1   Manuscript intended for publication in *Natural Hazards and Earth System Sciences* (NHESS)

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

6   Juliette Bazin*[1,2], Ludovic Ravanel[1], Sandrine Caroly[2]

8   [1] EDYTEM, Savoie Mont-Blanc University, CNRS, 5 Boulevard de la Mer Caspienne 73370 Le
9   Bourget-du-Lac, France
10   [2] PACTE, Grenoble Alpes University, INP, 46 Avenue Félix Viallet 38000 Grenoble, France
11   *Corresponding author: J. Bazin (juliette.bazin@univ-smb.fr)

13   This research was funded by the project ALCOTRA PrévRisk-CC AAP Interreg VI-A France-Italy
14   (ALCOTRA) 2021 - 2027

16   **Key words**
17   Glacial and periglacial hazards, Risk management, Risk perception, Geo-history, European Alps

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

34

35   ### 1. Introduction
36   Rock and glacier mass movements in high mountains pose significant risks to communities and
37   infrastructure. Numerous past examples show how glacial and periglacial processes have affected Alpine
38   valleys through large-scale and/or cascading phenomena (*e.g.*, Haeberli et al., 2016; Magnin et al.,
39   2023), and their frequency and volume appear to be increasing (Jacquemart et al., 2024). Recent
40   disasters in Bondo (Graubünden, CH) in August 2017 (Ancey, 2017; Walter et al., 2020), La Bérarde
41   (Isère, FR) in June 2024 (Mainieri et al., 2025), and Blatten (Valais, CH) in May 2025 following a
42   massive rock-ice avalanche from the Birch Glacier illustrates this intensification.
43   This study focusses on major hazards affecting valley floors: ice, rock, and mixed avalanches, glacial
44   lake outburst floods (GLOFs) and debris flows. These are defined as natural phenomenon impacting
45   Alpine territories (Moles, 1972; Bisquert et al., 2025). A process becomes a *risk* when it threatens lives,
46   economic assets, or the environment. The notion of an *event* is useful for historians as it marks "a cut, a
47   discontinuity", something "interesting", sufficiently "important" or "new" to be "told or enacted"
48   (Dosse, 2010; Giacona et al., 2017). The *issues* are thus the exposed elements with varying
49   vulnerabilities to each hazard (Defossez et al., 2018).

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 avalanches occur when a glacier section detaches and slides downslope (Alean, 1985; Richard, 2005; Faillettaz et al., 2015), 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 flows if sufficient sediment is available (Richard, 2005; Huss et al., 2007; Carrivick and Tweed, 2016; Ancey 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 these emerging, climate-related risks (Prudent-Richard et al., 2008; Stoffel et al., 2014; Jacquemart et al., 2024) is essential.

The database developed this study documents 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 identify differences between countries. A historical approach enables the analysis of change processes in risk management(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., 2021). It also aims to reduce uncertainty through new scientific knowledge (Margreth et al., 2011, 2017). While 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.

101
102 Building a historical database requires a diachronic approach, inspired by the concept of diachronic
103 monographs (Girard and Rivière-Honegger, 2015). This approach, illustrated by regional monographs
104 such as those of the Pyrenees (Desailly, 1990), highlights how temporal analysis helps explain current
105 territorial situations. Time is therefore essential, as it allows us to describe dynamics and explain
106 environmental or social processes. A diachronic monograph thus offers a detailed study of a system
107 defined in space and time to understand its mechanisms of change (Girard and Rivière-Honegger, 2015).
108 Temporal analysis is relevant not only when the hazard itself has a temporal dimension, but also when
109 it helps interpret contemporary conditions (Mendez, 2010). It is important to avoid actualism, *i.e.* the
110 idea that the present fully explains the past. Instead, the memory of disasters uses history to contextualise
111 and interpret events (Dollfus and D'Ercole, 1996). This leads to the notion of geohistorical trajectory
112 (Valette and Carozza, 2019), which identifies rupture points to reconstruct the evolution of hazards
113 (Hugerot et al., 2021). We adopt this geohistorical perspective to understand long-term risk management,
114 local practices, and the evolution of risk culture. Through studies such as those by Favier (2006) and
115 Fournier (2010) on avalanches and floods in the Grenoble basin (France), we learn how mountain
116 societies actively experienced and managed disasters.
117 Adopting a diachronic perspective also implies careful selection of sources. Practical archives
118 complement narrative sources (Fournier, 2010). Since the 19th century, researchers have sought to
119 reconstruct the chronology and characteristics of past floods to better anticipate future ones (Dourlens,
120 2004). Historical research thus becomes a complementary tool for prediction relying on long time-series
121 data. Yet, a full chronicle is impossible; many small or "common" events leave no trace in archives
122 (Giacona et al., 2019).
123 To overcome this bias, historical approaches help explain processes and mechanisms rather than
124 compiling exhaustive lists. Our study therefore provides both a broad view of Alpine risk management
125 and insights into the geophysical mechanisms of high mountain mass movement. This is also shown by
126 Ravanel and Deline (2008) and Ravanel et al. (2020), who used temporal analysis of rockfalls in the
127 Mont-Blanc massif (FR/IT) to reveal long-term dynamics.
128

3. Construction of the database

130
3.1. Inventory of major glacial and periglacial events in the Alps
132
3.1.1 Criteria used to identify events to be included in the database
134
135 Building a comprehensive long-term database is challenging as data availability before the 20th century
136 largely depends on societies' vulnerability (Giacona, 2019).
137 We adopted a qualitative approach, keeping events that significantly marked local history or the
138 environment, living traces in archives or collective memory.
139 Our criteria are grouped into four categories.
140
141 Extreme events:
142 We focused on rare or major events exceeding several thousand cubic metres or causing serious human
143 or environmental damage (Field et al., 2012; Bourrelier and Dunglas, 2009). Quantitatively, these
144 correspond to the far end of the frequency–intensity spectrum..
145
146 Events with feedback:
147 We consider known events that required extensive feedback (beyond simple observation of the event).
148 By this, we mean a detailed study to understand the hazard and improve knowledge of its mechanisms
149 (*e.g.* the Gietro glacier collapse in Switzerland in 1818; Wiegandt and Lugon, 2008).
150
151 Repeated events:

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

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

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

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

182   **3.1.2 Data sources**

184   The main source is the *Gridabase* inventory produced as part of the European research project
185   (« Gridabase - Glaciorisk », s. d., 2001-2003). The objective of this project was to identify, monitor and
186   prevent catastrophic glacial phenomena in order to better assess risks in a changing climatic and socio-
187   economic context (Peissier and Courtray, 2012). This joint database compiles 501 documented events
188   across Austria, France, Italy and Switzerland, including floods, GLOFs, and ice avalanches (Richard,
189   2005). At the end of 2004, the database contained 501 documented events in Austria, France, Italy and
190   Switzerland. The aim of *Gridabase* was to preserve as exhaustively as possible the memory and trace
191   of glacial events, even those of modest importance (which we have not taken into account here,
192   according to our criteria explained).

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

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

209   Scientific papers in geosciences constitute another large part of our documentation. They analyse certain
210   past glacial and periglacial events and seek to develop a deeper physical understanding of the hazards
211   and their causes. The same event may be analysed by different research teams using different methods
212   and approaches. The example of the Whymper hanging glacier (Mont-Blanc massif, Italy) is
213   representative: Margreth et al. (2011) analyse the monitoring system used to monitor the glacier;
214   Margreth and Funk (1999) discuss different scenarios of breakoff with snow recapture; Chiarle et al.
215   (2022) document the ruptures of the hanging glacier; Margreth et al. (2011) analyse the hazard and
216   propose adapting the safety system; and Dematteis et al. (2021) present various strategies for monitoring
217   the glacier, etc.

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

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

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

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

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

246   **3.2 Types of glacial and periglacial risk management**

249   **3.2.1 Definition of the seven pillars of risk management**

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

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

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

268 Pillar 2 : Preventive information
269 This pillar promotes a culture of risk through public information and education (Beccera and Peltier,
270 2011). By increasing awareness, citizens become active participants in prevention, improving collective
271 preparedness and crisis response.

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

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

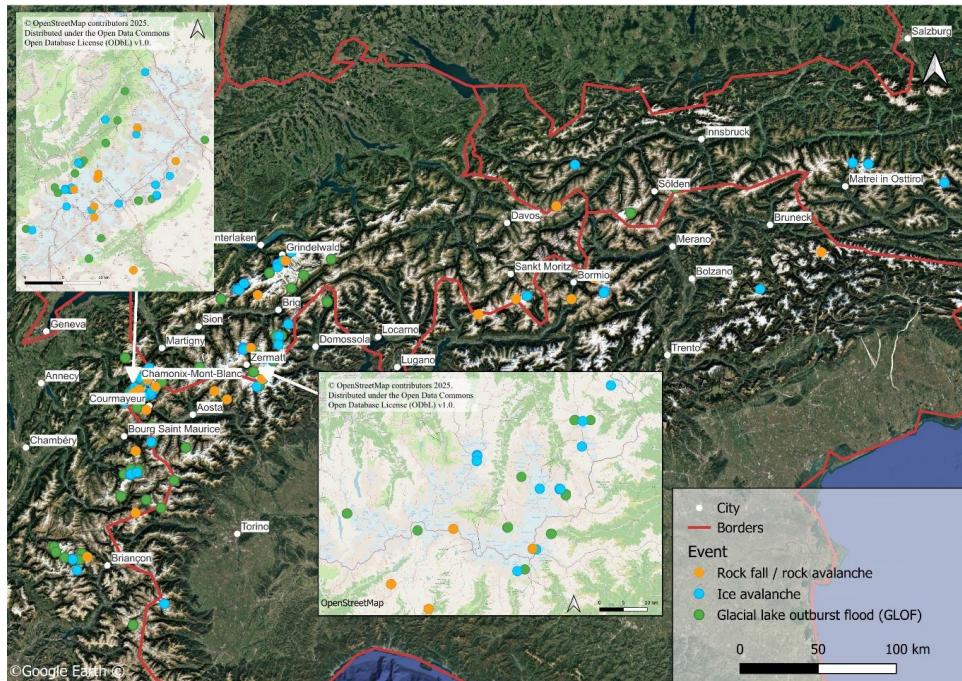
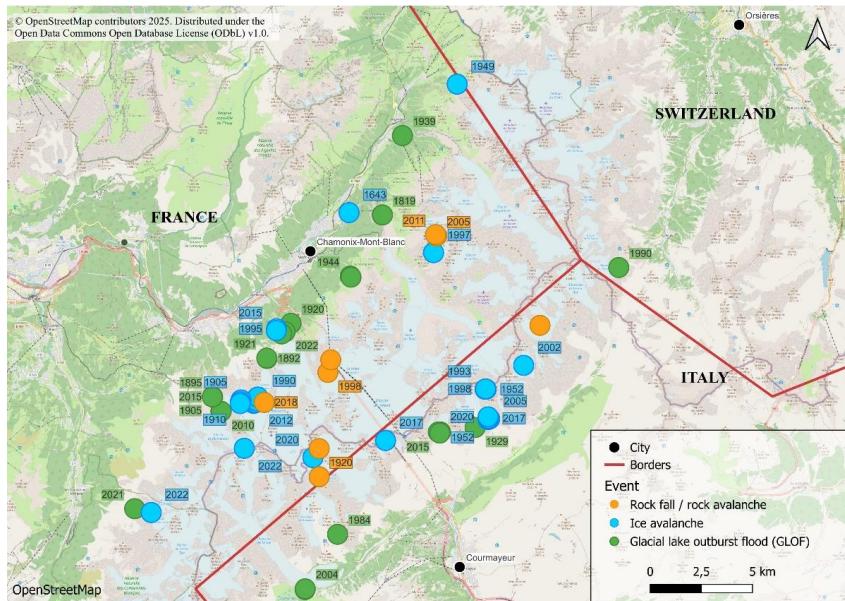
284 Pillar 5 : Reducing hazard, exposure and vulnerability
285 This pillar relies on cooperation between scientists and authorities to limit damage (Marco et al., 2012).
286 Actions include engineering works (*e.g.* dykes) to reduce exposure, warning and evacuation systems to
287 lower vulnerability, and source interventions such as artificial drainage of glacial lakes (Vincent et al.,
288 2010).

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

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

301 **3.2.2 Distribution of events according to the seven principles typology**

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

305 representation allows identification of trends and shifts in management practices, avoiding visual gaps
306 due to rare events.
307
308 **4. Results**
309 The study identifies 200 glacial and periglacial events from 109 Alpine catchment areas.
310
311 **4.1 Spatial and temporal distribution of the events**
312
313 **4.1.1 Distribution of the events across the Alps**
314
315 The spatial distribution of events (Fig. 1) shows marked concentration in certain areas, highlighting the
316 existence of particularly exposed or dynamically active zones. The Mont-Blanc massif (mainly its
317 French and Italian sides) stands out clearly as the area most densely affected by major events, all hazards
318 combined. It is followed by the Valais Alps (CH). In addition, GLOFs are overrepresented in the western
319 part of the Alps.
320 The western Alps have higher peaks than the rest of the Alps, steep slopes and extensive glacier cover,
321 making them a hotspot for glacial and periglacial mass movements. The Mont-Blanc massif and the
322 Valais Alps are among the most monitored and instrumented areas in the Alps, which may introduce a
323 'visibility' bias (*cf.* 5.1). As these areas are highly populated and/or frequented by tourists, events are
324 here better detected, documented and sometimes perceived as more significant.
325

326 *Fig. 1 Distribution of major glacial and periglacial events in the Alps.*
327

328

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

330

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

337

338 **4.1.2 Example of overlapping events in the same watershed**
339 Seven Alpine watersheds are the source of several events involving several types of hazards: Belvédère
340 glacier (IT), Brenva glacier (IT), Planpincieux glacier (IT), Taconnaz glacier (FR), Bossons glacier (FR),
341 Armancette glacier (FR), and Allalin glacier (CH).

342

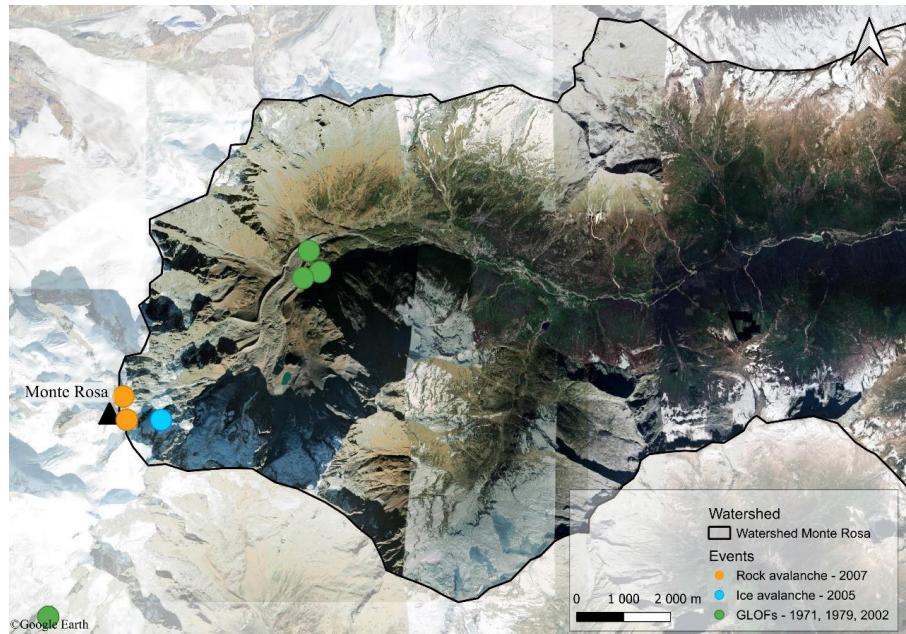



Fig. 3 Watersheds with multi-events: the example of the eastern side of Monte Rosa (4634 m a.s.l.).

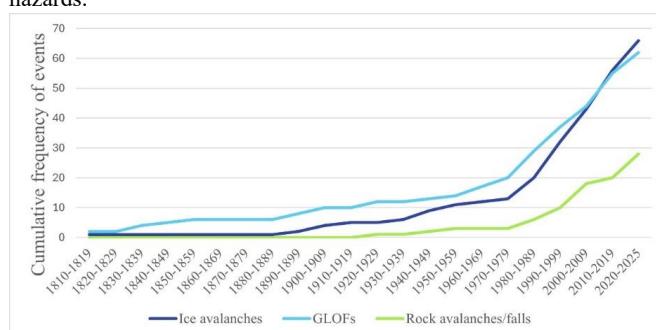
Areas with a high density of glaciers mechanically present an increased risk of destabilisation and/or the formation of glacial lakes and water pockets. Added to this is the presence of unstable rock faces located at altitudes where permafrost and rock glaciers are degrading, causing more rock avalanches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

4.2 Distribution of management pillars over time

4.2.1 Intensification of phenomena

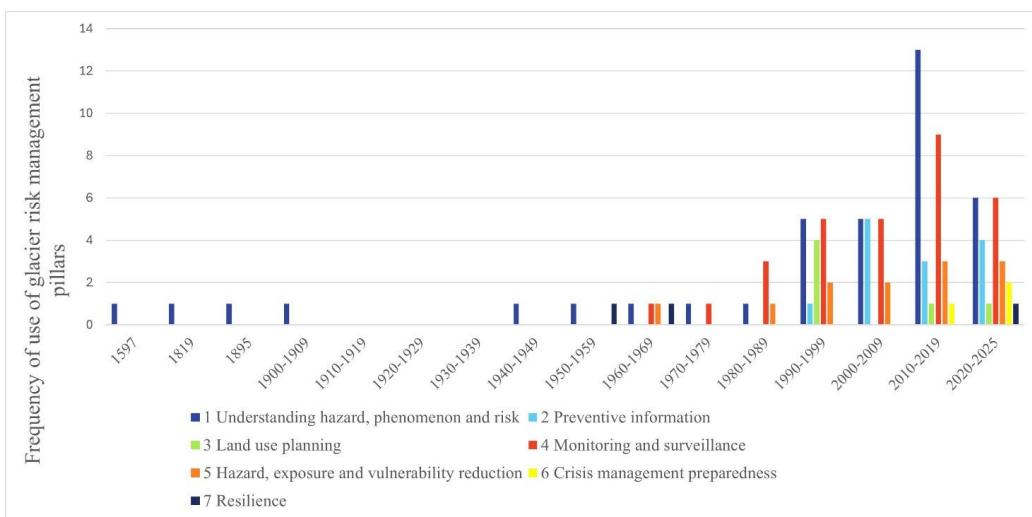
Considering source and event biases (*cf.* 5), we observe an intensification of glacial and periglacial hazards over time since the 1980s, across all Alpine countries (Fig. 4). It should be noted that this figure only considers events that required risk management and that have influenced our understanding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

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

366

367 Evolution over time of major event risk management for *ice avalanches* in the Alps (Fig. 5):
368 The Altels ice avalanche (CH) in 1895 marked the beginning of the need to understand hazards in high
369 altitude Alpine regions. This avalanche was of exceptional size, with 4×10^6 m³ of ice breaking away,
370 killing six people and burying 170 cattle over an area of one km² (Forel, 1895; Du Pasquier, 1896). For
371 a long time, this event was the reference point in terms of ice avalanches. "To what extent can we predict
372 such disasters, and to what degree will we be able to prevent them from happening again? Many Alpine
373 glaciers give rise to avalanches or ruinous debacles. (...) The same glaciers periodically give rise to the
374 same phenomena, so it is above all empirical knowledge of these phenomena that we need to acquire.
375 (...) An accurate knowledge of the dangerous points and the phenomena that occur there is absolutely
376 necessary. The era of independent personal research is over; it has produced all it could in this field (...).
377 What is needed now is more coordination, more method, more consistency in research" (Du Pasquier,
378 1896).

379

380
381 *Fig. 5 Temporal evolution of ice avalanche risk management in the Alps.*

382

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

395

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

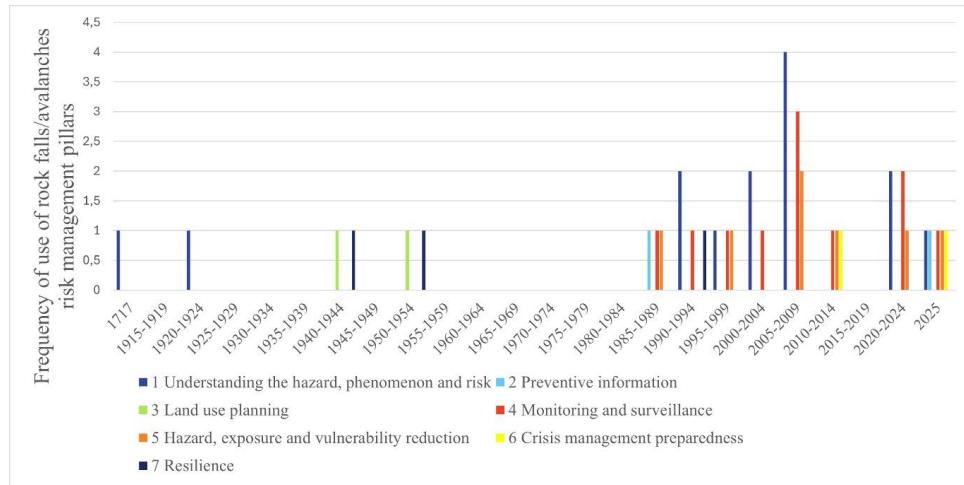



Fig. 6 Temporal evolution of risk management for rockfalls / rock avalanches.

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; 30×10^6 m³) illustrates proactive risk management (Chardon, 1990). In 2011, at Piz Cengalo (CH; 1.5 $\times 10^6$ m³), a series of preventive measures were put in place: alerting the population, closing trails, abandoning alpine buildings and protective structures (Ancey, 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 also been equipped: Aiguille du Midi (FR) since 2005, the south face of the Matterhorn (IT) and Les Drus (FR) 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).

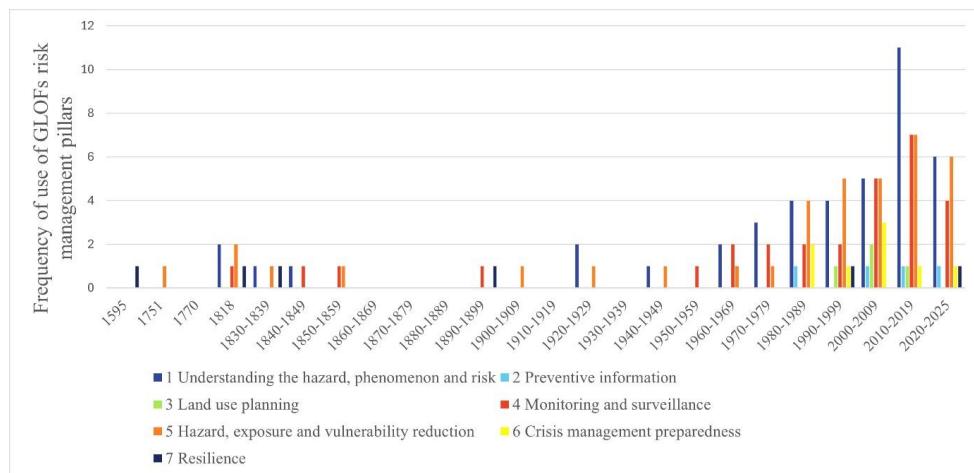
Evolution over time of risk management for major GLOF events in the Alps (Fig. 7):

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 5×10^6 m³ in 1751). Technical solutions such as the construction of a dam or the digging of a tunnel were considered as early as the 19th century (Vergnano et al., 2023).

Another notable example is the 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 18×10^6 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.

432 Monitoring of glaciers in relation to their potential to form lakes or water pockets became formalised
433 around a century ago, notably with systematic photogrammetric surveys of the Vernagtferner (AU), one
434 of the best-documented glaciers in the country due to its numerous GLOFs, the most notable of which
435 dates back to 1848 (Braun, 1995; *Gridabase - Glaciorisk*, s. d.).
436 However, the integration of populations through preventive information is a more recent development.
437 In 1986, with the case of the Arsine proglacial lake (FR), scientists alerted the authorities and the
438 population to the risk of overflow in the event of a serac falling into the lake (Hoinkes, 1969). This alert
439 led to the first official crisis management preparations involving local residents. The following year, in
440 Valtellina (IT), similar preventive measures were put in place in response to instability in Val Pola and
441 the heavy rainfall forecast (Chardon, 1990).
442

443
444 *Fig. 7 Temporal evolution of risk management for Glacial Lake Outburst Floods.*
445

446 **4.2.3 Disruptive events that have improved the management and understanding of glacial and**
447 **periglacial risks**
448

449 The creation of a timeline tracing risk management measures in response to past events has made it
450 possible to identify key moments marking disruptions and/or the emergence of new approaches. The
451 examples selected correspond to the first documented cases where a new specific form of risk
452 management was implemented or redefined: first predictions of collapses, first glacial and periglacial
453 monitoring systems, first actions to reduce exposure, vulnerability or hazard at source and on a larger
454 scale, and first large-scale multidisciplinary coordination in crisis situations.
455

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

467 unpredictable at the time and therefore inevitable, disasters began to be perceived not as evidence of
468 divine wrath, but as natural and physical processes (Carrivick and Tweed, 2016).
469
470 Monitoring and surveillance:
471 The first inventory known of a glacier in the Alps dates back to the end of the 19th century for the
472 Vernagtferner (AU), a glacier known for its numerous and destructive GLOFs over the last 400 years
473 (Hoinkes, 1969). A hundred years of systematic surveys were carried out using photogrammetry,
474 resulting in the first map and descriptive theory on glacier movement (Braun, 1995). Continuing with
475 this focus on intensive monitoring of glaciers and their associated risks, the Gietro glacier was one of
476 the first to be monitored since the 1960s. Surface movements, short-term flow movements, structure,
477 mass balance, volume changes, etc. are measured (Ancey, 2017). Similarly, the Matterhorn (CH-IT) has
478 been closely monitored and equipped with a microseismic monitoring system and thermometric
479 monitoring system since 2007, following recurrent rockfalls since 2003 (Occhiena and Pirulli, 2012).
480
481 Multidisciplinary network:
482 The rupture of the Tête Rousse water pocket in 1892 was a fundamental event in the early days of glacier
483 risk management. The debris flow that affected several villages downstream, causing 175 victims
484 (Mougin and Bernard, 1922), led to the establishment of a multidisciplinary network to identify the
485 causes of the disaster and implement measures. Engineers, glaciologists and foresters from the *Eaux et*
486 *Forêts* administration were brought together, commissioned by the local authorities (Marco et al., 2012),
487 to investigate, map, dig a drainage tunnel and enable increased monitoring of the glacier (Sirop et al.,
488 2022).
489 The collapse of the Allalin glacier tongue at Mattmark (CH) in 1965 also made history, not only because
490 of its 88 victims (Vivian, 1966), but also because of the urgent need for scientists to work together.
491 Indeed, glaciological and engineering studies were carried out immediately after the disaster in order to
492 protect rescue operations and construction work in the following years (Dalban Canassy et al., 2011).
493 Such a coalition of scientists has irrevocably advanced our understanding of the mechanism of phased
494 glacial rupture.
495 Still in this spirit of coordination between management actors, the case of the Rochemelon lake seems
496 significant. Trapped between the ice and the rock face, the lake grew continuously until 2004 (Vincent
497 et al., 2010), when fears of overflowing and spreading on the French side alerted scientists. This led the
498 authorities to take preventive action to drain the lake. French and Italian authorities, scientists, engineers,
499 technicians and rescue workers worked closely together in this crisis management operation. This
500 involved risk studies based on observation and measurement campaigns, alerts to the population, and
501 finally the draining of the lake at the end of 2004 and 2005. The Rochemelon crisis highlighted two
502 major points: (1) the importance of having the necessary investigative resources to understand the entire
503 phenomenon and its evolution at a very early stage and with sufficient precision, in order to translate
504 this into operational decisions; (2) the importance of ensuring, both upstream and during crisis
505 management, genuine continuity between scientific knowledge, its transfer to the authorities and its
506 translation into operational measures (Marco et al., 2012).
507
508 Predictive study:
509 In 1973, the first successful glacier rupture prediction was made at Weisshorn (CH) (Röthlisberger,
510 1981b). Scientists observed an acceleration of the upper part of the glacier, supplemented by warnings
511 from local mountain guides about a new transverse crevasse, indicating an unstable situation (Faillettaz
512 and Funk, 2013).
513
514 Reduction of exposure and vulnerability (evacuations, works, etc.):
515 The first known organised evacuations in response to gravitational hazards date back to 1987, in the
516 Adda valley (IT), in response to the 30×10^6 m³ rockslide in Val Pola (Dramis et al., 1995). The
517 instability of the slope, due to inconsistent geology, a steep gradient and heavy rainfall in the preceding

518   days, had led to warnings of a potential collapse (Chardon, 1990). Regarding glacial hazards, one of the
519   first documented evacuations took place in 1997 in Planpincieux (IT), due to the threat of collapse of
520   the Whymper hanging glacier (south face of Grandes Jorasses, 4208 m a.s.l.), which could have carried
521   away large masses of snow (Margreth and Funk, 1999). In the same year, researchers developed the first
522   safety concept for the village, based on several breakage scenarios derived from glacier monitoring and
523   avalanche studies (Margreth et al., 2011).
524   In terms of reducing exposure, vulnerability or hazard (Pillar 5), the Belvedere glacier (IT) is a
525   significant example. Following a lake's overflow in 1979, preventive work was undertaken: artificial
526   lowering of lake delle Locce and construction of downstream dams (Haeberli and Epifani, 1986). In
527   2002, faced with the threat of sudden drainage of the Effimero lake onto the village of Macugnaga, the
528   Italian Civil Protection Agency implemented several emergency measures: risk mapping, access
529   restrictions, enhanced monitoring, alert and evacuation procedures, and an artificial pumping system
530   (Haeberli et al., 2002).

532   This initiative is part of the ongoing development of Alpine projects dedicated to improving risk
533   understanding and management (*Glaciorisk*, 2001-2003; *PERMAdataROC*, 2000-2006; *GlariskAlp*,
534   2010-2013; PAPROG, since 2019, etc.).

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

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

561   **4.2.4 Proactive *vs*. reactive management**

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

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 1996.
In contrast, the 1965 Mattmark disaster 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, and the protective structures limited the damage to infrastructure in Bondo (Ancey, 2017).

5. Discussions

5.1 Distribution of management 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.

618 It should also be noted that certain ancient events are well documented in the archives through their
619 feedback, but have only recently been used as data for analysing and understanding the hazard (Pillar
620 1). These events therefore do not appear in Figures 5, 6 and 7, even though they meet the selection
621 criteria due to their value for understanding past phenomena. This is the case, for example, of the
622 Breithorn ice avalanche (CH) in 1597, which destroyed the village of Homattugletscher (Forel et al.,
623 1901); the devastating lake outbursts beneath the Rutor Glacier (IT) between the 15 and 17th centuries
624 (*Gridabase - Glaciorisk*); the Gietro glacier break-up in 1995, which claimed 140 lives (Ancey, 2017);
625 the rock avalanche scattered across the Triolet glacier (IT) in 1717 (Porter and Orombelli, 1981; Deline
626 et al., 2014); at the Allalin glacier between 1589 and 1850, documents report 26 significant and sudden
627 discharges (*Gridabase - Glaciorisk*), etc.
628
629 **5.2 Risk perception and culture in past centuries**
630
631 The documentary research carried out to compile this timeline did not include risk perception and culture
632 during events in the 19th century and earlier. We focused on contemporary methods (20th and 21st
633 centuries) of risk management, as these explain how things are done today. However, understanding risk
634 management in a more global context requires the perception of risk at the local level by placing it in its
635 historical and climatic context.
636 We wondered whether religious processions in mountain villages affected by glacial or periglacial events
637 were necessary to understand today's risk management. We have only mentioned them, without
638 exploring the idea of risk culture in ancient mountain societies in greater depth. The two most
639 outstanding examples remain the processions around 1818 to the Ussere Aletsch mountain pasture (CH),
640 where a cross was erected to "exorcise these terrible threats" (Coutterand, 2017) and to stop the
641 Märjensee lake from overflowing (21 times between 1813 and 1895). We also noted the example of the
642 Mer de Glace in Chamonix (FR), which threatened agricultural land. A procession was organised in the
643 valley by the coadjutor of Geneva to make the glacier recede in 1943-1944 (Mougin and Bernard, 1922).
644 It is therefore clear that at a time when religion was prevalent in society, processions were part of a
645 certain form of risk management. The fact that science and reason now prevail in the way we understand
646 risk and uncertainty motivated our decision not to include these examples. Even if "invoking the heavens
647 did not prevent attempts to understand the conditions for the development of disasters at the local level
648 (at least among the local elites*)*" (Favier, 2007).
649
650 **5.3 Biases linked to difficulties in compiling an exhaustive inventory of events**
651
652 Compiling an inventory that is exhaustive in relation to our decision-making criteria implies certain
653 limitations and the need to place the event in its context.
654
655 The source effect:
656 With the increase in glacial and periglacial events over time, we are facing biases related to the *source*
657 *effect* (*e.g.* Giacona et al., 2017). This increase is closely linked to the sources, *i.e.* the origin of the
658 information. As Giacona (2019) points out, "the spatial and temporal distribution of events is closely
659 dependent on that of the structure of the documentary corpus". Each event recorded is therefore
660 dependent on the quality and diversity of the sources that attest to it. The author thus hypothesises in his
661 geochronology of snow avalanches in the Vosges mountains that the rarity of sources in the distant past
662 limits the traceability of events, while the abundance, accuracy and increasing systematisation of data
663 in the recent past automatically increases their number.
664 The *source effect* therefore requires particular attention to variations in the volume of documentation.
665 For example, the installation of a webcam at the Gornergletscher (Huss et al., 2007), demonstrating
666 advances in technology, adds a source of detailed data. It will make it possible to create multiple
667 occurrences of hazards.
668

669   Land use and the event prism:

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

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

683

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

688

689   **6   Conclusions and perspectives**

690

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

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

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

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

718

719   *Author contributions.* JB, LR and SC designed the study and JB carried it out. JB prepared the
720   manuscript with contributions from all co-authors.
721
722   *Competing interests.* The authors declare that they have no conflict of interest.
723

724   **References**

725   Alean, J.: Ice Avalanches: Some Empirical Information about their Formation and Reach, J. Glaciol., 31,
726   324–333, https://doi.org/10.3189/S0022143000006663, 1985.

727   Allen, S., Frey, H., and Huggel, C.: GAPHAZ 2017: Assessment of Glacier and Permafrost Hazards in
728   Mountain Regions – Technical Guidance Document., Glacier and Permafrost Hazards in Mountains
729   (GAPHAZ), International Association of Cryospheric Sciences (IACS) and the International Permafrost
730   Association (IPA) - Zurich, Switzerland / Lima, Peru, 2017.

731   Allen, S., Frey, H., Haeberli, W., Huggel, C., Chiarle, M., and Geertsema, M.: Assessment Principles for
732   Glacier and Permafrost Hazards in Mountain Regions, in: Oxford Research Encyclopedia of Natural
733   Hazard Science, https://doi.org/10.1093/acrefore/9780199389407.013.356, 2022.

734   Philippe Morel: Quand les montagnes s'effritent ~~Propos recueillis par Philippe Morel~~ | Espazium:
735   https://www.espazium.ch/fr/actualites/quand-les-montagnes-seffritent, last access: 12 February
736   2025.

737   Ancey, C., Bardou, E., Funk, M., Huss, M., Werder, M. A., and Trewhela, T.: Hydraulic Reconstruction of
738   the 1818 Giétro Glacial Lake Outburst Flood, Water Resour. Res., 55, 8840–8863,
739   https://doi.org/10.1029/2019WR025274, 2019.

740   Gridabase - Glaciorisk: https://www.nimbus.it/glaciorisk/gridabasemainmenu.asp, last access: 27
741   May 2025.

742   Research Projects - GEORESEARCH: https://www.georesearch.ac.at/en/areas/research/research-
743   projects/, last access: 30 October 2025.

744   Bauder, A.: The Swiss Glaciers 2013/14 and 2014/15 - Glaciological Report No. 135/136, 145pp,
745   https://doi.org/10.18752/GLREP_135-136, 2017.

746   Beccera, S. and Peltier, A.: L'information préventive pour réduire la vulnérabilité aux risques
747   d'inondation, élaboration et efficacité d'une réponse sociale, Chang. Clim. Métarisque À Méta-Gouv.,
748   pp.35-53, 2011.

749   Bisquert, A., Mainieri, R., Carladous, S., Robert, Y., Giacona, F., Verry, P., and Eckert, N.: La base de
750   données événementielles RTM pour la connaissance des risques naturels en montagne : L'exemple du
751   département de l'Isère (France), J. Alp. Res. Rev. Géographie Alp., https://doi.org/10.4000/137kf,
752   2025.

753   Boudières, V. and Peisser, C.: Prévention des Risques d'Origine Glaciaire et Périglaciaire (ROGP) -
754   Synthèse des connaissances et des pratiques, PARN, 2013.

755   Bourrelier, P.-H. and Dunglas, J.: Des événements naturels extrêmes aux figures de la catastrophe:,
756   Ann. Mines - Responsab. Environ., N° 56, 41–47, https://doi.org/10.3917/re.056.0041, 2009.

757   Braun, L. N.: Les résultats principaux de 100 ans de recherche au Vernagtferner, Oetztal (Autriche),
758   Houille Blanche, 81, 109–110, https://doi.org/10.1051/lhb/1995054, 1995.

759 Carrivick, J. L. and Tweed, F. S.: A global assessment of the societal impacts of glacier outburst floods,
760 Glob. Planet. Change, 144, 1–16, https://doi.org/10.1016/j.gloplacha.2016.07.001, 2016.

761 Cathala, M., Magnin, F., Linsbauer, A., and Haeberli, W.: Modelling and characterizing glacier-bed
762 overdeepenings as sites for potential future lakes in the deglaciating French Alps, Géomorphologie
763 Relief Process. Environ., 27, 19–36, https://doi.org/10.4000/geomorphologie.15255, 2021.

764 Cauliez, R.: Mémoire M2 - Au-delà des eaux glacées. Pouvoirs gestionnaires et expériences populaires
765 sous le glacier de Tête-Rousse., Ecole Normale Supérieure, 229 pp., 2024.

766 Chardon, M.: Les catastrophes naturelles de l'été 1987 en Lombardie : crues,inondations,
767 écroulement de Val Pola, Rev. Géographie Alp., 78, 59–87, https://doi.org/10.3406/rga.1990.2767,
768 1990.

769 Chiarle, M., Iannotti, S., Mortara, G., and Deline, P.: Recent debris flow occurrences associated with
770 glaciers in the Alps, Glob. Planet. Change, 56, 123–136,
771 https://doi.org/10.1016/j.gloplacha.2006.07.003, 2007.

772 Chiarle, M., Viani, C., Mortara, G., Deline, P., Tamburini, A., and Nigrelli, G.: Large glacier failures in
773 the Italian Alps over the last 90 years, Geogr. Fis. E Din. Quat., 45, 19–40,
774 https://doi.org/10.4461/GFDQ.2022.45.2, 2022.

775 Coutterand, S.: Les glaciers des Alpes - Du temps des mammouths au XXIe siècle, Emmanuel Vandelle
776 Editions., 2017.

777 Dalban Canassy, P., Bauder, A., Dost, M., Fäh, R., Funk, M., Margreth, S., Müller, B., and Sugiyama, S.:
778 Hazard assessment investigations due to recent changes in Triftgletscher, Bernese Alps, Switzerland,
779 Nat. Hazards Earth Syst. Sci., 11, 2149–2162, https://doi.org/10.5194/nhess-11-2149-2011, 2011.

780 Dauphiné, A. and Provitolo, D.: Risques et catastrophes, Armand Colin,
781 https://doi.org/10.3917/arco.dauph.2013.01, 2013.

782 Defossez, S., Vinet, F., and Leone, F.: Diagnostiquer la vulnérabilité face aux inondations : progrès et
783 limites, in: Inondations 1: la connaissance du risque, 2018.

784 Deline, P., Akçar, N., Ivy-Ochs, S., and Kirkbride, M. P.: 1717 AD rock avalanche or Lateglacial glacier?
785 Unraveling with dating the Triolet deposit, Mont Blanc massif., in: Colloque International AFEQ - CNF
786 INQUA Q9 : Le Quaternaire : marqueurs, traçeurs et chronomètres, Lyon, France, 2014.

787 Dematteis, N., Giordan, D., Troilo, F., Wrzesniak, A., and Godone, D.: Ten-Year Monitoring of the
788 Grandes Jorasses Glaciers Kinematics. Limits, Potentialities, and Possible Applications of Different
789 Monitoring Systems, Remote Sens., 13, 3005, https://doi.org/10.3390/rs13153005, 2021.

790 Demolis, B., Kuss, D., and Serrano, C.: Etude du lac de la Patinoire à Pralognan la Vanoise (73), ONF-
791 RTM INRAE, 2021.

792 Desailly, B.: Crues et inondations en Roussillon : le risque, le discours et l'aménagement, Rev.
793 Géographique Pyrén. Sud-Ouest, 61, 515–519, https://doi.org/10.3406/rgpso.1990.3229, 1990.

794 Dollfus, O. and D'Ercole, R.: Les mémoires des catastrophes au service de la prévision et de la
795 prévention des risques naturels, 7–18, 1996.

796   Dosse, F.: Renaissance de l'événement, 1réd., Presses Universitaires de France,
797   https://doi.org/10.3917/puf.dosse.2010.01, 2010.

798   Dourlens, C.: La question des inondations au prisme des sciences sociales : un panorama de la
799   recherche publique, Ministère de l'Equipement, des Transports, du Logement, du Tourisme et de la
800   Mer, 112 pp., 2004.

801   Du Pasquier, L.: L'avalanche du glacier de l'Altels le 11 septembre 1895, Ann. Géographie, 5, 458–468,
802   https://doi.org/10.3406/geo.1896.5954, 1896.

803   Einhorn, B.: Changement climatique et risques naturels - Prévention, Gestion intégrée, Adaptation,
804   2017.

805   Einhorn, B. and Peisser, C.: Gestion intégrée du risque généré par les poches d'eau du glacier de Tête
806   Rousse – De la tragédie de 1892 à la gestion de crise de 2010, Grenoble, 2011.

807   Faillettaz, J. and Funk, M.: Instabilités glaciaires et prédiction, Société Vaudoise Sci. Nat., 159–174,
808   2013.

809   Faillettaz, J., Funk, M., and Vincent, C.: Avalanching glacier instabilities: Review on processes and early
810   warning perspectives, Rev. Geophys., 53, 203–224, https://doi.org/10.1002/2014RG000466, 2015.

811   Favier, R.: Sociétés urbaines et culture du risque. Les inondations dans la France d'Ancien Régime, in:
812   Les cultures du risque (XVIe-XXIe siècle), pp.49-86, 2006.

813   Favier, R.: L'histoire sociale des risques naturels en questions. Sources et problématiques nouvelles.,
814   155–172, 2007.

815   Field, C., Barros, V., Stocker, T., and Dahe, Q.: Managing the risks of extreme events and disasters to
816   advance climate change adaption, Cambridge university press, New York, 582 pp., 2012.

817   Fischer, L., Kääb, A., Huggel, C., and Noetzli, J.: Geology, glacier retreat and permafrost degradation as
818   controlling factors of slope instabilities in a high-mountain rock wall: the Monte Rosa east face, Nat.
819   Hazards Earth Syst. Sci., 6, 761–772, https://doi.org/10.5194/nhess-6-761-2006, 2006.

820   Flotron, A.: Movement Studies on a Hanging Glacier in Relation with an Ice Avalanche, J. Glaciol., 19,
821   671–672, https://doi.org/10.3189/S0022143000029592, 1977.

822   Fondazione Montagna Sicura and Regione Autonoma Valle d'Aosta: L'inventaire des glaciers de la
823   région autonome Vallée d'Aoste : mise à jour et Plan de prévention des risques glaciaires, 2012.

824   Forel, F. A.: L'Eboulement du glacier des Altels, Bureau des Archives, Genève, 513 pp., 1895.

825   Fournier, M.: Le riverain introuvable ! La gestion du risque d'inondation au défi d'une mise en
826   perspective diachronique : une analyse menée à partir de l'exemple de la Loire., Aménagement de
827   l'Espace et Urbanisme, Université François-Rabelais, Tours, 432 pp., 2010.

828   Giacona, F., Eckert, N., and Martin, B.: A 240-year history of avalanche risk in the Vosges Mountains
829   based on non-conventional (re)sources, Nat. Hazards Earth Syst. Sci., 17, 887–904,
830   https://doi.org/10.5194/nhess-17-887-2017, 2017.

831   Giacona, F., Martin, B., Eckert, N., and Desarthe, J.: Une méthodologie de la modélisation en
832   géohistoire : de la chronologie (spatialisée) des événements au fonctionnement du système par la

833   mise en correspondance spatiale et temporelle, Physio-Géo, 171–199,
834   https://doi.org/10.4000/physio-geo.9186, 2019.

835   Girard, S. and Rivière-Honegger, A.: Le choix et la pratique de la monographie diachronique.
836   Contribution à l'étude de l'efficacité environnementale de la territorialisation de la politique de l'eau.,
837   in: Environnement, politiques publiques et pratiques locales, 359–384, 2015.

838   Granet-Abisset, A.-M.: L'historien, les risques et l'environnement : un regard sur la nature et les
839   hommes, in: 23èmes Journées Scientifiques de l'Environnement - Risques environnementaux :
840   détecter, comprendre, s'adapter, Créteil, France, 2012.

841   Gruber, S. and Haeberli, W.: Permafrost in steep bedrock slopes and its temperature-related
842   destabilization following climate change, J. Geophys. Res. Earth Surf., 112, 2006JF000547,
843   https://doi.org/10.1029/2006JF000547, 2007.

844   Haeberli, W., Buetler, M., Huggel, C., Friedli, T. L., Schaub, Y., and Schleiss, A. J.: New lakes in
845   deglaciating high-mountain regions – opportunities and risks, Clim. Change, 139, 201–214,
846   https://doi.org/10.1007/s10584-016-1771-5, 2016.

847   Hoinkes, H. C.: Surges of the Vernagtferner in the Ötztal Alps since 1599, Can. J. Earth Sci., 6, 853–861,
848   https://doi.org/10.1139/e69-086, 1969.

849   Hugerot, T., Astrade, L., Gauchon, C., and Ployon, E.: De la carte diachronique à la trajectoire
850   géohistorique : modélisation du changement paysager d'un cône torrentiel, Mappemonde,
851   https://doi.org/10.4000/mappemonde.6704, 2021.

852   Huggel, C., Fischer, L., Schneider, D., and Haeberli, W.: Research advances on climate-induced slope
853   instability in glacier and permafrost high-mountain environments, Geogr. Helvetica, 65, 146–156,
854   https://doi.org/10.5194/gh-65-146-2010, 2010.

855   Huss, M., Bauder, A., Werder, M., Funk, M., and Hock, R.: Glacier-dammed lake outburst events of
856   Gornersee, Switzerland, J. Glaciol., 53, 189–200, https://doi.org/10.3189/172756507782202784,
857   2007.

858   Intergovernmental Panel On Climate Change (Ipcc) (Ed.): Annex I: Glossary, in: Climate Change 2022 -
859   Mitigation of Climate Change, Cambridge University Press, 1793–1820,
860   https://doi.org/10.1017/9781009157926.020, 2023.

861   Jacquemart, M., Weber, S., Chiarle, M., Chmiel, M., Cicoira, A., Corona, C., Eckert, N., Gaume, J.,
862   Giacona, F., Hirschberg, J., Kaitna, R., Magnin, F., Mayer, S., Moos, C., Van Herwijnen, A., and Stoffel,
863   M.: Detecting the impact of climate change on alpine mass movements in observational records from
864   the European Alps, Earth-Sci. Rev., 258, 29, https://doi.org/10.1016/j.earscirev.2024.104886, 2024.

865   Joffe, H. and Orfali, B.: De la perception à la représentation du risque: le rôle des médias, Hermès, n°
866   41, 121, https://doi.org/10.4267/2042/8962, 2005.

867   Kellerer-pirklbauer, A., Slupetzky, H., and Avian, M.: Ice-avalanche impact landforms: the event in
868   2003 at the glacier nördliches bockkarkees, hohe tauern range, austria, Geogr. Ann. Ser. Phys. Geogr.,
869   94, 97–115, https://doi.org/10.1111/j.1468-0459.2011.00446.x, 2012.

870   Kienholz, H., Krummenacher, B., Kipfer, A., and Perret, S.: Aspects of Integral Risk Management in
871   Practice - Considerations with Respect to Mountain Hazards in Switzerland, 45–50, 2004.

872   Laïly, B. and Demolis, B.: Glaciers blancs à risques - Retours d'expériences sur certaines crises, ONF-
873   RTM, 2019.

874   Leone, F., Meschinet de Richemond, N., and Freddy, V.: Aléas naturels et gestion des risques, Presses
875   Universitaires de France, 288 p. pp., 2021.

876   Link, S. and Stötter, J.: The development of mountain risk governance: challenges for application,
877   https://doi.org/10.5194/nhessd-3-429-2015, 16 January 2015.

878   Magnin, F., Ravanel, L., Ben-Asher, M., Bock, J., Cathala, M., Duvillard, P.-A., Jean, P., Josnin, J.-Y.,
879   Kaushik, S., Revil, A., and Deline, P.: De l'observation des écroulements aux solutions opérationnelles :
880   près de deux décennies d'études sur les risques cryo-gravitaires dans le massif du Mont-Blanc, Rev.
881   Géographie Alp., 111–2, https://doi.org/10.4000/rga.11644, 2023.

882   Mainieri, R., Blanc, A., Astrade, L., Baratier, A., Berthet, J., Deline, P., Le Roy, M., Misset, C., De
883   Montety, F., Robert, Y., and Schoeneich, P.: Les aspects géomorphologiques de la crue torrentielle du
884   torrent des Étançons à la Bérarde du 21 juin 2024, Géomorphologie Relief Process. Environ., 31,
885   https://doi.org/10.4000/14ipc, 2025.

886   Mair, V., Zischg, A., Lang, K., Tonidandel, D., Krainer, K., Kellerer-Pirklbauer, A., Deline, P., Schoeneich,
887   P., Cremonese, E., Pogliotti, P., Gruber, S., and Böckli, L.: PermaNET - Réseau d'observation du
888   permafrost sur le long terme - Rapport de synthèse, Interpraevent, Klagenfurt, 2011.

889   Marco, O., Laily, B., and Charles, F.: Mesures de protection et contraintes d'ingénierie en milieu
890   glaciaire : expérience des services intervenus sur les cas récents - ONF-RTM, 2012.

891   Margreth, S. and Funk, M.: Hazard mapping for ice and combined snowrice avalanches — two case
892   studies from the Swiss and Italian Alps, 159–173, 1999.

893   Margreth, S., Funk, M., Vagliasindi, M., and Broccolato, M.: Safety concept for hazards caused by ice
894   avalanches from the Whymper hanging glacier in the Mont Blanc Massif, International snow science
895   workshop proceedings 2010, Squaw Valley, CA, USA, 281–288, 2010.

896   Margreth, S., Faillettaz, J., Funk, M., Vagliasindi, M., Diotri, F., and Broccolato, M.: Safety concept for
897   hazards caused by ice avalanches from the Whymper hanging glacier in the Mont Blanc Massif, Cold
898   Reg. Sci. Technol., 69, 194–201, https://doi.org/10.1016/j.coldregions.2011.03.006, 2011.

899   Margreth, S., Funk, M., Tobler, D., Dalban, P., Meier, L., and Lauper, J.: Analysis of the hazard caused
900   by ice avalanches from the hanging glacier on the Eiger west face, Cold Reg. Sci. Technol., 144, 63–72,
901   https://doi.org/10.1016/j.coldregions.2017.05.012, 2017.

902   Mariétan, I.: Note de sciences naturelles sur la vallée de Saas, 88–102, 1953.

903   Mendez, A.: Processus: concepts et méthode pour l'analyse temporelle en sciences sociales,
904   Academia Bruylant, Louvain-la-Neuve, 2010.

905   Moles, A.: Notes pour une typologie des événements, Communications, 18, 90–96,
906   https://doi.org/10.3406/comm.1972.1261, 1972.

907   Mougin, P. and Bernard, C.: Étude sur le glacier de Tête-Rousse, 1922.

908 Mourey, J., Clivaz, C., and Bourdeau, P.: Analyser l'évolution des pratiques sportives en montagne peu
909 aménagée à partir des données de fréquentation des cabanes. Application aux Alpes Valaisannes,
910 Rev. Géographie Alp., https://doi.org/10.4000/rga.11110, 2023.

911 Occhiena, C. and Pirulli, M.: Analysis of Climatic Influences on Slope Microseismic Activity and
912 Rockfalls: Case Study of the Matterhorn Peak (Northwestern Alps), J. Geotech. Geoenvironmental
913 Eng., 138, 1012–1021, https://doi.org/10.1061/(ASCE)GT.1943-5606.0000662, 2012.

914 Peissier, C. and Courtray, V.: Séminaire technique - Synthèse et conclusions : Gestion des risques
915 d'origine glaciaire et périglaciaire - PARN, Ministère de l'Ecologie, du Développement Durable, des
916 Transports et du Logement - Direction Générale de la Prévention des Risques, Grenoble - World Trace
917 Center, 2012.

918 Pigeon, P.: Réflexions sur les notions et les méthodes en géographie des risques dits naturels, Ann.
919 Géographie, 111, 452–470, https://doi.org/10.3406/geo.2002.21624, 2002.

920 Porter, S. C. and Orombelli, G.: Alpine Rockfall Hazards: Recognition and dating of rockfall deposits in
921 the western Italian Alps lead to an understanding of the potential hazards of giant rockfalls in
922 mountainous regions, Am. Sci., 69, 67–75, 1981.

923 Prudent-Richard, G., Gillet, M., Vengeon, J.-M., and Descotes-Genon, S.: Changements climatiques
924 dans les Alpes : Impacts et risques naturels, ClimCHAlp - Interreg III B Alpine Space, 2008.

925 Ravanel, L.: Évolution géomorphologique de la haute montagne alpine dans le contexte actuel de
926 réchauffement climatique, 113–124, https://doi.org/10.3406/edyte.2009.1078, 2009.

927 Ravanel, L. and Deline, P.: La face ouest des Drus (massif du Mont-Blanc) : évolution de l'instabilité
928 d'une paroi rocheuse dans la haute montagne alpine depuis la fin du petit âge glaciaire,
929 Géomorphologie Relief Process. Environ., 14, 261–272,
930 https://doi.org/10.4000/geomorphologie.7444, 2008.

931 Ravanel, L., Magnin, F., Gallach, X., and Deline, P.: Évolution des parois rocheuses gelées de haute
932 montagne sous forçage climatique, 34–40, https://doi.org/10.37053/lameteorologie-2020-0090,
933 2020.

934 Raymond, M., Wegmann, M., and Funk, M.: Inventar gefährlicher Gletscher in der Schweiz,
935 Versuchsanstalt für Wasserbau Hydrologie und Glaziologie der Eidgenössischen Technischen
936 Hochschule Zürich, 2003.

937 Reghezza, M., Leone, F., and Vinet, F.: La vulnérabilité: un concept problématique., in: La vulnérabilité
938 des sociétés et des territoires face aux menaces naturelles - Analyses géographiques, vol. 1,
939 Montpellier III, 35–40, 2006.

940 Richard, D.: Caractérisation et gestion des risques d'origine glaciaire, CEMAGREF - Unité de recherche
941 ETNA, Grenoble, 2005.

942 Röthlisberger, H.: Eislawinen und Ausbrüche von Gletscherseen, Gletsch. Klima - Glaciers Clim. Jahrb.
943 Schweiz. Naturforschenden Ges. Wiss. Teil, 170–212, 1981b.

944 Schneiderbauer, S. and Ehrlich, D.: Risk, hazard and people's vulnerability to natural hazards - a
945 review of definitions, concepts and data, European Comission, 2004.

946   Gletschersee Grindelwald : Felssturz Schlossplatte: http://www.gletschersee.ch/index.cfm/treeID/21,
947   last access: 12 February 2025.

948   Sirop, M., Gagliardini, O., Serbource, P., and Bouvier, P.: La prévention des risques du glacier de Tête
949   Rousse : une action pluri-acteurs, 27–29, 2022.

950   Stoffel, M., Tiranti, D., and Huggel, C.: Climate change impacts on mass movements — Case studies
951   from the European Alps, Sci. Total Environ., 493, 1255–1266,
952   https://doi.org/10.1016/j.scitotenv.2014.02.102, 2014.

953   Valette, P. and Carozza, J.-M.: Géohistoire de l'environnement et des paysages, CNRS éditions, Paris,
954   2019.

955   Vannier, C., Lefebvre, J., Longaretti, P.-Y., and Lavorel, S.: Patterns of landscape change in a rapidly
956   urbanizing mountain region, Cybergeo, https://doi.org/10.4000/cybergeo.27800, 2016.

957   Vergnano, A., Oggeri, C., and Godio, A.: Geophysical–geotechnical methodology for assessing the
958   spatial distribution of glacio-lacustrine sediments: The case history of Lake Seracchi, Earth Surf.
959   Process. Landf., 48, 1374–1397, https://doi.org/10.1002/esp.5555, 2023.

960   Villeneuve, E., Pérès, F., and Geneste, L.: An approach to improve risk assessment using experience
961   feedback, in: Proceedings of IFIP Doctoral Spring Workshop "Product and Asset Lifecycle
962   Management, Huelva, Spain, 1–5, 2010.

963   Vincent, C.: Fluctuations des bilans de masse des glaciers des Alpes françaises depuis le debut du 20^e
964   siècle au regard des variations climatiques, Houille Blanche, 88, 20–24,
965   https://doi.org/10.1051/lhb/2002100, 2002.

966   Vincent, C., Garambois, S., Thibert, E., Lefèbvre, E., Le Meur, E., and Six, D.: Origin of the outburst
967   flood from Glacier de Tête Rousse in 1892 (Mont Blanc area, France), J. Glaciol., 56, 688–698,
968   https://doi.org/10.3189/002214310793146188, 2010.

969   Vivian, R.: La catastrophe du glacier Allalin, Rev. Géographie Alp., 54, 97–112,
970   https://doi.org/10.3406/rga.1966.3248, 1966.

971   Walter, F., Amann, F., Kos, A., Kenner, R., Phillips, M., De Preux, A., Huss, M., Tognacca, C., Clinton, J.,
972   Diehl, T., and Bonanomi, Y.: Direct observations of a three million cubic meter rock-slope collapse with
973   almost immediate initiation of ensuing debris flows, Geomorphology, 351, 106933,
974   https://doi.org/10.1016/j.geomorph.2019.106933, 2020.

975   Wiegandt, E. and Lugon, R.: 3 Challenges of Living with Glaciers in the Swiss Alps, Past and Present, in:
976   Darkening Peaks, edited by: Orlove, B., Wiegandt, E., and Luckman, B. H., University of California
977   Press, 33–48, https://doi.org/10.1525/9780520934245-004, 2008.

978   World Glacier Monitoring Service (WGMS): Fluctuations of glaciers 1985-1990, IAHS (ICSI) - UNEP -
979   UNESCO, 1993.

980