AVALANCHE RISK MANAGEMENT IN LONGYEARBYEN, SVALBARD

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ABSTRACT: Snow avalanches have impacted human life and infrastructure in Longyearbyen, Svalbard since the settlement's inception as a mining town in the early 20th century. In the last half-century, dramatic climatic changes superimposed upon a societal shift from a company-controlled town to an international tourist and research destination have changed the avalanche risk picture considerably. Rising temperatures, increased precipitation, and more intensive use of the terrain in and around the settlement have changed both patterns of avalanche hazard and human exposure. In this work, we describe how Longyearbyen's dynamic socioenvironmental setting together with a relatively high concentration of avalanche-specific research have influenced the development and implementation of avalanche risk mitigation strategies in Longyearbyen's High Arctic location. We detail the overlapping history of avalanche accidents, avalanche research, and risk management in Longyearbyen, with emphasis on the rapid risk management strategy transformation since a destructive avalanche struck the settlement in 2015. Risk mitigation strategies implemented in recent years included a wide range of organizational (avalanche forecasting, evacuation schemes) and structural measures (defense structures, catching dams). The diversity of applied measures and actors involved in their implementation makes Longyearbyen a relevant example of avalanche risk management challenges in areas undergoing rapid climatic change.

KEYWORDS: Climate change, risk management, Arctic, avalanche history

1. INTRODUCTION

Strategies to manage snow avalanche risk can evolve as socioenvironmental conditions change, new technology becomes available, and in response to influential avalanche accidents. In Longyearbyen, Svalbard, avalanche risk management approaches have undergone considerable transformation in the aftermath of an avalanche which struck the settlement in December 2015. Implementation of the current risk management concept in Longyearbyen builds upon multiple decades of snow and avalanche research, consulting work, and accumulated local knowledge in the High Arctic. However, with Svalbard's distinction as one of the planet's fastest warming locations (Isaksen et al., 2022; Rantanen et al., 2022), recent climatic changes have posed challenges to risk management strategy development in Longyearbyen. Longyearbyen's social context as a former mining town now based primarily on tourism and research has added additional complexity to risk management decisions.

Risk management strategies applied in Longyearbyen since the 2015 event have encompassed a wide range of the available avalanche mitigation measures and include both organizational and structural approaches. Collaboration between a host of local, national, and international actors has helped to develop a site-specific avalanche forecasting service utilizing a network of local avalanche observers and complete construction of structural defenses worth nearly 30 million Euros. Nevertheless, climate projections indicating a warmer, wetter future for Svalbard combined with social factors including high turnover amongst key personnel will continue to challenge avalanche risk management in Longyearbyen.

This work in many ways serves as a follow-up to the 2016 ISSW session concerning the 2015 avalanche (Hestnes et al., 2016; Indreiten and Svarstad, 2016; Issler et al., 2016; Jaedicke et al., 2016). We begin by briefly summarizing the history of applied and scientific avalanche work in and around Longyearbyen before detailing how risk management strategies have developed following the December 2015 and subsequent February 2017 destructive avalanche events. We conclude with some reflections and lessons learned from our experiences with avalanche risk management in a rapidly changing socioenvironmental setting.

2. HISTORICAL CONTEXT

Longyearbyen's proximity to the Longyear Valley's (Longyeardalen) coal-rich, steep mountain

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Figure 1: Photo, looking south over Longyearbyen, showing avalanche-prone locations in Longyeardalen, with the inset map displaying Longyearbyen's location in Svalbard.

slopes (Figure 1) has exposed the town to avalanche hazards since its settlement in 1906. Maximizing economic profit from the mines while minimizing infrastructure costs guided early development, with little consideration given to exposure to natural hazards or environmental and social concerns. Managed as a mining company town throughout most of the 20th century, relatively little documentation of avalanche events or risk management exist for much of the town's history. A slushflow from the Vannledningsdalen valley which destroyed the town hospital and resulted in three fatalities in 1953 serves as a noteworthy exception (NGI, 2012). In response to this event, company authorities decided to construct deflection dams, to our knowledge the first structural mitigation measures installed in Longyearbyen, along the lower reaches of the valley. As a direct mitigation measure, a bulldozer began clearing the snow in the late spring to inhibit slushflow formation during the snowmelt season. Additionally, informal historical accounts, together with photographs (Figure 2) indicate avalanche blasting occasionally occurred. Hestnes (2000) provides more detailed accounts of early avalanche work in Longyearbyen

Figure 2: Avalanche control via blasting in Longyeardalen, 1959. Photo by Erling Johan Nødtvedt courtesy of the Svalbard museum.

The community began to open to the outside world in the late 1980s following increased interest from the Norwegian state to establish a more open community in Svalbard. In 2002, Longyearbyen's Local Council (Lokalstyre in Norwegian) took over responsibility for governance of Longyearbyen as an elected governmental entity. Today, the Longyearbyen Local Council has responsibility for the area within Longyearbyen's city limits, while the Governor of Svalbard has overall responsibility for the management of Svalbard. Longyearbyen's demographics reflect the stipulations of the Svalbard Treaty, which while recognizing Norwegian sovereignty in Svalbard also allows citizens of all 48 signatory nations to live and work in Svalbard without a visa. Over 30% of Longyearbyen's 2500 inhabitants are non-Norwegian as of 2024 (Statistics Norway, 2024).

Longyearbyen's developmental arc from a company town to open, international community governed as a Norwegian territory has influenced avalanche risk management considerably in the last 40 years. First, risk acceptance decreased as the populations of families, residents working in industries other than mining, students, and tourists increased. Secondly, formalized snow and avalanche investigations began in the 1980s as the portion of the mining company responsible for community development contracted the Norwegian Geotechnical Institute (NGI) for support with avalanche risk assessments. NGI's contract work in Svalbard continued throughout the 1990s via avalanche hazard mapping projects, the establishment of a local avalanche monitoring framework, and recommendations for the design of structural mitigation measures. (Hestnes, 2000) and (Hestnes et al., 2016) provide English-language summaries of NGI's work during this period.

The University Centre in Svalbard (UNIS) was established in Longyearbyen in 1993 and grew throughout the 1990s as an Arctic center for education and research. Snow research at UNIS gained momentum in the late 1990s building upon historical snow research in Svalbard (Winther et al., 2003) via investigations of blowing and drifting snow near Longyearbyen and snow distribution in the region around Longyearbyen (Jaedicke, 2001, 2003; Thiis, 2000). Later work at UNIS focused explicitly on snow avalanche processes charactering the region's snow climate as High-Arctic maritime (Eckerstorfer and Christiansen, 2011a), investigated the prevalence and dynamics of cornice-fall avalanches (Eckerstorfer and Christiansen, 2011b; Vogel et al., 2012), and documented extensive slushflow and wet-slab avalanche activity (Eckerstorfer and Christiansen, 2010).

Concurrently, fatal avalanche accidents involving recreational snowmobilers near Longyearbyen in 2001, 2004, 2009, and again in January 2015 (e.g. NGI, 2024) heightened the societal awareness of avalanches in the region, and the Longyearbyen Red Cross developed a local avalanche rescue group to respond to accidents in the vicinity of Longyearbyen.

Hence, prior to 2015, avalanche work in Longyearbyen was characterized by scientific research and consulting reports with knowledge and recommendations which were not systematically operationalized into robust risk management strategies or by the development of a local search and rescue service and appropriate rescue strategies for Longyearbyen's setting.

3. CLIMATIC CHANGES

In addition to a dynamic social setting, dramatic climatic changes have characterized Longyearbyen's history – especially in recent years. Svalbard's climatically-sensitive location at the northernmost reaches of the Gulf Stream results in the warmest and wettest climate in High Arctic (Serreze and Barry, 2014). Annual air temperatures have increased as much as 5°C in the last half-century, with the most dramatic warming occurring during the winter months (Hanssen-Bauer et al., 2019; Nordli et al., 2020). This warming has corresponded with increasing extreme precipitation event frequency in recent decades (Lapointe et al., 2024; Serreze et al., 2015). More frequent winter heatwaves and rain-on-snow events (e.g. Salzano et al., 2023; Wickström et al., 2020) combined with shorter snow seasons (López-Moreno et al., 2016) are altering the region's snow avalanche regime with, for example, potentially more frequent mid-winter slushflow activity. Furthermore, a thickening active layer in the region's permafrost environment (e.g. Strand et al., 2021) combined with heavy rainfalls have resulted in noteworthy debris flow events in recent years (Christiansen et al., 2016).

4. CURRENT MITIGATION STRATEGY DEVELOPMENT

The fatal December 2015 avalanche which struck Longyearbyen occurred in a setting with a relatively high concentration of avalanche-specific research. Numerous reports had documented avalanche hazard in addition to suggesting potential mitigation strategies (e.g. Hestnes et al., 2016), and local competence had developed a strong avalanche search and rescue culture in Longyearbyen. However, adequate risk management routines had not been applied, and the resulting avalanche served as a watershed event after which rapid risk management strategy implementation began.

Here, we describe how risk management in Longyearbyen evolved in the aftermath of this event, challenged by the release of another destructive avalanche from the same slope in 2017 (NVE, 2017; Hancock et al., 2018) and by the effects of ongoing climatic changes on both the physical hazard processes and the organizational learning required to better address the risk to the community (Sydnes et al., 2021). We have structured our description based on the avalanche risk management framework (Figure 3) developed by Wilhelm et al. (2000), with the terminology adjusted after (Canadian Avalanche Association, 2016) and (Bründl and Margreth, 2021). Albrechtsen et al. (2024) provide an additional overview of implemented avalanche risk mitigation measures in Longyearbyen.

4.1 Indirect measures

Hazard mapping and land use planning, as indirect, long-term measures, typically form the basis for comprehensive avalanche risk management by defining the areas most susceptible to avalanche hazard and helping prioritize locations requiring risk reduction measures (Rudolf-Miklau et al., 2015). NVE and the Longyearbyen Lokalstyre contracted a new hazard mapping project in 2016 (Multiconsult AS, 2016) which was in turn revised for the avalanche paths on the western aspect of Sukkertoppen following the February 2017 avalanche (NVE, 2018b). These mapping works, combined with feasibility studies (Larsen, 2016; NVE, 2018a), helped lay the groundwork for the implementation of structural mitigation measures described in the following section.

Operational daily avalanche forecasting in Longyearbyen and Svalbard did not exist prior to December 2015. Plans were, however, underway to extend NVE's regional avalanche forecasting service to Svalbard, and NVE had already conducted a limited, 17-day test period near Longyearbyen in the spring of 2015 (Engeset et al., 2020). In the immediate aftermath of the 2015 avalanche, NGI

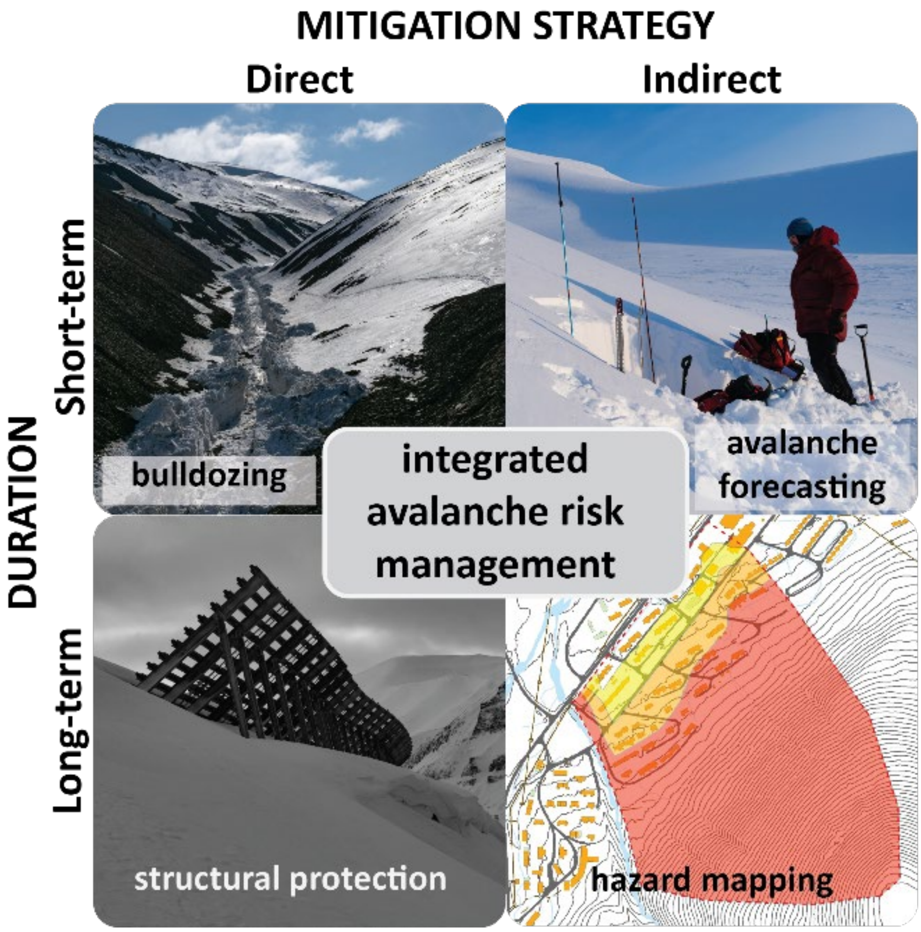

Figure 3: Example of mitigations strategies employed in Longyearbyen, after Wilhelm et al. (2000)'s risk management matrix. Hazard map from NVE (2018b).

established site-specific avalanche forecasting on contract from NVE (Brattlien et al., 2016; Jaedicke et al., 2016) as an indirect, short-term mitigation measure in the critical recovery phase.

This service persisted until the end of January 2016, when NVE's regional public avalanche forecasting service, varsom.no, expanded to include the region around Longyearbyen and public forecasters at NVE took over responsibility of assessing the need for, and if necessary conducting, site-specific warnings for infrastructure in Longyearbyen (Engeset et al., 2020). A group of local snow observers, trained by NVE and with considerable local knowledge of Longyearbyen's snow and avalanche setting, was set up to provide regular snow and weather observations to the NVE forecasters located on the Norwegian mainland.

The February 2017 avalanche challenged this system, again striking buildings under Sukkertoppen. On the day of the avalanche, the regional forecast included a High danger rating, but a site-specific forecast concluded with a low avalanche impact probability for infrastructure in Longyearbyen and no evacuations were ordered (NVE, 2017). Luckily, no injuries occurred despite the decision not to evacuate residents. A follow-up report in the wake of the incident helped clarify a path forward for site-specific forecasting in the area (NVE, 2017). Suggested improvements included better handling of uncertainty in the forecasting and risk communication process, the installation of additional snow and weather monitoring stations in locations relevant for forecasting, and more explicitly taking the impact of climate changes into account during the risk assessment.

As a first step in addressing these suggestions, three snow monitoring stations were installed in avalanche release areas situated in Longyeardalen the next fall (Prokop et al., 2018). These stations were, over the following seasons, substituted out for locally designed low-cost, low-power ultrasonic sensors (Hancock et al., 2023). As of the 2023/2024 winter season, six locally managed snow height monitoring stations supported site-specific avalanche forecasting in Longyearbyen.

NVE continued with the responsibility of site-specific avalanche forecasting until February 2019, when the forecasting model changed such that a private company, on contract from NVE, took over the forecasting role. UNIS, under contract from

Longyearbyen Lokalstyre, had organized the snow observer group beginning in 2018, and continued to do so. Skred AS took over the forecasting role in February 2019 and continued in this capacity through the 2021/2022 winter season after which NGI won a new two-year tender.

While the general forecasting model described by Øien et al. (2022) in which a contractor wrote site-specific forecasts supported by observations from the local snow observer group persisted from 2019 through the 2023/2024 season, continued research and iterative changes over the years helped to develop the system. The observer group expanded and continued gaining training and experience. Communication between observers in Longyearbyen and forecasters on the mainland improved as information-exchange routines formalized and as developing personal relationships lowered the threshold for informal communication (e.g. via phone calls between the forecaster and observer on duty). The snow sensor system became increasingly reliable, and both observers and forecasters became better accustomed to employing the data in hazard and risk assessments. The establishment of the Arctic Safety Centre at UNIS in 2020 and a corresponding increased focus on safety science contributed considerable research to the forecasting program, particularly with regards to the handling of uncertainty (Indreiten, 2020; Øien et al., 2023).

4.2 Direct measures

The primary short-term, direct mitigation measure employed in Longyearbyen – given that Norwegian regulations do not permit explosive control above inhabited infrastructure – involves the bulldozing of Vannledningsdalen prior to the spring melt to reduce slushflow hazard. This measure has been implemented annually since the 1953 slushflow, with 1989 serving as a notable exceptions Dozing of the valley was skipped this year, and a large slushflow released and damaged structures in Longyeardalen (Hestnes, 2000). Bulldozing in the spring has continued through winter 2023/2024, but rain-on-snow events have resulted in mid-winter slushflows reaching infrastructure in January 2012 (NGI, 2012) and, most recently March 2022.

As Svalbard's climate does not currently support forests which can serve as silvicultural protection, long-term, direct risk mitigation strategies have involved the construction of structural mitigation measures. Design of structural mitigation measures in Longyearbyen since 2015 has sought to address two primary avalanche problems: dry slab avalanches from Sukkertoppen and slushflows from Vannledningsdalen. The resulting structural protections have dramatically altered Longyearbyen's landscape (Figure 4), with an associated cost approaching 30 million euros.

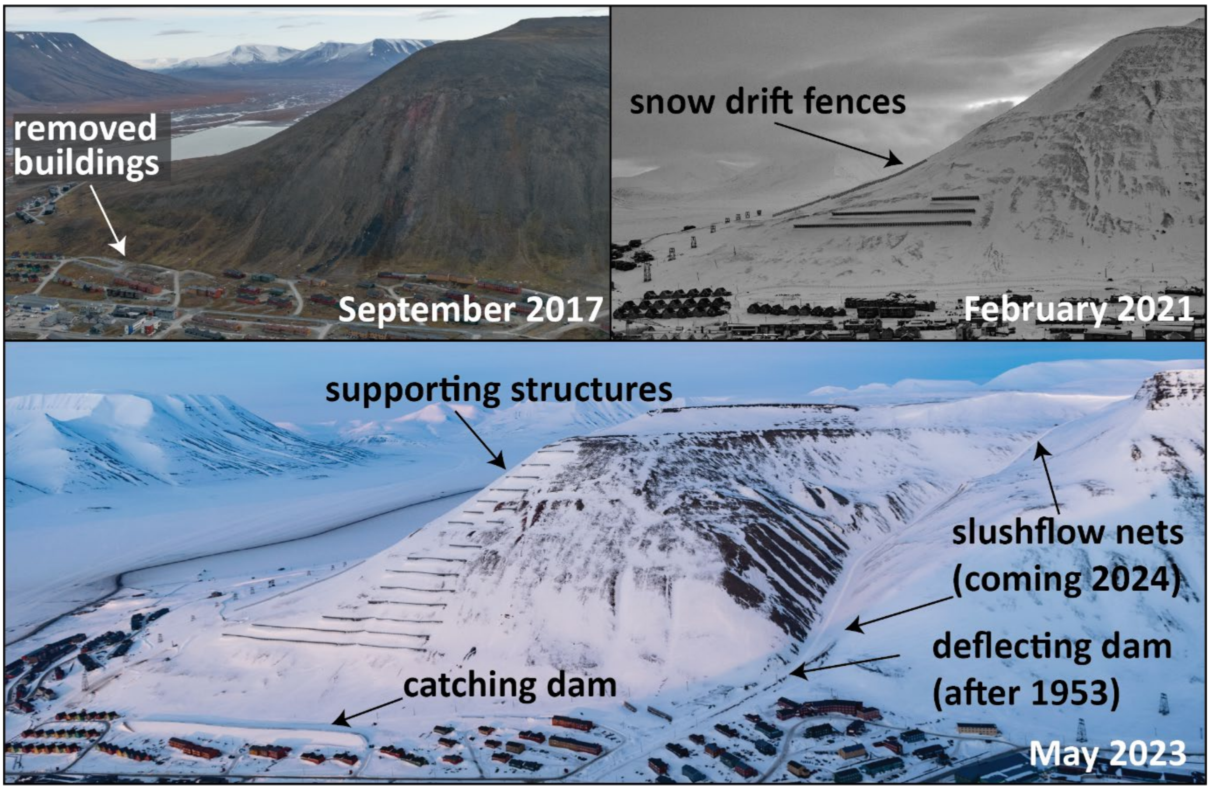

Figure 4: Changes to Sukkertoppen, September 2017 through May 2023. The buildings damaged in the 2015 and 2017 avalanches have been cleared in the first panel, and additional buildings have been removed to south (to the right of the catching dam) in the May 2023 panel.

Here, we summarize these measures and provide references to more detailed design and construction reports.

Structural protections installed on Sukkertoppen include snow drift fences upwind of the release area of the December 2015 avalanche, over 1500 m of supporting structures on the mountain's western aspect, and a 400 m long, ca. 6 m high catching dam at the foot of the slope (Figure 4). Design and construction of these measures has occurred in two phases. First, the northernmost three rows of supporting structures and the snow fences were installed prior to the 2018/2019 winter season. These structures sought to limit snow accumulation in the release area via the snow fences and hinder avalanche release with the supporting structures (Jonsson et al., 2018). A drainage canal on Sukkertoppen's northern slope helps divert ground and surface water from the solifluction-prone slope below the snow fences. Phase two, completed prior to winter 2022/2023, involved installing an additional 14 rows of supporting structures on Sukkertoppen's western aspect in addition to the catching dam at the base of the slope (Jónsson et al., 2019; Skred AS / HNIT Consulting, 2018).

Numerous reports have suggested potential structural protection measures for Vannledningsdalen dating back to the early 1990s (e.g. NGI, 2012). The existing management solution consisting of a deflection dam supplemented with bulldozing prior to the spring melt involved considerable residual risk, especially as mid-winter slushflow releases become more common. Planning for more comprehensive structural mitigtion measures in Vannledningsdalen began in 2018, with the selected design consisting of 14 nets placed perpendicular to the valley's axis at regular intervals. These nets, similar those used in debris flow mitigation but modified for slushflow processes, will seek to both reduce the possibility of slushflow release and help arrest any slushflows which do release (Skred AS / HNIT Consulting, 2021). The first net was placed in late 2023, and the rest will be completed in 2024

5. REFELECTIONS AND OUTLOOK

Since the 2015 avalanche, the development of a site-specific forecasting system and the construction of extensive structural protections have transformed avalanche risk management in Longyearbyen. Given Longyearbyen's distinction as one of the fastest warming locations on Earth, this provides a timely opportunity to reflect on climate change's effect on an integrated risk management approach.

Our experiences highlight the importance of flexible risk management strategies given the uncertainties characterizing avalanche risk in a changing climate. While structural protection offers reliable mitigation against expected, "design" events, shorter-term, indirect measures such as a robust forecasting program offer flexibility to adapt to unexpected or changing conditions. Effectively managing avalanche risk in a rapidly changing climate therefore involves an integrated risk management approach, where short-term mitigation strategies can help address shifting conditions over the design lifetime of structural protections.

In Longyearbyen, both long- and short-term strategies have attempted to address climate change related uncertainties. Jónsson et al. (2018) and (Jónsson et al., 2019) detail how projections of thawing permafrost and increasing debris flow frequency influenced structural protection design. A future transition from snow avalanches to slush and debris flows as described in Hanssen-Bauer et al. (2019) was, for example, a specific consideration in design of the catching dam at the base of Sukkertoppen (Skred AS / HNIT Consulting, 2018). The site-specific forecasting program complemented the structural protection strategy by adjusting to a changing risk picture each season as new structural protections were completed, buildings were removed, and slushflow and wet-snow avalanche problems became more prevalent. Here, the possibility to adapt observation and forecasting routines, instrumentation, and a collective understanding of the risk picture each season relied on a robust, flexible system and effective communication between local authorities, the observer group, and the forecasters on the mainland. This combination of structural and organizational measures provides redundancy via the defense-in-depth principle and increases the robustness of the overall risk management strategy (Albrechtsen et al., 2024).

Local knowledge and involvement played key roles in successful risk management strategy implementation in Longyearbyen. Increased collaboration between researchers, practitioners, and the local authorities via channels such as the Arctic Safety Centre has helped strengthen competence among all involved actors. This has included helping the end-user (in this case the local authorities responsible for evacuations or deciding upon structural protections) develop sufficient knowledge to make informed decisions, but also helping those responsible for the risk assessments (observers, forecasters, and engineers responsible for structural protection designs) to better communicate the results of – and uncertainty inherent to – their assessments. Improving communication and developing a common baseline understanding of the avalanche risk can promote more effective treatment of an uncertain future.

Longyearbyen's future is not without challenges. The complex socio-political setting with numerous responsible actors and high rates of turnover can impede cohesive strategy implementation over longer time periods. Continued work to improve communication between all involved actors and solidify existing routines is therefore necessary to ensure effective risk management persists in the future. Portions of town remain unprotected by structural measures, and the effects of the recently established structures remain uncertain. Intense climatic changes with new and unprecedented risk scenarios will therefore likely require ad hoc responses. Although daily avalanche forecasts may no longer be necessary, the local knowledge (Johannessen and Haavik, 2024) and instrumentation developed in Longyearbyen's forecasting program can provide a foundation for future short-term, indirect mitigation strategies to complement the structural measures.

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