EXPERIENCES ON EFFECTIVE APPLICATIONS OF SITE-SPECIFIC AVALANCHE WARNING IN AVALANCHE RISK MANAGEMENT

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ABSTRACT: Avalanche warning as a mitigation measure was introduced in Norway when the Norwegian Geotechnical Institute's (NGI) avalanche research station at Fonnbu was established in 1974. Methods, tools and products of the NGI's warning service have undergone continuous development in the ensuing years, exploring new methods, incorporating international research, and, in later years, European Avalanche Warning Services standards and guidelines. Some of the main milestones included the introduction of automated weather stations into the forecasting workflow in the early 1980s, the transition to the European Avalanche Danger Scale in 1993, and the implementation of a fully web-based service in 2006. In 2013, a shift from both regional and site-specific to solely site-specific projects resulted in a transition from communicating a danger level to avalanche impact probability as the primary hazard information in the forecasts. These developments later formed the framework for the site-specific avalanche warning guidelines implemented by the European Avalanche Warning Services in 2022. For NGI's forecasting projects, naturally released avalanches that threaten the exposed assets have always been the focus. During these years, risk objects in the forecasting projects have included construction sites, energy infrastructure, military exercises, settlements and roads. Forecasting project durations ranged from days, weeks or several seasons, to projects that operated over ten years in the same area. For the last 20 years, NGI has operated a fully digital workflow, with standardized routines and standard products for the customers. Two avalanche forecasters are on duty every morning, issuing site-specific assessments by e-mail and SMS to predefined risk owner recipient lists. Today, our database contains over 16 000 forecasts issued for over 60 different warning areas. Accidents, mishaps, and close calls have occurred, given the long time horizons of our forecasting programs. Train derailments, impacts on open roads and partly destroyed houses that were not evacuated, are all part of the experience. Looking back at these events and other close calls raises the question of how such events can be avoided in the future. The discussion shows that in most cases, the lack of risk communication, misunderstanding one's role in risk management, and the lack of well-defined action plans are the main reasons for accidents, while accidents due to incorrect assessments of avalanche impact probability are limited.

KEYWORDS: avalanche warning, risk management, risk communication

1. INTRODUCTION

Avalanches in the context of involuntary risk for infrastructure, settlements and work sites can be mitigated with a range of mitigation measures, often addressed as active / passive and permanent / temporary mitigation (McClung and Schaerer, 2022). Avalanche warning is defined as a temporary / passive mitigation, meaning that mitigation is effective only during operation of the warning service and that mitigation does not interfere with the natural environment. Commonly, avalanche warning is provided as a public regional warning service, covering large areas and concluding in a 1-5 danger level (Müller et al., 2025). For many specific risk management contexts, regional hazard information lacks the spatial precision required for risk assessments for individual objects at risk, such as specific houses, road sections or construction sites. Avalanche warnings for defined, individual risk objects are often addressed by specifying a finer spatial scale and/or risk object in the context of "applied" (McClung and Schaerer, 2022) or "operational" (Statham et al., 2017) avalanche warnings, or, in Europe, as "site-specific" avalanche warning services (EAWS, The European Avalanche Warning Services, 2022; Jaedicke et al., 2023). Guidelines and recommendations for such warning services are given for Canada (Campbell et al., 2016), Tyrol (Riedl and Land Tirol, 2021), Switzerland (Stoffel and Schweizer, 2007), France (Vengeon et al., 2021; Vengeon and Bolognesi, 2021), Europe (EAWS, The European Avalanche Warning Services, 2022) and Norway (NVE, 2026).

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Site-specific avalanche warning is based on a hazard assessment of the probability of an avalanche in defined avalanche paths to reach an object at risk. A predefined set of risk reduction measures corresponding to the given hazard level is then implemented (Jaedicke et al., 2023; Statham et al., 2017).

A workflow for site-specific warning systems is shown in Figure 1, where the black arrows show lines of dataflow and communication.

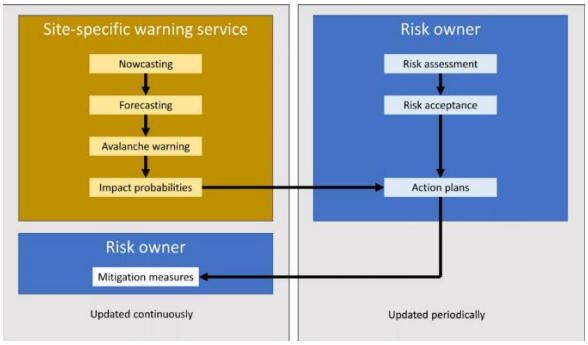


Figure 1: Workflow and responsibilities as suggested by the European Avalanche Warning Services (EAWS, The European Avalanche Warning Services, 2022)

Well-organized warning services address all responsibilities illustrated in Figure 1 to ensure a robust, functioning warning service. However, in most cases, the risk owner and the warning service are two independent entities. While the warning service is contracted to deliver a consistent service to the risk owner, the risk owner is normally not bound to follow any of the recommendations or its own action or mitigation plans. Challenges related to communication between the involved actors, unclarity regarding roles and responsibilities, and the inherent challenges of avalanche forecasting can result in disruption or failure of the illustrated workflow. These disruptions have differing effects on the efficacy of the risk reduction measure. This paper gives a historical context to risk management approaches in Norway and discusses where failures can occur and where the consequences are most severe.

2. NGI AVALANCHE WARNING

The avalanche warning service provided by the Norwegian Geotechnical Institute, NGI, started long before the introduction of standards and guidelines as a byproduct of standard weather observations at the NGI research station Fonnbu (Lied, 1974). Most of the observations were used for research on weather and avalanche activity, rather than providing a public warning service (Bakkehøi, 1987; Fitzharris and Bakkehøi, 1986). Until 2014, the Norwegian Meteorological Institute was responsible for avalanche warning, but only for natural avalanches at danger levels four and five (Meteorologisk Institutt, 2006). The warning was strictly connected to weather criteria, using very limited or no information on the state of the snowpack. In addition to the public met.no service, NGI provided detailed warnings for infrastructure, settlements, construction sites and special operations, such as large military exercises (Kronholm and Ellevold, 2012). In 2013, Varsom.no, a cooperation of the Norwegian Water and Energy directorate (NVE), the National Public Roads Administration (NPRA) and the Norwegian Meteorological Institute (met.no), began issuing the regional avalanche forecasts for Norway (Engeset et al., 2018). With the onset of the public regional warning service, the general data access and understanding of the avalanche situation improved significantly. For risk management for defined objects, like roads, railways, settlements and temporary activities such as construction sites, site-specific avalanche warnings remained necessary (Hancock et al., 2024; Jaedicke et al., 2025; Ratto et al., 2024).

Avalanche warning at NGI was initially organized in individual projects and documentation of the early projects is scarce. Already in the first years of the avalanche group at NGI, several recommendations and thresholds for avalanche warnings were delivered for roads, construction sites and settlements. However, the actual operation of the recommended routines and schemes was entirely left on site to the client. It is generally unknown if the plans were implemented. Operational avalanche warning provided by NGI avalanche forecasters started in 1981 with the national road 15, close to the NGI research station. The warning service was later extended to hydro power construction sites and selected settlements (Norges geotekniske institutt NGI, 1987, 1984).

2.1 *Risk management strategies*

The risk management strategies in the NGI avalanche warning projects developed from setting simple thresholds for improved safety to fully implemented risk management programs. In the earliest projects, hazards were generally identified by avalanches hitting existing objects, like constructions sites and road stretches. On public roads, even frequent avalanches were tolerated if no one was directly hit. After an accident or close call, ad hoc support, assessments and warning schemes were asked for, often without time for the required background assessments of the site. In such cases, NGI would provide a set of weather and snow thresholds that could lead

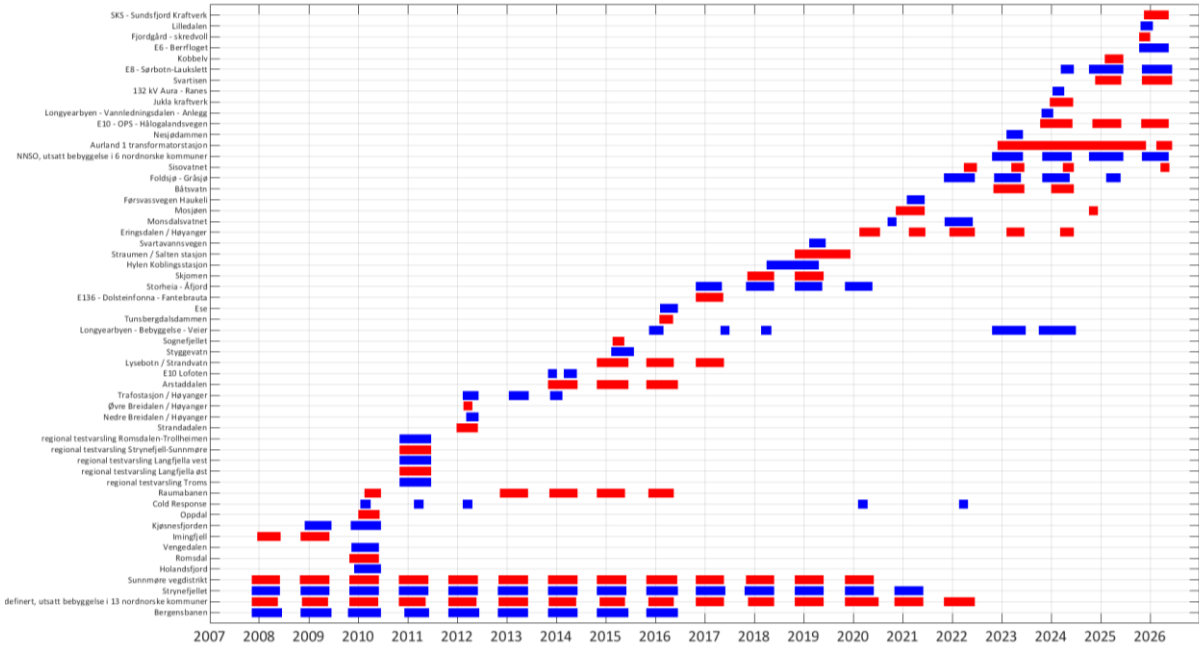


Figure 2: Duration of the avalanche warning project locations since 2006

to critical situations and avalanches against the objects, usually accompanied by some basic suggestions for mitigative actions. Operations were local and it was never verified if these criteria and actions actually were implemented.

Later, avalanche warnings were issued on a more regular basis, often on demand. A further development were agreements where avalanche warnings were to be sent by fax on NGIs own initiative, whenever danger level 4 or 5 were imminent. In these cases, the recipients of those faxes had very limited documentation and verified tools for implementation of the warnings. With many non-documented close calls, some basic routines emerged, such as "road open for convoy" at danger level 3 and "road closed for public, maintenance allowed" at danger level 4 and "road closed for all traffic" at danger level 5. Often such criteria were only known by managers, not documented and not communicated to the working staff.

Proper risk management spanning hazard assessment, risk analysis, and the implementation of mitigation strategies and operational actions emerged from the explicit risk frameworks for infrastructure and construction sites (International Organization for Standardization, 2018; Standard Norge, 2006). By applying these principles, avalanche warning becomes an imbedded aspect of a larger avalanche risk mitigation framework for a given location. The development of the different approaches is listed in Table 1.

Table 1: Overview of approaches in avalanche risk management in NGI avalanche warning (DL = regional danger level, IP = site specific impact probability).

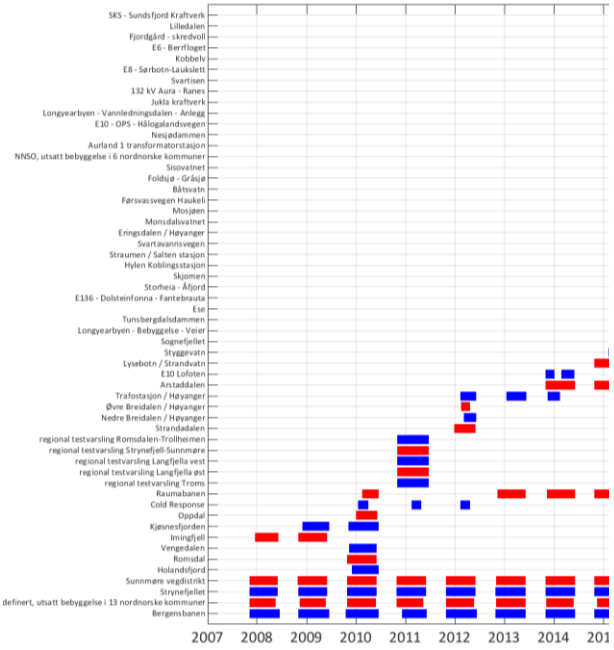
Period	*Warning issued*	*Action taken*
1974-1981	Local general	unknown
1981-1993	DL on a scale of 1-7	Road closures
From 1994	DL on a scale of 1-5	Road closures
Until 2002	Only at DL 4+5	No defined actions
From 2002	On demand, only at DL4 and DL5	Road closures, evacuations
From 2008	Daily, all five DLs	Closures, speed reduction, evacuations
From 2011	Daily, all five DLs	Start of risk analysis
From 2013	IP and DL	Actions based on risk analysis
From 2021	Only IP	Actions based on risk analysis and communicated daily.

2.2 *Warnings and warning areas*

Since 2006, all NGI avalanche warning has been centralized under a single internal manager and the warning service has been fully digital from the 2007/2008 season (Jaedicke et al., 2014).

The digital service has collected all issued warnings in a common database, which now includes over 16 000 warnings following the 2025/2026 season. In total, 60 different forecasting areas have been covered in the last 20 years, with project durations ranging from a couple of days to

over ten years (Figure 2



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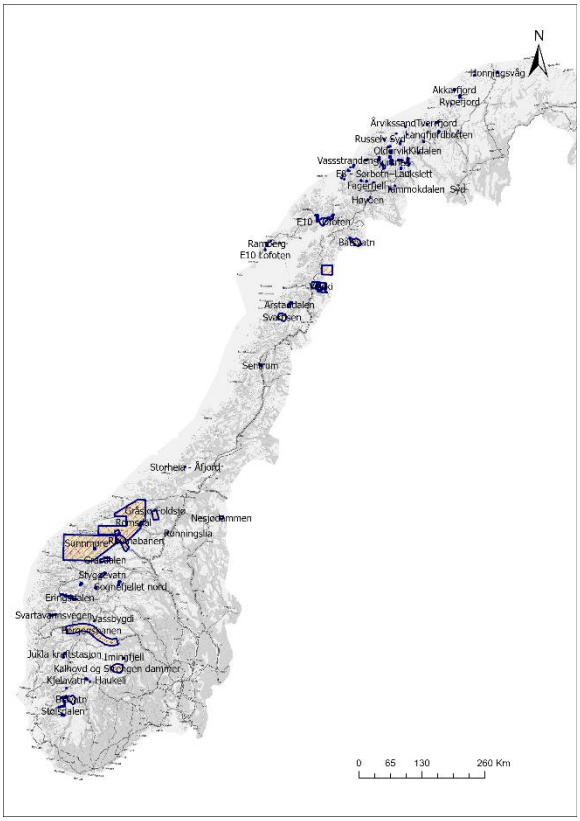


Figure 3: Map of mainland Norway, showing all warning projects from the last 20 years. In addition, there have been several projects on Svalbard.

Projects have covered locations throughout Norway and Svalbard (Figure 3). The internal organization and digitalized workflow allows for the inclusion of new project locations on short notice using a universal and standardized work and data flow (Jaedicke et al., 2014).

Data access and methods have changed significantly during these 20 years, but there is consistency in the most relevant data such as observed (stations) and forecasted weather (from met.no) as well as the assessments of weather, weather forecasts and avalanche danger. Other data series are added later (mainly from 2016 onwards) like self-evaluation and impact probability. In addition, outlines of relevant avalanches in the warning areas are recorded in recent years to improve the data for the avalanche warning.

3. RESULTS

3.1 Avalanche warnings and warning areas

The database of all issued warnings provides valuable insight into the assessments and success rate of the warnings. In general, the distribution of the regional danger level (as used in our site-specific forecasts until 2021) follows international trends, with danger level 2 as the most common, followed by danger level 3 and 1. Danger level four is seldom used and five was only applied in the extreme winter of 2008 at the national road 15 and the Bergen Railway. In contrast, the occurrence of the three levels of impact probability (low, middle, high) follows an extreme value distribution with most days at the lowest level. Unfortunately, event-based validation remains challenged by our reliance, in most projects, on risk owners to reliably report relevant avalanches. In 2016, a daily self-evaluation was introduced. The avalanche forecaster on duty is asked to evaluate if the previously assessed impact probability was too low, too high or just right and give a categorized reason for the deviation, such as too low temperature forecast or missing observations. Of the 6651 warnings with self-evaluation, the impact assessment from the previous day was evaluated to be correct in 6458 cases (97.1%), as too low (false negatives) 47 times (0.7%) and in 146 cases (2.2%) as too high (false positives). The most common reason for these deviations is in both cases (too low, too high) errors in the precipitation prognosis for the warning area. "Missing avalanche observations" contributed only to overestimated impact probability. Other causes, like wrong weather observation or misleading snow observations have not been assessed as being the cause for too low probability (Figure 3).

Time series analysis of the data is limited, since most warning areas only operate for a short period of time, and instrumentation, data access and methods change over time. One consistent question to register is whether the weather station for the warning area is active and delivers data. In only 240 of 16 000 warnings, the weather station was not operational. A simple correlation

between impact probability and precipitation observed or forecasted could be established.

3.2 Examples

In the following three examples of avalanche events we exemplify where the risk management system failed or succeeded. Examples are taken from NGI projects or other relevant events with interesting circumstances.

2007-02-22 Storkleven Bergen Railway

The passenger train from Bergen to Oslo drove into avalanche deposits from a recently released dry slab avalanche west of the Myrdal railway station. A work train had passed the section about two hours before and might have released the avalanche by its vibrations (Norges geotekniske institutt NGI, 2007). Impacting the avalanche debris, the passenger train derailed and partly slid down the embankment (Figure 4). The train consisted of two train sets; the second was not in use and remained on the tracks. There were no major injuries in the accident and since the train derailed between two power masts, electricity was not cut off.



Figure 4: The derailed train on the Bergen railway, 2007-02-22 (Photo NGI)

The passengers were evacuated into the second, empty trainset and heating could be maintained. The danger level provided by NGI that day was danger level 3 and natural avalanches could be expected to occur (danger level 2 the previous day). In their routines, The Norwegian Railway Administration did not implement any restrictions other than a general winter speed reduction at danger level 3. Therefore, NGI was not to send out any warnings at danger level 1-3. The railway administration was familiar with danger level 3 being a rather common situation and concluded that restrictions at danger level 3 would impact the regularity of the trains on too many days.

Therefore, restrictions were first implemented at danger level 4 and danger level 5. Lower danger levels were not communicated from the warning service to the railroad (Statens Havarikommisjon for Transport, 2008). Here, the basic risk analysis failed to acknowledge the hazard from natural avalanches already at danger level 3 for the railroad. After the accident, routines were changed such that daily warnings were issued at all danger levels.

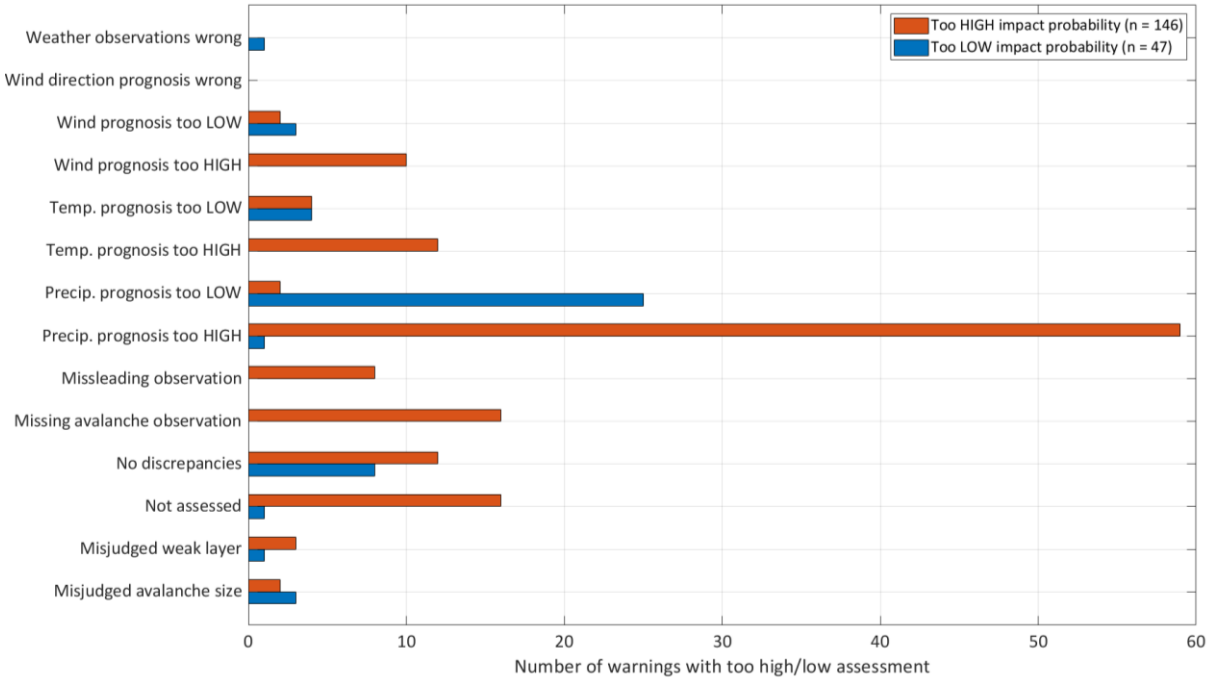


Figure 3: Distribution of reasons for deviation from the correct impact probability.

2023-03-30 Reinøya

A farm was destroyed by a major dry snow avalanche following a period of heavy snowfall and

elevated regional avalanche hazard in March 2023. Two fatalities and over 160 livestock perished (Figure 5). Avalanche susceptibility mapping of the area was conducted in 1997, but the maps were not actively used in the municipality risk analysis. Therefore, the area was never included in the Northern Norway Avalanche Surveillance network (Jaedicke et al., 2024). Karlsøy municipality, which Reinøya is a part of, left the network in 2020 after the physical mitigation of their only surveillance area, Vannvåg, was completed. Therefore, although site-specific avalanche warnings were issued for adjacent municipalities that day, avalanche assessments for exposed buildings on Reinøya – or Karlsøy municipality as a whole – were absent when the avalanche occurred. In this case, the hazard was mapped and documented, but the municipality was not actively using the susceptibility maps and was not aware of the exposed houses when they opted out from the surveillance program.



Figure 5: The avalanche path at Reinøya where an entire farm was swept to the ocean (Photo NVE, regobs.no).

Therefore, the authorities were oblivious to the risk at this location and site-specific avalanche warning was not covering the area (County Governor of Troms and Finnmark, 2023; NVE, 2023).

2025-03-30 Svartisen

The intake for the Svartisen power plant (Figure 6) is highly exposed to avalanches. The remote location and lack of road access require the use of helicopter transport during winter maintenance. During landing, loading and takeoff, the helicopter is exposed to avalanche hazard on top of the construction. A complete chain of risk management and communication routines ensured that: i) additional accommodation containers were not installed on the outside of the building and



Figure 6: The intake building at Svartisen is located under a 100 m high avalanche slope. The helipad is on top of the construction (Photo NGI).

ii) helicopter traffic was strictly regulated to follow the daily site-specific avalanche warning.

A large, natural avalanche occurred in March 2025, running over the intake building. Forecasted impact probability for the day was high, however, adherence to the predefined routines and action cards ensured that the avalanche did no harm. The project lasted two years and concluded without any avalanche related recordable incidents.

4. DISCUSSION

A rough analysis of the self-evaluation in over 6000 avalanche warnings shows that situations where the impact probability was assessed as too low is under 1%. Usually, misleading precipitation forecasts are the most commonly mentioned reason for deviations. Most of these involve over-forecast precipitation amounts which lead to overestimation of the impact probability. Missing or misleading snow or avalanche observations are only mentioned in a handful of cases to be the reason for the wrong impact probability. Failure of weather stations was only mentioned in 240 out of 16 000 warnings. This shows that one can in general assume that the assessments of the impact probabilities are sound and safe on most days.

The three examples show that the failures within the risk management chain at an exposed site is mostly caused by deficiencies in the hazard identification, risk understanding and implementation of proper routines in situations with elevated avalanche impact probability. Within the last 20 years of warning service, we could not identify a situation where a wrong assessment led to unexpected events and losses.

5. CONCLUSION

More robust, precise avalanche warnings are at high demand in a society where everything has to be fast on the one side and safe on the other. The results from this study show that improvements in avalanche warning should rather focus on the risk management side than on the technical side of the warnings themselves. New weather stations, more field observations and advanced modelling schemes can always add more data to the assessments. However, they will have limited effect if the hazard assessments are not properly applied in an integrated risk management strategy with clearly defined risk reducing actions, competent users, and dedicated managers. Avalanche forecasters need to expand their responsibility to see the larger risk management picture and participate actively in improving all aspects the risk management process.

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