user accounts and their permissions • Receives and analyzes technical issues • Generates exports (monthly/annual) for statistical monitoring, analysis and data consistency control • Trains new BD-RTM users
Agency Director	<ul style="list-style-type: none"> • Responsible for data production and quality at the department level • Organizes the distribution of roles and associated missions within the service • Ensures validation and approves data distribution
Agency Correspondent	<ul style="list-style-type: none"> • Participates in discussions on major BD-RTM issues with the National Administrator • Organizes the data collection and lists the requirements of users of the Agency's services • Assists in disseminating national information to users
Agency BD Manager	<ul style="list-style-type: none"> • Centralizes permissions for BD-RTM objects • Ensures data consistency by : defining data protocols and verifying and checking data entry • Ensures, by delegation of the Agency Director, the validation and approves the dissemination of data
Thematic Coordinator	<ul style="list-style-type: none"> • Ensures, by delegation from the Agency BD Manager, data consistency by: defining data protocols, verifying and checking data entry • Ensures, by delegation from the Agency BD Manager, the validation and approves the dissemination of data for a specific theme or a geographical area.
User	<ul style="list-style-type: none"> • Enters data according to protocols transmitted by the Agency BD Manager • Manages BD-RTM objects for which it has “validation” delegation. • Reports user issues in production to the National Administrator • Reports development requirements to the Agency Correspondent

Figure 2. a) Structure of the BD-RTM. Each variable has a direct dependency on another. For instance, an event is always linked to a site in the BD-RTM. However, the “Impact” variable is connected to multiple entities; it depends directly on an event, as well as an area and a municipality. b) The BD-RTM interface: on the right, the event description of a torrential flood in Claix on the 31/07/2021, and on the left, an interactive map showing the site (in yellow) and the event’s path (in red)



Methods

Historical Timeline on the Evolution of the Inventory Context

- 14 In order to illustrate the temporal origins of the data, a state of the art was conducted, including bibliographic research, consultation of archives from the ONF-RTM 38 service, and interviews with some RTM agents who participated in the creation of the BD-RTM or contributed to its maintenance. All these resources cover both national and departmental scales. Indeed, the national context must be considered to understand the changes within the ONF-RTM service in Isère. This review highlighted relevant indicators to represent the evolution of risk knowledge over time and the methods used to structure this knowledge. The indicators studied include the evolution of natural hazard regulations in France and structural changes since the late 19th century within what is today the ONF-RTM service: creation, different activity periods, affiliation with various structures, missions, and available resources (tools and employees). This state of art and its indicators have been summarized into a timeline (Fig. 3).

Example of Data Extraction and Processing at the Scale of Isère

- 15 For this study, data were extracted from the BD-RTM as of 31/12/2023 for the Isère department. For the purposes of this article, various variables were selected (Tab. 2).

Table 2. Fields recorded in the BD-RTM and used in this study. The “Impacts” descriptor combines various descriptive fields of damages observed during the event, including “Damages,” which correspond to direct impacts on material assets, and “Disruptions,” dealing with indirect impacts caused by the event (temporary or permanent interruptions of infrastructure and networks)

Descriptors	Field name	Description
Location	Commune	Commune impacted by the event
	SI_code	Event site number
	SI_name	Event site name
Date	an_evt	Event year
	date_evt	Event date
Typology	Ev_pheno	Type of hazard
Impact	Victims	Yes-No
	Damages	Yes-No
	Disruptions	Yes-No

- 16 The natural hazards considered for the analyses are the six main ones recorded in the BD-RTM: avalanches, landslides, torrential floods, rockfalls, gullying, and subsidence. These hazards represent those for which the ONF-RTM service has been commissioned by the Ministry of Ecological Transition, Energy, Climate, and Risk Prevention (MTEECPR). Floods, wildfires, and earthquakes were excluded from the analyses due to their incomplete inventory in the BD-RTM. Also, only events with the status “validated and disseminated”, meaning approved by the thematic coordinator and made available to the public, were included.
- 17 The cartographic representation of events was conducted at the scale of the sites. To facilitate visualization, each site is represented by its centroid. Based on known dates of events, annual chronologies (from 01/01 to 31/12) were constructed. These time series presented in the article begin in 1860, marking the implementation of the first policies related to RTM within the Administration of Waters and Forests (the law of 28/07/1860 on mountain reforestation, repealed by the law of 04/04/1882 on the restoration and conservation of mountain areas). Following the 1860 laws, RTM personnel became increasingly active, which initiated a period characterized by significant land acquisition, construction projects, and documentation (Fig. 3d).

Results

Contextualization of the Census and Data Capture

From the Origin of the Data...

- 18 There are two ways of recording events and enhancing the BD-RTM. On the one hand, through direct input from RTM agents (on the field), and on the other, through retrospective research in archives, which is necessary for the production of documents (risk prevention plans, communal hazard maps, flood prevention action programs, and watershed studies) (Fig. 3e). These historical investigations are conducted as part of occasional missions undertaken during specific research programs.

- 19 For the Isère department, the vast majority of historical events recorded in the BD-RTM originate from research conducted during a specific mission in the 1990s to the service archives and the departmental archives of Isère (Fig. 3e). This research enabled the consultation of the main documentary sources available:
1. The historical collections of the “Ponts et Chaussées”, the forestry services of the 18th century, and the departmental roads service (which include numerous testimonies of events impacting roads) preserved in the departmental archives of Isère.
 2. Historical reference publications, such as *Les inondations en France du VIe siècle à nos jours* by Maurice Champion (1864), *La restauration des Alpes* by Paul Mougin (1931), and the numerous articles and reports by Maurice Pardé (1925–1968), including those from 1929, 1937, and 1941.
- 20 Until the early 2000s, historical research was sporadically enriched by construction projects and documents that made it possible to collect old events described in the internal archives of the ONF-RTM service of Isère, in particular the acquisition files for state-owned forests (1880–1975) and the collection of historical photographs (1880–1955).
- 21 In parallel with this internal work by the ONF-RTM service, since the early 1970s, the national risk prevention agency has initiated a program for mapping hazards and risks. In 1980, a technical cartography organization was established in Isère, led by the ONF-RTM service under the administrative authority of the Prefect and its departments (DDE, DDAF). This policy has evolved alongside legislative changes (PER in 1982, PPR in 1995) and state organizational reforms (DDT in 2009), without altering its objectives to this day. As part of this initiative, field surveys have been conducted to gather data on historical hazards in the studied territories, generally involving municipalities and their elected officials, residents, and local knowledge holders. This extensive work carried out by ONF-RTM agents and specialized consulting firms, has significantly contributed to and continues to enhance the inventory of events in the BD-RTM and the database itself.
- 22 Finally, since the 1980s, a notable increase in the national workforce of ONF-RTM services has been observed (Fig. 3f). Moreover, there has been a shift in the predominant professions: technical and administrative support has been reduced from 38 employees in 1960 to 17 in 2013, making way for more technical specialists (engineers, geologists, hydraulic engineers), who were absent in 1960 but numbered 49 in 2013. These specialists now provide critical expertise on natural hazards, and improve the quality of information recorded into the database. The remaining workforce is made up of supervisors and technicians.

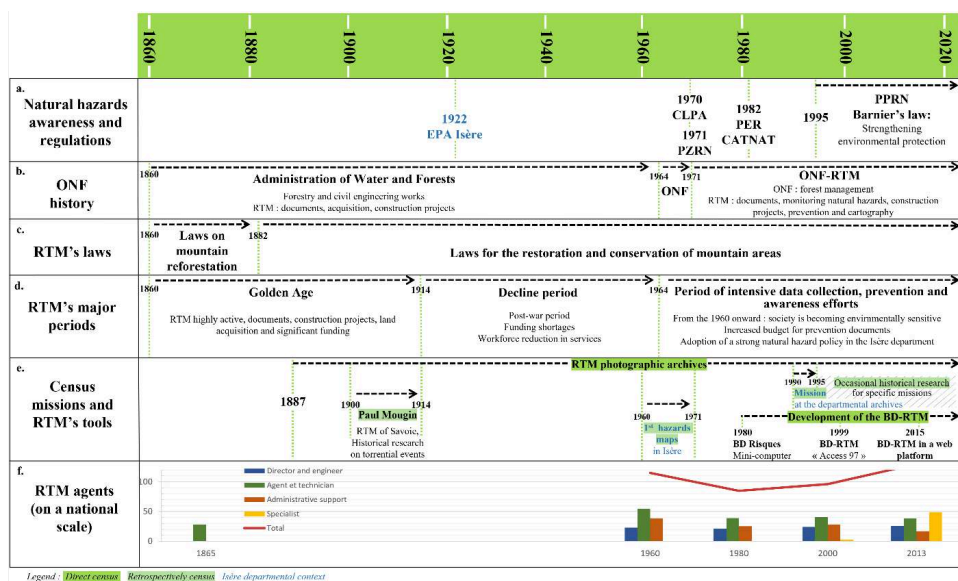
... to Its Structuring and Capture into the BD-RTM

- 23 The first RTM database, called “BD Risques”, was created in 1980 (Fig. 3e). Its objective was to gather information on significant events at the departmental scale, in order to communicate on natural hazards and produce prevention documents. At that time, the database was implemented on a mini-computer system. The procedure detailing by whom and how the BD Risques was managed during this period (1980–1999) remains undocumented to this day: there was no designated administrator, no fixed data input protocol, and each departmental service operated with its own organizational system.

During this same period, the first event records were introduced in paper format; in Isère, these records are still preserved in the archives of the ONF-RTM service.

- 24 From 1999 to 2015, the BD-RTM was made available under “Access 97” (Fig. 3e). In 2001, its development and deployment were commissioned and financed by ONF-RTM’s two supervisory ministries, with two specific objectives: the Ministry of Agriculture, for the inventory and monitoring of state-owned RTM structures, and the Ministry of the Environment, for the recording of natural hazard events in mountainous areas. Since then, the ONF-RTM service has implemented fixed and nationally-standardized protocols for inputting events into the BD-RTM, which in fact includes 12 departmental BD-RTMs based on the same model. Until 2015, specialized administrative employees were assigned full-time to input events into the database, using “digital event forms” completed by sector managers and technical experts.
- 25 In 2015, the unification of the various departmental BD-RTMs was initiated. This effort relied on the modernization of the data input tool, which was centralized into the previously introduced single web platform, accessible to all services (Fig. 3e). From now on, technical employees directly input data without the involvement of administrative personnel. This standardization has led to some difficulties in terms of data homogeneity, particularly with duplicate entries. But, on the other hand, the tool is becoming increasingly fluid and complete.

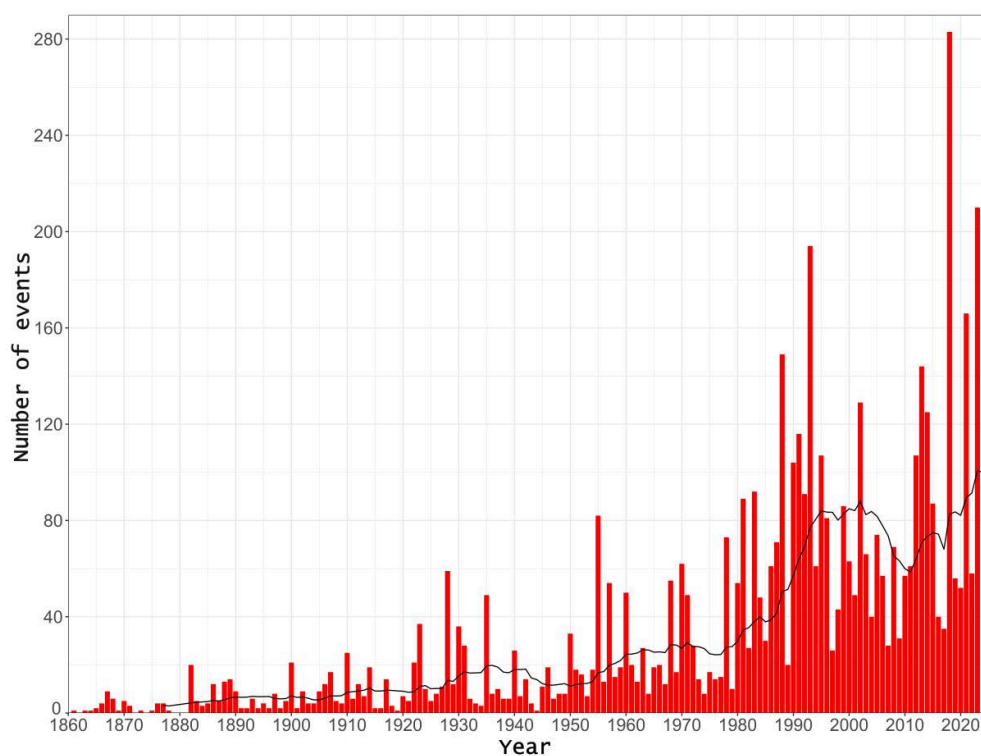
Figure 3. Synthetic timeline of the history of the RTM service since 1860, on a national scale. This timeline is divided into six categories: a) evolution of natural hazard regulations, b) history of the National Forestry Office (ONF), c) introduction of laws concerning the restoration of mountainous areas, d) major historical periods of the Restoration of Mountainous Areas service (RTM), e) creation and development of the BD-RTM, and f) evolution of the workforce in the services. Information in blue highlights specific elements unique to the Isère department. The hatched area corresponds to a period during which the RTM conducted specific historical research missions to produce Risk Prevention Plans (PPR) or similar documents. Information is sourced from: Carladous et al., 2016; Besson, 1996 ; Brugnot and Cassayre, 2002; Métaillé, 1988. Other abbreviations used: Permanent Avalanche Survey (EPA), Localization Map of Avalanche Phenomena (CLPA), Natural Hazard Zone Plan (PZRN), Predictive Natural Hazard Exposure Plans (PER), Natural Disaster State (CATNAT), Predictive Natural Risk Prevention Plan (PPRN)



Chronology of Events in Isère

- 26 On the 31st of December 2023, the BD-RTM recorded 5888 validated and disseminated events in Isère for the hazards included in the following illustrations (Tab. 3).
- 27 For 98.5% of these events, the year of occurrence is known and recorded in the BD-RTM. A precise date, indicating the exact day of the event, is available for 59% of the events, and the month of occurrence is known for 75%. In Isère, the earliest recorded event dates back to 1132. 13% of the events occurred before 1900, while 87% are dated between 1900 and 2023 (Fig. 4). The chronology by century reveals that the 19th century accounts for only 5.5% of the total events, distinctly lower than the 20th century, with 51% of the events (3,030 events), and the 21st century, with 36% of the events.

Figure 4. Chronological distribution of the total number of events recorded in the BD-RTM for the Isère department since 1860, showing raw annual event and a 15-year moving average (in black). Data exported on the 31/12/2023



- 28 The chronology reveals a trend of increasing numbers of recorded events. Between 1860 and 1999, an average of 25 events were recorded each year, whereas since 2000, almost 85 events have been documented each year (Fig. 4).
- 29 If we look at the seasonality of events, January (542 events), June (525 events), and July (491 events) are the months with the highest recorded events (Fig. 5). These three months alone account for 35% of the events for which the month of occurrence is known.

30 Independent time series were developed for the four main hazards (avalanches, landslides, rockfalls, and torrential floods; Fig. 6).

- Torrential floods represent the hazard with the highest number of recorded events in Isère, with a total of 2808 events: 1195 events (43%) between 1219 and 1980, and 1613 events (57%) between 1980 and 2023 (Fig. 6d). Since 1980, an average of 35 events have been recorded each year. July (382 events), June (346 events), August (293 events), and October (216 events) account for 44% of torrential flood events (Fig. 5).
- Landslides are the second most represented hazard in Isère, with 1239 recorded events (Tab. 3). 80% of these events were recorded between 1980 and 2023 (Fig. 6b). January is the month with the highest number of landslides (17%) (Fig. 5).
- Rockfalls total 853 events (Tab. 3). Approximately 66% of these were recorded between 1980 and 2023, with an average of 12 rockfalls per year (Fig. 6c). Over the same period, no clear seasonal trend is observed.
- Avalanches total 684 recorded events, which 58% occurred prior to 1980. This is the only hazard with a lower number of recorded events over the recent period (1980–2023; Fig. 6a). Avalanches mainly occur in January and February (45% of events) (Fig. 5).

Figure 5. Seasonal distribution by natural hazard of events recorded in the BD-RTM for the Isère department. 25% of the events in the database are missing information on the month of occurrence and are therefore not represented in this figure. Data exported on the 31/12/2023

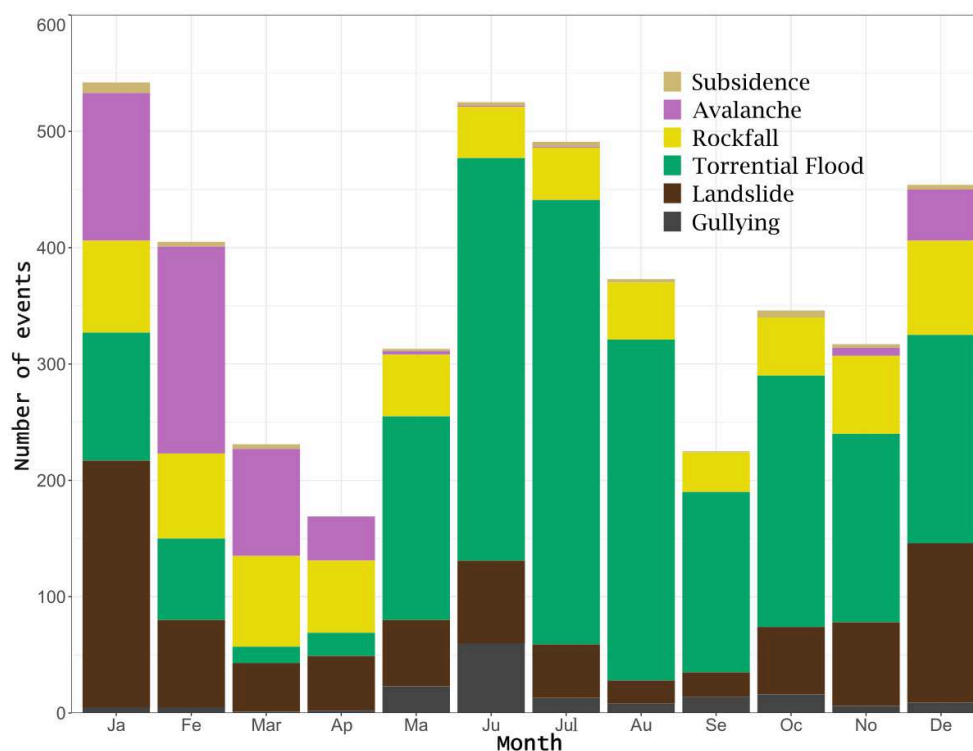
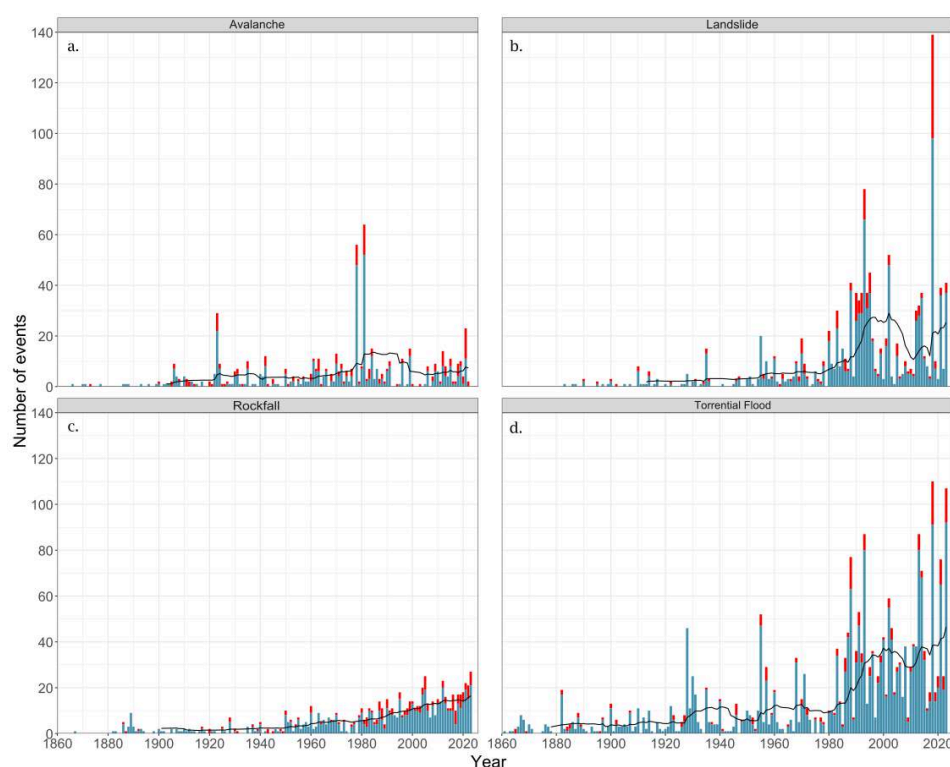


Table 3. Total number and percentage of events in the Isère department for the hazards recorded in the BD-RTM. Data exported on the 31/12/2023

Natural Hazard	Number of Events	Proportion (%)
Avalanche	684	12 %

Landslide	1239	21 %
Rockfall	853	14 %
Torrential Flood	2808	48 %
Subsidence	71	1 %
Gullying	233	4 %
Total	5888	100 %

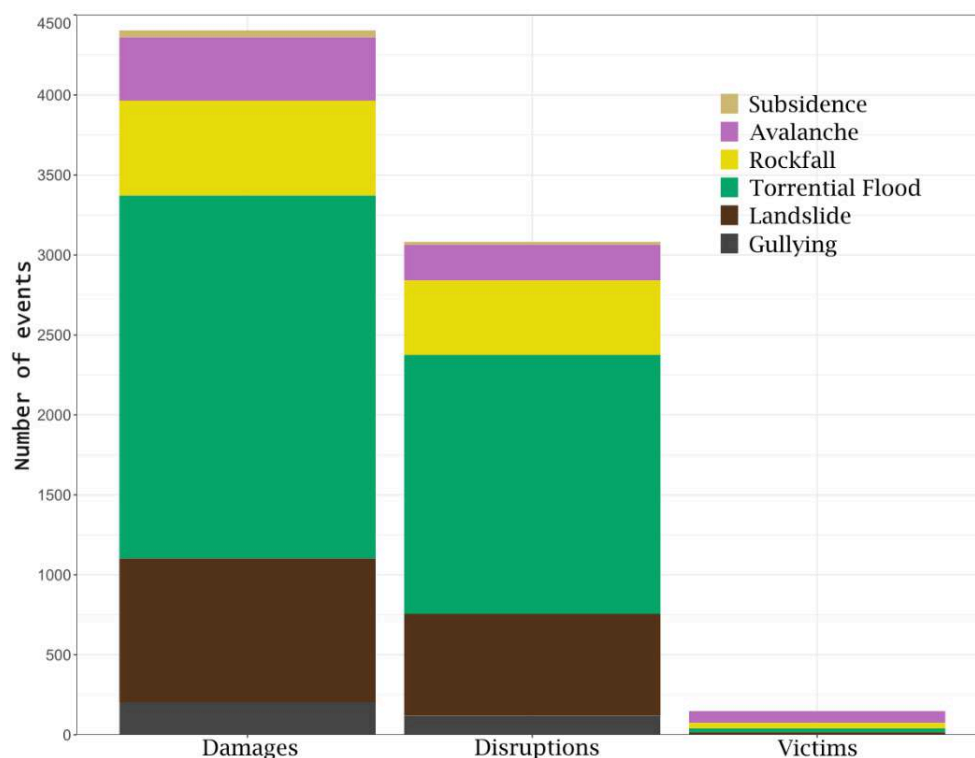
Figure 6. Chronological distribution of BD-RTM events in the Isère department since 1860, for the four main hazards (Avalanche [a], Landslide [b], Rockfall (c), and Torrential Flood [d]) showing raw annual event and a 15-year moving average (in black). Events causing impacts (direct damage), disruption (indirect damage) or victims are shown in blue, while events without impacts are shown in red. Data exported on the 31/12/2023



- 31 The BD-RTM also provides information on the impacts caused by events. Combining damages, disruptions, and casualties, 5040 events have recorded impacts (damages and/or disruptions and/or casualties), representing 85% of all events. The chronology highlights disparities across different hazards (Fig. 6). Avalanches (508 events) and rockfalls (697 events) account for the lowest proportion of events with impacts (Fig. 6a.c). However, while only 149 events resulted in at least one casualty, 49% of these were avalanches (Fig. 7). In contrast, landslides and torrential floods are the hazards with the highest number of events causing damages and disruptions (Fig. 6b.d, Fig. 7). Specifically, torrential floods account for 50% of events causing impacts (2542 events). The average number of events with impacts has been steadily increasing since

1980. The year 2018 stands out with a strong peak, where 91 events caused impacts in Isère (out of 110 total events that year), linked to Storm Eleanor in January 2018 (Fig. 6d). Regarding landslides, 1030 events causing impact were recorded, representing 20% of impact events (Fig. 7). The average number of impacts related to landslides follows the similar upward trend as torrential floods, with a marked increase since 1980 (Fig. 6b).

Figure 7. Distribution of events by the type of impact caused and by natural hazard types. A total of 4404 events caused damages (75% of all recorded events), 3082 events caused disruptions (52% of events), and 149 events caused at least one casualty, representing only 2% of the overall chronology

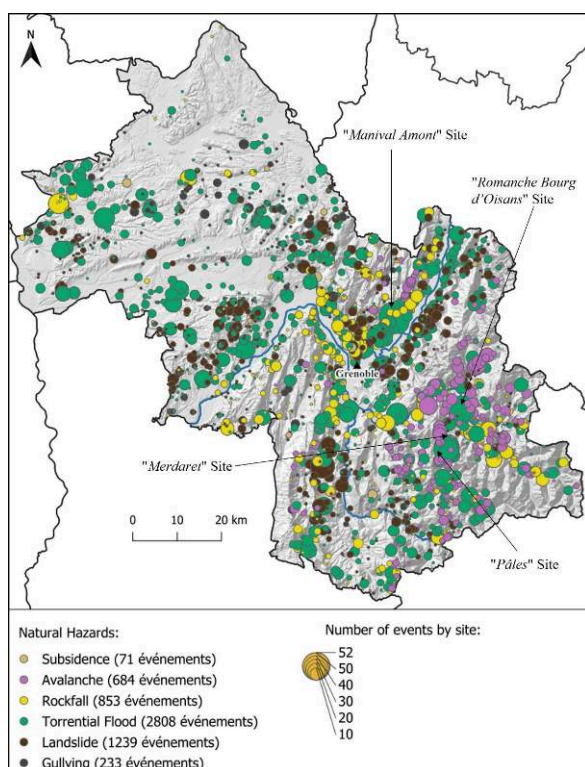


Spatial Distribution of Events in the Isère Department

- 32 In the Isère department, events have been recorded across 2082 sites (Fig. 8). This includes 259 avalanche sites, 268 rockfall sites, 641 torrential flood sites, and 473 landslide sites. The site with the highest number of recorded events is the torrential flood site “Manival Amont” (52 events), located in the villages of Saint-Ismier and Saint-Nazaire-les-Eymes. Three additional sites have reached the threshold of 40 events, and all correspond to torrential flood sites: the “Merdaret” site with 47 events (village of Chantelouve), the “Pâles” site with 45 events (village of Chantelouve), and the “Romanche Bourg d’Oisans” site with 45 events (village of Bourg d’Oisans). Approximately 81% of sites have fewer than 10 recorded events; moreover, 867 sites counted only one event. Only 3% of sites report between 10 and 40 events. For 89% of the events, the associated site is specified in the BD-RTM. The remaining 10% of events (593 events) have no precise location and have, therefore, been linked to the corresponding municipalities. For the most part, these events correspond to older events acquired through historical research.

- 33 The spatial distribution of events in Isère reveals a concentration in the southern part of the department, where the relief is high (Fig. 8). More specifically, events are predominantly recorded along the valleys, where human activities and associated vulnerabilities are significant. In particular, we can mention the Drac Valley and the Isère Valley (Fig. 1, Fig. 8).
- 34 Most avalanche events are located in the Oisans and Grandes Rousses mountain ranges, while torrential floods, rockfalls, and landslides are distributed more evenly across the department (Fig. 1, Fig. 8).

Figure 8. Spatial representation of the number of events per site recorded in the BD-RTM for the Isère department as of 31/12/2023. Each site is represented on the figure by a point materializing the centroid of the site. Events not linked to a specific site are represented by a point at the centroid of the municipality affected. The most active sites are identified with black arrows



Discussion

Spatio-Temporal Distribution of Events

- 35 This article traces the origins of the data currently recorded in the BD-RTM of Isère and the processes involved in event documentation. The evolution of risk prevention policies, as well as the structural organization and functioning of the ONF-RTM service, may provide a valid hypothesis to explain the observed and analysed distribution of events, particularly from temporal and spatial perspectives. Indeed, the chronology of different hazards shows a significant upward trend starting in the 1980s for torrential floods, landslides, and rockfalls (Fig. 6). This increase is due to the introduction of handwritten event records and the practice of documenting hazards when they have the potential to impact a stake or asset. During this period, there was a deliberate effort

to enhance risk knowledge by documenting and communicating the existence of natural hazards while maintaining written records. This type of evolution, heavily influenced by data sources, is fairly common in databases dedicated to natural hazards, especially when they integrate sources of varied origins (Giacona *et al.*, 2017; 2021).

- 36 Moreover, other factors contribute to explaining the spatio-temporal distribution of events, such as the evolution of anthropogenic stakes and the associated induced risks. Since the 20th century, the Isère department has experienced significant changes in anthropogenic factors, including population growth, urban expansion, and the development of road networks. Events in Isère are predominantly concentrated in the southern part of the department, where the relief is high, but also in valleys where anthropogenic stakes are numerous (Fig. 8). Mountainous areas are increasingly anthropized, accommodating new recreational activities. This territorial evolution has amplified vulnerability to natural hazards. Today, many events are documented due to the risks of impact on a stake and the reported damages, which explains why 85% of the events recorded in the BD-RTM for the Isère department caused impacts. This strong relationship between event databases and stakes/vulnerability is also relatively typical (Favier and Granet-Abisset, 2000; Giacona *et al.*, 2019a).
- 37 Similarly, the preferential localization and seasonality of events directly correspond to those of the associated phenomena (for example avalanches occurring in mountainous and high-altitude areas during the winter season). However, changes in the seasonality or preferential localization, and typology of events are increasingly well-documented and/or expected with climate change (e.g., Eckert *et al.*, 2024; Jacquemart *et al.*, 2024). Major events with significant consequences for populations and infrastructures appear to be occurring more frequently, or at least in locations where they were not previously expected. For instance, a major event in June 2024 impacted the Isère department: a torrential flood in the hamlet of La Bérarde (Écrins, France) on June 21, 2024, caused extensive damage, including the destruction of several houses and the evacuation of all residents (114 people). Such events are difficult to formally attribute to climate change, and require caution regarding any generalization of increased natural hazards. Yet these events highlight the growing severity of their consequences. In this regard, the information contained in the BD-RTM provides valuable insights for characterizing ongoing changes.
- 38 Finally, the analysis was conducted for a specific ONF-RTM service, the Isère department. Certain factors and tendencies, such as the seasonality of specific hazards, their relationship to geology and topography, or the evolution of the number of events linked to the national history of the RTM, are not exclusive to the context of Isère. However, other elements are more specific to the local context, such as significant archival research conducted during the 1990s. The analysis and extrapolation of the obtained results, therefore, require consideration of both local and national factors. This study would benefit from being replicated in other departments or even generalized to the entire database.

A First Step Towards Risk Awareness

- 39 Tracing the origin of data is essential for understanding the temporalities and dynamics of risks and hazards. To deepen analyses and make better use of the data, a socio-historical contextualization of event data is therefore a prerequisite. Giacona *et*

al. (2019a) propose a methodology comprising four steps: (1) establishing an event inventory (creation of a geochronology), (2) socio-historical and biophysical contextualization of the event inventory, (3) matching with an analysis of the spatio-temporal distribution of events, and finally, (4) prioritizing the controlling factors. This approach should now be fully applied to the events in Isère, in order to characterize and understand the evolution of mountain risks in the region.

- 40 At this point, we have focused on a very limited portion of this work, namely describing the data and conducting preliminary analyses of the factors behind it. The perspective now needs to be broadened to include the systematic documentation of contextual factors and the various components of risk. In particular, while it includes information on impacts, the BD-RTM, by its construction and history, is mainly built around the occurrence of hazards. In order to understand changes in risk evolution, we must integrate the information into a much more systemic analysis, including aspects such as analysis of risk perceptions, management procedures, and the complex interactions between risks and risk management, for example.

Conclusions and Perspectives

Strengths, Limits and Possible Developments of the BD-RTM

- 41 The BD-RTM is the result of the unique history of the ONF-RTM service, explaining the nature of its data and numerous advantages. Firstly, this database is multi-hazard: it is currently the only French database that records events for various types of natural hazards specific to mountainous territories. Secondly, it has a wide temporality: the oldest events in Isère recorded in the database date back to 1132. While these very old events are few and isolated, 13% of the recorded events are still dated prior to 1900. Thirdly, events in the BD-RTM are recorded on a fine spatial scale, enabling them to be localized by associating them with specific risk zones, such as avalanche paths, torrents, and watersheds; an attribute that is not always found in other French databases. Fourthly, the BD-RTM is continuously updated: it can be enriched through historical research (retrospective observation) in parallel with real-time observation (recording of new events). Fifthly, the BD-RTM provides extensive information on events, including the damages they may have caused. Lastly, the BD-RTM has the advantage of following strict input protocols that have barely changed over time, at least since the early 2000s.
- 42 Nevertheless, the specific context of the BD-RTM also results in certain weaknesses. Firstly, the information originates from temporally heterogeneous sources. This article focuses on the specific case of Isère, but significant disparities exist in the data across departments, at least until the early 2000s. Secondly, the database's goal of serving as an observatory for natural hazards in mountainous areas can be considered only partially achieved. In fact, other hazards, such as wildfires and earthquakes, can also affect mountainous areas. These hazards can, through cascading processes, trigger events such as avalanches or rockfalls. Structurally, the BD-RTM could be expanded to enhance its role as a territorial observatory. However, the ONF-RTM services are not explicitly tasked with this, and other specialized databases already exist for specific hazard, such as PROMETHEE for wildfires and SISFrance for earthquakes. A more effective approach might involve fostering interconnectivity between these databases

to facilitate cross-referencing for territorial applications. Thirdly, the BD-RTM is supplemented by historical research, which is typically conducted on occasional missions by the RTM service during specific research programs. This punctual research enhances the database but also contributes to a collection of heterogeneous events, complicating the contextualization process mentioned earlier. For instance, not all villages have PPRs (Risk Prevention Plans), meaning they do not benefit from systematic archival reviews or an oral memory collection; work that would be interesting to systematize, but which requires substantial resources.

Expanding the Potential Uses

- 43 At this point, the use of the BD-RTM data for operational purposes other than local risk management remains relatively limited. Indeed, the database was initially created to provide the knowledge of risk that is essential for effective and adaptive management. It was, therefore, initially a technical tool for RTM agents. Consequently, it remains relatively unknown by the scientific community and, as noted earlier, has specific characteristics that complicate the direct analysis of event series. Nonetheless, some studies addressing the behavior and frequency of natural hazards in the Alps in relation to various factors, such as climate change, have already used BD-RTM data (Jomelli *et al.*, 2011 ; Leone *et al.*, 2011 ; Pavlova *et al.*, 2011 ; Leone *et al.*, 2014 ; Einhorn *et al.*, 2015 ; Jomelli *et al.*, 2015 ; Lallias-Tacon *et al.*, 2017 ; Jomelli *et al.*, 2019 ; Creutin *et al.*, 2022 ; Mas *et al.*, 2022). The conclusive results of these studies, such as the response of debris flows to global warming, demonstrate the interest and quality of the data compiled in the database. More specifically, while the spatial and temporal distribution of events primarily reflects the influence of data sources, it also contains rich information regarding risks and natural hazards knowledge. Expanding the exploitation of this existing data will be crucial to address specific issues such as triggering conditions, temporal evolution of activity, and damage characteristics associated with different natural hazards.
- 44 To foster such developments, efforts are underway to improve the tool and its functionalities, (accessibility, querying, etc). However, a deeper contextualization of the data at both national and local scales, accounting for source effects, will certainly be a critical prerequisite for obtaining robust results. This will probably require strengthened collaboration between researchers and managers to enhance data quality and its utilization. Such a dialogue would contribute more broadly to the implementation of prevention strategies more adapted to climatic and environmental threats, and consequently to more effective sustainable management of natural hazards.

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NOTES

1. This article uses the specific terminology of the Restoration of Mountainous Areas Service of the French National Forestry Office to accurately reflect the language and practices of this institution. In this way, the terms “hazard”, referring to a natural process, and “event”, relating to a natural hazard whose trace has been preserved in the BD-RTM, are clearly distinguished in the article.

ABSTRACTS

Databases of natural hazards play a crucial role for assessing related risks and in mitigating their impacts on the environment. In the mountainous regions of France, potentially destructive events are both numerous and diverse, however, only a limited number of databases containing information on past occurrences exist. The database of the RTM service (Restoration of Mountainous Areas service, BD-RTM) consolidates such information through a multi-hazard

approach over an extended timeframe, integrating systematic observations and a retrospective compilation of various sources. This article outlines the key features of this unique database. Focusing on the Isère department (38), which records the highest number of events among the 12 areas covered by the BD-RTM, we present (1) the history of the database, particularly the origins of the data and its structural framework, and (2) the richness and diversity of the recorded information. On the 31st of December 2023, the BD-RTM had documented 5,888 events in the Isère department, with nearly 70% consisting of torrential floods and landslides. Furthermore, 85% of the recorded events resulted in damages. A notable increase in the frequency of events is evident from the 2000s onwards, with an average of 85 events recorded annually since that time. All the information is accessible for further spatial and temporal analyses, including statistical and historical assessments, as well as integration with other data

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Keywords: database, natural hazards, mountain, natural risk assessment

Mots-clés: Les bases de données événementielles sont importantes pour la compréhension des risques d'origine naturelle et la limitation des dommages associés. En France, en zones de montagne, les phénomènes naturels potentiellement dommageables et les enjeux sont nombreux et diversifiés, mais les bases de données recensant les informations liées aux événements du passé sont peu nombreuses. La base de données du service de Restauration des terrains de montagne de l'Office national des forêts (BD-RTM) capitalise l'information selon une appr, celui recensant le plus d'événements sur les 12 couverts par la BD-RTM, (1) l'historique et la structure de cette base de données, notamment l'origine des données, sont présentés et (2) la richesse et la diversité des informations consignées sont illustrées. Dans la BD-RTM, 5888 événements sont recensés en Isère au 31/12/2023, dont près de 70 % sont des crues torrentielles et des glissements de terrain. Également, 85 % des événements enregistrés ont causé des dommages. Une nette augmentation dans la chronologie des événements est visible à partir des années 2000, en moyenne 85 événements sont répertoriés chaque année. Ces informations sont disponibles pour des analyses spatiales et temporelles plus approfondies : statistiques, historiques, couplages avec d'autres données, etc.

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