Roles and Activities of Local Stakeholders Faced with Alpine Permafrost Warming: A Comparative Exploratory Analysis of Three Contexts and Networks of Actors

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Abstract

Mountain permafrost warming resulting from climate change increases gravitational hazards. This interdisciplinary study compared the networks of actors involved in managing such hazards in three regions of the European Alps. Interviews were conducted with 40 people (members of local authorities, mountain professionals and private citizens) in Chamonix and the Vanoise massif (France) and in the canton of Valais (Switzerland). Data were analysed qualitatively and quantitatively using interaction matrices and network diagrams. Communal authorities played a central role but partnered with many other public and private actors. In Valais, collaboration to protect infrastructure and inhabited areas centred around communal and cantonal authorities. In Chamonix, the network of actors gave a significant role to mountain professionals. In Vanoise, the network of local actors was less dense and less well-defined, although they had high expectations regarding awareness-raising and prevention. Sources of tension existed in all three networks, particularly between authorities and mountain professionals. To strengthen community resilience, authorities should develop more mechanisms for citizen participation in risk management.

Keywords

Ergonomics, activity analysis, natural hazards, permafrost, public policy networks, risk management

8,827 words (with bibliography, but without title, affiliations, highlights, abstract and keywords)

1. Introduction

Climate change is increasing the frequency and intensity of natural hazards (Banholzer et al., 2014; Barnes et al., 2019; Fuchs et al., 2017; Head, 2009; Merz et al., 2020; Ward et al., 2020). Mountain regions are particularly at risk, because of rising temperatures and changes in precipitation regimes and extremes (Gobiet et al., 2014; Papathoma-Köhle et al., 2019; Schlögl et al., 2021). This paper focus on the management of hazards resulting from permafrost warming in Alpine regions. Large-scale landslides or rockfalls threaten villages, farms, roads, infrastructure and high-mountain routes (Deline et al., 2021). Many stakeholders are impacted in their daily activities, from public authorities and natural hazard experts to citizens, mountain professionals and amateur mountaineers.

To address the complex issues raised by climate change, authorities are moving away from the traditional 'command and control' model of operation and towards greater collaboration with a wide range of actors: other public administrations, businesses, local associations and residents, etc. Multi-actor networks play an important role in the development and implementation of public policies (Ferlie et al., 2011). In this context, this paper explores and compares the networks involved in managing natural hazards related to the degradation of mountain permafrost, in three regions of the European Alps with different risk management practices, as well as various geomorphological, economic, social, and political features. The main objective was to understand how local public and private stakeholders cope with these emerging risks and to what extent they join forces within actor networks. Our research questions were the following: 1) Which networks are involved in managing these emergent hazards? 2) What are the different actors' roles? 3) Which sources of tensions and dilemmas characterise their interactions?

How best to manage these emerging risks is still being developed, and the networks for doing so are not very well established. Better mutual understanding between stakeholders is likely to develop more collaborative practices and strengthen community resilience (Berkes & Ross, 2013; Lerch, 2017; Mayer, 2019; Paton et al., 2001). The hazards associated with permafrost have been studied mainly by Earth scientists (e.g. Biskaborn et al., 2019; Bodin et al., 2015; Huggel et al., 2012; Ravanel & Deline, 2008). However, addressing community resilience also requires interdisciplinary collaboration with human sciences. We therefore assembled an interdisciplinary team with expertise in activity-centred ergonomics and geosciences. The following section presents the key theoretical elements of the study.

2. Four concepts for analysing permafrost risk management

In this section, we will briefly review the hazards associated with mountain permafrost warming and explain why it can be considered a 'wicked problem'. The second subsection presents the evolution of risk governance, towards greater collaboration between the States and other stakeholders, within 'public policy networks'. The third subsection introduces the concept of 'ergonomic activity analysis' as a means of understanding how the different actors in a network cope with these hazards. The theoretical part concludes with the notion of 'community resilience'.

2.1 Alpine permafrost degradation: a wicked problem

Mountain permafrost refers to any lithospheric material whose temperature remains constant at or below 0°C (Huggel et al., 2012). Monitoring of permafrost temperatures shows an upward trend, however (Biskaborn et al., 2019; Bodin et al., 2015). This warming destabilises rock slopes and rock glaciers (a mixture of ice and slowly moving rock debris). These phenomena can trigger rockfalls, landslides, mudslides and the acceleration or breaking up of rock glaciers. Several events have left their marks on the Alps in recent decades, including the collapse of the Bonatti Pillar in the Mont Blanc massif in 2005 (Ravanel & Deline, 2008) and the mudflow that damaged the village of Bondo in Switzerland in 2017 (Deline et al., 2021).

Authorities and other local stakeholders' actions are hampered by the complex nature of these phenomena, which can be considered 'wicked problems' (Crowley, 2009; Head & Alford, 2015; Howes et al., 2015; Lazarus, 2009; Rittel & Weber, 1973). This term refers to tricky or intractable problems that elude attempts to define and solve them. Such problems are characterised by the involvement of many actors, all driven by conflicting visions, issues and values. Explanations and courses of action are always partial. Any adaptive measures implemented may have unforeseen side effects. Besides, learning by trial and error is not an option, as the problems often involve unique configurations and, given the severity of their consequences, tolerance for error is low.

The hazards associated with climate change are 'wicked problems'. Indeed, they result from the complex and dynamic interaction of natural processes and human influences. Their management involves a wide variety of stakeholders with different backgrounds and conflicting interests (for example, between economic and environmental conservation issues). These risks have major consequences. Although mitigation and adaptation measures are known, their implementation faces many obstacles. Authors have recommended dealing with such problems by shifting from traditional hierarchical risk management to a more horizontal form of governance that mobilises public policy networks.

2.2 Public policy networks as a way of tackling 'wicked problems'

Having to deal with climate change and increases in disasters has reinforced the shift towards networked forms of governance. Authorities' traditional form of operation, based on a division into specialised silos, a top-down approach and institutional inertia, is no longer sufficient (Frey & Calderón Ramírez, 2019; Head, 2009; Head & Alford, 2015). According to Crowley (2009), there is a need for hybrid modes of governance, combining horizontal and diverse collaborative networks with more traditional elements of public policy. The authorities should help stakeholders develop a common understanding of the problem at hand. Solutions should be codesigned between them and should not rely only on regulation. This requires more collaboration and coordination, the inclusion of a diversity of voices, adaptive forms of leadership, mutual learning within stakeholder networks, fostering citizen engagement, and a shift towards more flexible State processes and structures (Head, 2009; Head & Alford, 2015). These principles have been included in the United Nations' Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations International Strategy for Disaster Reduction, 2015).

However, there are several barriers to such developments, such as unpopular climate change policies, changes in political make-up, conflicting objectives and mistrust between jurisdictions, the weight of traditional departmental structures and cultures, the use of different languages between agencies, the multi-level constitutional arrangement of legislative powers, restrictions on human resources, etc. (Howes et al., 2015). A better understanding of the needs, objectives and activities of each stakeholder is a first step towards improved collaboration. Ergonomic activity analysis can be one way of achieving this.

2.3 Analysing the activities of field actors

Preventing and responding to disaster events resulting from permafrost warming involves many actors. Local, regional and national authorities share responsibilities for land-use planning, risk assessment, the construction of protective infrastructure, and public information; they must also intervene when events occur. These missions are carried out by a variety of professionals, including natural hazards specialists, civil protection officers and locally elected officials, among others. They perform their duties in close contact with the population. They must manage complex situations, with limited financial and human resources. On their side, private actors such as mountain guides, hut wardens, ropeway operators, tourist offices, amateur mountaineers, farmers and citizens are confronted with the consequences of permafrost warming on their own activities. They also have to make decisions in uncertain conditions, for example on the choice of climbing or hiking routes, the temporary closure of cable cars, or the information they give to their customers.

The analysis of daily work activities underpins activity-centred ergonomics (Gaillard, 2014). Ergonomics is defined as 'the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance' (Wilson, 2000, p. 560). The activity-centred approach to ergonomics specifically examines how humans self-regulate their activity in real time, in the face of unpredictable events and considerable inter- and intra-individual variability. Based on observation, interview and simulation methods, this approach is particularly well suited to analysing actual work behaviours and can be extended to investigate non-work related activities.

Ergonomists have conducted little research into the management of natural hazards. However, they have gradually broadened their scope towards a holistic approach involving socio-technical systems. Thanks to their expertise in the management and prevention of emerging industrial and health risks, they can provide a new perspective on the risks posed by natural hazards (Caroly & Bonneterre, 2022; L'Allain et al., 2015). From a developmental perspective (Caroly & Barcellini, 2015), ergonomics enriches the way stakeholders perceive their own activities and those of the people with whom they interact. When applied to the analysis of public policy networks, activity-centred ergonomics can be used to qualify the nature of the links within a network, to identify sources of tension between stakeholders and even to participate in the development of better cooperation, to foster community resilience.

2.4 Community resilience

Resilience refers to the processes and capacities that enable systems to overcome, resist, adapt to, and recover from profound crises. It is a central component of the Sendai framework. Inspired by a salutogenetic approach, it differs from the more traditional concepts of vulnerability and loss. Specifically, the concept of community resilience highlights the possibility for a community to draw on its resources and skills—two pivotal notions in activity-centred ergonomics, as well—to deal with the situation. Many factors contribute to this: a participative form of governance, a close-knit community, social support networks, a diversified and innovative economy, the existence of infrastructures, civil courage, flexibility, systems thinking, and many others (Berkes & Ross, 2013; Lerch, 2017; Mayer, 2019; Paton et al., 2001).

Mayer (2019) draws attention to the importance of analysing the community context in interventions aimed at building resilience. Because of differences in culture, language, political and institutional organisation and access to resources, there is probably no universally valid model. This is why we have chosen an inter-regional comparative approach for this study, described in the next section.

3. Methods

3.1 Sample

Two of the three regions studied were in France: the Chamonix valley and the Vanoise massif. The third region was the canton of Valais in Switzerland. The research team was made up of researchers from French and Swiss universities, partners of the Risk Institute at Grenoble Alpes University. They had well-established professional and relational networks in these regions. In addition, there have been regular contacts between natural risk management specialists in the Valais and the Chamonix valley. Besides, the three regions differ from one another in a number of ways.

Valais is an Alpine canton, bordering Italy and France. It encapsulates the upper Rhone valley and is home to 46 peaks over 4,000 m and nearly 700 glaciers. The population is 350,000, with a third living in towns. The mean population density is 67 inhabitants/km^2. The Valais is a tourist destination, well-known for its ski resorts, but it is also home to diverse industries. Agriculture and livestock farming mark the landscape. The region is exposed to numerous natural hazards. Local communal authorities are responsible for protecting the population. Each one has a natural hazards unit and field observers and maintains hazard maps produced by specialised firms. The cantonal authorities assist and advise them via a cantonal natural hazards commission, a cantonal crisis management body and a specialised natural hazards department. Finally, the Swiss Confederation has a supervisory and support role. A specific feature of the Valais is its well-developed permafrost monitoring network.

The Chamonix Mont-Blanc valley is an international mountaineering destination. The mountain slopes are steep, and some glaciers still descend to a very low altitude. Chamonix lies at an altitude of 1,000 m. The Aiguille du Midi cable car (3,842 m) provides access to the high mountains. In 2019, the valley had 8,640 inhabitants, with a density of 74 inhabitants/km^2. A quarter of jobs are in tourism, with a large majority of seasonal employees. Part of the population is relatively stable, lives nearby, knows each other and still shares a common culture of risk. The association of local communes has a Prevention and Protection Department. It is run in conjunction with the ropeway operators and the local tourist office, *La Chamoniarde* (an independent information, prevention and mountain rescue association, which is also a unit of the commune of Chamonix). One of the authors (LR) has been very active in raising awareness of permafrost-related hazards among local stakeholders. The region's strong dependence on high-mountain tourism, which increases its vulnerability to permafrost warming, also makes it an interesting case to study.

Finally, the Vanoise massif is located on the French–Italian border. It hosts fewer tourists but includes a national park with glaciers and mountain trails. Pastoral farming is an important

activity. Towns and villages are spread out along the Haute Maurienne valley, with a relatively low population density. Ski resorts are located at altitudes ranging from 1,000 to 1,300 m. In the Tarentaise valley, the population density is higher. In both valleys, half of the jobs are seasonal, especially in winter. The Vanoise Park covers 146,500 ha and 29 communes with a combined population of nearly 37,000. It includes 18 ski areas; snow sports and hiking activities are quite developed. The working population is mainly composed of employees, artisans and unskilled workers. A few aluminium factories still operate. To ensure the population's protection and to prevent disasters, the communes share the implementation of a Communal Emergency Plan. The State helps them by carrying out work and risk assessments on roads. The actors are scattered across the area but have the capacity to work together when needed. In comparison with the other two regions, the systems for monitoring and managing the risks associated with permafrost are less extensive there.

We constructed a convenience sample of 40 people, stratified by region and by category and subcategory of actor: public authorities (natural hazards specialist, local authority, trail operator, road operator), mountain professionals (mountain guide, mountain rescue professional, hut warden, ropeway operator or planner, tourist office representative) and local citizens (amateur mountaineer, resident, farmer). These subcategories were chosen to reflect the variety of actors and activities affected by permafrost warming, with one or two people per subcategory and region. They were recruited through the researchers' networks and by contacting the relevant agencies. We also used snowball sampling to access harder-to-reach populations. The participants included 4 women and 36 men (mean age 44.8 years, standard deviation 13.1; Table 1).

3.2 Data collection

Semi-structured interviews were conducted during the summer of 2021 at participants' workplaces or homes. The interview guide included open questions on: (1) professional background, (2) perceptions of permafrost, permafrost warming and related risks, (3) description of personal or professional roles in managing these risks, (4) description of interactions with other actors involved in risk management and (5) description of existing means of prevention and protection, and suggestion of new ones. The Human and Earth scientists worked together to formulate the questions and pretest them.

To help participants answer as concretely as possible, we presented them with topographical maps showing the extent of the permafrost in their region. We also described three real-world events to them, each one presented on a laminated A4 page with pictures, date, location, causes, consequences and the measures implemented afterwards. Each case presented a particular effect of permafrost degradation: a rockfall on a mountaineering route, the destabilisation of a cable car pylon due to ground deformation, and a large-scale rockfall caused directly by a melting glacier,

which resulted in eight deaths, several mudslides and the partial destruction of a village. Participants were invited to use these case descriptions to reflect on what their role would be in similar situations. The use of such 'intermediate objects' helps participants to project themselves into situations they might encounter in the future (Rodrigues & Rocha, 2023).

Table 1. Participants' roles, sex and age

	Professionals (n=17)			**Authorities (n=12)**			**Local citizens (n=11)**		
Valais (n=14)	Mountain guide	M	50	Geologist, Natural Hazards Department	M	60	Amateur mountaineer	M	24
	Mountain rescuer	M	44	Deputy Mayor in a mountain community	M	55	Amateur mountaineer	M	54
	Hut warden	M	42	Representative of a hiking association	M	32	Resident	M	69
	Hut warden	M	35	Head of Section, Cantonal Road Dept.	M	43	Farmer	M	31
	Cable car planner	M	51						
	Tourist office director	M	28						
Vanoise (n=12)	Guide	M	68	Expert, Mountain Land Restoration Unit	M	46	Amateur mountaineer	M	18
	Rescuer	M	56	Mayor	M	66	Resident	M	53
	Hut warden	M	55	Hut and trail technician	M	37	Farmer	M	46
	Ropeway operator	M	59	Urban planning risk-prevention officer	M	39			
	Tourist office representative	M	43						
Chamonix (n=14)	Mountain guide	F	45	Natural hazards manager (association of communes)	M	30	Amateur mountaineer	M	18
	Mountain rescuer	M	40	Deputy Mayor (resp. for mountains, the economy and tourism)	M	65	Amateur mountaineer	M	58
	Hut warden	F	30	Head of trails and paths (association of communes)	M	40	Resident	F	28
	Ropeway operator	M	51	Head, Departmental Roads Dept.	M	50	Farmer	M	48
	Tourist office representative	M	46						
	Director of *La Chamoniarde*	F	38						

M=male; F=female

3.3 Data analysis

The interviews were audio-recorded and transcribed. Data were processed using a qualitative approach to social network analysis (SNA). SNA reveals the structure of networks and the roles, influence and relationships between actors. It shows how actors' constraints and opportunities vary, depending on their degree of centrality. It also helps to highlight how network structures differ depending on the context (Borgatti et al., 2009). This approach is still little used in research on natural hazard management (Frey & Calderón Ramírez, 2019; Jones & Faas, 2017). Most often, it is based on quantitative indicators (Varone et al., 2019), which can take only little account of the context in which stakeholders' activities occur and of their concrete interactions (Frey and Calderón Ramírez, 2019). There is a need for qualitative analyses, which provide a deeper understanding of the context and content of network structures (Luxton & Sbicca, 2021). These are particularly well suited to exploring new or unexplored forms of networks and the concrete practices, interactions and communication patterns within networks (Hollstein, 2011).

We extracted data from each transcript using a grid with the following headings: professional activity, roles in hazard management, nature and intensity of interactions with other stakeholders, and sources of tension between them. The aim was to provide an idiosyncratic account of each person's situation and explore how these situations combine to form a complex set of relationships. An interaction matrix was built for each region, listing every relationship identified and its nature, based on the extracted data. From these matrices, network diagrams were drawn up. We qualitatively identified central and peripheral actors, the nature of their interactions and their sub-networks. We focused on finding similarities and differences between the regions. Quantitative indices were computed to measure network density and actors' degrees of centrality.

4. Results

4.1 Actors' roles

Actors' roles were classified into eight categories based on a content analysis of their interviews (Table 2).

- Authorities

The main roles fulfilled by the authorities concerned risk assessment, monitoring hazardous areas, hazard mapping, planning and investing in protective infrastructure, trail maintenance and supporting applied research. These types of actions were frequently mentioned by actors in Valais, mentioned to a lesser extent by those in the Chamonix valley, and only rarely mentioned in the Vanoise massif.

Table 2. Actors' roles

Roles	Authorities	Professionals	Population
Designing, monitoring and maintaining infrastructure and assessing risks	×	×	
Coordinating actors and managing risks	×		
Receiving and transmitting information	×	×	×
Responding to an event	×	×	
Adapting professional or personal practices		×	×
Preserving the attractiveness of local tourism		×	
Being generally vigilant in one's day-to-day activities			×
No role mentioned			×

A second role involved coordinating stakeholders. In Valais, communal safety officers coordinate the people involved in surveillance, crisis management and establishing emergency plans. They are supported by specialists from the cantonal Natural Hazards Department, who provide assistance with training, creating risk maps, authorising construction permits, technical advice and infrastructure subsidies. In the Chamonix valley, each communal authority is responsible for risk and land management but is supported by specialists employed or requested by the local association of communes. Those communal authorities also issue the decrees and decisions regulating local sporting practices. In the Vanoise massif, the communal representative interviewed, in charge of a small village, claimed no direct role in coordination.

A third recurring role concerned information and communication. Communes manage the transmission of information upstream or in reaction to specific events (e.g. responding to requests from citizens following rockfalls, reporting dangerous areas, etc.). The Chamonix authorities insisted on the importance of communicating about risks, but without giving any prescriptions or prohibitions to users. Hiking trail operators in the Valais and Mont Blanc regions mentioned their roles in informing users about risks or trail closures.

Authorities' final task consist of interventions relating to natural events. In Valais, communes intervene via their crisis management teams, with the support of the cantonal Natural Hazards Department, raising the alarm, closing off accesses and managing the event. In Chamonix, hazards are managed by the deputy mayor responsible for safety and by the association of communes' prevention specialist, as per the procedures established in the Communal Emergency Plan. In Vanoise, the communal authorities mentioned mainly their responsibility for managing specific events, such as rockfalls.

- Mountain professionals

One essential role fulfilled by mountain guides, ropeway operators, hut wardens, tourist offices and mountain rescuers is the transmission of information on mountain conditions, either among those professionals themselves or to clients. This role was mentioned by hut wardens and rescuers in both French regions and, to a lesser extent, by guides and ropeway operators. A second role is leading adaptations to mountaineering practices. Guides change the seasons, times of day and itineraries of their excursions depending on the evolution of mountain terrain and weather conditions. Rescuers also mentioned the need to do this, for example, when they postpone a rescue operation due to poor conditions. A third role—disaster response—is at the heart of mountain rescuers' activities. The fourth role of the monitoring and maintenance of infrastructures was mentioned by several actors. For example, wardens repair or adapt any itineraries to their huts that are damaged by rockfalls; they also participate in the construction design choices concerning those mountain refuges. Ropeway operators take hazards into account when planning and designing new infrastructure, when monitoring existing installations and when assessing and repairing damage. Tourist offices mentioned the last role of maintaining the attractiveness of mountain regions in the context of global warming.

- Local population

Local inhabitants, amateur mountaineers and farmers talked about how they adapt their personal or professional practices. Mountaineers change their itineraries, and farmers their working methods (compensating for surface areas lost to rockfalls, moving livestock to less risky grazing, experimenting more sustainable agricultural practices, etc.). Amateur mountaineers and local inhabitants described being vigilant in both their leisure and work activities as a secondary role. Several stakeholders mentioned their involvement in passing on information and observations as a third role. For example, mountaineers mentioned an indirect prevention role in ensuring the safety of other climbers. On the other hand, the inhabitants in Valais and the Chamonix valley said they had no role to play in this.

4.2 The network of actors in Valais

The network identified in the canton of Valais is represented in Figure 1. The authorities are shown on a white background, mountain professionals on a light-grey background and the local population on a black background—other actors (not interviewed but mentioned by participants) are on a dark-grey background. The thick solid arrows indicate the closest interactions, followed by the thin solid arrows and, lastly, the dashed arrows. The network is centred on two administrative actors: a cantonal authority (the Natural Hazards Department) and the communal authorities in charge of public safety. The cantonal authority has the highest number of outgoing or bidirectional arrows (9/43 network arrows in total). These correspond to different forms of support, monitoring and instructions. The communal authorities have the highest number (8) of

inbound arrows, reflecting the diversity of feedback and financial, technical and methodological support they receive. These actors also have 6 bidirectional arrows, linking them to cantonal services, their inhabitants, the cantonal tourist office, private technical firms and researchers. Communal authorities also display the highest degree of centrality (14/43 arrows). The communal and cantonal authorities form a sub-network that also includes auxiliary (technical firms and researchers) and other administrative services. Another sub-network comprises mountain professionals and amateur mountaineers. It is separate from the authorities' sub-network, except regarding feedback from guides and hut wardens. Finally, two categories of actors remain isolated: local inhabitants and, even more so, farmers.

4.3 The network of actors in the Chamonix valley

The central actors in this network (Figure 2) are the hut wardens (11/49 arrows), the local association for mountain information, prevention and rescue (*La Chamoniarde*) (10), and the valley's prevention and protection specialist (10). They are closely linked to other influential actors, including researchers (8), rescuers attached to the High-Mountain Gendarmerie Unit (8), communal authorities (7), mountain guides (7), ropeway operators (7) and local inhabitants (7).

The mountain hut wardens have an information brokerage role. They exchange information on the state of mountain routes with guides and researchers, raise awareness among climbers, monitor infrastructure with the valley's prevention and protection specialist, and adapt itineraries with the valley trails manager. *La Chamoniarde* stresses on climbers the importance of passing on information about the state of mountain routes to hut wardens, who then inform other climbers and relay news back to *La Chamoniarde*. The association also collaborates with rescuers and researchers for prevention and awareness-raising. The valley prevention and protection specialist collaborates with several actors: hut wardens for monitoring infrastructure, private technical firms and researchers. He shares local experiences with the neighbouring Italian authorities and the operator of the departmental road network.

Researchers play a significant role. In addition to collaborating with various actors on scientific studies and monitoring projects, they actively raise awareness and issue alerts. Mountain rescuers intervene in the event of accidents, provide information and raise awareness. During major events, they collaborate with hut wardens to carry out ground searches and assess whether routes are passable. They report back to the valley prevention and protection specialist and collaborate with researchers on risk management and prevention. The most important activities for mountain guides are informal exchanges of information and participation in opening up new routes. Ropeway operators mainly cooperate with authorities and researchers regarding the development and management of their infrastructure. Communal authorities commission, facilitate or are partners in studies by academic researchers. They also collaborate with private

engineering offices and ropeway operators. As for the local inhabitants, they are mainly in contact with the authorities (communes and the association of communes) and *La Chamoniarde*. Five of the inhabitants' 7 arrows are incoming: the inhabitants are targets of information and awareness-raising messages rather than drivers of risk management. The same applies to amateur mountaineers and tourists (3/4 arrows are incoming).

Adapting the itineraries for access to mountain huts and developing new routes were recurrent themes, mentioned 8 times. Mountain professionals look for new routes in collaboration with the valley trail operator (association of communes) and researchers. Finally, three actors seem to have more peripheral roles: the valley tourist office and, above all, the departmental entities of the Prefecture (the department's chief administration) and the road network operator.

4.4 The network of actors in the Vanoise massif

Four actors stand out more strongly in this network: the communal authorities (9/31 arrows in total), the national gendarmerie rescue unit (8), the protection and risk prevention specialist (7) and the Val Cenis ropeway operator (6). The communal authorities display a high proportion of incoming arrows (4/9), receiving information, support and alerts from various actors (guides, rescuers, farmers, the road operator, etc.). They collaborate with the ropeway operator on risk prevention and management and work with the protection and prevention specialist on risk assessment. Interactions with the local population involve closing off access to specific areas when danger is imminent.

Half of the arrows involving the rescue unit are outgoing. This actor is in charge of providing preventive information for professionals and citizens, participates in communal safety committees and plays a central role in disaster response. The protection and risk prevention specialist is attached to the National Forest Office (ONF) through the Mountain Land Restoration (RTM) unit. His role is to support and collaborate with the ropeway operator and communal and departmental authorities to prevent and evaluate natural risks. The ropeway operators collaborate with many actors (communes, the prevention and risk protection specialist, private engineering firms and the Prefecture) on issues involving building and monitoring infrastructure.

The local population (4 arrows; 3 incoming) was mainly described as a target for preventive information. Mountain guides (4 arrows; 2 outgoing) provide information on mountain conditions and communicate and cooperate with the rescue unit. The road network operator stated that he could play a role in implementing and disseminating preventive measures recommended by scientific studies. As for farmers (4 arrows; 2 outgoing), our sole participant from this group mentioned that, above all, his role is alerting the authorities when necessary. Finally, other actors

(hut wardens, amateur mountaineers and the tourist office) are little connected or not connected to the rest of the network.

4.5 Comparison of networks

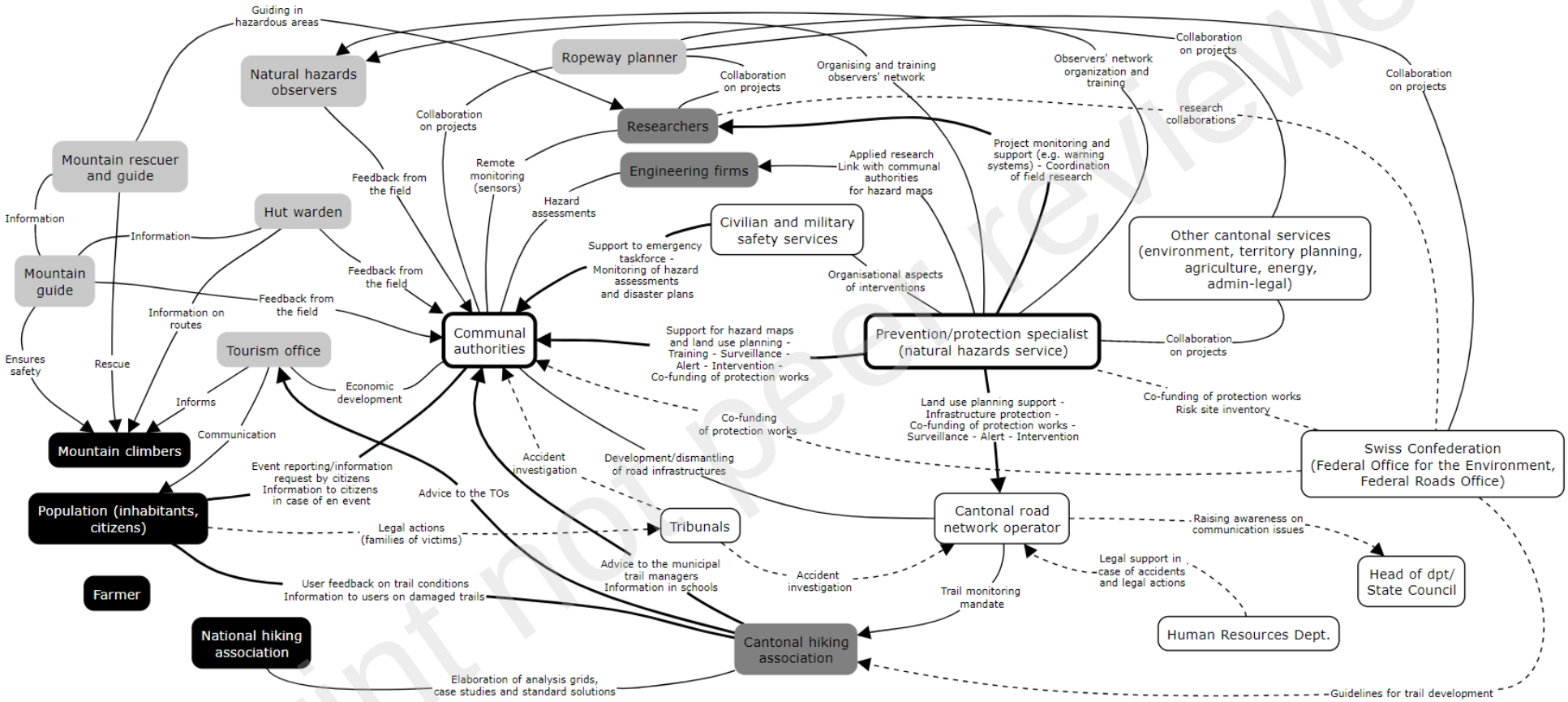
A density index was calculated for each network by dividing its number of relationships by its number of actors. The densest network was in the Chamonix valley, with an index of 2.72 (49/18), followed by Valais (1.95; 43/22) and the Vanoise massif (1.82; 31/17). Table 3 shows the degree of centrality of each actor in each region (number of individual links divided by the total number of links in the network).

Table 3. Actors' degree centrality by category and region (number and percentage of links)

	Valais (43)	**Chamonix (49)**	**Vanoise (31)**
Authorities			
Prevention and protection specialist	9 (20.9%)	10 (20.4%)	7 (22.6%)
Communes	14 (32.6%)	7 (14.3%)	9 (29.0%)
Road operator	6 (14.0%)	1 (2.0%)	4 (12.9%)
Hiking trail operator	6 (14.0%)	3 (6.1%)	1 (3.2%)
Professionals			
Hut warden	3 (7.0%)	11 (22.4%)	1 (3.2%)
Mountain guide	4 (9.3%)	7 (14.3%)	4 (12.9%)
Rescue unit	3 (7.0%)	8 (16.3%)	8 (25.8%)
Tourist office	4 (9.3%)	5 (10.2%)	0 (0.0%)
Information, prevention and rescue association	NA	10 (20.4%)	NA
Ropeway operator	4 (9.3%)	7 (14.3%)	6 (19.4%)
Population			
Amateur mountaineer	4 (9.3%)	4 (8.2%)	2 (6.5%)
Local resident	4 (9.3%)	7 (14.3%)	4 (12.9%)
Local farmer	0 (0.0%)	1 (2.0%)	4 (12.9%)

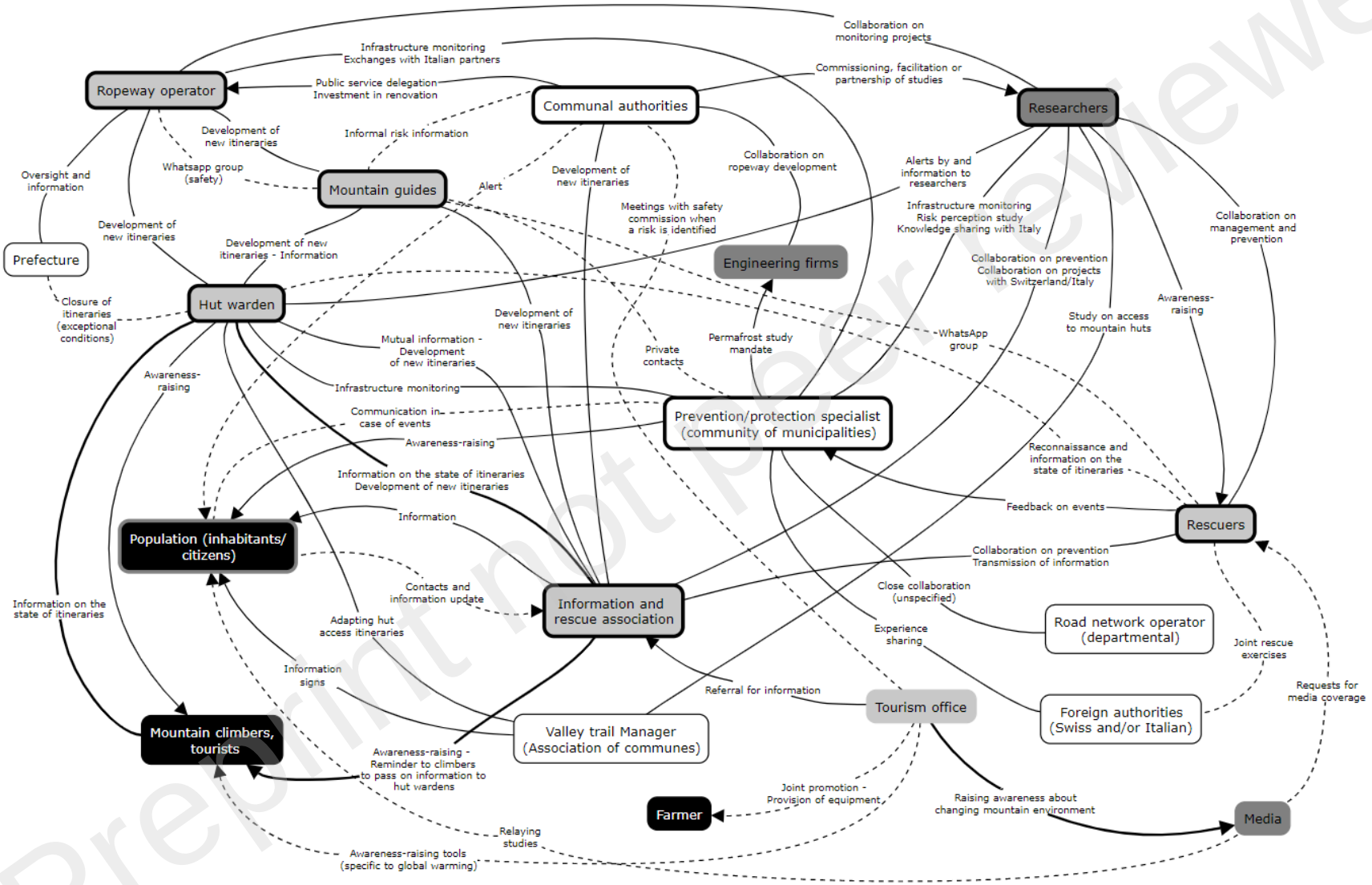
NA: not applicable

Figure 1: Network of actors in the Valais



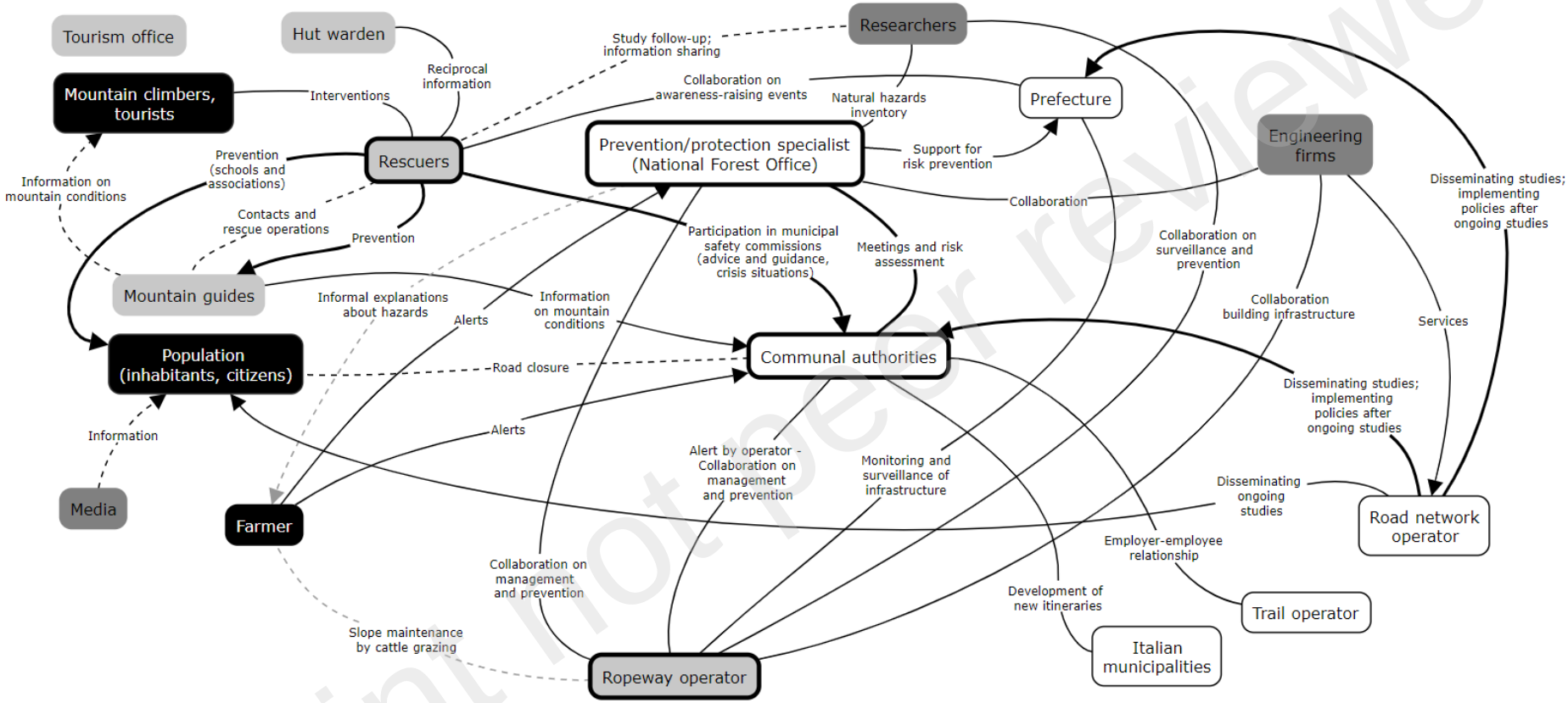
Arrows: unidirectional relationships. Lines: bidirectional relationships

Figure 2: Network of actors in the Chamonix valley



Arrows: unidirectional relationships. Lines: bidirectional relationships

Figure 3: Network of actors in the Vanoise massif



Arrows: unidirectional relationships. Lines: bidirectional relationships

Table 3 shows similarities and differences between the regions. The risk prevention and protection specialists are central in all three. However, their positions are somewhat different: at the cantonal level in Valais, at an inter-communal level in the Chamonix valley, and at the departmental level in Vanoise. Local communal authorities are also key players, particularly in Valais. Several actors have a peripheral status: the road and hiking trail operators, tourist offices, the three sub-categories of the local population and, to a lesser extent, mountain guides.

The three networks differ in several respects. The Valais is characterised by three sub-networks. The main one is among public authorities, structured around the relationship between the prevention and protection specialist (Natural Hazards Department) and the communal authorities responsible for public safety. The road operator and hiking trail operator are relatively central, too. Other governmental agencies and auxiliary bodies (private engineering firms and researchers) are also part of this sub-network. Mountain professionals constitute a second sub-network, and representatives of the general population a third. These two sub-networks are weakly linked to the authorities. Rescue units play a minor role. Unlike in France, where they are part of the national gendarmerie, in Valais, they are employees in private helicopter rescue companies. Interactions mainly involve exchanges of information with mountain guides and rescue operations themselves, but not prevention or awareness-raising. Finally, few actors mentioned links with ropeway operators.

In the Chamonix valley, the network comprises a central sub-network, formed mainly of mountain professionals, the prevention and protection specialist and the communal authorities, supported by researchers. This is the only region where researchers stand out as central actors. The network is less centralised than in Valais and the authorities occupy a less important place in it. The network includes one specific actor absent in the other regions: the *La Chamoniarde* association, which is linked to the vast majority of the other actors and plays a driving role in information and prevention. Another specificity is the central position of hut wardens. The interactions in this network are particularly linked to adaptations made to mountain hiking routes and to cable car safety. The local road operator, working at the departmental level, and the Prefecture are on the fringe. Finally, this is the region where the role of the media was most mentioned.

Vanoise is also characterised by a fairly decentralised network. Links particularly involve the mapping of natural risks, public information, the management of cable cars, and interventions in case of disasters. The prevention and protection specialist, communal authorities, rescue units and the ropeway operator form a sub-network. Another more peripheral sub-network focuses on mountaineering, with guides, rescue units, amateur mountaineers and hut wardens. One commonality between the Vanoise massif and the Chamonix valley is its collaboration with foreign

authorities—an element not mentioned by actors in Valais. One difference between the two regions concerns public authorities, whose roles seem to be more marked in the Vanoise massif.

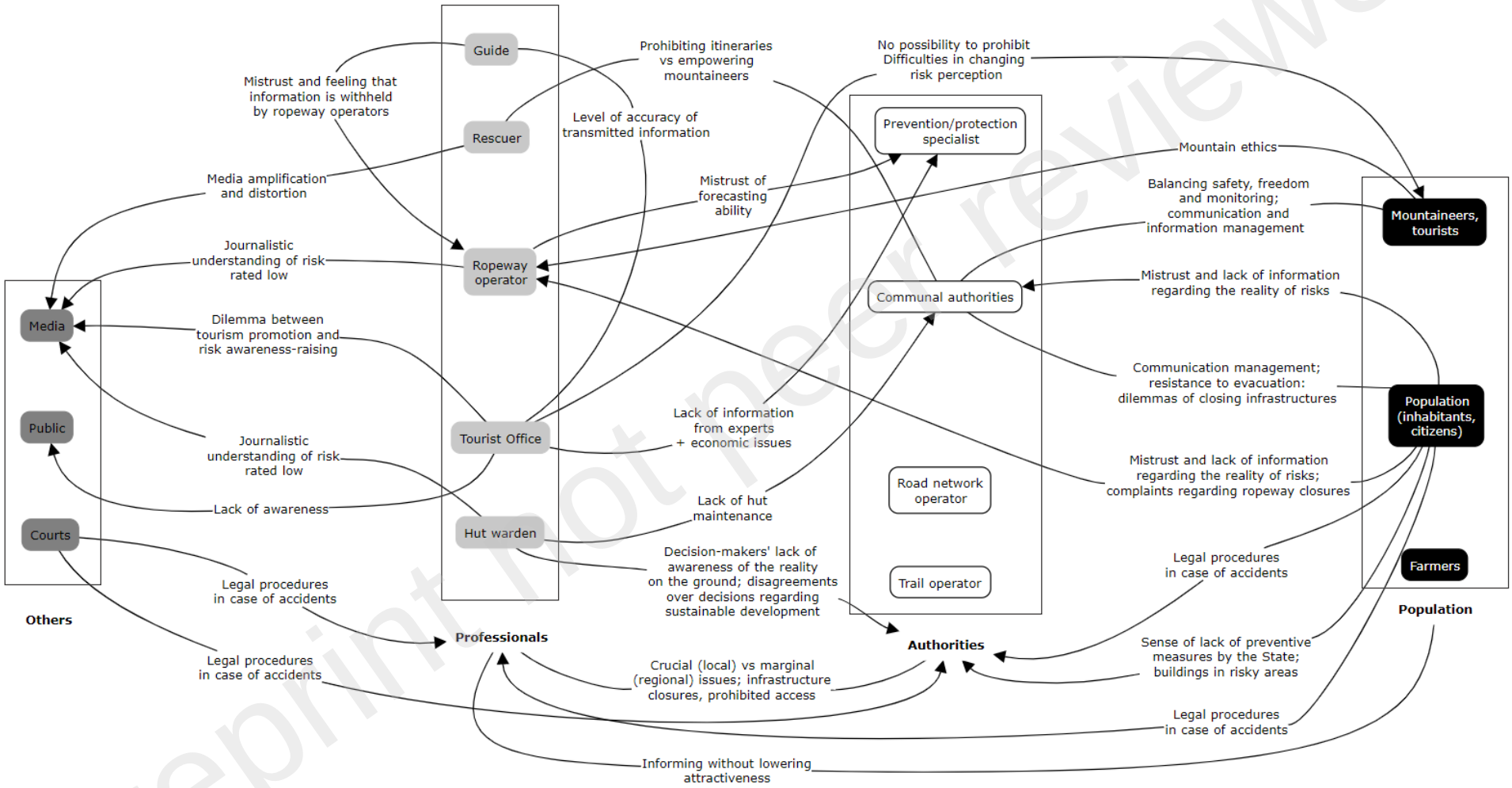
4.6 Sources of tension and dilemmas

Figure 4 shows the main sources of tension and dilemmas across these networks. Five actors stand out: communal authorities, ropeway operators, tourist offices, local inhabitants and the media. Communal authorities sometimes have to shut down a route, close infrastructure or even order an evacuation. This can draw them into conflict with mountain professionals over the economic stakes, with amateur mountaineers who value freedom or with inhabitants who want autonomy in decision-making. Public authorities are also confronted with the difficulty of communicating effectively with the public about mountain hazards. Furthermore, communal administrations own significant infrastructure, sometimes located in risky areas, such as mountain huts. Maintenance and repair costs can put a strain on their finances, and delays to essential work can jeopardize hut wardens' safety. Finally, public authorities are always at risk of legal proceedings in the event of accidents, and they may seek to protect themselves against this.

Some local inhabitants and guides expressed their distrust of ropeway operators. They questioned their infrastructure's vulnerability to climate change and whether the information provided by their operators was complete and reliable. However, the operators pointed out that experts' forecasts were also unreliable. Questions about the long-term viability of cable cars in the face of global warming also revived the ethical debate between the supporters of a wild-mountain ethos and groups whose economic prosperity depends on tourism.

Economic issues are also at the heart of the activities of tourist offices. They are caught in a contradictory position between their duty to provide honest information to tourists and their concerns about preserving the region's attractiveness. They are also confronted with the difficulties of raising public awareness about mountain hazards, either because visitors lack receptiveness to these issues or because the information from guides or natural hazards experts is unprecise. Other mountain professionals are also concerned about the potentially negative effects of public awareness on the attractiveness of their services. They fear the economic repercussions of infrastructure closures and bans on accessing certain areas, as well. Mountain professionals and regional authorities also prioritise the risks associated with permafrost warming differently. At the level of an entire region, other non-related hazards, affecting more people, may be considered a priority. At a very local level, actors such as mountain hut wardens may consider permafrost-related issues critical.

Figure 4: Sources of tension and dilemmas between actors



Local inhabitants sometimes expressed their incomprehension or mistrust about the lack of preventive measures taken by the authorities or, on the contrary, about those very measures after they had been taken: authorisations to build in risky areas, infrastructure closures, evacuation orders, and so on. Finally, several mountain professionals expressed criticism of the role of the media. They blamed them for amplifying or distorting the true risks inherent in the mountains.

5. Discussion

Through an interdisciplinary collaboration, we analysed an emerging natural hazard of geomorphological and climatic origin from the viewpoints of the networks of public and private actors trying to manage it and implement adaptation processes. Activity-centred ergonomics helped us to understand the missions, tasks and ways in which actors individually and collectively faced these risks.

5.1. Inter-regional comparison

Many differences between the regions could be explained by their territories' characteristics, by the functioning of their public authorities, and by the geographical and social proximity of the actors involved. The configuration identified in Valais focuses on local authorities and on the protection of infrastructure and inhabited areas. The cantonal department responsible for dealing with natural hazards has no official mission regarding the prevention of hazards that might affect amateur mountaineers, mountain professionals, and the owners of high-altitude infrastructure. Nevertheless, this department plays a central role in the network. This seems to be due, in large part, to the personal sympathies of its managers, as well as their links with academic circles. Their desires to keep abreast of the latest developments in high mountain conditions, so that they are best able to support local communes, also play a role. The lack of any formal link between the local population and this department is due to Switzerland's political and administrative structure—the State only intervenes in support of its local communes—and the size of the territory involved.

In the Chamonix valley, the network is based more around mountain professionals and their collaboration with the risk prevention specialist reporting to the association of the valley's communes. Local actors indicated almost no interactions with the departmental-level and national-level authorities. Several stakeholders expressed their distrust of the departmental authorities. One local elected official insisted on the importance of getting people to take responsibility themselves, thus avoiding any authoritarian State intervention, for example, closing high-mountain routes. The Chamonix network is the densest of the three, with many bidirectional arrows on its network diagram suggesting a close collaboration between the valley's actors. These results give the impression of a homogeneous network within a tightly-knit mountain community.

The Vanoise massif network is the least dense and least structured. Four actors stand out: rescue units, local authorities, the ropeway operator and the ONF–RTM protection and prevention specialist. The ropeway operator's significance could probably be explained by its economic importance. The Vanoise region is the one where the risks are least known. Actors had high expectations regarding awareness-raising and preventive actions, but the region's monitoring and information systems seems less developed than in Valais or Chamonix.

5.2. How networks of actors function

One common feature in all three regions is the central role of communal authorities. Nevertheless, according to Head (2009), the implementation of effective measures at the local level requires support and strategic direction from higher levels within the State because of the limited resources available. Besides, local elected representatives are connected to a multitude of other public, private and associative actors (Head & Alford, 2015; Varone et al., 2019). Indeed, due to their complex nature, permafrost-related hazards are 'wicked problems' (Crowley, 2009; Head & Alford, 2015; Rittel & Webber, 1973) that local authorities cannot manage alone (Coles & Buckle, 2004) and that require the pooling of many resources and combined actions. Some non-State actors within these networks can acquire leverage, sometimes informally (Frey & Calderón Ramírez, 2019), as shown by the influence of mountain professionals in Chamonix. Also in Chamonix, Earth scientists' research work and efforts with the media have had an important effect on how permafrost hazards are considered. Previous studies conducted in this region have highlighted the strategies adopted by mountain guides to adapt to the effects of climate change (Mourey et al., 2020), the risks of infrastructure such as cable cars and mountain huts becoming unstable (Duvillard et al., 2021; Ravanel et al., 2013), the reduced access to high-altitude refuges and the limited possibilities of adapting mountain routes (Mourey & Ravanel, 2017). These studies confirmed an observation by Head (2009), who stated that modelling the impacts of climate change at the regional and local levels was essential to raising awareness about the need to act.

The literature highlights the difficulties in how public policy networks function. For example, Ferlie *et al*. (2011) noted the absence of real inter-organisational learning. Crowley (2009) pointed out that working together in a network involves the risks of duplication, conflicting messages and overloaded meetings and planning. Howes et al. (2015) highlighted barriers to increased inter-agency collaboration. Scolobig et al. (2015) pointed out that local participation can create situations of conflict between private and public interests, and that citizens are not always willing to share responsibility for disaster risk management with the authorities. Our study also identified sources of tension between the actors involved. These relate mainly to fears about liability in the event of a disaster, risk communication, the economic repercussions of adaptive measures decreed from above, relations between public authorities and the population,

and the balance that should be struck between freedom of practice in nature and safety restrictions. These sources of tension were mainly found in the relations between the authorities and mountain professionals.

5.3 Strengths, weaknesses and research perspectives

This study is one of the few to have linked public policy network analysis and natural hazard management. To the best of our knowledge, no previous publication has addressed this issue using an activity-centred ergonomics approach. Using a qualitative methodology led to us developing a detailed understanding of emerging local networks, of actors' roles and tasks, and of the contents of their relationships. From an ergonomic perspective (Gaillard, 2014), we tried to represent real life rather than official or theoretical interaction networks. This method allowed us to respond to the need for a micro-analysis of the concrete interactions called for by several authors (e.g., Frey and Calderón Ramírez, 2019; Hollstein, 2011; Luxton & Sbicca, 2021).

The networks described were partly dependent on our selection of participants. They were the result of self-reported relationships with other actors and not of a systematic observation of their activities. Furthermore, in each region, each category of actor was only represented by one or two people. Nevertheless, the inter-regional differences revealed were not random. They could be explained by the territorial and topographic characteristics of the regions, which reinforces the plausibility of our findings. An interesting line of research for the future would be to complete this exploratory analysis using a systematic and quantitative study of the documentation describing the official relationships between the actors interviewed.

6. Conclusion

Community resilience depends on how highly authorities value the resources provided by local actors and how they integrate them into community-based approaches (Berkes & Ross, 2013). Our findings highlighted the diversity of networks involved in permafrost-warming risk management. They illustrated the importance of considering a region's particular characteristics when attempting to define public policies and measures for ensuring safety and adaptation to climate change. Indeed, effective actions carried out in one region cannot be replicated blindly in another (Mayer, 2019). Network analysis makes it possible to identify the key stakeholders and existing modes of interaction. Providing these analyses to local actors stimulated reflection on the adaptations needed for them to strengthen their collaboration. We believe that all three regions would benefit from identifying or developing structures that could involve their citizens more in risk management. Indeed, the citizens are mainly considered as targets of awareness-raising campaigns rather than as important links in the chain. The workshops organised at the end of this

study showed that the inhabitants expected to be involved in the reflection on permafrost-related disaster prevention. The keen interest demonstrated by local stakeholders should inspire Human and Earth scientists to develop further interdisciplinary research-action projects to strengthen the resilience of communities in the face of emerging risks.

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