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Managing glacial and periglacial hazards in the Alps: a geohistorical approach

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Glacial and periglacial hazards, Risk management, Risk perception, Geo-history, European Alps

Abstract
Through a geo-historical study, we compile an inventory of glacial and periglacial events that have prompted risk management actions in the European Alps over the last centuries. This management is analysed through seven guiding principles/pillars: hazard understanding, preventive information, land-use planning, monitoring and surveillance, hazard-vulnerability-exposure mitigation, crisis management preparedness, and resilience. The objective of this research is to examine how risk management methods have evolved over time and across different Alpine countries. The western Swiss Alps and the French Alps, home to the highest elevations, have experienced most of the major events.
Certain events, such as the 1892 collapse of the Tête Rousse glacier's water pocket, represent key turning points that mark a rupture or renewal in how risks are perceived and addressed. Today, glacial and periglacial risk management benefits from improved understanding of both hazards and vulnerabilities. Our geo-historical analysis highlights that the inclusion of the population in crisis management has become an increasingly significant factor in making-decision processus. However, current risk management practices remain limited and would benefit from more participatory approaches, which in turn depends partly on the perception of hazards and their integration into management practices.

1. Introduction

Rock and glacier mass movements in high mountains pose significant risks to communities and infrastructure. Numerous past examples show how glacial and periglacial processes have affected Alpine valleys through large-scale and/or cascading phenomena (*e.g.*, Haeberli et al., 2016; Magnin et al., 2023), and their frequency and volume appear to be increasing (Jacquemart et al., 2024). Recent disasters in Bondo (G[illegible]bünden, CH) in August 2017 (Ancey, 2017; Walter et al., 2020), La Bérarde (Isère, FR) in June [illegible] (Mainieri et al., 2025), and Blatten (Valais, CH) in May 2025 following a massive rock-ice avalanche from the Birch Glacier illustrates this intensification.
This study focusses on major hazards affecting valley floors: ice, rock, and mixed avalanches, glacial lake outburst floods (GLOFs) and debris flows. These are defined as natural phenomenon impacting Alpine territories (Moles, 1972; Bisqu[illegible]l., 2025). A process becomes a *risk* when it threatens lives, economic assets, or the environment. T[illegible]tion of an *event* is useful for historians as it marks "a cut, a discontinuity", something "interesting", sufficiently "important" or "new" to be "told or enacted" (Dosse, 2010; Giacona et al., 2017). The *issues* are thus the exposed elements with varying vulnerabilities to each hazard (Defossez et al., 2018).

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Rockfalls and rock avalanches in high mountains are mainly triggered by permafrost degradation and/or glacial debuttressing (Fischer et al., 2006; Gruber and Haeberli, 2007; Huggel et al., 2010). They may directly impact valley areas or provide material that triggers debris flows (Walter et al., 2020).
Ice avalan[illegible]cur when a glacier section detaches and slides downslope (Alean, 1985; Richard, 2005; Faillettaz e[illegible]015), destroying infrastructure, forests and lives, as in the 1965 Allalin glacier collapse on the Mattmark dam (Dalban Canassy et al., 2011). Indirectly, they can trigger snow avalanches (Margreth and Funk, 1999) or debris flows when ice temporary dams a watercourse (Richard, 2005).
GLOFs arise when a glacial lake or a water suddenly drains, releasing large volumes of water that can evolve into debris [illegible] if sufficient sediment is available (Richard, 2005; Huss et al., 2007; Carrivick and Tweed, 2016; [illegible] et al., 2019). Their impacts can devastate entire valleys, as seen in the Bagnes valley below the Gietroz glacier in 1595 and 1818 (Vincent et al., 2010; Ancey et al., 2019).
Integrated management of th[illegible]erging, climate-related risks (Prudent-Richard et al., 2008; Stoffel et al., 2014; Jacquemart et al., [illegible]s ess[illegible]
The database developed this study docu[illegible] glacial and periglacial events across the European Alps over the past two centuries that e required risk management (*i.e.* with implementation of one or more principles of risk management). Our aim is to assess the frequency and intensity of such events, trace historical trends, and identi[illegible]fferences between countries. A historical approach enables the analysis of change processes in risk [illegible]agement(Giacona et al., 2017, 2019), beyond mere event description (Girard and Rivière-Honegger, 2015).
We seek to understand how Alpine glacial and periglacial hazards have shaped scientific knowledge and risk management practices.
The paper first outlines the theoretical and historical framework of risk management, followed by the methods used to construct the database and apply the seven principles of risk management. Results describe the spatial and temporal distribution of events and corresponding management actions. Finally, we discuss the data's limitations and the challenges of future prevention in a changing climate..

2. State of the art and theoretical positioning

The concepts used here need to be defined to clarify our approach. A risk refers to the probability of damage resulting from interactions between a physical process (hazard) and vulnerability (Pigeon, 2002). The hazards studied occur at high altitudes (above 2,000-2,500 m a.s.l.) and may reach valley floors, threatening infrastructure, livelihoods, ecosystems and populations (IPCC, 2023). Mountains valleys are thus considered vulnerable because of their exposure to such hazards. Vulnerability also depends on resilience and sensitivity, *i.e.* system's ability to absorb shocks and the degree of damage it can sustain (Reghezza et al., 2006; Schneiderbauer and Ehrlich, 2004; Defossez et al., 2018). Exposure reflects the spatial and social closeness between hazard sources and affected communities.

The ongoing expansion of urbanised areas in high Alpine valleys increases potential losses and justifies effective risk management (Allen et al., 2017). The later encompasses actions and strategies to anticipate, reduce and respond to hazards (Leone et al., [illegible] It also aims to reduce uncertainty through new scientific knowledge (Margreth et al., 2011, 2017[illegible]le similar to other Alpine hazards, glacial and periglacial processes are distinguished by their rapid evolution and exceptional magnitude (Richard, 2005). Anticipation remains complex because these hazards evolve with the cryosphere: glacier retreat, de-icing of rock faces, permafrost degradation, formation or disappearance of glacial lakes, and changing glacier thermal regimes, etc. (Mainieri et al., 2025). Their rarity combined with high intensity (Boudières and Peisser, 2013). As historical experience; therefore, traditional approach based solely on hazard characterisation (Richard, 2005) are necessary but not sufficient (Allen et al., 2017). By analysing past events, we can improve our understanding of triggering and propagation mechanism, refine susceptibility assessments, and better mitigate impacts (Carrivick and Tweed, 2016). Rather than seeking an exhaustive inventory of events, the focus is on lessons learned from major occurrences, especially regarding how societies have managed risks.

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Building a historical database requires a diachronic approach, inspired by the concept of diachronic monographs (Girard and Rivière-Honegger, 2015). This approach, illustrated by regional monographs such as those of the Pyrenees (Desailly, 1990), highlights how temporal analysis helps explain current territorial situations. Time is therefore essential, as it allows us to describe dynamics and explain environmental or social processes. A diachronic monograph thus offers a detailed study of a system defined in space and time to understand its mechanisms of change (Girard and Rivière-Honegger, 2015). Temporal analysis is relevant not only when the hazard itself has a temporal dimension, but also when it helps interpret contemporary conditions (Mendez, 2010). It is important to avoid actualism, *i.e.* the idea that the present fully explains the past. Instead, the memory of disasters uses history to contextualise and interpret events (Dollfus and D'Ercole, 1996). This leads to the notion of geohistorical trajectory (Valette and Carozza, 2019), which identifies rupture points to reconstruct the evolution of hazards (Hugerot et al., 2021). We adopt this geohistorical perspective to understand long-term risk management, local practices, and the evolution of risk culture. Through studies such as those by Favier (2006) and Fournier (2010) on avalanches and floods in the Grenoble basin (France), we learn how mountain societies actively experienced and managed disasters.
Adopting a diachronic perspective also implies careful selection of sources. Practical archives complement narrative sources (Fournier, 2010). Since the 19th century, researchers have sought to reconstruct the chronology and characteristics of past floods to better anticipate future ones (Dourlens, 2004). Historical research thus becomes a complementary tool for prediction relying on long time-series data. Yet, a full chronicle is impossible; many small or "common" events have no trace in archives (Giacona et al., 2019).
To overcome this bias, historical approaches help explain processes and mechanisms rather than compiling exhaustive lists. Our study therefore provides both a broad view of Alpine risk management and insights into the geophysical mechanisms of high mountain mass movement. This is also shown by Ravanel and Deline (2008) and Ravanel et al. (2020), who used temporal analysis of rockfalls in the Mont-Blanc massif (FR/IT) to reveal long-term dynamics.

3. Construction of the database

3.1. Inventory of major glacial and periglacial events in the Alps

3.1.1 Criteria used to identify events to be included in the database

Building a comprehensive long-term database is challenging as data availability before the 20th century largely depends on societies' vulnerability (Giacona, 2019).
We adopted a qualitative approach, keeping events that significantly marked local history or the environment, living traces in archives or collective memory.
Our criteria are grouped into four categories.

Extreme events:
We focused on rare or major events exceeding several thousand cubic metres or causing serious human or environmental damage (Field et al., 2012; Bourrelier and Dunglas, 2009). Quantitatively, these correspond to the far end of the frequency–intensity spectrum..

Events with feedback:
We consider known events that required extensive feedback (beyond simple observation of the event). By this, we mean a detailed study to understand the hazard and improve knowledge of its mechanisms (*e.g.* the Gietro glacier collapse in Switzerland in 1818; Wiegandt and Lugon, 2008).

Repeated events:

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When an extreme process has been repeated several times in the same watershed. The most significant breaks have been taken into account here. This is for example the case of the Bockkarkees hanging glacier (AU), which has generated more than 70 ice avalanches since 1933, the largest of which reached five million m³ in 1945 and two to three million m³ in 1964 and 1975 (*Gridabase*; Kellerer-Pirklbauer et al., 2012).

Change in risk perception
Finally, if an event significantly influenced risk perception, we included it in the inventory, even if it did not meet all of the above criteria. The Marmolada glacier collapse in 2022 (Fran[illegible] al., 2024) is one such example: although the phenomenon did not reach the valley and only affected mountaineers, its consequences (11 victims) had a significant impact on public opinion and highlighted the need to better locate potential glacial phenomena (Chiarle et al., 2022).

We initially sought to start our inventory in 1985-1990, marking the first visible signs of the climate crisis in the Alps (Ravanel, 2009; Ravanel et al., 2020), up to 2025. However, earlier key events such as the 1892 Tête Rousse outburst (Mougin et Bernard, 1922).
were too significant to omit.
We therefore extended our period back to the early 19th century, whenever reliable sources were available.

For each event, we collected the following data: location (country, region, mountain range, orientation, name of the glacier or summit), date(s) of rupture, identified causes, destabilised and/or deposited volumes, runout distance (propagation), possible cascading effects, damage and casualties, monitoring methods, event or crisis management, and sources used.
This method was applied to three types of glacial and periglacial hazards: ice avalanches, torrential hazards including GLOFs and debris flows, and rock falls/rock avalanches.
In the case of cascading processes, we selected the one with the most devastating effects, generally the one furthest downstream. For example, if a serac fall causes a lake to overflow, we recorded the torrential process. If a serac fall causes an ice jam, we record the ice break-up and the subsequent propagation.

3.1.2 Data sources

The main source is the *Gridabase* inventory produced as part of the European research project (« Gridabase - Glaciorisk », s. d., 2001-2003). The objective of this project was to identify, monitor and prevent catastrophic glacial phenomena in order to better assess risks in a changing climatic and socio-economic context (Peissier and Courtray, 2012). This joint database compiles 501 documented events across Austria, France, Italy and Switzerland, including floods, GLOFs, and ice avalanches (Richard, 2005). At the end of 2004, the database contained 501 documented events in Austria, France, Italy and Switzerland. The aim of *Gridabase* was to preserve as exhaustively as possible the memory and trace of glacial events, even those of modest importance (which we have not taken into account here, according to our criteria explained).

Another source used is the *RTM Database*. This is a French database developed by the *Restauration des Terrains de Montagne* service of the *Office National des Forêts* (ONF-RTM). Since the end of the 19th century, it has recorded the following six processes: avalanches, gully erosion, subsidence, landslides, rockfalls and debris flows (Bisquert et al., 2025). We have retained glacial and periglacial events consisting of rock glacier ruptures, rockfalls linked to permafrost degradation and debris flows generated by cascade processes.
The RTM has also produced numerous reports analysing glacial and periglacial events. These reports indicate the recognised causes of the rupture, the trajectory of the materials, the estimated volume, any damage and a history of the various processes in the same catchment area. Some studies report on risk

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management, in which the RTM is involved through preliminary studies prior to the (ice, rock-, lac dam) collapse, including modell[illegible]g. Lac de la Patinoire or the retrospective analysis of the Étançons torrent flood in the Écrins [illegible] (FR) in 2024, (Cathala et al., 2021; Demolis et al., 2021; Mainieri et al., 2025) and crisis management through operational measures (*e.g.* artificial draining of Rochemelon lake in 2005; Vincent et al., 2010; Cathala et al., 2021).

Scientific papers in geosciences constitute another large part of our documentation. They analyse certain past glacial and periglacial events and seek to develop a deeper physical understanding of the hazards and their causes. The same event may be analysed by different research teams using different methods and approaches. The example of the Whymper hanging glacier (Mont-Blanc massif, Italy) is representative: Margreth et al. (2011) analyse the monitoring system used to monitor the glacier; Margreth and Funk (1999) discuss different scenarios of breakoff with snow recapture; Chiarle et al. (2022) document the ruptures of the hanging glacier; Margreth et al. (2011) analyse the hazard and propose adapting the safety system; and Dematteis et al. (2021) present various strategies for monitoring the glacier, etc.

The inventory of Chiarle et al. (2022) on Italian glacier ruptures and on debris flows in the Alps (Chiarle et al., 2007) and the one of Jacquemart et al. (2024) on Alpine mass movements recorded in 30 years of scientific literature have been a good way to cross-reference our sources.

French mi[illegible]l reports, combined with those of the *Pôle Alpin des Risques Naturels* (PARN), gave us a clear idea of how countries in the Alpine arc manage disasters related to glacial and periglacial processes. They describe past and ongoing projects (*Glaciorisk, PERMAdataROC, PermaNET, GlariskAlp, GLAMOS, Prevrisk-CC, PermaRisk, SAMCO, PAPROG*, etc.), prevention measures, monitoring methods and examples, crisis management and available feedback. *GEORESEARCH*, a research institution, also brings together research projects on monitoring efforts, glacial and periglacial movements and quantitative risk analysis in the Alps (*FROST.INI, Futurelakes, GlacierRocks, AlpSenseRely*, etc.) (*cf.* « Research Projects - GEORESEARCH », s. d.).

The *World Glacier Monitoring Service* (WGMS) publishes data on glacier fluctuations around the world every five years, from 1959 to 2010. Each volume of the WGMS includes a chapter on notable events involving these glaciers.

The local press helps reveal the societal impact of mass movements, reporting on damages and the risk management measures implemented. However, this source requires critical recontextualization, as it may reflect various biases (framing, selection, confirmation, political) and sometimes lacks technical accuracy due to limited resources or urgency (Joffe and Orfali, 2005). Despite these limitations, the press offers valuable insight into risk perception from a societal perspective, which scientific literature often only partially addresses.

We completed the data collection when data from several sources coincided. Some additional information was added (hypotheses about causes, etc.).

3.2 Types of glacial and periglacial risk management

3.2.1 Definition of the seven pillars of risk management

On Alpine risk management systems (from local to national levels) and scientific literature, Kienholz et al., (Kienholz et al., 2004) and Link and Stötter (Link and Stötter, 2015) developed a classification of risk prevention and management methods. In Switzerland, since the 1980s, natural hazard management

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has followed the "Risk Minimisation Concept" and "Integral Risk Management" principles, aiming not to eliminate risks entirely but to reduce them to an acceptable level through comprehensive assessment, prevention, mitigation, and crisis preparedness. After an event, the post-crisis or regeneration phase focuses on learning from experience to improve future measures.
In France, similar principles are formalized in public policy and summarized by the PARN for glacial and periglacial risk prevention. These principles were used to classify the management strategies identified in our database

Pillar 1 : Understanding hazards, phenomena and risks
This pillar focuses on improving knowledge of hazardous phenomena through the study of past events, archives, field monitoring, modelling, and feedback (Villeneuve et al., 2010; Faillettaz et al., 2015). It includes site inventories and vulnerability assessments—the foundation for prevention projects such as GlaRiskAlp (2010–2013) and hazard mapping in Valais.

Pillar 2 : Preventive information
This pillar promotes a culture of risk through public information and education (Beccera and Peltier, 2011). By increasing awareness, citizens become active participants in prevention, improving collective preparedness and crisis response.

Pillar 3 : Integration into land-use planning
Here, risk is incorporated into spatial planning tools such as hazard maps and prevention plans to reduce exposure and vulnerability (Schneiderbauer and Ehrlich, 2004). These maps, combining modelling and spatial analysis to support evidence-based decision-making (Allen et al., 2022).

Pillar 4 : Monitoring and surveillance
Monitoring at-risk sites identified in Pillar 1 enables early detection and warning (Giordan et al., 2020; Cathala et al., 2024). For instance, the Gornersee lake (CH) is monitored annually through automatic cameras, depth measurements, and seismic sensors to anticipate GLOF hazards (WGMS, 1993; Huss et al., 2007).

Pillar 5 : Reducing hazard, exposure and vulnerability
This pillar relies on cooperation between scientists and authorities to limit damage (Marco et al., 2012). Actions include engineering works (*e.g.* dykes) to reduce exposure, warning and evacuation systems to lower vulnerability, and source interventions such as artificial drainage of glacial lakes (Vincent et al., 2010).

Pillar 6 : Crisis management preparedness
It covers planning, training, and coordination measures to anticipate and manage crises, through contingency plans, simulations, and the integration of glacial and periglacial risks into training (Einhorn and Peisser, 2011; Link and Stötter, 2015).

Pillar 7 : Resilience
Defined as a system's ability to absorb shocks and recover, resilience involves resistance, adaptation, and reorganisation capacities (Reghezza et al., 2006; Dauphiné and Provitolo, 2013). Even if the initial state cannot be fully restored, the aim is to establish a new threshold that is considered acceptable by society (Einhorn, 2017).

3.2.2 Distribution of events according to the seven principles typology

Once the typology defined, each event was linked to the corresponding management pillars. Events were grouped by decade (or by five-year period for rock hazards) to ensure temporal clarity. This

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representation allows identification of trends and shifts in management practices, avoiding visual gaps due to rare events.

4. Results

The study identifies 200 glacial and periglacial events from 109 Alpine catchment areas.

4.1 Spatial and temporal distribution of the events

4.1.1 Distribution of the events across the Alps

The spatial distribution of events (Fig. 1) shows marked concentration in certain areas, highlighting the existence of particularly exposed or dynamically active zones. The Mont-Blanc massif (mainly its French and Italian sides) stands out clearly as the area most densely affected by major events, all hazards combined. It is followed by the Valais Alps (CH). In addition, GLOFs are overrepresented in the western part of the Alps.
The western Alps have higher peaks than the rest of the Alps, steep slopes and extensive glacier cover, making them a hotspot for glacial and periglacial mass movements. The Mont-Blanc massif and the Valais Alps are among the most monitored and instrumented areas in the Alps, which may introduce a 'visibility' bias (*cf.* 5.1). As these areas are highly populated and/or frequented by tourists, events are here better detected, documented and sometimes perceived as more significant.

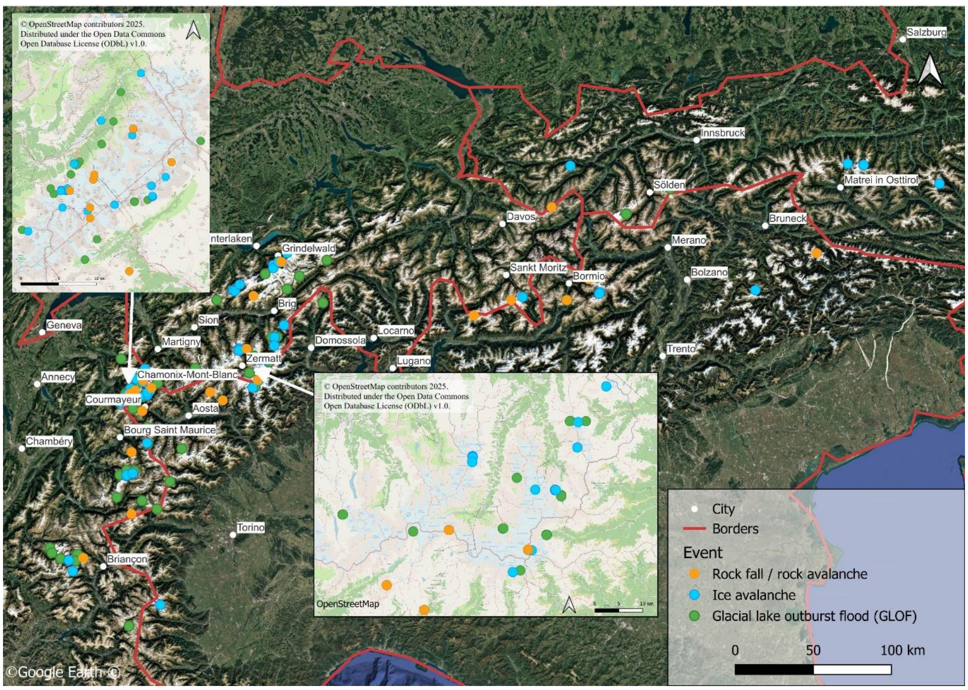

Fig. 1 Distribution of major glacial and periglacial events in the Alps.

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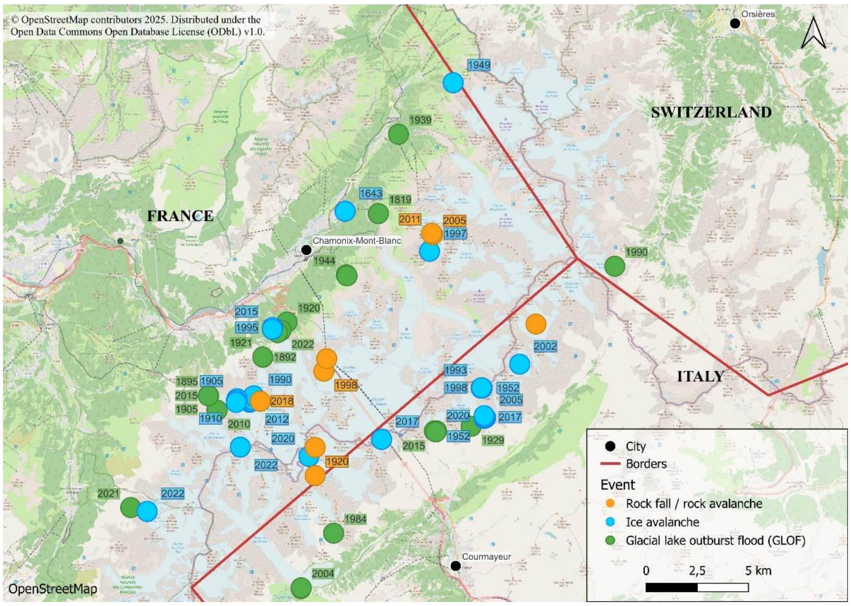

Fig. 2 Distribution of major events in the Mont-Blanc massif from the 17th to present days.

Figure 2 shows the overlapping and diversity of glacial and periglacial hazards affecting the Mont-Blanc massif. By bringing together major events that occurred between the 17th and today, it reveals the historicity of these dynamics: hazards are not isolated or punctual, but are part of a long trajectory, sometimes recurring, sometimes unique. This representation demonstrates that Alpine massifs are territories where several types of hazards coexist and can impact the same areas, making their management more complex.

4.1.2 Example of overlapping events in the same watershed

Seven Alpine watersheds are the source of several events involving several types of hazards: Belvédère glacier (IT), Brenva glacier (IT), Planpincieux glacier (IT), Taconnaz glacier (FR), Bossons glacier (FR), Armancette glacier (FR), and Allalin glacier (CH).

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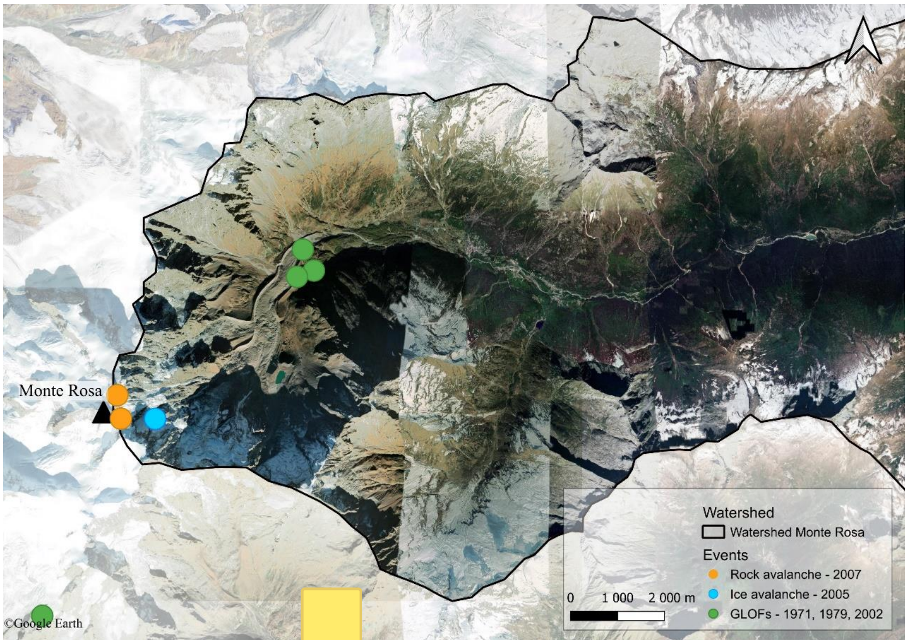

Fig. 3 Watersheds with multi-events: the example of the eastern side of Monte Rosa (4634 m a.s.l.).

Areas with a high density of glaciers mechanically present an increased risk of destabilisation and/or the formation of glacial lakes and water pockets. Added to this is the presence of unstable rock faces located at altitudes where permafrost and rock glaciers are [illegible]ling, causing more rock avalanches and rockfalls.

4.2 Distribution of management pillars over time

4.2.1 Intensification of phenomena

Considering source and event biases (*cf.* 5), we observe an intensification of glacial and periglacial hazards over time since the 1980s, across all Alpine countries (Fig. 4). It should be noted that this figure only considers events that required risk management and that have influenced our understanding of hazards.

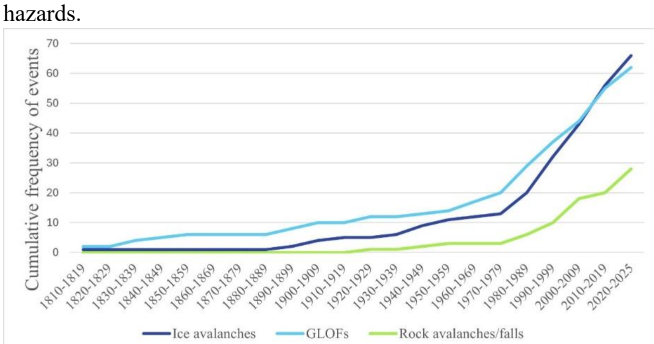

Fig. 4 Cumulative frequencies of recorded glacial and periglacial events, requiring risk management, in the Alps.

4.2.2. Evolution over time of the pillars used

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Pillars 2 (Preventive information) and 3 (Land use planning) appear only from the 1990s onward, while Pillar 6 (Crisis preparedness) has been applied for roughly two decades. Pillar 1 (Understanding the hazard) remains the oldest and most consistently used.

Evolution over time of major event risk management for *ice avalanches* in the Alps (Fig. 5):
The Altels ice avalanche (CH) in 1895 marked the beginning of the need to understand hazards in high altitude Alpine regions. This avalanche was of exceptional size, with 4×10^6 m^3 of ice breaking away, killing six people and burying 170 cattle over an area of one km^2 (Forel, 1895; Du Pasquier, 1896). For a long time, this event was the reference point in terms of ice avalanches. "To what extent can we predict such disasters, and to what degree will we be able to prevent them from happening again? Many Alpine glaciers give rise to avalanches or ruinous debacles. (...) The same glaciers periodically give rise to the same phenomena, so it is above all empirical knowledge of these phenomena that we need to acquire. (...) An accurate knowledge of the dangerous points and the phenomena that occur there is absolutely necessary. The era of independent personal research is over; it has produced all it could in this field (...). What is needed now is more coordination, more method, more consistency in research" (Du Pasquier, 1896).

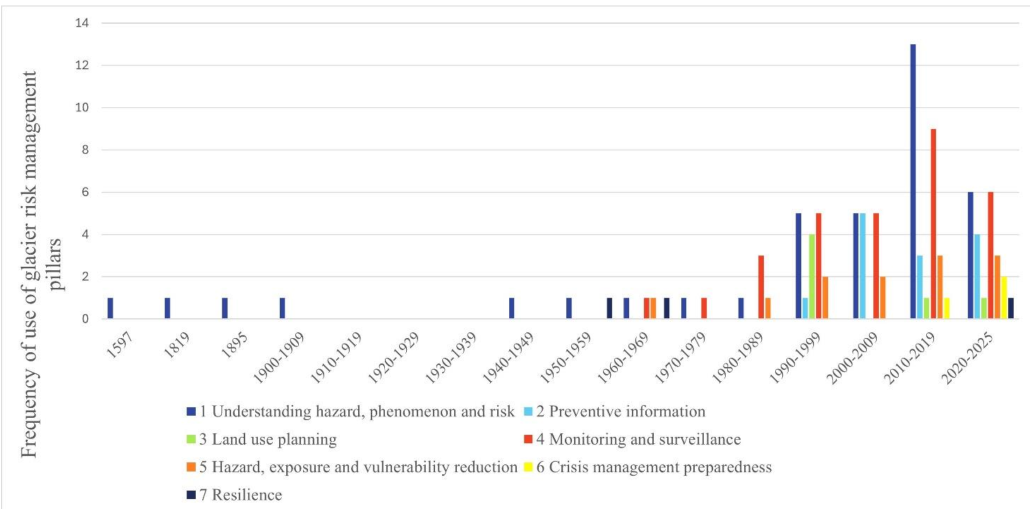

Fig. 5 Temporal evolution of ice avalanche risk management in the Alps.

If preventive information (pillar 2) appears so late, it implies that decision-makers are taking late action to communicate simplified information to the population concerned. It is linked to crisis management preparedness (Pillar 6). The example of the Val Ferret valley (IT), where the terminal tongue of the Planpincieux glacier is monitored since 2014, is coupled with rapid response in terms of civil protection and information for the population (FMs, 2012). The aim of glacier monitoring activities is to continuously track the evolution of the glacier and detect signs of instability in order to activate civil protection procedures to close the road and/or evacuate the village.
We also integrate the French Avalanche Phenomenon Location Maps (CLPA) into the land use planning (Pillar 3) even though they concern the risk of snow avalanches. These maps first appeared in the 1970s, but the events of 1984 and 1993 at the Bourgeat glacier (FR) provide information on ice avalanches that triggered snow avalanches (RTM - ONF, 2000). We therefore consider the CLPA to be sometimes mixed (snow-ice risk management) in the Chamonix valley (FR).

Evolution over time of risk management for major rockfall / rock avalanche events in the Alps (Fig. 6):

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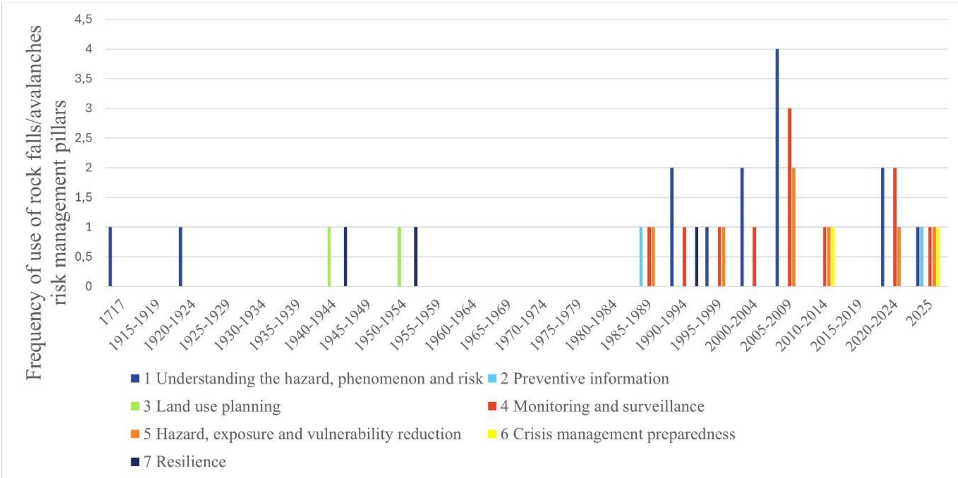

Fig. 6 Temporal evolution of risk management for rockfalls / rock avalanches.

The figure 6 has been divided into five-year periods in order to better highlight recent dynamics, as the majority of rockfall events occurred after 1980.

The reduction in vulnerability, exposure and hazard (Pillar 5) is particularly evident in these rockfall events. In 1987, the preventive evacuation in response to debris flow and the Val Pola rockslide (CH; 30 × 10⁶ m³) illustrates proactive risk management (Cha[illegible] 1990). In 2011, at Piz Cengalo (CH; 1.5 × 10⁶ m³), a series of preventive measures were put in[illegible]: alerting the population, closing trails, abandoning alpine buildings and protective structures (A[illegible]cey, 2017).

Monitoring unstable rock faces is a key management tool (Pillar 4). Since 1986, the eastern face of Monte Rosa (IT) has been regularly monitored due to an increase in mass movements (Fischer et al., 2006). Other iconic sites have al[illegible]n equipped: Aiguille du Midi (FR) since 2005, the south face of the Matterhorn (IT) and Les Dru[illegible] since 2007.

Finally, projects such as EU AlpinSpace *PermaNET* have helped to structure knowledge on alpine permafrost, with a harmonised database covering the entire Alps (Mair et al., 2011).

Evolution over time of risk management for major GLOF events in the Alps (Fig. 7):

GLOFs are the best documented events in the archives, due to their high recurrence and significant impact over time. Their frequent evolution into debris flows amplifies the damage in valleys, making them easier to trace and document.

Efforts to reduce vulnerability and exposure appear earlier for GLOFs than for other hazards. This is because the response strategies are similar to those used for floods, which are better known to the public and authorities (whether or not the hazard is related to climate change). Thus, from the end of the 16th century, the recurrent outflow of the Margherita glacial lake at the Rutor glacier (IT) was the subject of studies commissioned by the Duke of Savoy (12 events between 1430 and 1680; discharge of 5 × 10⁶ m³ in 1751). Technical solutions such as the construction of a dam or the digging of a tunnel were considered as early as the [illegible]ntury (Vergnano et al., 2023).

Another notable example [illegible] episode involving the Gietro glacier in 1818, where the attempt to channel the water *via* a tunnel through the ice dam triggered the discharge of 18 × 10⁶ m³ reaching the town of Martigny (Wiegandt and Lugon, 2008).

These repeated events gradually led to the implementation of specific measures: dykes, dams, storage chambers, subglacial drilling, siphoning or draining of lakes, solidification of morainic barriers, warning systems, and even restrictions on access to risk areas.

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Monitoring of glaciers in relation to their potential to form lakes or water pockets became formalised around a century ago, notably with systematic photogrammetric surveys of the Vernagtferner (AU), one of the best-documented glaciers in the country due to its numerous GLOFs, the most notable of which dates back to 1848 (Braun, 1995; *Gridabase - Glaciorisk*, s. d.).
However, the integration of populations through preventive information is a more recent development. In 1986, with the case of the Arsine proglacial lake (FR), scientists alerted the authorities and the population to the risk of overflow in the event of a serac falling into the lake (Hoinkes, 1969). This alert led to the first official crisis management preparations involving local residents. The following year, in Valtellina (IT), similar preventive measures were put in place in response to instability in Val Pola and the heavy rainfall forecast (Chardon, 1990).

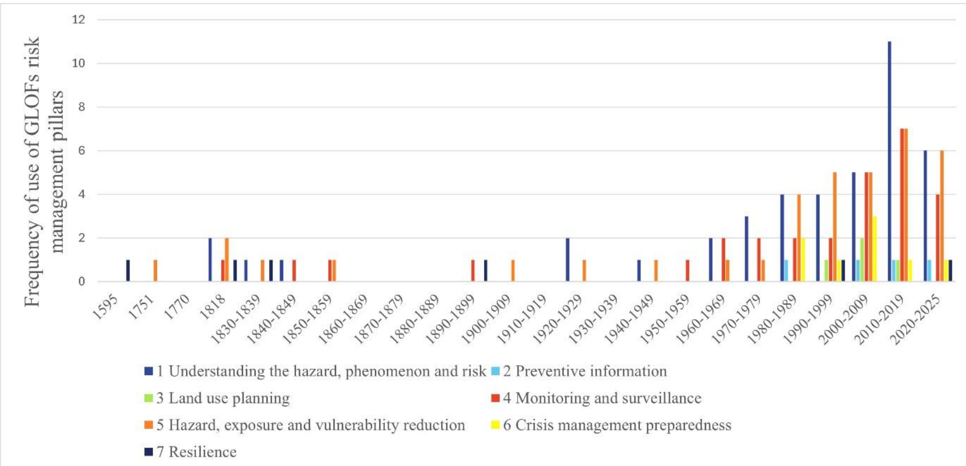

Fig. 7 Temporal evolution of risk management for Glacial Lake Outburst Floods.

4.2.3 Disruptive events that have improved the management and understanding of glacial and periglacial risks

The creation of a timeline tracing risk management measures in response to past events has made it possible to identify key moments marking disruptions and/or the emergence of new approaches. The examples selected correspond to the first documented cases where a new specific form of risk management was implemented or redefined: first predictions of collapses, first glacial and periglacial monitoring systems, first actions to reduce exposure, vulnerability or hazard at source and on a larger scale, and first large-scale multidisciplinary coordination in crisis situations.

Change of scale:
First, we note a change of scale in the management approach, moving from a commonly local management scheme, *i.e.* of the affected area and village, to national management. A notable example of this is the Gietro glacier case in 1818, which devastated the Bagnes valley (Ancey et al., 2019). At that time, glaciological studies were in their infancy. This event showed that a better understanding of the processes involved could lead to more effective interventions. Scientific advances thus contributed to the development of preventive measures and promoted the emergence of regional and national intervention policies, gradually replacing the local and reactive approaches that had prevailed until then (Wiegandt and Lugon, 2008). The case of the Gietro is therefore also significant in terms of the need for science to understand and know how to respond, from the decision-maker point of view. The disaster brought about a change in social attitudes towards risk and in the way, people reacted. Although

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unpredictable at the time and therefor[illegible]itable, disasters began to be perceived not as evidence of divine wrath, but as natural and physical processes (Carrivick and Tweed, 2016).

Monitoring and surveillance:
The first inventory known of a glacier in the Alps dates back to the end of the 19th century for the Vernagtferner (AU), a glacier known for its numerous and destructive GLOFs over the last 400 years (Hoinkes, 1969). A hundred years of systematic surveys were carried out using photogrammetry, resulting in the first map and descriptive theory on glacier movement (Braun, 1995). Continuing with this focus on intensive monitoring of glaciers and their associated risks, the Gietro glacier was one of the first to be monitored since the 1960s. Surface movements, short-term flow movements, structure, mass balance, volume changes, e[illegible] measured (Ancey, 2017). Similarly, the Matterhorn (CH-IT) has been closely monitored and ec[illegible]d with a microseismic monitoring system and thermometric monitoring system since 2007, following recurrent rockfalls since 2003 (Occhiena and Pirulli, 2012).

Multidisciplinary network:
The rupture of the Tête Rousse water pocket in 1892 was a fundamental event in the early days of glacier risk management. The debris flow that affected several villages downstream, causing 175 victims (Mougin and Bernard, 1922), led to the establishment of a multidisciplinary network to identify the causes of the disaster and implement measures. Engineers, glaciologists and foresters from the *Eaux et Forêts* administration were brought together, commissioned by the local authorities (Marco et al., 2012), to investigate, map, dig a drainage tunnel and enable increased monitoring of the glacier (Sirop et al., 2022).
The collapse of the Allalin glacier tongue at Mattmark (CH) in 1965 also made history, not only because of its 88 victims (Vivian, 1966), but a[illegible]ecause of the urgent need for scientists to work together. Indeed, glaciological and engineering s[illegible]s were carried out immediately after the disaster in order to protect rescue operations and construction work in the following years (Dalban Canassy et al., 2011). Such a coalition of scientists has irrevocably advanced our understanding of the mechanism of phased glacial rupture.
Still in this spirit of coordination between management actors, the case of the Rochemelon lake seems significant. Trapped between the ice and the rock face, the lake grew continuously until 2004 (Vincent et al., 2010), when fears of overflowing and spreading on the French side alerted scientists. This led the authorities to take preventive action to drain the lake. French and Italian authorities, scientists, engineers, technicians and rescue workers worked closely together in this crisis management operation. This involved risk studies based on observation and measurement campaigns, alerts to the population, and finally the draining of the lake at the end of 2004 and 2005. The Rochemelon crisis highlighted two major points: (1) the importance of having the necessary investigative resources to understand the entire phenomenon and its evolution at a very early stage and with sufficient precision, in order to translate this into operational decisions; (2) the importance of ensuring, both upstream and during crisis management, genuine continuity between scientific knowledge, its transfer to the authorities and its translation into operational measures (Marco et al., 2012).

Predictive study:
In 1973, the first successful glacier rupture prediction was made at Weisshorn (CH) (Röthlisberger, 1981b). Scientists observed an acceleration of the upper part of the glacier, supplemented by warnings from local mountain guides about a new transverse crevasse, indicating an unstable situation (Faillettaz and Funk, 2013).

Reduction of exposure and vulnerability (evacuations, works, etc.):
The first known organised evacuations in response to gravita[illegible] hazards date back to 1987, in the Adda valley (IT), in response to the 30×10^6 m^3 rockslide[illegible]l Pola (Dramis et al., 1995). The instability of the slope, due to inconsistent geology, a steep gradient and heavy rainfall in the preceding

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days, had led to warnings of a potential collapse (Chardon, 1990). Regarding glacial hazards, one of the first documented evacuations took place in 1997 in Planpincieux (IT), due to the threat of collapse of the Whymper hanging glacier (south face of Grandes Jorasses, 4208 m a.s.l.), which could have carried away large masses of snow (Margreth and Funk, 1999). In the same year, researchers developed the first safety concept for the village, based on several breakage scenarios derived from glacier monitoring and avalanche studies (Margreth et al., 2011).
In terms of reducing exposure, vulnerability or hazard (Pillar 5), the Belvedere glacier (IT) is a significant example. Following a lake's overflow in 1979, preventive work was undertaken: artificial lowering of lake delle Locce and construction of downstream dams (Haeberli and Epifani, 1986). In 2002, faced with the threat of sudden drainage of the Effimero lake onto the village of Macugnaga, the Italian Civil Protection Agency implemented several emergency measures: risk mapping, access restrictions, enhanced monitoring, alert and evacuation procedures, and an artificial pumping system (Haeberli et al., 2002).

This initiative is part of the ongoing development of Alpine projects dedicated to improving risk understanding and management (*Glaciorisk*, 2001-2003; *PERMAdataROC*, 2000-2006; *GlariskAlp*, 2010-2013; PAPROG, since 2019, etc.).

Institutional understanding of risk:
We are experiencing a shift in the way Alpine institutions and societies understand risk. Taking the idea from Link and Stötter (2015), the management of mountain risks has evolved from '*hazard protection*' to '*hazard management*' and now to '*risk management*'.
Before 1950 (considered the period of hazard protection), the aim was to reduce exposure by focusing on structural protection (through protective works) and institutionalising natural hazards through legislation. There are many traces of such works in the 19th century archives: one example is the galleries dug into the ice of the Allalingletscher glacier in 1834 to lower its lake (glacial-morainic dam) and reduce the already high frequency of ice breaks (Mariétan, 1953). Between 1589 and 1850, documents report 26 significant and sudden discharges (Raymond et al., 2003).
After 1950, efforts were made to gain a deeper understanding of hazards and their processes (*via* frequency-intensity calculations and time series): this was the age of *hazard management*. This also marked the beginning of hazard mapping (Link and Stötter, 2015).
Then, from the end of the 20th century, risk management was introduced. "[It] follows a holistic idea of reducing risk over the long term through the harmonisation of prevention, mitigation and reconstruction" (Link and Stötter, 2015). The concepts of vulnerability and risk acceptance were incorporated into society.

It should also be noted that before the 2000s, hazards were considered *in response* to the event. The study focused on the event alone in order to understand its causes and prevent it. It was only with subsequent disasters (and more distant ones such as Kolka Karmadon in Russia in 2002) that cascading phenomena and their downstream impacts began to be questioned and considered as a single phenomenon (Allen et al., 2022). The importance of considering the plurality of possible scenarios is gradually becoming apparent in risk management approaches.

4.2.4 Proactive *vs.* reactive management

Our typology of glacial and periglacial risk management distinguishes between proactive and reactive approaches. Management is said to be *proactive* when it is based on anticipatory measures to prevent potential risks; it is *reactive* when it intervenes after the event, with a view to understanding, reconstruction and resilience.
Fig. 8 illustrates the implementation of the various principles of glacial and periglacial hazards management, which operate independently but can be combined. For example, Monitoring and

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Surveillance (Pillar 4) is frequently associated with that of Exposure, Vulnerability or Hazard Mitigation (Pillar 5).

With regard to torrential hazards associated with glacial lakes, scientists raised the alarm in 1985 about the risk of the Arsine proglacial lake (FR) overflowing and threatening the Guisane valley (Peissier and Courtray, 2012). Under pressure from researchers and the media, the authorities carried out a partial artificial draining of the lake.
In a proactive way, an early warning system was installed in 2008 on the Grindelwaldgletscher glacial lake (CH). Equipped with a pressure sensor, it automatically transmits an alert to the natural hazard prevention service in the event of a critical drop in water level. This system worked perfectly during the emptying episode on 30 May 2008 (Bauder, 2017).
Conversely, the overflowing of the Patinoire lake (FR) in 1964, which caused damage as far as the village of Pralognan, prompted a reactive response. The managers conducted a review based on testimonies and field visits (Cathala et al., 2021). A study of the susceptibility of the moraine dam to failure was conducted, followed by modelling of the potential impact on the main town. In 2019, the watershed was identified as a priority for in-depth analysis.

The Whymper hanging glacier illustrates proactive, anticipatory management: in 1997, movement measurements enabled prediction of an imminent ice avalanche, prompting the evacuation of Planpincieux due to potential downstream impacts (Margreth and Funk, 1999). The site has been continuously monitored since 1[illegible]
In contrast, the 1965 Mattmark [illegible]r linked to the Allalin glacier exemplifies reactive management. Authorities focused on crisis response, searching for survivors and investigating causes through a multidisciplinary team. The event later became a major political issue, leading to a trial to assign responsibility.

For the hazard of *rock falls*, the example of Piz Cengalo concerns both *reactive* management that preceded *proactive* management, in the context of two major events. At the end of 2011, Cengalo experienced its first rock avalanche (Walter et al., 2020) at a time when the upper Val Bondasca was fortunately empty. The local authorities set up a process to monitor the rock face. As a debris flow occurred the following summer, the municipality built a 50,000 m^3 storage area and a protective wall upstream of the village. This facility complemented the alarm system installed at the top of the valley, giving residents a few minutes to evacuate the village and allowing the closure of threatened traffic routes. The municipality also decided to close hiking trails and abandon some Alpine buildings (Ancey, 2017). In 2017, a rock slope failure that turned into a rock avalanche and then debris flows travelled down the Val Bondasca over a distance of 3 km. The total volume of rock, sediment and water amounted to 3.1 × 10^6 m^3 (Walter et al., 2020). Specialists observed an acceleration of movement within the mountainside and alerted the local authorities. Although the scale and speed of the flows exceeded initial estimates, the warning system worked, [illegible]e protective structures limited the damage to infrastructure in Bondo (Ancey, 2017).

5. Discussions

5.1 Distribution of m[illegible]ment principles

An eighth principle – *Feedback* – was initially considered, but it appeared systematically in all documented events. Feedback is the very condition for an event's existence in archives: its narration and memory make it visible historically. Therefore, it is implicitly included in all other pillars.

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It should also be noted that certain ancient events are well documented in the archives through their feedback, but have only recently been used as data for analysing and understanding the hazard (Pillar 1). These events therefore do not appear in Figures 5, 6 and 7, even though they meet the selection criteria due to their value for understanding past phenomena. This is the case, for example, of the Breithorn ice avalanche (CH) in 1597, which destroyed the village of Homattugletscher (Forel et al., 1901); the devastating lake outbursts b[illegible] the Rutor Glacier (IT) between the 15 and 17th centuries (*Gridabase - Glaciorisk*); the Gietro glacier break-up in 1995, which claimed 140 lives (Ancey, 2017); the rock avalanche scattered across the Triolet glacier (IT) in 1717 (Porter and Orombelli, 1981; Deline et al., 2014); at the Allalin glacier between 1589 and 1850, documents report 26 significant and sudden discharges (*Gridabase - Glaciorisk*), etc.

5.2 Risk perception and culture in past centuries

The documentary research carried out to compile this timeline did not include risk perception and culture during events in the 19th century and earlier. We focused on contemporary methods (20th and 21st centuries) of risk management, as these explain how things are done today. However, understanding risk management in a more global context requires the perception of risk at the local level by placing it in its historical and climatic context.

We wondered whether religious processions in mountain villages affected by glacial or periglacial events were necessary to understand today's risk management. We have only mentioned them, without exploring the idea of risk culture in ancient mountain societies in greater depth. The two most outstanding examples remain the processions around 1818 to the Ussere Aletsch mountain pasture (CH), where a cross was erected to “exorcise these terrible threats” (Coutterand, 2017) and to stop the Märjensee lake from overflowing (21 times between 1813 and 1895). We also noted the example of the Mer de Glace in Chamonix (FR), which threatened agricultural land. A procession was organised in the valley by the coadjutor of Geneva to make the glacier recede in 1943-1944 (Mougin and Bernard, 1922). It is therefore clear that at a time when religion was prevalent in society, processions were part of a certain form of risk management. The fact that science and reason now prevail in the way we understand risk and uncertainty motivated our decision not to include these examples. Even if "invoking the heavens did not prevent attempts to understand the conditions for the development of disasters at the local level (at least among the local elites*)*" (Favier, 2007).

5.3 Biases linked to difficulties in compiling an exhaustive inventory of events

Compiling an inventory that is exhaustive in relation to our decision-making criteria implies certain limitations and the need to place the event in its context.

The source effect:

With the increase in glacial and periglacial events over time, we are facing biases related to the *source effect* (*e.g.* Giacona et al., 2017). This increase is closely linked to the sources, *i.e.* the origin of the information. As Giacona (2019) points out, "the spatial and temporal distribution of events is closely dependent on that of the structure of the documentary corpus". Each event recorded is therefore dependent on the quality and diversity of the sources that attest to it. The author thus hypothesises in his geochronology of snow avalanches in the Vosges mountains that the rarity of sources in the distant past limits the traceability of events, while the abundance, accuracy and increasing systematisation of data in the recent past automatically increases their number.

The *source effect* therefore requires particular attention to variations in the volume of documentation. For example, the installation of a webcam at the Gornergletscher (Huss et al., 2007), demonstrating advances in technology, adds a source of detailed data. It will make it possible to create multiple occurrences of hazards.

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Land use and the event prism:

The increase or absence of sources may be due to the presence or absence of vulnerable population in the area under study. Indeed, if there is no human community there to observe the phenomena, they cannot be recorded. The newly increased presence of humans in high mountains through the development of mountaineering (Mourey et al., 2023) or growing urbanisation in mountain valleys (Vannier et al., 2016) has greatly expanded the capacity for observation. Conversely, villages or mountain pastures that are now abandoned were witnesses to hazards in the past.

Even when glacial or periglacial hazards occur, how societies perceive and relate to risk determines how these hazards are recognized and managed. A hazard may take place without being recorded if it is not considered significant. As Giacona (2019) notes, an event only gains social existence when it is perceived as a disruption in time. Risk perception changes over time and depends on collective experience, interests, social roles, and knowledge (Granet-Abisset, 2012). Moreover, the growing observation of high-mountain hazards reflects increasing social expectations for safety, responsibility, and prevention. Social pressure thus drives the production and diversification of information sources.

Beyond the individual witness and their experience and perception, the role of regulatory mechanisms and the emergence of projects on glacial risks play a decisive role in the production of the event as such. Projects such as *Glaciorisk* have also been instrumental in creating a collection of events, bringing together phenomena associated with glaciers.

6 Conclusions and perspectives

This study departs from traditional approaches that focus primarily on post-event causes or hazards characterization, and instead examines the methods of management. While raw event inventories offer insights into the frequency of phenomena, they rarely address organisational dynamics, decision-making processes, or the capacity for anticipation or adaptation. Our analysis seeks to explore these dimensions. By analysing 200 events since the early 19th century (some even earlier, though less frequent), we observed a temporal intensification of events accompanied by increasingly formalised management practices that left archival records from the 19th century to the present day. The pursuit of knowledge about hazards emerges as a common foundation across all forms of management. In contrast, measures aimed at reducing exposure and vulnerability have mainly targeted GLOFs and debris flows. All high-altitude Alpine massifs are affected, but our sources reveal a concentration of major events in France and western Switzerland, particularly those linked to GLOFs.

The completeness of this long-term inventory remains constrained by biases in the available sources and event recognition.

The management of glacial and periglacial risks has evolved in response to major events and to the growing understanding of the processes involved. Forecasting, instrumentation, and monitoring of potentially unstable zones have expanded, while contingency and evacuation plans are increasingly implemented. Efforts to reduce exposure and vulnerability are being adapted to both evolving hazards and the pressures of urbanisation in mountain regions. Since the beginning of the 21st century, there has been a surge in scientific initiatives aiming to anticipate mass-movement phenomena in the high Alps. Scientific knowledge is now shared more actively across national borders, and risk management is becoming progressively more comprehensive and holistic. Processes are more and more analysed not in isolation, but as interconnected or cascading phenomena.

Future research could address the limited involvement of local communities in risk management. At present, experts generete knowledge, managers implement protective measures, and authorities decide on preventive actions. This separation raises a crucial question: could greater participation by local populations improve the way their vulnerabilities, resilience, and detailed, experience-based knowledge of risk-prone areas are integrated into management strategies?

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