

# Snow avalanche hazard assessment and risk management in northern Quebec, eastern Canada

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**Abstract** In the northern environments of Quebec (eastern Canada), snow avalanche hazards have been ignored for a long time because no major incident was recorded before the tragedies of Blanc-Sablon (Lower North Shore of the St. Lawrence River) in 1995 and Kangiqsualujjuaq (Nunavik) in 1999. To enhance risk reduction at these sites, this research on process characteristics describes prone terrain, run-out distance and triggering factors, and prompted efforts (permanent and temporary measures) made to mitigate and prevent future snow avalanche tragedy from short, steep slopes. Considering the high vulnerability of these communities related to the growing population of Nunavik and the lack of knowledge of avalanches on the Lower North Shore, acceptable risk was based on the implementation of a snow avalanche forecasting and warning program over 3 years, the first one in eastern Canada. Community participation and the involvement of the municipal and provincial authorities have enabled the efficient operation of the program and accentuate the sensitivity and resilience of the populations to avalanche hazard and risk, as evidenced by the subsequent identification of avalanche sites by the communities themselves. These case studies demonstrate the importance of adequate and safe land planning, notably in the context of climate change, and particularly for isolated northern communities.

**Keywords** Snow avalanche · Risk management · Warning system · Northern Quebec · Lower North Shore · Nunavik

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## 1 Introduction

Snow avalanches are a severe natural hazard, threatening recreation, transportation, resource industries, property and lives in Canada (Stethem et al. 2003). Since the mid-1800s, historical records indicate that more than 700 fatalities have been related to snow avalanches (Campbell et al. 2007). Although most snow avalanche fatalities occur in western Canada, many such incidents have also been reported on the short slopes of eastern Canada (Liverman et al. 2001; Héту et al. 2011, 2015). Archival research, coroner's investigations and newspaper searches indicate that snow avalanches are the second most deadly major natural hazard after landslides in the province of Quebec (Landry et al. 2013), with over 73 victims reported between 1825 and 2009 (Héту et al. 2011). Most have occurred near residential or public buildings [i.e., in 1995 in Blanc-Sablon (St. Lawrence North Shore), 1999 in Kangiqsualujjuaq (east of Ungava Bay) and 2000 in Château-Richer (northeast of Quebec city)], highlighting the danger related to snow mass wasting on short slopes and also indicating that snow avalanche hazard is much higher than in most other regions in Canada where snow avalanches more often occur remotely and do not result in infrastructural damage. Although major snow avalanches that cause property damage are relatively rare, the tragedies in Blanc-Sablon (1995) and Kangiqsualujjuaq (1999) have contributed to alerting the government and public security services to the risks of potential damage to property, particularly in unrecognized avalanche-prone areas such as the northern communities of Quebec.

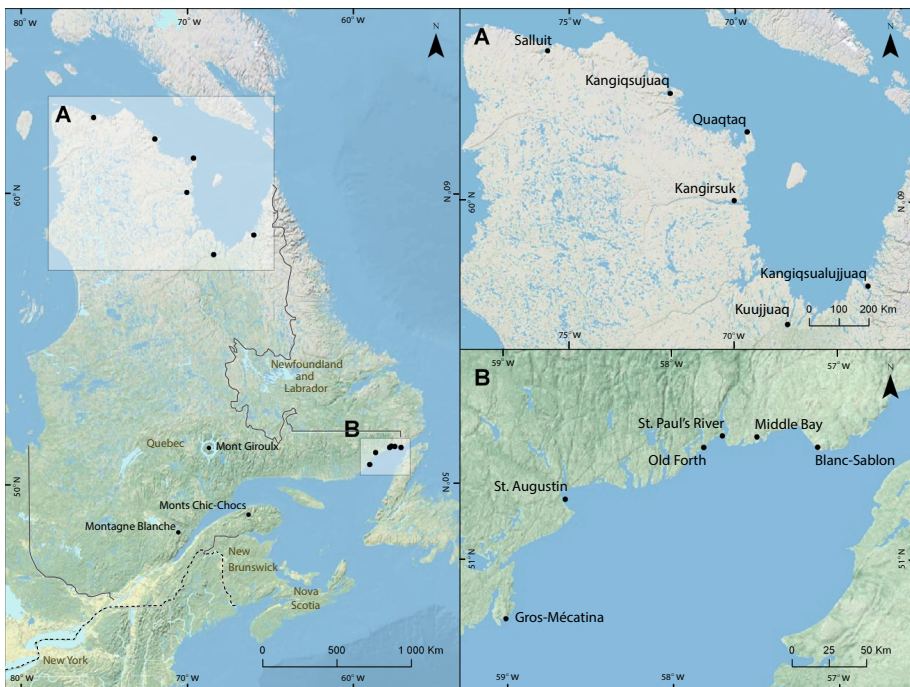
In the province of Quebec, there is no structural protection nor any systematic daily forecasting procedures to reduce snow avalanche risks, as compared to western Canada (Haegeli and McClung 2003) and European Alpine countries (Salm 1997; Jomelli et al. 2007), where most severe snow avalanche problems have been mitigated by permanent protection measures such as snowpack support structures, deflecting dikes, dams or sheds (Schweizer et al. 2009). In addition to these permanent protection measures, most western and central European countries use snow avalanche prevention plans for land-use planning in order to minimize the impacts of avalanches. Nevertheless, snow avalanches are still a threat for inhabitants in mountainous environments such as Iceland (Decaulne 2005, 2007) and Romania (Voiculescu and Onaca 2013, 2014). In northern communities of Quebec, snow avalanche hazard assessment and management represent a difficult task for the following reasons: (1) the lack of avalanche surveys and datable material for the reconstruction of past significant events (no tree-ring dating possibility, poor soil development and absence of buried organic matter, very few loose material for the building of characteristic landforms in the run-out zones); (2) the scarcity of weather stations providing good quality data and long-term records; and (3) a poor perception of the risk by the communities and land managers, given the spatiotemporal distribution of catastrophic events (i.e., involuntary risk resulting in several injuries and death) related to snow avalanches.

The aim of this paper is twofold: (1) to provide an overview of the snow avalanche hazard assessment and risk management in the northern communities of Quebec, with an emphasis on the snow avalanche monitoring program which was implemented until the prescribed relocation of buildings from high-hazard zones was completed, and (2) to draw attention to an issue that remains largely misunderstood in the province of Quebec, as well as elsewhere, due to the physiographic, climatic and cultural particularities of where snow avalanches occur.

## 2 Snow avalanche hazards in the province of Quebec

The province of Quebec is the largest Canadian province, with an area of 1.5 million km<sup>2</sup>. Extending north and south of the Canadian Shield, Quebec has a very diverse landscape, consisting of the Laurentian Plateau, the Appalachians, and the St. Lawrence Lowlands. The presence of several large water bodies (Fig. 1; Hudson Bay, Ungava Bay, the Gulf of St. Lawrence) and its location adjacent to the northern USA (continental climatic influence), the Maritime provinces and Labrador impose diverse and variable climatic influences due to the alternating high- and low-pressure systems associated with westerly atmospheric circulation.

The winter season in Quebec is particularly long (4–5 months in the south and 5–8 months in the north) and is characterized by annual snowfall totaling at least 200 cm, and more than 500 cm in the eastern part of the province and in mountainous regions (Environment Canada 2011). Snow cover persists on average from November till mid-April and until June in the far north. Hot air masses and humidity coming from the Gulf of Mexico are usually responsible for intense winter snowfalls and blizzards. Storms usually increase in intensity from west to east in the St. Lawrence Valley. Low-pressure weather systems from the east coast generally bring fresh and humid conditions from the North Atlantic. The freezing of major water bodies as of December each year, particularly the



**Fig. 1** Location of the study areas in Province of Quebec and the villages and municipalities investigated in Nunavik (a) and on Lower North Shore of the St. Lawrence River (b), respectively. The deadly accidents that occurred in the mountainous environments of Quebec and related to snow avalanches are also shown on the left side: Monts Groulx in central Quebec, Montagne Blanche in the highlands of the Saguenay River and Monts Chic-Chocs in Gaspésie

Hudson Bay, allows the fast influx of cold, dry air masses from the Arctic into the province. Every year this results in a period of extreme cold even in the southeast part of the province.

## 2.1 Record of snow avalanche accidents

The results of archival research supplemented by field surveys provided a record of 43 deadly avalanches in Quebec since 1825, totaling 73 deaths and more than 50 people injured (Héту et al. 2011). Surprisingly, only four deadly accidents occurred in the mountainous environments of Quebec: one in the Saguenay highlands (Montagne Blanche 1985), one in the Groulx Mountains (1996) and two in the Chic-Chocs Mountains of the Gaspé Peninsula (March 2000, two accidents 1 week apart). While snow avalanches are generally associated with mountainous environments, most of the deadly avalanches in Quebec occurred instead on the steep banks of the St. Lawrence River, in areas that are densely populated. Therefore, it appears that the climatic and physiographic characteristics of Quebec are favorable for snow avalanche occurrence despite the lack of high-elevation relief; the highest peak in southern Quebec is Mount Jacques-Cartier, at 1270 m asl.

The recent survey by Héту et al. (2011) on mortality resulting from snow avalanches also revealed that the typical victim of a deadly avalanche in Quebec is a young boy killed in his home or while playing on a short but steep slope near his home, during or immediately following a snowstorm (80 % of cases occurred during a snowstorm or in the 48 h following the storm event). As previously mentioned, snow avalanches are not restricted to mountain ranges. However, the reader will find additional information concerning the spatiotemporal distribution of snow avalanches in mountainous environments of Quebec in previous works (Larocque et al. 2001; Boucher et al. 2003; Dubé et al. 2004; Germain et al. 2005, 2009, 2010; Héту 2007; Fortin et al. 2011). The majority of known accidents occurred on short slopes ( $\leq 80$  m of relief), corresponding to a gravel pit, steep slopes along a river, escarpments of marine or fluvial terraces, etc. (Héту et al. 2011). The inclination of the slopes was  $\geq 30^\circ$  with a surface plane at the top (terrace, plateau, agricultural field, etc.), which is typically very poorly vegetated, creating conditions conducive to snow drifting and formation of cornices (Héту and Bergeron 2004; Germain et al. 2005). The breakdown of cornices and wind slabs have also been reported in association with several accidents, including those of Blanc-Sablon (the Lower North Shore of the St. Lawrence River) in 1995 and of Kangiqsualujjuaq (Nunavik, east of Ungava Bay) in 1999 (Fig. 1), testifying that snow avalanche occurrence on short slopes has been underestimated both in the literature and within inhabited areas (i.e., local administration, policy and population). Indeed, the important amount of snow accumulated in the starting zone appears a more important prerequisite to trigger large and destructive snow avalanches than the slope relief.

## 2.2 Snow avalanche risk perception

Similar to incidents reported from the adjacent province of Newfoundland and Labrador (Batterson et al. 1999; Liverman et al. 2001; Government of Newfoundland and Labrador 2007; Liverman 2007), the majority of deaths from avalanches in Quebec have occurred while people were inside or near a building (37 deaths and 42 injured), most often their place of residence (8 incidents and 24 deaths). This finding is particularly important because it clearly shows the lack of knowledge of snow avalanche hazards by comparison

to western Canada (Jamieson and Stethem 2002), the USA (Page et al. 1999; Atkins and Williams 2000) and other alpine areas where most of the avalanche accidents are related to recreational outdoor activities and therefore a voluntary risk rather than uninformed home placement decisions (Irwin and Owens 2004; Jarry and Sivardière 2000).

The average age of the victims (~20 years) is another element indicating a misperception of snow avalanche risk in Quebec. Indeed, archival research has revealed numerous young victims, in particular children under 10 years of age (Héту et al. 2011). This situation is likely related to the nature of the accidents (occurring in residential areas) that prevailed historically in Quebec and the demographic characteristics at that time period (large families of the nineteenth century), including for several deadly avalanches (1825, 1869, 1875, 1898) which destroyed many houses in Quebec City and Lévis (Héту et al. 2011). Such accidents involving buildings and dwellings are characteristic of countries that have no policy concerning snow avalanche hazards. For example, Decaulne (2007) reported a similar situation in Iceland where the growth of the population on newly occupied terrain without having knowledge and consciousness of hazards resulted in catastrophic events. Countries that have implemented such policies have significantly reduced this type of accident (Jamieson and Stethem 2002). It should be noted here that deaths in Quebec and in Newfoundland and Labrador represent at least 20 % of avalanche victims across Canada since the middle of the eighteenth century (Campbell et al. 2007).

For accidents occurring after 1950, and reported in previously published compilations or in newspapers (Stethem and Schaerer 1979, 1980; Schaerer 1987; Jamieson and Geldsetzer 1997; Jamieson and Brooks 1998; Héту and Bergeron 2004; Campbell et al. 2007; Sécurité publique Canada 2007; Héту et al. 2011), it appears that Quebec is experiencing an increase in deaths associated with recreational outdoor activities, a trend also observed in most industrial countries (Atkins and Williams 2000; Jamieson and Stethem 2002). Winter sports are currently booming in Quebec, especially activities in the backcountry (skiing, alpine touring, snowshoing, ice climbing, etc.). Given this increase of people in the backcountry, where the activities are much more difficult to regulate and the intervention of rescuers more complex, it is expected that the number of accidents could increase further in the next few years (Héту et al. 2011). In this context, should we really be surprised by some narrowly avoided tragic events, such as occurred on March 4, 2003, when a major snow avalanche buried 14 skiers on the Mount Hog's Back in the central highlands of the Gaspé Peninsula (Gagnon 2003)? In addition, the absence of accidents involving snow avalanches for many years—the last tragedy prior to the fatal accident in 1995 in Blanc-Sablon on the Lower North Shore of St. Lawrence River dates back to 1968, in Quebec City (Héту et al. 2011)—has certainly contributed to the misperception of the risk reality by the entire population of Quebec.

### 3 Geographic characteristics of northern Quebec

Because of their unique geography, biophysical and socio-demographic characteristics, the isolated northern regions of Quebec deserve special attention. Indeed, their remoteness from major cities and their limited accessibility, largely dependent on weather conditions—and the use of snowmobiles as a means of transport in the winter—give these regions particularities that must be taken into account for a secure land planning.

### 3.1 The Lower North Shore

The Lower North Shore Territory has a surface area of 5803 km<sup>2</sup> and is located along the north shore of the Gulf of St. Lawrence between the Natashquan River and the Newfoundland and Labrador border (Fig. 1). This region has been inhabited for at least 8000 years by a succession of aboriginal populations and later cultures leading to the modern Innu and Inuit.

The territory is subdivided into municipalities (Pakuashipi, La Romaine, St. Augustine, Gros-Mécatina, Lower North Shore, Bonne-Espérance and Blanc-Sablon). Remains of communities that fished for cod, lobster and salmon for more than a century are numerous (Lac-Salé, Baie de la Terre, Musquaro, etc.), although many became deserted in the 1960s–1970s, or more recently with the decline of North America cod fishery and its closure by Canada in 1992. Despite the decline of commercial fishing, there are just over a dozen communities remaining today, and major settlements on this 400-km-long coastline include Natashquan, Kégaska, La Romaine, Chevery, Harrington Harbour, Whale Head, Mutton Bay, La Tabatière, St. Augustine, Old Forth, St. Paul's River, Middle Bay, Brador Bay and Blanc-Sablon (Fig. 1). Across these subarctic, oceanic barrens resides a declining population of about a few thousand people (Table 1) connected to the rest of the country in the summer by a weekly supply ship and expensive flights, and in the winter, most reliably, by a snowmobile trail glazed with ice. These conditions combined resulted in an important decline (−10.5 to −19.8 %) of the population over the last decades (Table 1).

The general topography is characterized by a low-elevation plateau, generally less than a few hundred meters high, and corresponds to the typical relief of the Canadian Shield, dissected by glacial valleys. More than half of the territory is within a 100-m elevation band. The glacial deposits are discontinuous and thin. The vegetation is scarce and shrubby, particularly in the eastern part of the region. The entire Lower North Shore is located south of the known limit of sporadic permafrost in Quebec and Labrador, with an average air temperature in Blanc-Sablon of 0.2 °C for the period 1970–2000 (station 71,808, 51°27'N and 57°11'W, 37 m asl). The proximity of the Atlantic Ocean influences the air temperature very slightly due to the cold mass of water coming from the Labrador Current, which enters the Strait of Belle Isle, favoring the introduction of icebergs once the sea-ice cover breaks up in the spring (Dionne 1984). The average January temperature, the coldest month, is −13.3 °C, while in August, the warmest month, it barely reaches 12.6 °C. Annual rainfall totals 1066 mm with snowfall from October to May (Dionne 1984). Snowfall is mainly concentrated between December and March, with an average of

**Table 1** Socio-demographic characteristics of the Lower North Shore communities affected by snow avalanches

Municipality	Area (km <sup>2</sup> )	Density (Pop/km <sup>2</sup> )	Population			
			1996	2001	2006	2011
Blanc-Sablon	247.53	4.5	1248	1201	1263	1118
Bonne-Espérance <sup>a</sup>	646.73	1.1	906	852	834	732
St. Augustin	1254.28	0.4	683	626	599	478
Gros-Mécatina	804.80	0.6	622	573	566	499

<sup>a</sup> The municipality of Bonne-Espérance includes the villages of Old Forth, Middle Bay and St. Paul's River  
Source: Statistics Canada, Census profiles of 1996, 2001, 2006 and 2011

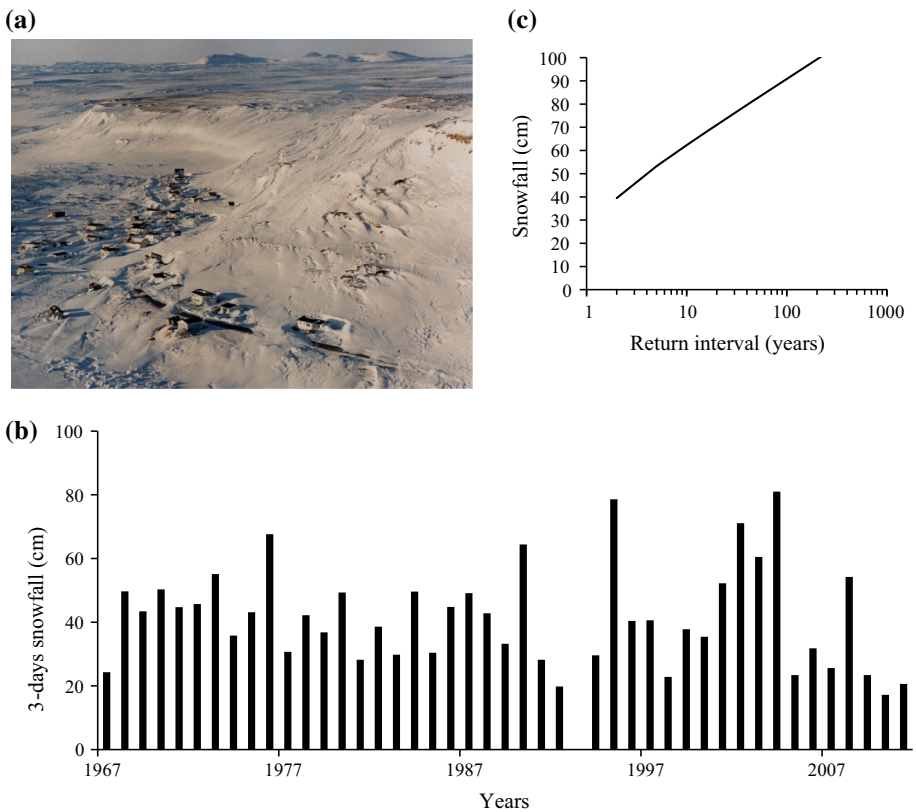


332 cm. Each month of the cold season is characterized by one or more periods of thaw accompanied by rain. Prevailing winds are from the southwest in the summer and the northeast in the winter, reaching 150 km/h during blizzards. The occurrence of winter warm spells and the omnipresence of winds favor a shallow snowpack, despite the fact that daily snowfall may exceed 40 cm.

3.1.1 The deadly snow avalanche of Blanc-Sablon

Between March 8 and 10, 1995, approximately 80 cm of snow accumulated in the village of Blanc-Sablon (51°29' N; 57°10' W), which is located between the Gulf of St. Lawrence and Mount Bonenfant (90 m escarpment; Fig. 2), coinciding with strong winds ( $\geq 100$  km/h). On March 10, an avalanche swept down the escarpment: hitting one house and destroying two sheds at the base of Mount Bonenfant. The estimated cost of lost property was CAN \$80 000, but more importantly, two people were killed.

The avalanche was released in a shallow depression near the top edge of the escarpment (Fig. 2). This small depression, barely a few tens of meters in width in the upper part of the slope, acted as a funnel for the northeast winds, which then overloaded the slope.



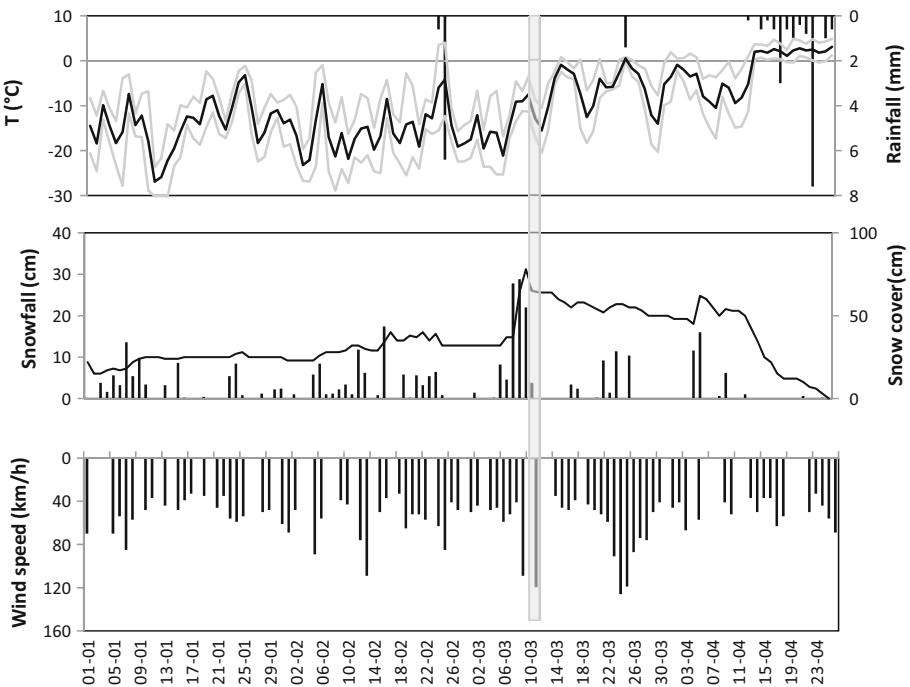
**Fig. 2** a Aerial view of the Mount Bonenfant in Blanc-Sablon; b interannual variability of snow precipitation for the period 1967–2011; and c return interval of cumulative snowfall for three consecutive days

Considering the extent of the plateau above Mount Bonenfant and the absence of vegetation, the amount of snow transported by the wind was considerable.

The inclination of the slope in the starting zone a few days after the event was approximately  $25^\circ$ , the minimum threshold for the triggering of snow avalanches (McClung and Schaerer 1993). The width of the run-out zone was approximately 75 m, and the measured run-out length was also 75 m. The meteorological station recorded a total of 78.5 cm of snow precipitation during 3 consecutive days, corresponding to a return period of 40 years (Fig. 2). Moreover, 2 weeks prior to the avalanche accident, there was a warm spell with temperature up to  $4^\circ\text{C}$  combined with 7 mm of rain (Fig. 3). The temperature dropped after this warm period and formed an ice crust that probably acted as a gliding surface when the avalanche released (Jamieson 1997; Government of Québec 2000).

### 3.2 The Nunavik territory

Located north of the  $55^\circ$  parallel, the Nunavik region is a large territory ( $>500,000\text{ km}^2$ ) flanked to the west by Hudson Bay and to the east by Ungava Bay and Labrador, with the Hudson Strait comprising its northern boundary. Occupied for at least 3500 years, today there are 14 villages totaling approximately 12,000 individuals (Fig. 1), mainly Inuit ( $\sim 90\%$ ). The highest population growth in Canada (i.e., 50% under the age of 20 years), the isolation of the communities, the long duration of winter conditions, the major climatic changes observed and the distinct social and economic lifestyle characterize this unique



**Fig. 3** Weather conditions (min, max and average temperatures, snowfall and snow cover thickness, wind speed) for the period of January 1 to the end of April 1995 at Blanc-Sablon. The snow avalanche occurred on March 10 following major 3-day snowfall and strong winds (blizzard  $>100\text{ km/h}$ )



region and population. Indeed, the socio-demographic characteristics included a significant increase in population (+34.9–46.3 % during the period 1996–2011) and many new dwellings (Table 2). Unfortunately, many of these have been erected in hazards zones prone to snow avalanches, land sliding or rock falls (Lied and Domaas 2000).

Various factors affect the climate, depending on whether you are on the coast or on the upper plateaus inland. Precipitation diminishes from south to north. Winters are harsh with strong winds. At the meteorological station of Kuujuuaq (Station 71,906, 58°06'N and 68°25'W, 39 m asl), the main town in the region, the average annual temperature is −5.7 °C. Precipitation totals 526.8 mm of which 50 % falls as snow, typically between October and May. Compared with the wet and cold maritime climate which characterizes the Lower North Shore of the St. Lawrence, winter warm spells with temperatures above 0 °C are unusual between December and March. The average January temperature is −24.3 °C, while that of July is 11.5 °C. Finally, in this subarctic environment, climate also manifests itself through other extremes that should be mentioned, including strong winds exceeding 150 km/h and important snowfalls occurring within 24 h periods.

### 3.2.1 The catastrophic avalanche event of Kangiqsualujjuaq

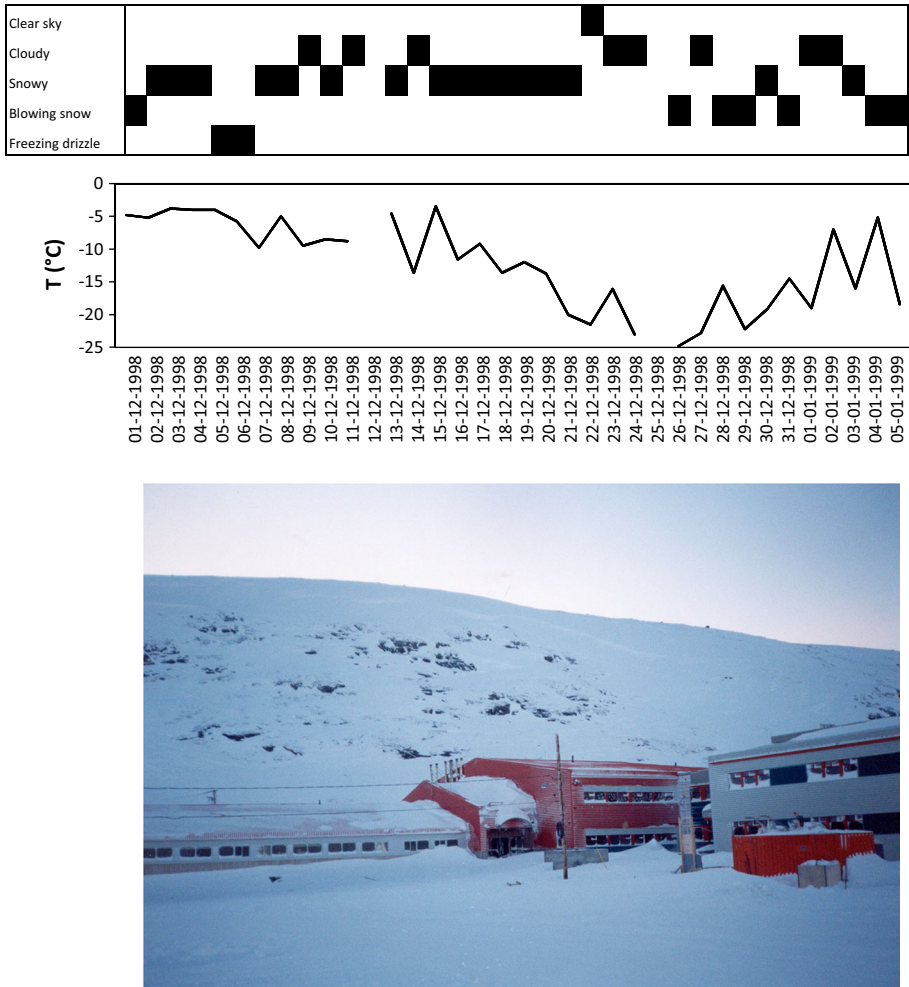
Established in 1959, the village of Kangiqsualujjuaq is located in the extreme north of Quebec, east of Ungava Bay (58°41'N; 65°57'W), in a valley sheltered from the prevailing winds from the southwest and northwest, due to the presence of a small mountain ridge 130 m high, which is oriented from the southeast to the northwest. The population of Kangiqsualujjuaq is extremely isolated; winter access to the community is completely dependent on air transportation and as such on meteorological conditions. Over the years, several buildings were constructed at the base of the cliff where the slope is greater than 38°, more than steep enough to foster the formation and release of snow avalanches.

At approximately 01h45 on January 1, 1999, a dry slab avalanche released from the slope above the school, where most of the village was gathered to celebrate New Year's Eve (Fig. 4). The rapid loading of snow in the starting zone likely triggered the avalanche. The snow profiles observed a few days later indicated that the avalanche likely failed on top of December crust or in the weak layer of faceted crystals below the November crust (Schaerer et al. 1999; Fig. 4). Unfortunately, the availability and the quality of meteorological data preclude a better understanding of the triggering conditions and the properties of the snow cover. The avalanche ran down the 38° slope across 40 m of flat ground and stuck the southwest walls of the gymnasium and school. The observed damage indicated an impact pressure of approximately 10 kPa (Schaerer et al. 1999). With a death toll of nine and 25 people injured, this is the worst snow avalanche-related disaster known in Quebec and in eastern Canada—except for the one that occurred in an Inuit settlement near Nain

**Table 2** Socio-demographic characteristics of the Nunavik villages affected by snow avalanches

Village	Population				Dwelling	
	1996	2001	2006	2011	1996	2011
Kangiqsualujjuaq	648	710	735	874	121	191
Kangirsuk	394	436	466	549	86	163
Quaqtaq	257	305	315	376	58	91
Kangiqsujuaq	479	536	605	696	95	174
Salluit	929	1072	1241	1347	171	315

Source: Statistics Canada, Census profiles of 1996, 2001, 2006 and 2011



**Fig. 4** Weather observations and average temperature in Kangiqsualujjuaq for the period of December 1, 1998, to January 5, 1999. No quantitative data on precipitation were available for the relevant period. View of the school that was heavily impacted by snow avalanche on January 1. The fracture indicating the starting zone of the avalanche is visible in the *upper part* of the slope (Courtesy of the Ministry of Public Safety)

(Labrador) in 1782, resulting in 22 fatalities (Liverman 2007). It is difficult to imagine a worse scenario in this isolated community than one where the death toll exceeds 1 % of the total population, including five children, and where the response of rescue teams was delayed due to weather conditions.

As a preventative measure taken the day after the avalanche, the Quebec Ministry of Public Safety recommended the establishment of a 100-m exclusion zone at the base of the cliff. Although avalanches from this steep slope had already occurred in the previous decade, notably in 1993 (Lied and Domaas 2000), these were not associated with infrastructural damage or human injury. The report of coroner Jacques Bérubé would indicate in the weeks following the avalanche that the tragedy was the result of negligence on the

behalfes of certain involved parties, related to the construction and renovation of the school since 1974, and also to managing risks inherent to snow avalanches, particularly in the days leading up to the avalanche, as municipal and civil security authorities were apparently aware of the dangerous conditions.

If the population was aware of the possibility of a snow avalanche due to past events, notably because several small avalanches were observed in the 1980s and 1990s (Hétu and Dubé 1995), the absence of hazard zoning and the estimated return interval of  $\geq 50$  years of the tragedy of 1999 (Lied and Domaas 2000) have resulted in a misperception and an underestimation of the risk, especially by municipal authorities. This ignorance is surely linked to the absence of large mountain ranges and known large previous events and can perhaps explain in part the absence of an emergency plan by the Kangiqsualujuaq municipality, the Nunavik regional administration and the local police at that time.

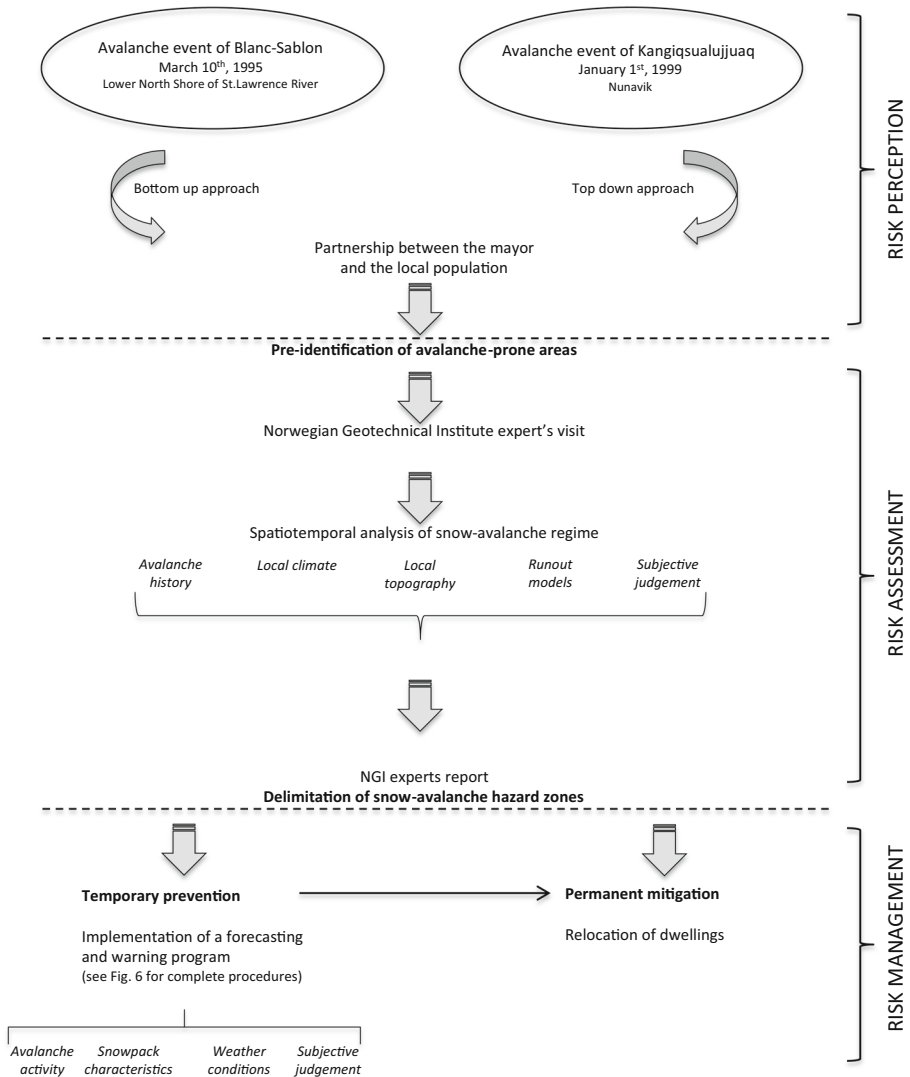
## 4 The process of hazard assessment and risk management

In the months following the tragedy of Kangiqsualujuaq, the report of the coroner suggested several recommendations to improve safety measures in the isolated communities of northern Quebec. The Quebec Minister of Public Safety was also brought into identify potential snow avalanche sites and to intervene where risks to human life and safety were apparent (Fig. 5). This top-down approach to risk assessment and management contrasts strongly with the situation of the Blanc-Sablon avalanche event in 1995, for which people have been trying to get their houses removed from the base of the avalanche slope until 2001 (i.e., a bottom-up approach). Several measures in line with the coroner's report were taken by the Ministry. Indeed, in the spring of 1999, the Quebec Ministry of Public Safety and a federal minister delegated from Indian and Northern Affairs Canada signed a 5-year contract (1999–2004) with the *Kativik Regional Administration*, through which the Quebec Ministry of Public Safety dedicated CAN \$700 000 per year to establish a regional civil security organization, as well as 14 such organizations at the municipal level in each of the fourteen Nunavik villages in order to favor a sustainable land management.

### 4.1 Hazard zoning

The following winter, the Norwegian Geotechnical Institute (NGI) was asked by the Commission of Public Safety of Quebec to assess snow avalanche hazards and possible mitigation measures for villages on the Lower North Shore of the St. Lawrence River and in Nunavik. Two experts from the NGI, along with representatives from the Quebec Ministries of Public Safety and of Natural Resources, visited 14 communities, seven in the Lower North Shore region of Quebec and seven in the far North (Lied and Domaas 2000). The specific sites visited and potentially prone to snow avalanches had previously been identified by the mayor with the local population for each village (Fig. 5). The snow avalanche hazard evaluation consisted mainly of delimiting the spatial extension of the hazard zones based on the calculated run-out distance of avalanches with a frequency of 1/100 per year. In addition, the calculated run-out distance of avalanches with an expected frequency of 1/1000 per year was calculated, which is used in the National Building Code of Norway.

The calculation of the run-out distance of snow avalanches was based on local topography (avalanche terrain and release areas), local climate, avalanche history,



**Fig. 5** Holistic concept of risk analysis for northern communities of Quebec

topographic/statistical ( $\alpha/\beta$  model; Lied and Bakkehoi 1980; Lied and Toppe 1983) and numerical run-out models (PCM, NIS, PLK; Perla et al. 1980; Bakkehoi et al. 1983; Perla et al. 1984; Norem et al. 1987) and the experience and subjective judgement of the NGI experts (Fig. 5). However, because of the scarcity of historical observations of snow avalanches and the lack of geomorphic and dendroecological impacts in most of the sites, it was not possible to perform a proper statistical analysis to predict avalanche run out for a given return period. Indeed, the scarcity of the vegetation due to the climate or fire regime makes its use difficult for the reconstruction of past avalanche events. Moreover, most of the run-out models have not been developed and calibrated for use on short slopes (i.e., less than a 100 meters in height; Jones and Jamieson 2004). Therefore, the lines drawn on the

maps for extreme avalanche frequency (1/100 and 1/1000 per year) should be considered as a best estimate based on the local information gathered, rather than an exact calculation of run-out distances. This statement turns out to be particularly true in northern Quebec, where oral and written histories are limited, as well as aerial photographs and weather stations with reliable long-term records.

#### 4.2 Permanent mitigation measures: relocation of dwellings

Considering the cost-benefit analysis of different mitigation measures, such as catching dams, wire rope nets, concrete walls and supporting constructions, but also in order to respect the environmental esthetic and the risk perception of the local communities, it was decided to relocate the exposed buildings out of the hazard zones (Fig. 5). The idea behind this approach was to prevent development in hazardous areas, emphasizing the importance of having a proactive land-use and growth management policy designed to prevent, rather than simply react when a disaster strikes.

In addition, the great unknown in the application of return periods is the impact of climate change (Germain et al. 2009). If a major shift in climatic patterns occurs, then our concept of return periods, which is largely based on historical and regional patterns of snow avalanche occurrence, may become invalid. This is particularly the case for the villages of Nunavik, where several witnesses referred to greater recent climate variability and particularly as concerns snowstorms (Lied and Domaas 2000). From a risk perspective, this could be a major problem if larger avalanches begin to occur more frequently or in different regions than historic experience suggests they should (Stethem et al. 2003). Consequently, the Government of Quebec has applied the NGI approach to avalanche hazard mapping to the northern communities in order to keep the risk levels as low as possible and acceptable for future facility location.

For the relocation of private homes, various scenarios were presented to the owners, namely: (1) the residence would be relocated to a safe area, if it could be moved from an engineering standpoint; otherwise (2) the owner had the option of a newly constructed home or of buying an existing one located in a safe area of the municipality; or (3) to take a fixed amount of compensation, corresponding to the estimated value of the property, and to leave the hazard area. Financial assistance was granted to the municipality for the chosen relocation scenarios. The value of the aid is equal to the costs actually incurred for the residence relocation, the construction of a new home or the purchase of an existing home, as determined by the Minister. The real estate value of homes could only be used by also taking into account the geographic distance from major cities and transport networks, and the high cost of building materials in these remote locations. Also, given the high number of dwellings to relocate or rebuild, the program was maintained over several years, particularly because new demands for expertise (i.e., expert assessment of additional potential hazard zones) have repeatedly come to the Government of Quebec during the years since the program was initiated.

#### 4.3 Implementation of a regional snow avalanche forecasting and warning program

Considering the amount of relocation work and the associated time, it would take to relocate all affected residents out of the hazard zones (the program was carried out over 4 years), a regional snow avalanche forecasting and warning program was implemented in many villages in the interim (Fig. 6). Because the extent to which the risk prevention

Avalanche hazard classification	Snowfall intensity (cm/h)	New snow accumulation <sup>1</sup> (cm)
1. Low	> 1	> 15
2. Moderate	> 2	> 20
3. Considerable	> 5	> 30 <sup>2</sup>
4. High		> 50 <sup>3</sup>
5. Very high		> 80

Wind speed (km/h)	Remarks
> 15	The snow can be transported
> 25	Cornice formation
> 40	The snow can be carried in the air
> 55 <sup>4</sup>	Strong eddying effect can develop on the leeward side of ridges
> 90 <sup>5</sup>	The situation becomes rapidly unsafe

<sup>1</sup> The snowpack will usually begin adjusting to a new load within 48 hours after a loading event.  
<sup>2</sup> New snow accumulation of 30 cm during a period of 24 hours may create Avalanche Hazard Considerable.  
<sup>3</sup> New snow accumulation of 50 cm during a period of 24 hours may create Avalanche Hazard High or Very High.  
<sup>4</sup> Heavy snowdrift due to wind > 55 km/h, 1-3 days after periods of snowfall > 20 cm, may create avalanche hazard: 3 Considerable, or 4 High.  
<sup>5</sup> At wind speed exceeding 90 km/h, the hazard situation must be continuously assessed.

Avalanche Risk Classification	Wind speed (m/s) – 10 minutes average				
	0-8	8-15	15-20	20-25	> 25
Low	> 15 cm	0	0	0	
Moderate	> 20 cm	> 15 cm	> 5 cm	0	
Considerable	> 30 cm	> 20 cm	> 15 cm	> 5 cm	
High	> 50 cm	> 30 cm	> 20 cm	> 10 cm	
Very high	> 80 cm	> 50 cm	> 30 cm	> 20 cm	

Notice of Avalanche Risk Assessment	
No Danger Safe conditions	No evacuation
Conditions possibly becoming unsafe in a matter of 12 hours	Temporary Evacuation
Alert Dangerous conditions	Prolonged evacuation

**Fig. 6** Avalanche risk classification based on threshold values for: **a** snowfall intensity and new snow accumulation during 24–72 h (*numbers* in table refer to accumulated new snow depth measured at observation site in sheltered surroundings and for temperatures below 0 °C) and **b** wind speeds. The matrix of avalanche risk is thereafter simplified for better public awareness

measures are effective depends mainly on whether the population is aware of the threats to which they are exposed, information was given to the inhabitants about snow avalanche hazards and risk. The purpose of this monitoring program was to insure an acceptable safety level for the people living in snow avalanche hazard zones until relocation of all susceptible dwellings and buildings was complete.

More than 20 avalanche patrollers were trained in the observation of weather, snowpack, avalanches and search and rescue in each village. Twice a day, the patrollers were required to measure the snow height in the starting zones, make general observations on the snowpack (fracture, cornice, etc.) and record the weather conditions (temperature, precipitation, wind). This information was transmitted to the avalanche forecaster located at Blanc-Sablon. After the analysis of snow avalanche conditions at the local scale by the avalanche forecaster, also taking into account the weather forecasts for the next 12 h at a regional scale (Fig. 6), the latter would send a notice of avalanche risk assessment to the municipal office of each community, the Public Safety (Lower North Shore region) and the Kativik Regional Government (Nunavik), which were responsible for coordinating, if necessary, the remobilization procedure (evacuation) and emergency plans. The notice of avalanche risk assessment was based on the following color code: *green* → no danger, safe conditions and no evacuation; *yellow* → conditions possibly becoming unsafe within a span of 12 h, temporary evacuation; and *red* → alert and dangerous conditions, prolonged evacuation. The preventive evacuation was implemented based on the experience of local people during snowstorm events (e.g., strong winds and white-out conditions), which make the deployment of any evacuation measures or search and rescue activities very difficult, such as during the 1995 tragedy in Blanc-Sablon.

The International Avalanche Danger Scale (Table 3) was used for avalanche hazard assessment on a daily basis, although the public warning was restricted to the three color

**Table 3** International Avalanche Danger Scale

Classification	Avalanche release probability, avalanche size and local distribution of dangerous areas
<b>1. Low</b>	Triggering is generally possible only with high additional loads and on few extremely steep slopes. Only a few small natural avalanches (sluffs) possible.
<b>2. Moderate</b>	Triggering possible in particular with high additional loads, particularly on the steep slopes. Large natural avalanches are not likely but human triggered ones are possible.
<b>3. Considerable</b>	Triggering possible even with low additional loads, particularly on the steep slopes indicated in the warning. In some occasions, medium and occasional large natural avalanches may occur. Human triggered ones are probable.
<b>4. High</b>	Triggering probable even with low additional loads on many steep slopes. In some occasions, many medium and several large natural avalanches are likely. Human triggered ones are likely.
<b>5. Very high</b>	Numerous large natural avalanches are likely, even in only moderately steep terrain. Human triggered ones are almost certain.

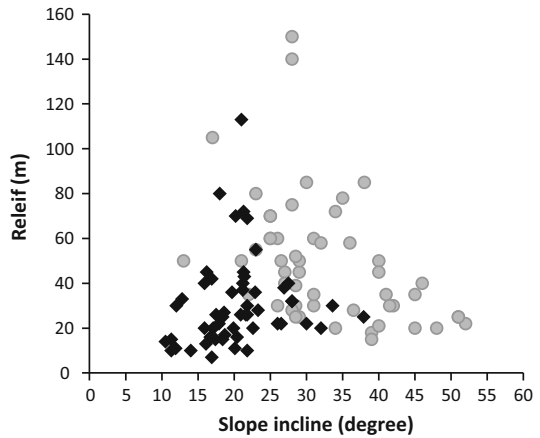
code described above. Because snow avalanches in the past were related to major snowstorms, the hazard rating was based on a multi-scale approach: (1) from quantitative measurements of wind speed and new snow accumulation recorded in the starting zones of snow avalanche paths and at the weather stations and (2) also from radar and satellite images at a regional and continental scales, although both regions (Lower North Shore and Nunavik) are still not entirely or regularly covered by these images. In order to get as precise weather information as possible, patrollers recorded weather data by hand in a sheltered area in the village, which allowed unsafe conditions near the starting zone of the avalanches to be avoided. In order to reduce the most common biases in snow avalanche forecasting, such as inconsistency, illusory correlations, selective perception, etc., we have used specific threshold values for wind speeds and new snow accumulation (Fig. 6), which are considered key variables for avalanche release in northern environments of Quebec (Jamieson 1997; Lied and Domaas 2000). As a dynamic approach is crucial to correspond with these diverse hazards and related conditions, potential snow avalanche hazard was considered not as a single, isolated event, but rather as a complex feature reflecting the interaction between steep terrain, snow cover and short- and long-term variability in synoptic atmospheric circulation.

## 5 Discussion and conclusion

Cutter (1996) illustrates the interactions between vulnerability, hazard and risk particularly well. The vulnerability of a specific place and for a specified hazard is a function of both biophysical and social factors. Biophysical vulnerability is based on the type of hazard, the frequency with which the hazard occurs and the geographical context of the hazard event (Cutter et al. 2000). Human vulnerability is rather influenced by social factors such as age, gender, education, disabilities and socio-demographic characteristics (Cutter et al. 2000). Based on this, a risk assessment must consider not only the hazard event itself, but also the underlying vulnerability of the potentially impacted population. Therefore, a risk assessment must also consider the coping capabilities of the population. In this study, the northern communities of Quebec show a high level of social vulnerability in both the



**Fig. 7** Relief of potential avalanche site plotted against slope incline. *Gray circles* correspond to the preselection of sites by municipal land planners and visited by the NGI experts. *Black diamonds* are the sites identified by local communities during the years for which a snow avalanche forecasting and warning program was implemented



Lower North Shore of the St. Lawrence River (a poor and aging population with a high level of misperception about snow avalanches; Table 1) and Nunavik (a poor and young population, very free outdoor living, lack of emergency plan; Table 2). Biophysical vulnerability is also high in both physiographic regions, considering their remoteness from major cities and their low accessibility, largely dependent on weather conditions. In this respect, search and rescue operations appear particularly difficult because snow avalanches mainly occur during snowstorms and extreme weather conditions (Figs. 2, 3).

The ineffective bottom-up approach following the fatal snow avalanche event of Blanc-Sablon in 1995 may be explained by the misperception of the risk and hazard reality by the entire population of Quebec, including the Ministry of Public Safety, considering that the last tragedy before the event of Blanc-Sablon dated back to 1968, in Quebec City (Héту et al. 2011). Conversely, the magnitude of the disaster of Kangiqsualujuaq in 1999 has promoted a rapid response of the Government (a top-down approach). This collective and individual consciousness about snow avalanche hazard and risk is also evident in the requests for expertise (i.e., pre-identified avalanche sites versus subsequent requests by the communities; Fig. 7). Indeed, the 52 sites investigated by the NGI have an average slope inclination of 32.5° and an average relief of 49 m, in comparison with subsequent requests (average slope incline of 20.5° and relief of 31 m) (Fig. 7). Although it appears obvious that experts investigated the most prominent avalanche-prone areas, the request for more surveys testifies of the concerns of local populations as well as probably the misunderstanding of potential source area of snow avalanches, particularly in these cases where no wet or slush avalanche sites were identified. However, that does not mean that wet and slush avalanches could not occur especially in these regions affected by strong climate variability. This awareness has nevertheless facilitated and promoted the implementation of a snow avalanche forecasting and warning program with an appropriate involvement of the population. The avalanche forecasting process was linked to the engineering analyses for land-use planning in avalanche terrain (run-out distance, return period and vulnerability) and subjective judgment (inductive reasoning and intuitive elements) (Fig. 5). The warning system implemented allowed an efficient preventive evacuation when the local conditions and weather forecast indicated a potential of snow avalanche release, such as during the winter of 2004, when more than 80 cm of snow fell in three consecutive days in

Blanc-Sablon (Fig. 2b), although no large snow avalanche was recorded. This successful snow avalanche monitoring program was the first one in eastern Canada.

In spite of the historical records of fatalities related to snow avalanche activity in the province of Quebec (Héту et al. 2011, 2015), this natural hazard has been unintentionally neglected and even ignored by residents and municipal planners until the tragedies of Blanc-Sablon in 1995 and Kangiqsualujjuaq in 1999. Evidently, these incidents have occurred in areas where no avalanche zoning had been applied. Some may argue that because such avalanches have a return period of greater than 50 years, residents and land planners may not have a perception of the risk. Indeed, the specificity of these northern environments—short steep slopes and the scarcity of datable material related to the biophysical conditions—makes snow avalanche hazard zoning a difficult task even without considerations to the ongoing and future climatic changes. In these environments, blizzards and snowfalls, as well as steep slope aspect, are key variables in avalanche initiation. Indeed, snow drifting from the plateau to the steep slopes favors cornice formation and large accumulation of snow down wind-exposed rock walls where the deadly avalanches were initiated. The observations for the last ~10 years revealed that snow avalanches are climatically controlled and are primarily a response to major precipitations events with strong winds (Héту 2007; Germain et al. 2009; Fortin et al. 2011; Héту et al. 2011). The success of the avalanche forecasting and warning system was based on an effective risk-decision matrix where risk perception and risk assessment were preconditions for risk management. This also relied on a dynamic partnership of local communities and Public Safety, which was an essential condition for a fully integrated approach to disaster and risk management, implying social aspects of the populations.

In Arctic Canada and northern Quebec, there is still a lack of research addressing the potential impacts of climate change on the establishment of risk zones and adaptation strategies in northern communities (Ford 2009; Ford et al. 2010; Vincent et al. 2013). Newton et al. (2005) have recommended that applied research in this domain be carried out in collaboration with northern communities and native groups to insure the inclusion of local perspectives and understandings of climate conditions. In this respect, recent scientific output suggests that climate change is likely to cause shifts in the global pattern and intensity of natural hazards, in some regions increasing the exposure of populations to severe disasters. Potential future risks underline the importance of research and intervention work aimed at strengthening local capacity to cope with natural hazards such as snow avalanches (e.g., Allard and Lemay 2012).

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