UNCERTAINTY ASSESSMENT AND COMMUNICATION IN SITE-SPECIFIC AVALANCHE WARNING – A MODEL AND A CHECKLIST

Knut Øien[1]*, Eirik Albrechtsen[2], Kalle Kronholm[3], Hallvard Nordbrøden[3], Holt Hancock[4], and Martin Indreiten[4]

[1] *SINTEF Digital, Trondheim, Norway*
[2] *Norwegian University of Science and Technology, Trondheim, Norway*
[3] *Skred AS, Norway*
[4] *Arctic Safety Centre, University Centre in Svalbard, Longyearbyen, Norway*

ABSTRACT: A fatal avalanche disaster hit Longyearbyen, the world's northernmost settlement and the administrative center of Svalbard, Norway, in 2015. A site-specific avalanche warning system was introduced as a short-term risk mitigation measure immediately following this event. This system was in place when another avalanche hit the settlement in 2017, fortunately without fatalities. An investigation report following the second avalanche pointed to the need for better handling of uncertainty, e.g., by introducing an uncertainty checklist as part of the avalanche warning. This paper focuses on the development of such a checklist. The work stems from an evaluation of the site-specific avalanche warning system which was carried out in collaboration with relevant stakeholders. The stakeholders provided specific input regarding applicable ideas for handling uncertainty in the steps of a risk governance framework. This process allowed us to identify, structure, and model uncertainty factors arising from the various phases of the risk governance framework (framing, data collection, risk assessment, decision-making, and risk treatment) and avalanche forecasting workflows. Based on the resulting uncertainty model, we developed an uncertainty checklist for avalanche forecasters which we then tested in site-specific avalanche warnings at various locations in Norway during the 2022/2023 avalanche season. In our initial test periods, we found the checklist added value to avalanche risk assessments by increasing forecaster awareness of the different uncertainty factors included in the checklist. The communication of uncertainty to the risk owner, through the avalanche forecast, needs some further clarification and continued dialog with the risk owners.

KEYWORDS: Snow avalanche, avalanche forecasting, avalanche warning, risk, uncertainty.

1. INTRODUCTION

A fatal avalanche struck Longyearbyen, the world's northernmost settlement and the administrative center of Svalbard, Norway, in 2015. This led to the enactment of both short-term and long-term measures to better protect the settlement against avalanches.

A short-term measure was the introduction of a site-specific avalanche warning system, which was in place when another avalanche hit the settlement in 2017, fortunately without fatalities. An investigation report (Landrø et al., 2017) following the second avalanche pointed to the need for better handling of uncertainty, e.g., by introducing an uncertainty checklist as part of the avalanche warning. The report stated that *"the local forecast must communicate uncertainty in the assessments and basic data to a greater extent. A checklist should be introduced to highlight uncertainty."* This paper focuses on the development of such a checklist.

* *Corresponding author address:*
Knut Øien, SINTEF Digital, Norway;
tel: +47 930 58815
email: knut.oien@sintef.no

Uncertainty is an inherent part of any risk assessment, including avalanche forecasts (CAA, 2016). However, there are no standards for site-specific avalanche warning systems, as it is for regional avalanche warnings (e.g., Jaedicke et al., 2018; Engeset et al., 2020). Furthermore, guidelines for site-specific avalanche warning programs (e.g., Stoffel and Schweizer, 2008; EAWS, 2022) do not provide a commonly accepted method to explicitly address uncertainty. The recent European Avalanche Warning Services (EAWS) document on site-specific avalanche warning (EAWS, 2022) states that *"estimates about the release probability and avalanche runout probability for an individual path generally have a high uncertainty. This uncertainty needs to be considered when decisions on temporary measures are taken."* Further, it is stated that the site-specific warning *"should include an estimate of uncertainty of the applied data and the avalanche assessment."* However, the document includes no specific advice on how to assess and present uncertainty.

Based on a risk governance framework (see explanation below), avalanche hazard models, avalanche forecasting workflows, and input from stakeholders and document reviews, we developed an uncertainty model consisting of 12 uncertainty factors. In doing so, we "sought out the sources of uncertainty" as advocated by Atkins (2013). From this model, we created an uncertainty checklist to help assess each individual uncertainty factor in addition to the overall uncertainty in the avalanche forecast. We intended this checklist to add value to the forecast by increasing awareness of uncertainty factors among the forecasters, thereby promoting more systematic and comprehensive uncertainty assessments. This can lead to more robust decisions by risk owners, given effective communication of uncertainty to the risk owners.

The term *site-specific* avalanche warning is used in this document, unless quoting or referring to older documents which used the term *local* avalanche warning when considering individual avalanche paths.

While *risk management* focuses on practical actions and strategies to address specific risks, *risk governance* is about establishing the overarching framework that enables an organization to effectively manage risks in alignment with its overall goals and values. Effective risk governance lays the foundation for a comprehensive approach to risk management across organizations and the stakeholders involved. Risk governance also considers that as the level of knowledge changes, the need for participation will also change. To manage risks with significant uncertainty, greater stakeholder involvement is required (IRGC, 2017).

Avalanche risk is the probability of harm or cost resulting from interaction between avalanche hazard and a specific element(s) at risk (CAA, 2016 based on Statham, 2008). *Uncertainty* is the state (even partial) of deficiency of information related to understanding or knowledge of an event, its consequence or likelihood (ISO, 2009).

Abbreviations used include ADAM (Avalanche Danger Assessment Matrix), CMAH (Conceptual Model of Avalanche Hazard), IRGC (International Risk Governance Council) and RAMMS (Rapid Mass Movements Simulation).

2. METHODOLOGY

This work stems from an evaluation of the site-specific avalanche warning system used in the 2021/2022 avalanche season (Øien et al., 2022) which was carried out in collaboration with local stakeholders, including both the site-specific warning services (avalanche forecasters) and risk owners (local authorities). Here, the stakeholders provided specific input regarding applicable ideas for handling uncertainty in the steps of a risk governance framework (adapted from IRGC, 2017) in Longyearbyen, of which site-specific avalanche warning plays a key role. The risk governance framework is illustrated in Figure 1.

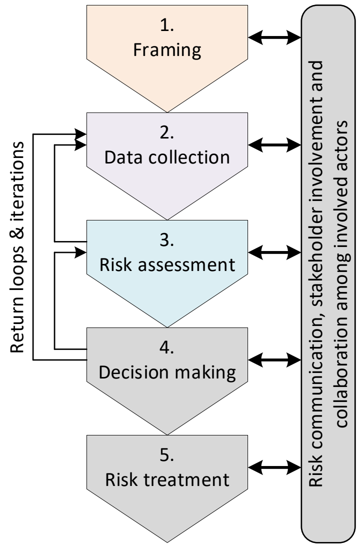

Figure 1: Risk governance framework.

The framework consists of five steps from framing to risk treatment. The uncertainty assessment covers steps 1-3. Uncertainties related to steps 4-5 also exist, but these are beyond the control of the avalanche forecaster performing the uncertainty assessment.

Some return loops and iterations are indicated in the figure. They include dialogue between avalanche forecasters (Step 3) and snow observers (Step 2), such as request for additional snow observations. There may be dialogue between the decision makers (Step 4) and the avalanche forecasters (Step 3), which can include deciding on the need for detailed forecasts. Finally, direct communication between the decision makers (Step 4) and the snow observers (Step 2) may include requesting additional data (Øien et al., 2022).

The stakeholder input and document reviews allowed us to identify, structure, and model uncertainty factors arising from the various phases of the risk governance framework (i.e., framing, data collection, risk assessment, decision-making, and risk treatment), cf. Figure 2.

Examples of uncertainty factors, or sources to uncertainty, are shown in Figure 2. They represented preliminary findings, for which subsequent changes were made. As already noted, the uncertainty factors for steps 4 and 5 are outside the control of the avalanche forecasters, illustrated with dashed boxes in the figure. Thus, the uncertainty assessment, as well as the uncertainty model and checklist, only cover steps 1-3. This is the assessment that the avalanche forecasters should communicate to the decision makers. In addition, there are uncertainties related to both the decisions and the actions taken.

The uncertainty model was developed based on the structuring of uncertainty factors arising from the various phases of the risk governance framework, cf. Figure 2, but it was also influenced by avalanche forecasting workflows based on avalanche hazard assessment models such as the Conceptual Model of Avalanche Hazard (Statham et al., 2017) and the Avalanche Danger Assessment Matrix (Müller et al., 2016).

Based on the resulting uncertainty model (see Section 3.1), we developed an uncertainty checklist (see Section 3.2) for avalanche forecasters which we then tested in site-specific avalanche warnings at various locations in Norway during the 2022/2023 avalanche season (cf. Chapter 4). The checklists were not tested in Longyearbyen due to a change of forecaster contractor before the 2022/2023 avalanche season. Therefore, it was only tested on mainland Norway (by the previous contractor in Longyearbyen).

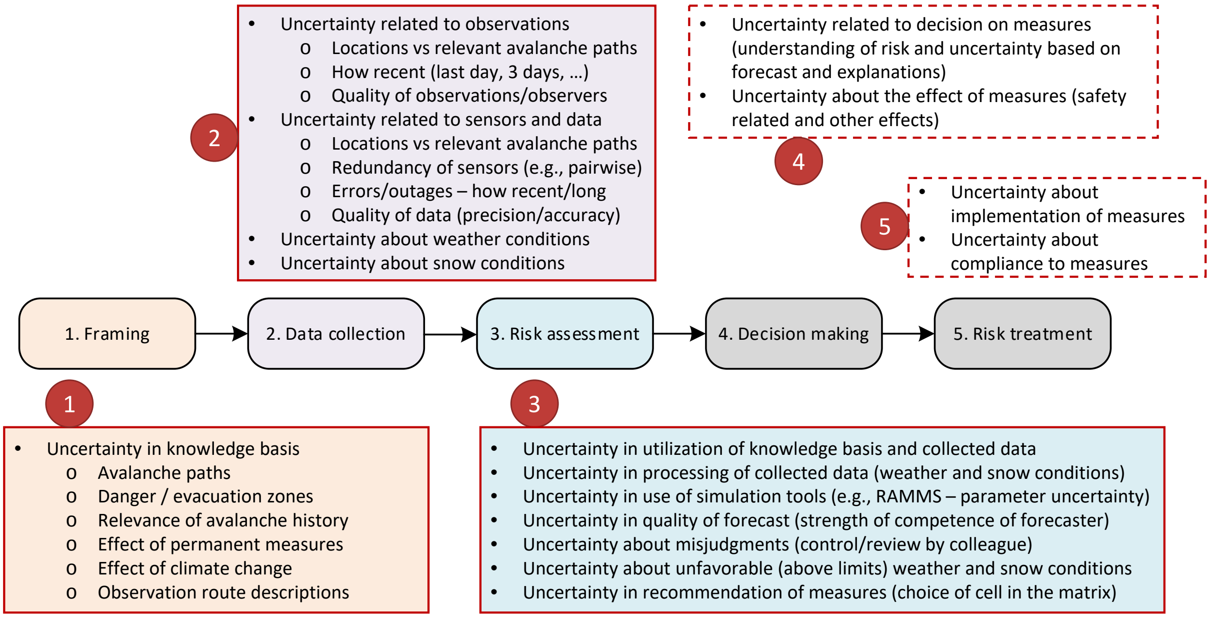

Figure 2: Examples of uncertainty factors in the various phases of the risk governance framework.

3. RESULTS

The results consist of an uncertainty model and an uncertainty checklist. These are accompanied by guidance on definitions/explanations of each uncertainty factor and guidance on how to assess both individual uncertainty factors and the overall aggregated uncertainty.

3.1 Uncertainty model

The uncertainty model is illustrated in Figure 3.

It consists of 12 uncertainty factors or sources, linked to the relevant steps in the risk governance framework. It is illustrated with thick boxes which factors that are based on avalanche hazard models (ADAM and CMAH). The numbering follows the sequence of the avalanche forecast workflow. Examples of descriptions of uncertainty factors are provided below (for uncertainty factors 1-3).

Basic documents: Uncertainty in basic information is affected by e.g., inadequate or outdated avalanche path mapping, inadequate documentation of avalanche history, inadequate description of exposed buildings/infrastructure/objects and lack of an overview of relevant observation routes.

Sensors and data: Uncertainty in sensors and data is affected by uptime, redundancy (location of sensors in pairs), different sensor types, degree of coverage of sensors, measurement accuracy and location in the terrain which can affect measurement accuracy/error display, placement in relation to current avalanche paths, influence of weather and darkness, etc.

Observations: Uncertainty in snowpack observations and avalanche observations is affected by the extent of observations, the quality of the observations, localization and relevance in relation to current avalanche paths and proximity in time in relation to the date of the avalanche forecast.

3.2 Uncertainty checklist

The uncertainty checklist, with an example in blue text, is provided in Figure 4.

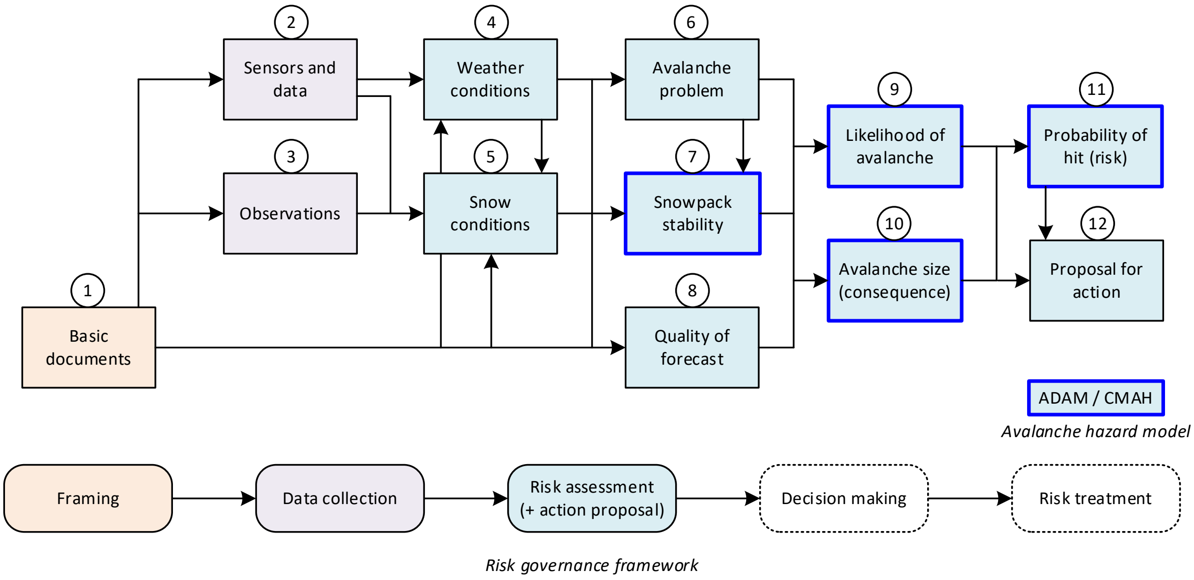

Figure 3: Uncertainty model.

Uncertainty assessment				
UNCERTAINTY - Total assessment		**Low**	**Medium**	**High**
The uncertainty in the warning is high due to a lack of observations and data, including snow depth. Uncertain avalanche size.				X
FACTORS/SOURCES TO UNCERTAINTY	**Low**	**Medium**	**High**	**Specification (for Medium and High uncertainty)**
UNCERTAINTY IN KNOWLEDGE BASIS				
1. Basic documents		X		*Uncertainty about basic information on which wind directions that give large snow accumulation*
UNCERTAINTY IN COLLECTED INFORMATION				
2. Sensors and data			X	*Uncertain snow depth as the snow depth sensors are out of order*
3. Observations			X	*Few available observations (only blurred images)*
UNCERTAINTY IN ASSESSMENTS				
4. Weather conditions - nowcast and forecast	X			
5. Snow conditions - nowcast and forecast		X		*Uncertainty about which layer the avalanche loosens*
6. Avalanche problem - nowcast and forecast	X			
7. Snowpack stability - nowcast and forecast	X			
8. Quality of forecast	X			
9. Likelihood of avalanche	X			
10. Avalanche size (consequence)			X	*Uncertainty about avalanche size and runout length*
11. Probability of hit (risk)	X			
12. Proposal for action	X			

Figure 4. Uncertainty checklist (with example).

The 12 uncertainty factors/sources from the uncertainty model are listed chronologically from top to bottom according to the avalanche forecast workflow and they are grouped according to the first three phases of the risk governance framework. Then each uncertainty factor is assessed as low, medium or high uncertainty by the forecasters. Factors with medium or high uncertainty need to be specified (shown with blue text in the last column for the example in Figure 4). Finally, an overall uncertainty is assigned based on the assessments of the individual factors, both descriptive and by assigning low, medium or high overall uncertainty (“Total Assessment”). The uncertainty checklist therefore seeks to clarify what we know and what we don't know, and to what degree.

Guidance is provided both for assignment of uncertainty of individual factors and for the overall aggregated uncertainty.

As an example, high uncertainty should be assigned to an individual factor *"when the conditions affecting uncertainty, according to the definition of the individual factor in question, are considered to be present to a large extent."* Further, high overall uncertainty should be assigned *"in case of high uncertainty on individual conditions, especially conditions no. 9-11, probability of avalanche, avalanche size and probability of hit (risk)."*

Both the uncertainty model and checklist were subject to scrutiny by the avalanche forecasters with corresponding adjustments prior to testing.

4. DISCUSSIONS

There are numerous factors affecting uncertainty, and the selection of 12 factors obviously does not represent an exhaustive list. However, the time and effort invested in uncertainty assessment must be balanced against the overall time and effort spent on avalanche forecasting. It needs to be efficient and provide added value. Also, note that the number of 12 factors may be misleading, since some of the factors include several "sub-factors".

The uncertainty checklist was tested in site-specific avalanche warnings separately by two avalanche forecasters at four different locations in Norway during the 2022/2023 avalanche season.

In our initial test periods, we found the checklist added value to avalanche risk assessments by specifically directing forecaster attention to, and thus increasing forecaster awareness of, the different uncertainty factors included in the checklist. To illustrate this, we can use *uncertainty in quality of forecast* as an example. This is described as *"uncertainty in the quality of the forecast, influenced by e.g., experience of forecasters both in general and with local conditions of the area in question, the extent to which forecasters carried out quality assurance (QA) in the previous week, thoroughness of handover, thoroughness of QA and consultation with other forecasters or relevant professionals."* The forecasters are aware of this uncertainty factor (and underlying sub-factors), but it can be overlooked as the forecasters may be biased by previously used and more conspicuous uncertainty factors, and also be satisfied with stating only one or two uncertainty factors in the forecast. Out of order snow depth sensors have been a common uncertainty factor. Forecasters may use the same uncertainty factor repeatedly if the situation persists, without considering other uncertainty factors. With a checklist, the forecasters are forced to explicitly consider all the uncertainty factors, so in addition to creating awareness, the checklist works as a reminder.

We also experienced during the testing that some of the factors are more prone to subjectivity than others, which indicates a need for experience-sharing – to ensure conceptual and vernacular agreement – between forecasters. Even for the same forecaster a change in "acceptance" of an uncertainty factor could occur over time, with a tendency to assess a lower uncertainty level later in the period on duty. This is another bias that calls for experience-sharing.

We also found the uncertainty checklist needs to be an integrated part of the forecast, both in terms of the forecaster's workflow and the digital template via which the avalanche forecast is delivered. This facilitates a more efficient uncertainty assessment. The latest version is such an integrated checklist, where we have placed the checklist into the avalanche forecast template according to the information pyramid (cf., e.g., EAWS, 2022).

The main purpose of the uncertainty assessment is to make the forecasters aware of weak knowledge in the forecast and based on this consider further investigations to reduce uncertainty and to communicate this to the decision-makers. A robust decision requires the decision-makers to understand the uncertainties. Communication of uncertainties could be strengthened through visualization, e.g., by using maps which indicate where snow observations (with dates and other information) and sensors etc. are located in relation to the critical avalanche path(s).

Also, the overall uncertainty could be visualized as part of the risk picture, e.g., if risk matrices are used, the effect of uncertainty on risk could be an arrow in the neighboring cell(s), upwards, downwards and/or sideways. This is somewhat similar to the use of rectangles by Statham et al. (2017). An underlying assumption of this approach is that risk and uncertainty are different concepts as stated by Atkins (2013): *"There is a big difference between risk and uncertainty and to treat them as synonyms is dangerous"* and he is well aware of the ISO 31000's conceptual definition of risk as the effect of uncertainty on objectives. He also states that *"instead of focusing solely on risk, we must also focus on uncertainty"*, but warns about *"unfortunately, uncertainty is a difficult concept to understand, so people generally ignore it."* This is also true for professional avalanche services, and one of the aims with the uncertainty checklist is to make the uncertainties understandable by explicitly addressing the factors that contributes to uncertainty. We believe that making all contributions to uncertainty visible justifies the overall assessment of uncertainty (Øien et al., 2022), i.e., the assessment of the individual uncertainty factors in the checklist is necessary and contributes to justify the overall assessment. It is not sufficient to jump directly to an overall assessment of uncertainty.

Several checklists exist in the avalanche community, such as the avalanche characterization checklist by Atkins (2004), and examples of contributions to or sources of uncertainty are described, e.g., by Stoffel and Schweizer (2008) and CAA (2016), but to our knowledge no structured, publicly-available checklist exists that specifically addresses uncertainty in avalanche forecasts.

From a decision-maker perspective, the added value of the uncertainty checklist is a more robust decision. Although the need for communicating uncertainty is repeatedly stressed, e.g., in CAA (2016): *"Uncertainty is an important part of hazard/risk assessments. Hence, it should be explicitly communicated to the risk owner …"*, there is a need for further clarification and dialog with the relevant risk owners. The receivers must be able to comprehend and make use of the uncertainty message.

5. CONCLUSIONS

We have developed an uncertainty checklist based on an uncertainty model, which is theoretically founded on a risk governance framework, avalanche hazard models, and avalanche forecasting workflows.

The checklist is for practical application balanced against the overall time and effort in providing avalanche forecasts, and it is included in the avalanche forecast template to make the uncertainty assessment efficient.

Some adjustments were made prior to testing, whereas the initial testing did not reveal any additional need for adding or removing uncertainty factors. However, continued use may lead to further adjustments, also regarding guidance on definitions and evaluations, making the uncertainty assessment less prone to the subjective view of each forecaster.

The checklist provides added value to the forecasters in terms of awareness and serves as a reminder of the individual uncertainty factors to consider during the preparation of the avalanche forecast. This has been evidenced by the forecasters during the initial test period.

The checklist is also assumed to provide added value to the risk owners in terms of more robust decisions. Communicating uncertainty to the risk owners is stressed and strongly encouraged in many publications in the avalanche community (e.g., Atkins, 2013; CAA, 2016). Improved handling of uncertainty was also identified as an urgent need by all stakeholders in our work. However, the use of the checklist for communicating uncertainty to the risk owners, resulting in more robust decisions, remains to be evidenced.

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