

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

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## Key words

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

**Abstract.** Glacial and periglacial hazards such as ice or rock avalanches, glacial lake outburst floods, and debris flows have caused severe damage in populated Alpine mountain regions throughout history. The objective of this research is to investigate how risk management methods have evolved over time and across different countries in the European Alps. Through a geo-historical study, we compile an inventory of events that have triggered risk management actions over the past centuries. This management is analysed using eight guiding pillars: hazard understanding, preventive information, land-use planning, monitoring and surveillance, hazard-vulnerability-exposure mitigation, crisis management preparedness, response, and resilience.

Certain events, such as the discharge of the water pocket of the Tête Rousse glacier (FR) in 1892 or the collapse of the Allalin glacier (CH) in 1965, represent key turning points that mark a shift or renewal in how risks are perceived and addressed. Today, glacial and periglacial risk management benefits from a better understanding of both hazards and vulnerabilities. Our geo-historical analysis highlights that the inclusion of the local populations in crisis management has become an increasingly significant factor in decision-making processes. However, current risk management practices remain limited and would benefit from more participatory approaches, which in turn partly depend on the perception of hazards and their integration into management practices.

## 1 Introduction

Rock and ice mass movements in high mountain areas pose significant risks to populations and infrastructure. Numerous past events show how glacial and periglacial processes can deeply affect Alpine valleys through large-scale and/or cascading phenomena (*e.g.*, Haeberli et al., 2016; Magnin et al., 2023). Their frequency and volume appear to be increasing (Ravanel and Deline, 2008, 2015; Jacquemart et al., 2024) as illustrated by recent disasters in Bondo (Graubünden, CH) in August 2017 (Walter et al., 2020), La Béarde (Isère, FR) in June 2024 (Mainieri et al., 2025), and Blatten (Valais, CH) in May 2025 (Büntgen et al., 2025).

This study focuses on major hazards affecting valley floors: ice, rock, and mixed avalanches, glacial lake outburst floods (GLOFs) and periglacial debris flows. These hazards are defined as natural phenomena impacting Alpine territories (Moles, 1972; Bisquet et al., 2025). A process becomes a *risk*

52 when it threatens lives, economic assets, or the environment. The notion of an *event* is useful for  
53 historians as it marks “a cut, a discontinuity”, something “interesting”, sufficiently “important” or “new”  
54 to be “told or enacted” (Dosse, 2010; Giacona et al., 2017). *Issues* are thus the exposed elements with  
55 varying vulnerabilities to each hazard (Defossez et al., 2018).

56 Permafrost warming and/or glacial debuttressing are contributing factors to rockfalls and rock  
57 avalanches (Fischer et al., 2006; Gruber and Haeberli, 2007; Huggel et al., 2010; Fischer et al., 2012).  
58 They may directly impact valley areas or provide material that triggers debris flows (Walter et al., 2020).  
59 An ice avalanche occurs when a glacier section detaches and moves quickly downwards (Alean, 1985;  
60 Richard, 2005; Faillettaz et al., 2015), destroying infrastructure, forests and lives, as illustrated by the  
61 collapse of the Allalin glacier (CH) onto worker accommodations during the construction of the  
62 Mattmark dam in 1965 (Dalban Canassy et al., 2011). Indirectly, they can trigger snow avalanches  
63 (Margreth and Funk, 1999) or debris flows when ice temporarily dams a stream (Richard, 2005).

64 GLOFs arise when a glacial lake or another water body suddenly drains, releasing large volumes of  
65 water that can evolve into debris flows if sufficient amounts of sediment are available (Richard, 2005;  
66 Huss et al., 2007; Carrivick and Tweed, 2016; Ancey et al., 2019). Their impacts can devastate entire  
67 valleys, as seen in the Bagnes valley below the Giétro glacier (CH) in 1595 and 1818 (Vincent et al.,  
68 2010; Ancey et al., 2019).

69 Integrated management of these risks (Prudent-Richard et al., 2008; Stoffel et al., 2014; Jacquemart et  
70 al., 2024) is essential for prevention because it allows for a holistic, coordinated approach that  
71 anticipates, mitigates, and adapts to complex, interconnected climate and emerging risks before they  
72 escalate into crises. We base our approach on the key components of risk management: hazard, exposure,  
73 and vulnerability (Niggli et al., 2024).

74 The database developed in this study documents glacial and periglacial events across the European Alps  
75 over the past two centuries that required risk management. Prevention measures from a political  
76 perspective are not uniform across Alpine countries. We have chosen to primarily present examples from  
77 France, Switzerland and Italy. Although Austria is also cited according to the sources we collected. The  
78 authors acknowledge the limitations of this study, particularly the challenges associated with obtaining  
79 comprehensive data; nevertheless, it is conceived as an exploratory approach. As such, it may serve as  
80 an initial step toward the development of a broader collaborative framework. The purpose is not only to  
81 provide a detailed account of the risk management measures implemented, but also to assess the  
82 frequency and intensity of such events and to trace historical management trends. An historical approach  
83 enables the analysis of change processes in risk management (Giacona et al., 2017, 2019), beyond mere  
84 event description (Girard and Rivière-Honegger, 2015).

85 We thus seek to understand how Alpine glacial and periglacial hazards have shaped scientific knowledge  
86 and risk management practices.

87 The paper first outlines the theoretical and historical framework of risk management, followed by the  
88 methods used to construct the database and apply the eight pillars of risk management which we have  
89 identified. The results describe the spatial and temporal distribution of events and corresponding  
90 management actions. Finally, we discuss the limitations of the data and the challenges of future  
91 prevention under a changing climate.

92  
93

94 **2 State of the art and theoretical positioning**

95  
96 The concepts used here require clarification to frame our approach. A *risk* refers to the probability of  
97 damage resulting from interactions between a physical process (the *hazard*), *exposure*, and *vulnerability*  
98 (Pigeon, 2002). The hazards we study occur at high altitudes (> 2,000-2,500 m a.s.l.) and may reach  
99 valley floors, threatening infrastructure, livelihoods, ecosystems, and populations (IPCC, 2023).  
100 Mountain valleys are thus considered vulnerable due to their exposure to such hazards, a condition  
101 reinforced by the concentration of people and infrastructure, which increases susceptibility to cascading  
102 effects (IPCC, 2023; Niggli et al., 2024). Vulnerability also depends on *resilience* and *sensitivity*, *i.e.* the

103 system's ability to absorb shocks and the degree of damage it can sustain (Schneiderbauer and Ehrlich,  
104 2004; Defossez et al., 2018). *Exposure* reflects the spatial and social proximity between hazard sources  
105 and affected communities (IPCC, 2022).

106 The continued expansion of urban areas in high Alpine valleys, driven by tourism and socioeconomic  
107 development (Hock and Rasul, 2022), combined with climate-induced changes in the cryosphere,  
108 increases potential losses (Huggel et al., 2015) and underscores the need for effective *risk management*  
109 (Allen et al., 2017). The latter encompasses strategies to anticipate, reduce, and respond to hazards  
110 (Leone et al., 2021) and aims to reduce uncertainty through scientific advances (Margreth et al., 2011,  
111 2017). While comparable to other Alpine hazards, glacial and periglacial processes evolve rapidly under  
112 climate change and can reach extreme magnitudes (Haeberli et al., 1999; Richard, 2005). Anticipation  
113 remains difficult because these hazards co-evolve with a rapidly changing cryosphere: glacier retreat,  
114 de-icing of rock faces, permafrost warming and associated slope movements, formation or  
115 disappearance of glacial lakes, and changes in glacier thermal regimes (Mainieri et al., 2025). High  
116 erosion rates in recently deglaciated or warming permafrost areas further increase debris-flow  
117 susceptibility (Huggel et al., 2015).

118 As historical experience shows, approaches based solely on hazard characterisation (Richard, 2005) are  
119 necessary but not sufficient (Allen et al., 2017). Analysing past events improves understanding of  
120 processes and supports better risk mitigation (Carrivick and Tweed, 2016). Rather than compiling  
121 exhaustive inventories, this study focuses is on lessons learned from major events, particularly how  
122 societies have managed risks over time.

123 Building a historical database requires a diachronic approach, inspired by diachronic monographs  
124 (Girard and Rivière-Honegger, 2015). This perspective (*e.g.* Desailly, 1990; Mendez, 2010) uses time  
125 to explain current territorial and risk dynamics. Such an approach allows the identification of  
126 geohistorical trajectories and rupture points in hazard evolution (Valette and Carozza, 2019; Hugerot et  
127 al., 2021). We adopt this framework to analyse long-term risk management, local practices, and the  
128 evolution of risk culture (Dollfus and D'Ercole, 1996). Studies such as Favier (2006) and Fournier  
129 (2010) on avalanches and floods in the Grenoble basin (FR), or Niggli et al. (2024) on GLOFs, illustrate  
130 how mountain societies have experienced and managed hazards.

131 Adopting a diachronic perspective also requires careful source selection (biases are discussed in § 5.2).  
132 Archival records complement narrative sources (Fournier, 2010). Since the 19<sup>th</sup> century, historical  
133 reconstructions have supported risk anticipation (Dourlens, 2004). However, exhaustive chronologies  
134 remain unattainable, as many small or frequent events leave no archival trace (Giacona et al., 2019).

135 To address this limitation, historical approaches prioritise the analysis of processes and mechanisms  
136 over completeness. Our study thus provides a synthetic view of Alpine risk management. Similar  
137 approaches, such as the temporal analysis of rockfalls in the Mont-Blanc massif (Raveland and Deline,  
138 2008; Raveland et al., 2020), reveal long-term dynamics.

139 Long-term monitoring initiatives also demonstrate the sensitivity of mountain environments to climate  
140 change, such as the EU-PACE project (Permafrost and Climate in Europe), which highlights the role of  
141 permafrost in slope stability and geohazards (Harris et al., 2001; Etzelmüller et al., 2020).

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143

### 144 **3 Construction of the database**

145

#### 146 3.1 Inventory of major glacial and periglacial events in the Alps

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##### 148 3.1.1 Criteria used to identify events to be included in the database

149

150 Building a comprehensive long-term database is challenging as data availability before the 20<sup>th</sup> century  
151 largely depends on societal vulnerability and record-keeping (Giacona, 2019).

152 We adopted a qualitative approach, retaining events that significantly marked local history or the  
153 environment, living traces in archives or collective memory. Our criteria are grouped into four  
154 categories.

155

#### 156 ***Extreme events***

157 We focused on rare, high-magnitude events exceeding several thousand cubic metres or causing serious  
158 damage (Bourrelrier and Dunglas, 2009; Field et al., 2012). Quantitatively, these correspond to the upper  
159 end of the frequency–intensity spectrum.

160

#### 161 ***Events with feedback***

162 We include events that led to in-depth post-event analyses aimed at improving process understanding,  
163 beyond simple observation (e.g. the Giétro glacier collapse in 1818; Wiegandt and Lugon, 2008).

164

#### 165 ***Repeated events***

166 We consider events repeatedly occurring within the same watershed, focusing on major one. For  
167 example, the Bockkarkees hanging glacier (AT) has produced >70 ice avalanches since 1933, including  
168 events reaching  $5 \times 10^6$  m<sup>3</sup> in 1945 and  $2\text{-}3 \times 10^6$  m<sup>3</sup> in 1964 and 1975 (*Gridabase*; Kellerer-Pirklbauer  
169 et al., 2012).

170

#### 171 ***Change in risk perception***

172 Events that significantly influenced risk perception are included, even if they do not meet the previous  
173 criteria. Risk culture varies across Alpine countries and is shaped by historical events. Event memory  
174 differs by context, making risk perception a social and political issue. The Mattmark disaster marked a  
175 major policy shift, moving away from the legally criticized notion that natural hazards are inherently  
176 unpredictable toward a more predictive approach to hazard analysis, as reflected in the Federal  
177 Government's establishment of a glacier hazard working group (Capozzi, 2011; Joris, 2025). Similarly,  
178 the Tête Rousse disaster (FR) established in France the idea of glaciers as internal, hidden, yet  
179 predictable hazards. The Marmolada glacier (IT) collapse in 2022 (Francesca et al., 2024), although  
180 limited to high-altitude impacts, caused 11 fatalities and strongly influenced public opinion, highlighting  
181 the need to better identify glacial hazards (Chiarle et al., 2022). It also led to the creation of a national  
182 working group and the publication of guidelines (Dipartimento della Protezione Civile, 2025).

183

184 We initially intended to start our inventory in 1985-1990, marking the first visible signs of the climate  
185 crisis in the Alps (Ravel, 2009; Ravel et al., 2020), up to 2025. However, earlier key events such as  
186 the 1892 Tête Rousse outburst (Mougin et Bernard, 1922) were too significant to omit. We therefore  
187 extended the analysis back to the early 19<sup>th</sup> century, where reliable sources exist.

188 For each event, we collected the following data: location (country, region, mountain range, orientation,  
189 glacier or summit name), rupture date(s), causes, mobilised volumes, runout distance, cascading effects,  
190 damage and casualties, monitoring methods, crisis management, and sources.

191 This method was applied to three hazard types: ice avalanches, torrential hazards (including GLOFs and  
192 debris flows), and rockfalls/rock-ice avalanches.

193 For cascading processes, we record the most impactful downstream process. For example, if a serac fall  
194 triggers lake overflow, the torrential process is retained. If permafrost degradation destabilises a moraine  
195 dam, we document the resulting breach and downstream propagation.

196

#### 197 **3.1.2 Data sources**

198

199 We used the *Gridabase* inventory produced as part of the European research project (« Gridabase -  
200 Glaciorisk », s. d., 2001-2003). This database compiles 501 documented events across Austria, France,  
201 Italy, and Switzerland, including floods, GLOFs, and ice avalanches (Richard, 2005). The aim of  
202 *Gridabase* was to preserve as comprehensively as possible the memory and trace of glacial events

203 (Peissier and Courtray, 2012), including those of modest importance (excluded here according to our  
204 criteria). However, investigations initiated by the Swiss Parliament highlighted that changing  
205 environmental conditions exceeded historical empirical references, requiring broader system  
206 assessments (Rickenmann and Zimmermann, 1993). *Gridabase* therefore presents a retrospective and  
207 partial perspective, which we accounted for in our analysis. In addition, for Italian Alps, we used the  
208 *Geoclimalp* cartographic inventory (Nigrelli et al., 2024; geoclimalp, 2026), which contains > 700 mass  
209 movements > 1500 m a.s.l. between 2000 and 2022.

210 Other sources include local databases such as the *RTM Database* or the regional *Catasto Dissesti*. The  
211 former is a French database developed by the *Restauration des Terrains de Montagne* (RTM) public  
212 service of the *Office National des Forêts*. Since the late 19<sup>th</sup> century, it has recorded a wide range of  
213 geomorphic processes, including avalanches, gully erosion, subsidence, landslides, rockfalls and debris  
214 flows (Bisquert et al., 2025). The *Catasto Dissesti* is a regional mapped inventory of hydrogeological  
215 and gravitational phenomena in Aosta Valley, enriched since the 1990s and regularly updated for risk  
216 prevention (Giardino et al., 2010). We retained from both databases glacial and periglacial events,  
217 including rock glacier ruptures, permafrost-related rockfalls and debris flows generated by cascading  
218 processes.

219 The RTM has also produced numerous technical reports on glacial and periglacial events. These  
220 documents, sometimes, unpublished, describes causes, trajectories, volumes, damage, and process  
221 histories within catchment. They also document risk management actions, from modelling and early  
222 warning to operational interventions (e.g. Patinoire lake in 1964; Étançons torrent in 2024; (Cathala et  
223 al., 2021; Demolis et al., 2021; Mainieri et al., 2025) and crisis management through operational  
224 measures (e.g. artificial draining of Rochemelon lake, FR, in 2005; Vincent et al., 2010; Cathala et al.,  
225 2021).

226 Many events documented by Swiss authorities were also included, such as the flood protection measures  
227 implemented at the Gruben glacier (Haeberli et al., 2001).

228 Scientific papers constitute a major part of our dataset, providing detailed analyses of hazard  
229 mechanisms and management strategies. Individual events are often studied by multiple teams using  
230 complementary approaches. The Whymper hanging glacier and the Planpincieux glacier (IT) illustrate  
231 this: studies address monitoring systems, rupture scenarios, hazard assessment, and evacuation strategies  
232 (Margreth and Funk, 1999; Margreth et al., 2011; Schindelegger, 2019; Dematteis et al., 2021; Troilo,  
233 2025).

234 The inventories of Chiarle et al. (2007, 2022), Jacquemart et al. (2024), and Niggli et al. (2024) were  
235 used to cross-check and validate our dataset.

236 Ministerial reports (e.g. Lacroix et al., 2022), the study of Magnin et al. (2023), and output from the  
237 *Pôle Alpin des Risques Naturels* (PARN), provide insights into how Alpine countries manage glacial and  
238 periglacial risks. They document research projects, monitoring strategies, prevention measures, and  
239 crisis management practices (e.g. *Glaciorisk*, *PERMAdataROC*, *PermaNET*, *GlariskAlp*, *GLAMOS*,  
240 *PERMOS*, *Prevrisk-CC*, *PermaRisk*, *SAMCO*, etc.). The *PAPROG* initiative fosters multidisciplinary  
241 collaboration between researchers and practitioners to improve knowledge and management of glacial  
242 risks. Similarly, *GEORESEARCH*, coordinates projects on monitoring, cryospheric dynamics, and  
243 quantitative risk analysis in the Alps (*FROST.INI*, *Futurelakes*, *GlacierRocks*, *AlpSenseRely*, etc.).

244 The *World Glacier Monitoring Service* (WGMS) provides global data on glacier fluctuations (1959-  
245 2010), including notable hazard events.

246 Finally, the local press provides insights into the societal impact of mass movements and associated  
247 management responses. However, this source requires careful critical interpretation, as it may reflect  
248 biases and lack technical accuracy (Joffe and Orfali, 2005). Despite these limitations, it remains valuable  
249 for analysing societal risk perception.

250

## 251 3.2 Types of glacial and periglacial risk management

252

### 253 3.2.1 Definition of the eight pillars of risk management

254  
255 Based on Alpine risk management systems (from local to national levels) and scientific literature,  
256 Kienholz et al., (2004) and Link and Stötter (2015) developed a classification of risk prevention and  
257 management methods. More recently, the Risk Management Cycle (RMC) – or Disaster Risk  
258 Management (DRM) – has been conceptualised. It encompasses all policies, strategies, and actions  
259 aimed at preventing, reducing, and managing disaster risks, as well as preparing for, responding to, and  
260 recovering from their impacts (Tagarev et al., 2021). In Switzerland and Nordic countries, since the  
261 1980s, natural hazard management has followed the principles of “Risk Minimisation” and “Integral  
262 Risk Management” (Nyberg et al., 2026), which aim to reduce risks to acceptable levels through  
263 assessment, prevention, mitigation, and preparedness, rather than eliminate them. Post-crisis phases  
264 focus on learning to improve future measures.

265 In France, similar principles are embedded in public policy and summarized by the PARN for glacial  
266 and periglacial risk prevention (Boudières and Peisser, 2013). In Italy, the *Dipartimento della Protezione*  
267 *Civile* (2025) has produced a methodological framework defining objectives for understanding glacial  
268 and periglacial phenomena. It outlines key pillars such as monitoring, public information, and crisis  
269 resilience.

270 All these principles were used to classify the management strategies identified in our database.

271

### 272 ***Pillar 1 : Hazards, phenomena, and risks understanding***

273 This pillar improves knowledge through past-events analysis, archives, monitoring, modelling, and  
274 experience feedback (Villeneuve et al., 2010; Faillettaz et al., 2015). It includes inventories and  
275 vulnerability assessments (e.g. GlaRiskAlp project; (Lucchesi et al., 2014; Nigrelli et al., 2013). Within  
276 DRM, this corresponds to risk identification and preparedness (Tagarev et al., 2021).

277

### 278 ***Pillar 2 : Preventive information***

279 This pillar promotes risk culture through public information and education (Beccera and Peltier, 2011),  
280 enabling citizens to actively contribute to preparedness and crisis response (OECD, 2018).

281

### 282 ***Pillar 3 : Integration into land-use planning***

283 Risk is integrated into planning tools such as hazard maps and preventive plans to reduce exposure and  
284 vulnerability (Schneiderbauer and Ehrlich, 2004). These tools combine modelling and spatial analysis  
285 to support decision-making (Allen et al., 2022).

286

### 287 ***Pillar 4 : Monitoring and surveillance***

288 Monitoring at-risk sites (cf.: Pillar 1) enables early detection and warning (Giordan et al., 2020; Cathala  
289 et al., 2024), supporting emergency preparedness. For example, Gornensee lake (CH) is monitored using  
290 cameras, depth measurements, and seismic sensors to anticipate GLOF hazards (WGMS, 1993; Huss et  
291 al., 2007). In Italy, glaciers such as Freney, Brenva, Grandes Jorasses, and Planpincieux are monitored  
292 using time-lapse imagery to assess flow velocity (Dematteis et al., 2024). Satellite observations  
293 complement field monitoring, especially for remote or large-scale events, though in the Alps they are  
294 often used post-event to analyse processes (e.g. Marmolada glacier collapse in 2022; (Bondesan and  
295 Francese, 2023; Olivieri and Bettanini, 2023; Francese et al., 2024) or to monitor supraglacial lakes  
296 hazards (e.g. Lys glacier or the Forni glacier, IT; (Davide et al., 2021; Fugazza et al., 2018). However,  
297 field-based observation remains central in the Alpine context. Field observations and human-based  
298 warning systems remain central, including observer networks such as “*Regards d’Altitude*” (ONF-RTM,  
299 2025).

300

### 301 ***Pillar 5 : Reducing hazard, exposure, and vulnerability***

302 This central pillar in risk / disaster risk management encompasses measures aimed at reducing three  
303 interconnected components of risk: hazard, exposure, and vulnerability. These three components are  
304 addressed together here because, in practice, risk managers and decision-makers rarely operate by

305 formally distinguishing between them. Mitigation strategies typically combine technical interventions  
306 and community capacity-building within integrated action plans. Artificially separating them would not  
307 reflect the reality of operational risk management. This is also consistent with the approach taken in this  
308 study, where the analysed policies and measures were designed and implemented in an integrated  
309 manner, making it difficult to disentangle the contribution of each component independently.  
310 In mountain contexts specifically, hazards can almost never be fully avoided; the focus therefore lies on  
311 limiting their frequency, magnitude, or spatial extent (at the source or along their path). Mitigation  
312 measures are commonly divided into two broad categories. Structural (or engineering) measures involve  
313 physical interventions. Non-structural measures include early warning systems, evacuation protocols,  
314 risk communication for examples. Together, these measures aim to reduce potential damage by acting  
315 on the hazard itself, on the elements exposed to it, or on the ability of communities and systems to cope  
316 with and recover from adverse events (Vincent et al., 2010b; Tagarev et al., 2021).  
317 For GLOFs, measures include drainage, water-level regulation, and structural stabilisation (Niggli et al.,  
318 2024). Exposure is reduced through channel management and protective structures, while vulnerability  
319 is lowered by improving preparedness and response capacities.

320

### 321 ***Pillar 6 : Crisis management preparedness***

322 This pillar corresponds to measures taken to improve response capacity (Tagarev et al., 2021). It includes  
323 planning, training, and coordination measures implemented before crises, such as contingency plans,  
324 simulations, and risk integration into training (Einhorn and Peisser, 2011; Link and Stötter, 2015).

325

### 326 ***Pillar 7 : Response***

327 Response refers to immediate actions during or after an event to manage impacts, save lives, and ensure  
328 safety (OECD, 2018). It includes emergency assistance and implementation of crisis plans (Tagarev et  
329 al., 2021).

330

### 331 ***Pillar 8 : Resilience***

332 Resilience is defined as a system's ability to absorb shocks and recover, involving resistance, adaptation,  
333 and reorganisation (Reghezza et al., 2006; Dauphiné and Provitolo, 2013). The objective is not full  
334 recovery but achieving a new acceptable equilibrium (Einhorn, 2017). This phase also provides  
335 opportunities to improve future risk reduction measures (Tagarev et al., 2021).

336

## 337 3.2.2 Distribution of events according to the eight pillars typology

338

339 Once the typology has been established, each event was assigned to the relevant management pillars  
340 mobilised in response. Events were then grouped by decade (or by five-year intervals for rock hazards)  
341 to improve temporal readability. This approach highlights changes in management practices over time  
342 while limiting visual discontinuities associated with rare events.

343

344

## 345 **4 Results**

346

347 This study identifies 200 glacial and periglacial events across 109 Alpine catchment areas in France,  
348 Switzerland, Italy, and Austria. These events were selected based on their magnitude, impacts, or  
349 influence on the evolution of glacial and periglacial risk management practices.

350

### 351 4.1 Spatial and temporal distribution of the events

352

#### 353 4.1.1 Distribution of the events across the Alps

354

355 The spatial distribution of events (Fig. 1) shows a marked concentration in certain areas, highlighting  
 356 particularly exposed or dynamically active zones. The Mont-Blanc massif (mainly its French and Italian  
 357 sides) clearly emerges as the most densely affected area, across all hazard types. It is followed by the  
 358 Valais Alps (CH). GLOFs are also more frequent in the western Alps.  
 359 The western Alps high elevations, steep slopes, and extensive glacier cover, making them particularly  
 360 prone to mass movements. The Mont-Blanc massif and the Valais Alps are among the most monitored  
 361 and instrumented regions, which may introduce a ‘visibility bias’ (cf. 5.2). High population density and  
 362 tourism further enhance event detection and documentation, potentially amplifying their perceived  
 363 significance.  
 364 Figure 1 presents major events that occurred between the 17<sup>th</sup> century and today, revealing the long-term  
 365 dynamics of these hazards. They are not isolated events but part of long-term, sometimes recurring  
 366 trajectories. This representation shows that multiple hazard types coexist within the same Alpine  
 367 massifs, increasing the complexity of risk management.

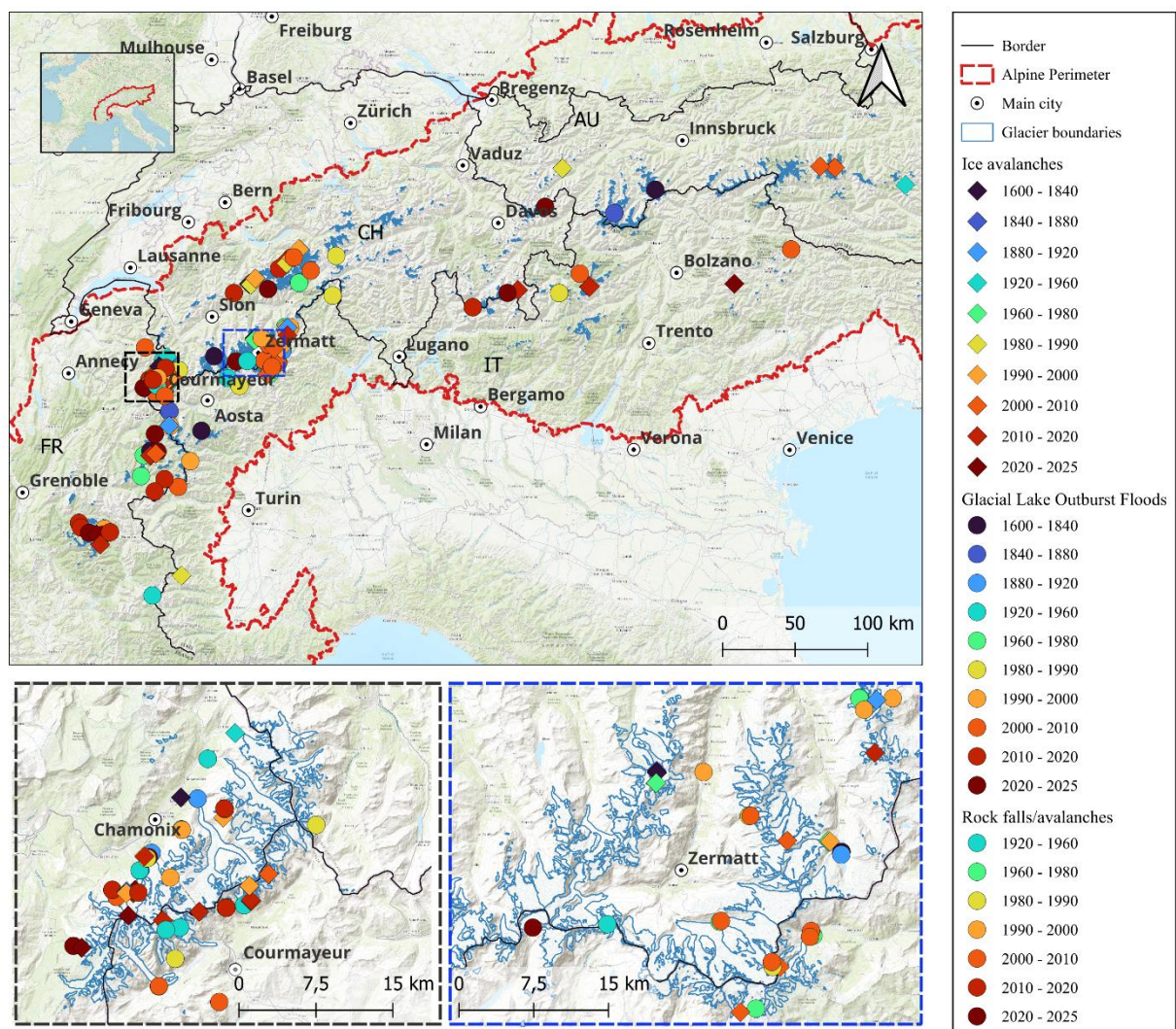


Figure 1. Distribution of major glacial and periglacial events inventoried in the Alps.

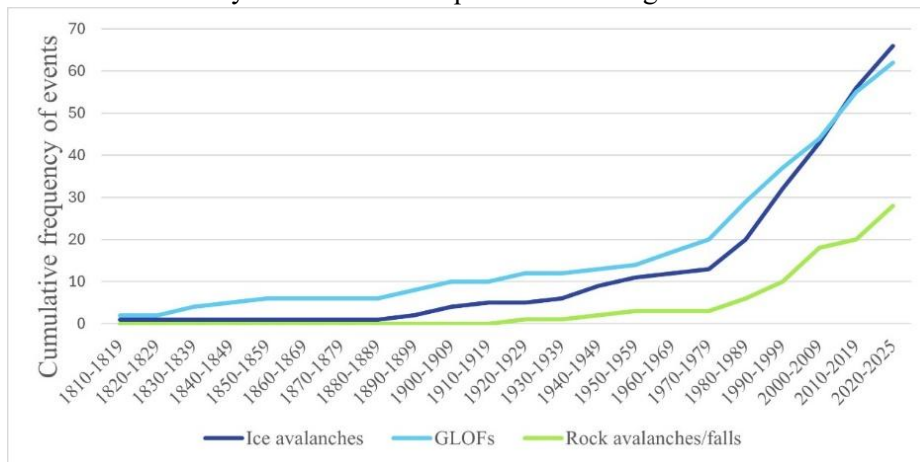
368 4.2 Distribution of management pillars over time

369

370 4.2.1 Phenomena intensification

371

372 Keeping in mind potential source and event biases (*cf.* § 5), we nevertheless observe an intensification  
 373 of hazardous glacial and periglacial events since the 1980s across all Alpine countries (Fig. 2). This  
 374 trend is based solely on events that required risk management and contributed to hazard understanding.



375  
 376 **Figure 2.** Cumulative frequencies of inventoried glacial and periglacial events requiring risk management in the Alps.

377  
 378 4.2.2. Evolution over time of the pillars used  
 379

380 This section examines how risk management and prevention methods have evolved over time through  
 381 significant glacial or periglacial events. Events are analysed according to the management pillars  
 382 mobilised at the time.

383 For the three types of events, Pillars 2 (Preventive information) and 3 (Land use planning) appear only  
 384 from the 1990s onward, while Pillar 6 (Crisis preparedness) has been implemented more recently. Pillar  
 385 1 (Hazard understanding) remains the most consistently used. It also continues to be applied  
 386 retrospectively, as past events are reanalysed to improve risk knowledge.

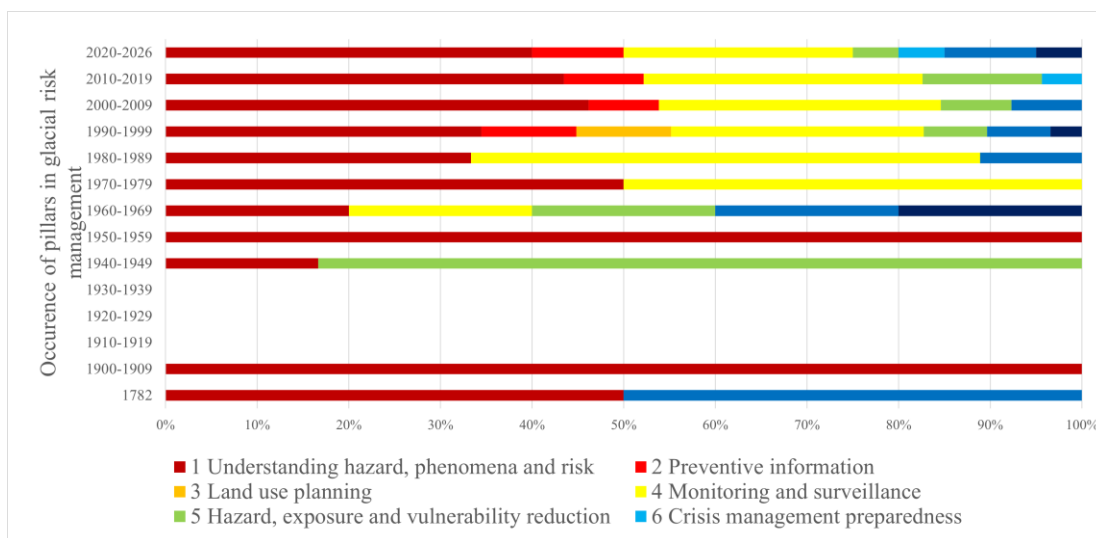
387 The evolution over time of risk management associated with major *ice avalanche* events in the Alps is  
 388 presented in Figure 3. The graph shows two main phases: a long period (1597-1950) dominated almost  
 389 exclusively by Pillar 1 (Understanding hazard), followed by a gradual and accelerating diversification  
 390 of management approaches from the 1950s and 1960s onwards.

391 The Altels ice avalanche (CH) in 1895 marked a turning point in the recognition of the need to  
 392 understand high-altitude hazards. This avalanche was of exceptional size, with  $4 \times 10^6$  m<sup>3</sup> of ice breaking  
 393 away, killing six people and burying 170 cattle over an area of 1 km<sup>2</sup> (Forel, 1895; Du Pasquier, 1896).  
 394 For a long time, this event served as a benchmark for ice avalanches. "To what extent can we predict  
 395 such disasters, and to what degree will we be able to prevent them from happening again? Many Alpine  
 396 glaciers give rise to avalanches or ruinous debacles. (...) The same glaciers periodically give rise to the  
 397 same phenomena, so it is above all empirical knowledge of these phenomena that we need to acquire.  
 398 (...) An accurate knowledge of the dangerous points and the phenomena that occur there is absolutely  
 399 necessary. The era of independent personal research is over; it has produced all it could in this field (...).  
 400 What is needed now is more coordination, more method, more consistency in research" (Du Pasquier,  
 401 1896).

402 The predominance of Pillar 1 over several centuries should not be interpreted as a lack of institutional  
 403 response to glacial and periglacial hazards. It rather reflects the fact that, within the epistemic and  
 404 institutional context of the time, the production of knowledge and the documentation of phenomena  
 405 constituted the primary and legitimate form of risk management. At that time, management was largely  
 406 confined to the academic sphere (naturalists, cartographers, scientific academies), long before it became  
 407 integrated into engineering and spatial planning. This observation suggests that contemporary categories  
 408 of risk management should not be retrospectively applied to these periods. If preventive information  
 409 (Pillar 2) appears late, this indicates that decision-makers only gradually began to communicate  
 410 simplified risk information to exposed populations. This development is closely linked to the emergence

411 of crisis preparedness (Pillar 6). It also raises the question of the role assigned to local communities in  
 412 risk management, which has long remained expert-driven, with limited structured communication with  
 413 residents. The example of the Val Ferret (IT), where the terminal tongue of the Planpincieux glacier has  
 414 been monitored since 2014, illustrates this evolution. Monitoring is coupled with rapid civil protection  
 415 responses and public information measures (Giordan et al., 2020; Dematteis et al., 2024). The aim is to  
 416 continuously track glacier dynamics, and detect instability, and activate procedures such as road closures  
 417 or village evacuation.

418 This study also integrates avalanche hazard maps, such as the *Carte de Localisation des Phénomènes*  
 419 *d'Avalanche* (CLPA; Avalanche Phenomenon Location Maps) in France, *Catasto valanghe* in Aosta  
 420 valley (Italy), Indication of avalanche hazards (ATH) for Switzerland, *Wildbach und Lawinenverbauung*  
 421 (WLV) for Austria, into land-use planning (Pillar 3), even though they primarily address snow  
 422 avalanches. These maps first emerged in the 1970s, but events such as those at the Bourgeat glacier (FR)  
 423 in 1984 and 1993 show that ice avalanches can trigger snow avalanches (RTM-ONF, 2000, unpublished).  
 424 We therefore consider these mapping tools as addressing combined snow-ice hazards.  
 425



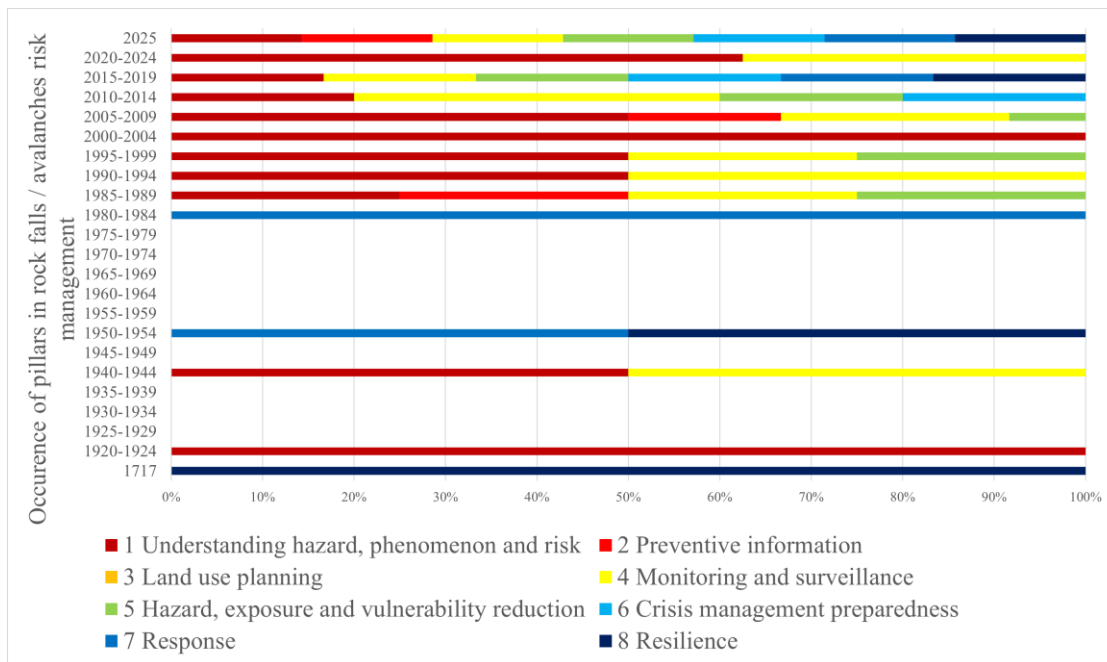
426 **Figure 3.** Temporal evolution of ice avalanche risk management in the Alps.  
 427

428 The evolution over time of risk management for major rockfall and rock avalanche events in the Alps is  
 429 presented in Figure 4. It is divided into five-year intervals to better highlight recent dynamics, as most  
 430 rockfall events have occurred since 1980.

431 The reduction in vulnerability, exposure, and hazard (Pillar 5) is particularly evident in these events. For  
 432 example, the 1987 Val Pola rockslide (CH;  $30 \times 10^6 \text{ m}^3$ ) involved preventive evacuation, illustrating  
 433 proactive risk management (Chardon, 1990). In 2011, at Piz Cengalo / Bondo ( $1.5 \times 10^6 \text{ m}^3$ ), preventive  
 434 measures included public alerts, trail closures, evacuation of alpine buildings, and installation of  
 435 protective structures (Bohnenblust, 2017).

436 Monitoring unstable rock faces is a key management tool (Pillar 4). Initially sporadic (1940–1944), it  
 437 became more systematic from the mid-1980s. Its increasing prominence in recent years (especially  
 438 2020–2024) reflects growing investment in instrumental monitoring systems, driven by both the  
 439 perceived intensification of hazards and advances in measurement technologies. Since 1986, the eastern  
 440 face of Monte Rosa (IT) has been regularly monitored due to increasing mass movements (Fischer et  
 441 al., 2006). Other emblematic sites have since been equipped, including Aiguille du Midi (FR) since  
 442 2005, the Matterhorn south face (IT) and Les Drus (FR) since 2007.

443 Finally, projects such as the EU AlpinSpace *PermaNET* program and the *PACE* project have contributed  
 444 to structuring knowledge on Alpine permafrost, through harmonised datasets and coordinated  
 445 monitoring across the Alps (Harris et al., 2001; Mair et al., 2011).  
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447  
448

**Figure 4.** Temporal evolution of risk management for rockfalls / rock avalanches.

449 The evolution over time of risk management for major GLOF events in the Alps is presented in Figure  
450 5. Unlike other hazards, GLOFs are documented as early as the 16<sup>th</sup> century, reflecting their high  
451 visibility and destructing impacts in populated valleys. Their severity ensured systematic recording in  
452 administrative and local archives, especially as their transformation into debris flows amplifies  
453 downstream damage. The Bagnes valley and the Giétro glacier, for example, generated extensive records  
454 from the 16<sup>th</sup> century onwards due to the scale of the destruction (Ancey et al., 2019).

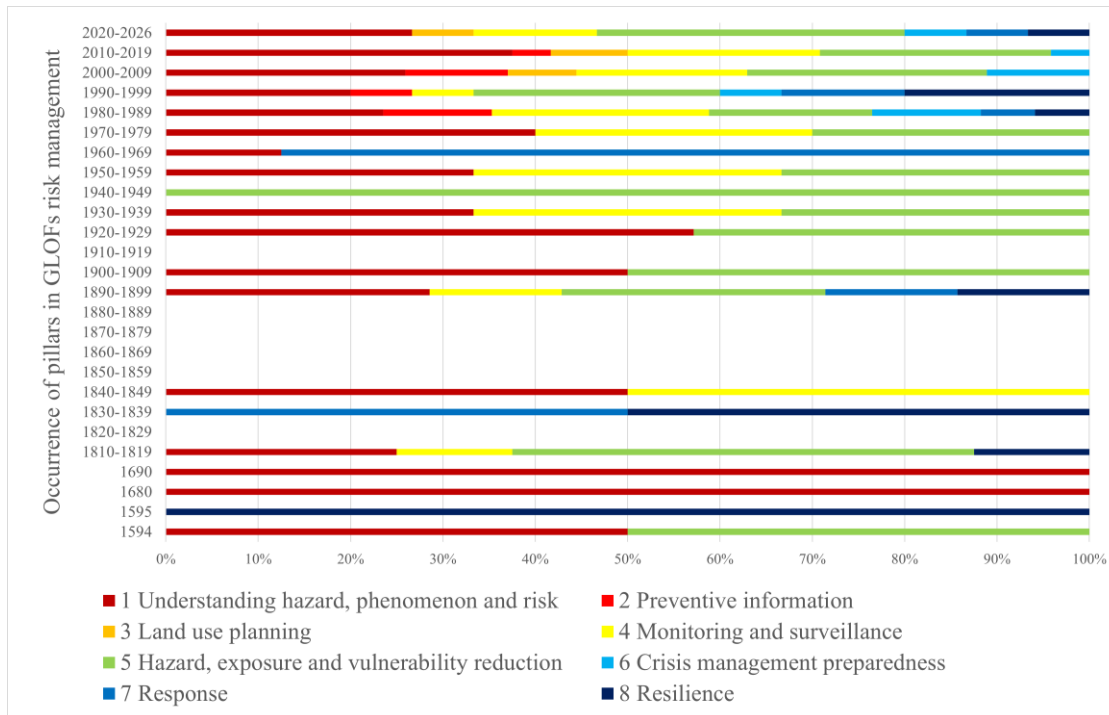
455 The period 1850-1889 is absent from the graph, which is paradoxical from a climatic perspective.  
456 Although post-Little Ice Age warming favoured lake formation and potentially increased GLOF  
457 occurrence, this gap likely reflects missing data rather than reduced activity.

458 Efforts to reduce vulnerability and exposure appear earlier for GLOFs than for other hazards. Efforts to  
459 reduce vulnerability and exposure appear earlier for GLOFs than for other hazards. Early responses  
460 relied on direct engineering interventions (drainage, tunnels, dykes) in densely populated valleys,  
461 preceding formalised risk management frameworks. This reflects a pragmatic, engineering-driven  
462 approach shaped by local socio-economic constraints. Thus, from the late 16<sup>th</sup> century, recurrent  
463 outbursts of the Margherita glacial lake (Rutor glacier, IT) prompted studies commissioned by the Duke  
464 of Savoy (12 events between 1430 and 1680; discharge of  $5 \times 10^6$  m<sup>3</sup> in 1751). Technical solutions such  
465 as dam and drainage tunnels were already considered in the 19<sup>th</sup> century (Vergnano et al., 2023).

466 Another notable example is the Giétro glacier event in 1818. A tunnel was constructed to drain the ice-  
467 dammed lake, thereby reducing the magnitude of the floods and preventing major downstream damage  
468 (Wiegandt and Lugon, 2008). Also, at the foot of the Gruben Glacier, flood prevention work was carried  
469 out at two lakes after the 1970 outburst. For the proglacial lakes, the moraine dams were reinforced with  
470 concrete injections; and the thermokarst lake was drained through an artificial channel in 1995 (Haeberli  
471 et al., 2001).

472 These recurrent events progressively led to diversified measures, including dykes, dams, storage basins,  
473 subglacial drilling, siphoning, lake drainage, and moraine stabilisation, as well as warning systems. In  
474 parallel, glacier monitoring became increasingly formalised, notably through photogrammetric surveys  
475 of the Vernagtferner (AU), one of the best-documented glaciers due to its frequent GLOFs, the most  
476 notable of which dates back to 1848 (Braun, 1995; *Gridabase - Glaciorisk*, s. d.).

477 However, the integration of populations through preventive information is more recent. For instance,  
478 the 1986 Arsine proglacial lake case (FR) marked one of the first instances where scientific warning led  
479 to coordinated crisis preparedness involving local populations (Lailly and Demolis, 2019).



481  
482 **Figure 5.** Temporal evolution of risk management for Glacial Lake Outburst Floods.

483 4.2.3 Disruptive events that have improved the glacial and periglacial risk management and  
484 understanding

485  
486 The construction of a timeline tracing risk management responses to past events has enabled the  
487 identification of key turning points marking disruptions and/or the emergence of new approaches.  
488 Selected examples correspond to first documented implementations of new management practices  
489 (prediction, monitoring, mitigation, and coordinated crisis response).

490  
491 **Scale change**

492 Risk management has shifted from local (village-scale) responses to national frameworks. The Giétro  
493 glacier disaster in 1818 illustrates this transition (Ancey et al., 2019). At that time, glaciology was still  
494 emerging, yet the event demonstrated that improved process understanding could support more effective  
495 interventions. Scientific advances progressively supported the development of preventive measures and  
496 favoured the emergence of regional and national policies, replacing earlier reactive local approaches  
497 (Wiegandt and Lugon, 2008). The disaster also marked a shift in risk perception, as hazards began to be  
498 understood as natural processes rather than divine punishment (Carrivick and Tweed, 2016).

499  
500 **Monitoring and surveillance**

501 The first known glacier inventory in the Alps dates back to the late 19<sup>th</sup> century (Vernagtferner), an area  
502 characterised by frequent GLOFs over the past 400 years (Hoinkes, 1969). Systematic photogrammetric  
503 surveys over a century enabled the first detailed analyses of glacier dynamics (Braun, 1995). Monitoring  
504 intensified during the 20<sup>th</sup> century; the Giétro glacier has been monitored since the 1960s, including  
505 measurements of flow velocity, structure, and mass balance. More recently, heavily instrumented sites  
506 such as the Matterhorn have integrated multi-sensor monitoring systems (Weber et al., 2025) following  
507 recurrent instabilities (Occhiena and Pirulli, 2012).

508  
509 **Multidisciplinary network**

510 The 1892 Tête Rousse disaster was a foundational event in glacier risk management. The debris flow  
511 has affected several villages downstream, causing 175 victims (Mougin and Bernard, 1922). It led to the

512 formation of multidisciplinary teams combining engineers, glaciologists, and foresters to investigate  
513 causes and implement mitigation measures (Marco et al., 2012; Sirop et al., 2022).  
514 Similarly, the 1965 Allalin glacier collapse at Mattmark (88 fatalities; Vivian, 1966) triggered  
515 coordinated scientific and engineering responses (Dalban Canassy et al., 2011). This led to the creation  
516 of a national working group on glacier hazards in Switzerland and the development of systematic hazard  
517 assessment methods (Haeberli, 1983; Haeberli et al., 2004). A coalition of scientists has irrevocably  
518 advanced the understanding of the mechanism of phased glacial rupture and sparked discussion on  
519 practical methods of risk assessment at the international level (Huggel et al., 2004).  
520 The Rochemelon lake case further illustrates this coordination. Cross-border collaboration enabled  
521 monitoring, risk assessment, public warning, and controlled drainage of the lake (Vincent et al., 2010).  
522 This case highlighted the need for continuity between scientific knowledge, decision-making, and  
523 operational action (Marco et al., 2012, unpublished).

524

#### 525 ***Reduction of exposure and vulnerability (evacuations, works, etc.)***

526 The first known organised evacuations for gravitational hazards occurred in 1987 (Val Pola rockslide;  
527  $30 \times 10^6 \text{ m}^3$ ; Dramis et al., 1995). Early warnings based on slope instability enabled preventive  
528 evacuation (Chardon, 1990). For glacial hazards, evacuations such as Planpincieux (1997) were based  
529 on scenario modelling and monitoring data (Margreth and Funk, 1999; (Margreth et al., 2011). These  
530 approaches marked the emergence of anticipatory risk management. Engineering measures also  
531 developed, as illustrated by the Belvedere glacier (IT) and the Effimero lake crisis (2002), where  
532 combined strategies (monitoring, mapping, evacuation planning, and artificial drainage) were  
533 implemented (Haeberli et al., 2002).

534

#### 535 ***Predictive study***

536 In 1973, the first successful glacier collapse prediction was achieved at Weisshorn (CH) (Röthlisberger,  
537 1981b). Scientists observed an acceleration of the upper part of the glacier, accompanied by warnings  
538 from local mountain guides (Faillettaz and Funk, 2013). Subsequent advances enabled short-term  
539 predictions based on displacement monitoring, such as the Whymper glacier collapse forecast 10 days  
540 in advance (Faillettaz et al., 2016). Authorities adapted responses accordingly, restricting access while  
541 avoiding unnecessary evacuation. These decisions increasingly relied on modelling and scenario-based  
542 approaches (Schindelegger and Kanonier, 2019).

543 These developments are part of broader research programmes (e.g. *Glaciorisk*, *PERMAdataROC*,  
544 *GlariskAlp*, *PAPROG*, etc.), aimed at improving hazard understanding and management.

545

#### 546 ***Institutional risk understanding***

547 Swiss National Research Programmes (NRPs), significantly contributed to the institutionalisation of risk  
548 knowledge. Projects under NRP 31, 48, and 61 advanced understanding of climate-driven hazards,  
549 spatial planning tools, and emerging glacial lakes (Haeberli et al., 1999, 2016; Rothenbühler, 2006).  
550 More broadly, Alpine risk management has evolved from “hazard protection” to “hazard management”  
551 and ultimately to “risk management” (Link and Stötter, 2015).

552 Before 1950, strategies focused on structural protection (protective works) and exposure reduction  
553 (legislation). There are numerous traces of such works in 19<sup>th</sup> century archives. For example, galleries  
554 were excavated within the ice of the Allalingsletscher glacier in 1834 to lower the level of its lake  
555 (dammed by the glacier tongue) and reduce the already high frequency of ice break-offs (Mariétan,  
556 1953). Between 1589 and 1850, documents report 26 major sudden outburst events (Raymond et al.,  
557 2003).

558 After 1950, improved process understanding led to hazard mapping (Link and Stötter, 2015) and  
559 probabilistic approaches; this was the age of *hazard management*.

560 Since the late 20<sup>th</sup> century, risk management has adopted a holistic perspective (Link and Stötter, 2015),  
561 integrating vulnerability and risk acceptance. Before the 2000s, hazard management was considered *in*  
562 *response* to an event. Recent approaches increasingly consider cascading processes (e.g. Evans et al.,

563 2009) and multiple scenarios, reflecting the growing complexity of cryospheric hazards under climate  
564 change (Allen et al., 2022).

565 Historically, the scope of hazard assessment has progressively expanded from glacier-related processes  
566 to include permafrost degradation and emerging landforms such as proglacial lakes. Current frameworks  
567 now adopt integrated, forward-looking approaches that account for long-term cryosphere evolution and  
568 cascading risks (Allen et al., 2017).

569

#### 570 4.2.4 Proactive vs. reactive management

571

572 Our typology of glacial and periglacial risk management distinguishes between proactive and reactive  
573 approaches. Management is considered *proactive* when it relies on anticipatory measures to prevent  
574 potential risks. Within the Disaster Risk Management (DRM) framework, prevention, mitigation  
575 (including spatial planning, protection measures), long-term adaptation to natural and socioeconomic  
576 changes, and the development of response and recovery capacities are all proactive strategies (Tagarev  
577 et al., 2021).

578 Management is *reactive* when it occurs during or after an event, aiming to manage the emergency,  
579 analyse impacts, and improve future risk reduction measures (Tagarev et al., 2021).

580 The different principles of glacial and periglacial hazards management can operate independently but  
581 are often combined. For instance, Monitoring and Surveillance (Pillar 4) is frequently coupled with  
582 Exposure, Vulnerability or Hazard Mitigation (Pillar 5).

583 Regarding torrential hazards associated with glacial lakes, a proactive example is the 1985 warming on  
584 the Arsine proglacial lake, which led to partial artificial drainage (Peissier and Courtray, 2012).  
585 Similarly, an early warning system installed in 2008 at the Grindelwaldgletscher glacial lake (CH) based  
586 on pressure sensors, enabled automatic alerts and proved effective during a drainage event (Bauder,  
587 2017). Or the artificial lowering of the water level of Lake delle Locce and the construction of dams on  
588 the main torrent downstream of the Belvedere Glacier (Haeberli and Epifani, 1986).

589 Conversely, the 1964 overflow of the Patinoire lake (FR), which caused damage downstream as far as  
590 the village of Pralognan, prompted a reactive response. Post-event analyses included field surveys,  
591 susceptibility studies, and impact modelling, leading to its later designation as a priority monitoring site  
592 (Cathala et al., 2021).

593 The Whymper hanging glacier illustrates proactive management: in 1997, displacement measurements  
594 enabled prediction of an imminent collapse, prompting evacuation of Planpincieux (Margreth and Funk,  
595 1999). Continuous monitoring and preparedness measures have since been implemented (Faillettaz et  
596 al., 2015, 2016). Similarly, the Forni glacier is monitored using satellite and terrestrial laser scanning to  
597 detect instabilities (Fugazza et al., 2018).

598 In contrast, the 1965 Mattmark disaster (Allalin glacier) exemplifies reactive management. Authorities  
599 focused on emergency response and post-event investigation. The event later triggered political debate  
600 and highlighted the limits of predictability at the time (Ricciardi, 2016).

601 For rock avalanches, the Piz Cengalo case illustrates the transition from reactive to proactive  
602 management. Following a first event in 2011, monitoring systems and protective infrastructure were  
603 implemented (Walter et al., 2020). These included a storage basin, protective barriers, and early warning  
604 systems enabling rapid evacuation (Bohnenblust, 2017). Legal proceedings are still ongoing regarding  
605 the safety precautions taken prior to the event (Joris, 2025).

606 In 2017, a major rock avalanche and subsequent debris flows ( $3.1 \times 10^6 \text{ m}^3$ ) affected the Val Bondasca.  
607 Despite underestimation of flow magnitude, early warning systems and protective measures  
608 significantly reduced damage (OECD, 2018). This case demonstrates the effectiveness of combining  
609 past-event analysis, monitoring, and preparedness, although some casualties still occurred (Walter et al.,  
610 2020).

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## 613 5 Discussions

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5.1 Cascading processes affecting increasingly vulnerable populations

As shown by the events documented in this study, chain reactions in glacial and periglacial environments tend to amplify beyond their initial triggering processes (OECD, 2018; Jacquemart et al., 2024), posing increasing challenges for risk management. This trend is closely linked to rising exposure in Alpine region. Mountain valleys have experienced significant urbanisation and infrastructure development in recent decades, increasing pressure on historically exposed areas (Hock and Rasul, 2022). This growing exposure is compounded by systemic vulnerability due to infrastructure interdependence: the destruction of a road, bridge, or energy network during a cascading event can isolate communities and hinder response capacities, as illustrated by La Bérarde in 2024 (Blanc et al., 2024). Risk management systems have long treated hazards separately, but this segmented approach is increasingly inadequate for complex, interacting phenomena affecting multiple components of populated territories. There is therefore a need for integrated and future/scenario-based approaches (Allen et al., 2017, 2022) that model process interactions while accounting for the spatial distribution of populations and infrastructure (Tacnet et al., 2010; Nyberg et al., 2026). These challenges are further intensified by climate change, which increases the likelihood of cascading processes in densely populated Alpine valleys.

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

Compiling an inventory that aims to be exhaustive according to defined selection criteria entails limitations and requires contextualisation of each event.

***The data source effect***

The apparent increase in events over time partly reflects biases related to data availability (e.g. Giacona et al., 2017). This *data source effect* is closely linked to the nature and distribution of information sources. As Giacona (2019) notes, the spatial and temporal distribution of events depends strongly on the structure of the documentary corpus. Each recorded event therefore depends on the quality and diversity of available sources. Scarcity of historical records limits traceability in earlier periods, whereas recent data abundance increases event detection.

The data source effect thus requires careful consideration of variations in documentation volume. For instance, technological advances such as webcam monitoring (e.g. Gornergletscher) generate continuous and detailed observations, increasing the number of recorded events (Huss et al., 2007).

***Land use and the event prism***

The presence or absence of sources is also influenced by human occupation. The growing presence of people in high mountains – through mountaineering (Mourey et al., 2023) and valley urbanisation (Vannier et al., 2016) – has significantly increased observation capacity. Conversely, abandoned settlements and pastures were once important witnesses to past hazards.

Even when hazards occur, their recognition depends on societal perception. An event may remain unrecorded if it is not perceived as significant. As Giacona (2019) argues, an event gains social existence only when it is perceived as a disruption. Risk perception evolves over time and is shaped by collective experience, knowledge, and social context (Granet-Abisset, 2012). Increasing attention to high-mountain hazards also reflects rising societal expectations for safety and accountability, which in turn drive the production and diversification of information sources.

5.3 Resilience and response as late-developed concepts rather than absent practices

The emergence of Pillar 8 (Resilience) from the 1980s-90s onwards, and its consolidation after 2000, should be interpreted cautiously. It does not indicate a prior absence of resilience from Alpine communities, but rather the late institutionalisation of the concept in scientific and policy frameworks.

665 Post-event reconstruction dynamics existed well before this period, but were not conceptualised within  
666 this framework, introducing an interpretative bias in diachronic analysis.

667 Similarly, Pillar 7 (Response) appears from the 1950s and remains present thereafter, without becoming  
668 dominant. Its consistent but limited representation suggests that emergency response has always existed  
669 but is less documented due to lower formalisation, leading to potential under-representation in the  
670 database.

671 The use of a ninth separate pillar representing ‘*Experience feedback*’ was considered, since the  
672 experience gained from an event enables a “structured process of capitalising on and utilising knowledge  
673 resulting from the analysis of positive and/or negative events” (Villeneuve et al., 2010).

674 Feedback is the very condition for an event’s existence in archives: its narration and memory make it  
675 historically visible. It therefore applies to every event, and would have created a bias in relation to the  
676 other pillars. Therefore, it is implicitly included in Pillar 1.

677

#### 678 5.4 National discrepancies in prevention

679

680 The study highlights that risk reduction measures are not uniform across Alpine countries and reveals a  
681 geographical bias towards France, Switzerland, and Italy. This heterogeneity reflects significant  
682 differences in legislative, institutional, and cultural frameworks for risk management. . International  
683 cooperation and governance initiatives such as GAPHAZ exist to try to bridge these differences (Allen  
684 et al., 2022).

685 In France, spatial planning relies on binding national regulations, and scientific action plans are also  
686 defined at the national level. In Switzerland, management is largely devolved to the cantons,  
687 encouraging locally adapted approaches but potentially generating inequalities depending on available  
688 resources. In Italy, administrative fragmentation and regional disparities hinder the implementation of  
689 coherent policies at the scale of catchments.

690 These governance differences affect both data comparability and the ability to derive cross-cutting  
691 insights. More broadly, they highlight the need for stronger transnational Alpine governance. Given that  
692 hazards transcend political borders, enhanced institutional coordination is essential for effective and  
693 equitable risk prevention.

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## 696 **6 Conclusions and perspectives**

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698 This study moves beyond traditional approaches that focus primarily on post-event causes or hazards  
699 characterization, and instead examines management practices. While event inventories inform on  
700 frequency, they rarely capture organisational dynamics or adaptative capacities. Our analysis addresses  
701 these dimensions.

702 By analysing 200 events since the early 19<sup>th</sup> century (some even earlier, though less frequent), we  
703 observe both an intensification of events and a progressive formalisation of management practices,  
704 reflected in archival records. The growing number of simultaneously mobilised pillars in recent years  
705 indicates a shift from single-discipline approaches to multi-actor, multi-scale governance. Beyond  
706 increased event reporting, this reflects the maturation of institutional Alpine risk management  
707 frameworks. Although all high-altitude massifs are affected, our data highlights a concentration of major  
708 events in France and western Switzerland, , particularly for glaciers, new lakes and permafrost-affected  
709 /glacially de-buttressed rock faces. The completeness of this long-term inventory remains constrained  
710 by sources and perception biases.

711 Risk management has evolved in response to both major events and improved process understanding. It  
712 continues to rapidly change far beyond historical and empirical antecedence. Forecasting,  
713 instrumentation, and monitoring of unstable zones have expanded, alongside contingency planning and  
714 evacuation strategies. Measures to reduce exposure and vulnerability increasingly account for evolving  
715 hazards and urbanisation pressures. Since the early 21<sup>st</sup> century, scientific initiatives aimed at

716 anticipating high-mountain mass movements that have multiplied. Knowledge exchange across borders  
717 has intensified, supporting more integrated and holistic risk management approaches. Hazards are now  
718 increasingly analysed as interconnected or cascading phenomena. As risk management grows more  
719 complex, the social sciences emerge as an indispensable complement to natural sciences, bringing to the  
720 fore dimensions – community vulnerability, risk perception, territorial identity, institutional dynamics –  
721 that physical approaches alone cannot capture.

722 Switzerland appears as a leading actor in the institutionalisation of monitoring and hazard assessment,  
723 particularly for glaciers and rock faces. Multidisciplinary collaboration and international knowledge  
724 exchange are rapidly advancing.

725 Across many regions worldwide, glacial and permafrost environments now differ markedly from the  
726 conditions under which settlements and infrastructure developed. Historical and empirical knowledge  
727 alone is therefore insufficient to anticipate future glacier- and permafrost-related risks. This calls for  
728 integrated, forward-looking approaches, based on continuous observation, repeated expert assessments,  
729 and rapidly evolving technologies. Risk analysis must adopt a systemic perspective, covering the full  
730 chain from hazard sources to socio-economic impacts.

731

732 *Data availability.* Raw inventory data is available on data.InDoRES

733 (<https://doi.org/10.48579/PRO/JA5PDT>)

734 *Author contributions.* JB, LR and SC designed the study and JB carried it out. JB prepared the  
735 manuscript with contributions from all co-authors.

736

737 *Competing interests.* The authors declare that they have no conflict of interest.

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