UiT The Arctic University of Norway

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Unpacking uncertainty in regional avalanche forecasting

A quantitative case study of uncertainty in forecasting regional avalanche danger

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Summary

When assessing a risk, a future event, uncertainty is vital as we cannot know what will happen. Having an active relationship to uncertainty can reduce it and help the decision-makers make informed decisions. Avalanche forecasting is widely used by outdoor recreational and local authorities for emergency preparedness use. Therefore, an additional focus on uncertainty in this field benefits people making decisions to manage avalanche danger. This thesis aims to answer the question: *What are ways to reduce uncertainty in regional avalanche forecasting?*

Through a survey that collected data on how the forecasters assessed the uncertainty they met in the forecasting process, this thesis has identified situations with high uncertainty, the source of these uncertainties and how forecasters face these situations and sources, as well as how they can manage it in the future.

The thesis concludes that high uncertainty does not follow the forecasted danger level. However, it follows certain avalanche problems. The uncertain avalanche problems are connected to different sources of uncertainty, and they can be categorised as reducible or non-reducible. Uncertainty from weather forecasts cannot be easily reduced, but sources of uncertainty like snowpack uncertainty or few field observations can be reduced. Some uncertainties can be reduced by collecting more or better data. Other ways to deal with uncertainty is to make it explicit in the bulletins or try to understand it better with discussing with fellow experts.

Acknowledgement

This thesis marks the end of my master's degree at UiT The Arctic University of Norway.

Writing this thesis has been a very long process and partly individual work. I used it as an opportunity to explore a new subject I did not know that much about when I started, and it ended up being an important learning opportunity for me.

There are many people I owe a thanks to. First, I would like to thank the Norwegian Avalanche Warning Service for allowing me to conduct research in their organisation. I would also like to thank every forecaster that has taken the time to answer my survey at the end of their very busy days. I've had very skilled people to help me along the way. Markus Landrø, Håvard Boutera Toft, and Jens Andreas Terum, thank you for the discussions and help forming and this study and its analysis. My main supervisor throughout my five years in Tromsø and during both my bachelor thesis and this master thesis, Are Kristoffer Sydnes, thank you for having patience with me and keeping me on the right track. I'm sure we're both glad I won't be writing a new thesis any time soon.

I hope this thesis serve as a steppingstone to further research on the subject and facilitates discussions and focus on uncertainty in both forecasting and decision making. And lastly, that it is an interesting read.

Kristoffer Karlsen
Tromsø, 10th of December 2023

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The future is uncertain and inescapably subjective; it does not exist, except in the minds of people attempting to anticipate it.

John Adams

1 Introduction

Snow avalanches are one of the natural hazards that have taken a substantial amount of life in Norway since the start of the 20th century. It has been over 300 fatal avalanche events registered with over 600 fatalities (Olje- og energidiepartementet, 2012). And since the fall of 2008 it is reported 104 fatalities due to avalanches or cornice breaks (NVE, n.d.-b). Most avalanche fatalities in later years happen because of people using avalanche terrain in wintertime for recreational use, like ski touring or snowmobiling. And the type of avalanche accident matches the trend that people are increasingly using the mountains as a recreational playground (Engeset et al., 2018).

It is not only in the mountain avalanches are a hazard. With a changing climate and new weather pattern during winter avalanche could become even more common in the avalanche-prone parts of Norway (Hisdal et al., 2021). More extreme events, such as the weather that created the avalanche cycle in Troms, Northern Norway late March 2023, that included a large avalanche that swept a farm and its inhabitants into the fjord (NVE, n.d.-b), should be expected.

Avalanches are a natural process that can occur without human influence and only result in damages to things which we might not value, such as forests, wildlife and so on. Meaning we create avalanche risk only when we expose ourselves to the hazard. Studies show that 90% of fatal avalanche events are triggered by the victims themselves or someone in their group (McClung & Schaerer, 2022), meaning that most avalanche victims have an important role in "creating" the risk they expose themselves too (Jamieson et al., 2015). Not all have knowingly put themselves in these hazardous situations. Houses have been built in runout-zones without the owners or the local authorities being aware of the risk.

There are many tools available for mitigating damages from avalanches and preventing avalanche accidents. Forecasting avalanche hazard is one of the dynamic ways to do this, compared to more permanent measures such as avalanche walls and moving of avalanche-prone infrastructure. Forecasting can provide decision-makers with a tool to make informed decisions at the right time to prevent avalanches from causing more damage than needed and give outdoor activity users a tool to make better decisions while navigating avalanche terrain during the winter. Forecasting avalanche danger is a prediction of how the hazardous situation will develop over time. It is based on an understanding and analysis of the current situation, a weather forecast and its combined effect on the future snowpack (Vernay et al., 2015). When trying to predict the future, as you do in avalanche forecasting, uncertainty is always involved (Rausand & Haugen, 2020).

The effect of avalanche forecasts on preventing accidents and the general safety of those who travel or stay in avalanche terrain is challenging to measure and to directly connect whether it has been instrumental in avoiding accidents. However, user surveys of the Norwegian Avalanche Warning Service from 2013 to 2016 have shown that users increasingly believe that avalanche warnings have played a part in avoiding accidents (Bjordal et al., 2017). On several occasions, the avalanche warning has also been decisive in the decisions to taking preventive measures when high avalanche danger is expected.

The leading target groups for the Norwegian Avalanche Warning Service are outdoor activity users and preparedness operators/authorities, but it is also an open product available for everyone (NVE, n.d.-a). Everyone has a mindset that influences how they approach situations (Atkins, 2014). An emphasis on uncertainty in the avalanche forecasts can help influence the mindsets of the users to approach the avalanche danger situation with either a more conservative approach or that there is a need to make their own assessment because the product is based on a poor base of knowledge (Atkins, 2014). This exemplifies why uncertainty in the forecast has a vital role in how people make decisions and should think about the avalanche forecast.

1.1 Background

Why is it relevant to conduct research on uncertainty in avalanche forecasting processes regarding societal safety and risk management? Before we can answer this, we need to put avalanche forecasting into a risk management perspective.

Avalanche forecasting is a method to provide a product to decision-makers for them to take informed decisions to managed avalanche risk. Avalanche forecasts is comparable to risk analysis or hazard assessments, as it is an analysis of the likelihood of avalanche happening (probability) and the potential destructive size (consequence) in the next days ahead. But why is uncertainty such an important element of this that we should expand our knowledge regarding this?

Risk is conventionally defined as the probability and consequence of something that can go wrong (Rausand & Haugen, 2020), and risk analysis is used as a method to examine and describe risk. It is important to remember that risk concerns something that has not happened yet (Adams, 1995), or something that could have happened (Engen et al., 2016). What is not clearly stated in the conventional definition of risk is the element of uncertainty (Aven, 2017). As Adams (1995) points to, risk is about some future event, something that has not happened yet, thus giving it an element of uncertainty. And as avalanche forecasting is a prediction of a future risk, it also includes an element of uncertainty.

So now that we know and understand how uncertainty plays a vital role in the concept of risk, why is it important that we continue to research and explore this in the concept of risk analysis? Uncertainty plays a vital role because it is important for how people use risk analysis. An example is that people often choose investments with low uncertainty and low payoff over high uncertainty and high payoff. This shows that including uncertainty in risk analysis can play a part in facilitating for risk aversion, people taking less risk. Showing or giving focus to uncertainty can also plays a part in the decision about whether to spend more resources on acquire additional information, possibly increasing the overall quality of the analysis (Morgan & Henrion, 1990).

There are systematic ways to include uncertainty into the questions that make up risk and into risk analysis (Aven, 2017; Aven et al., 2017; Goerlandt & Reniers, 2016; Kiureghian & Ditlevsen, 2009), however this is not something that is done in the regional avalanche forecasting. A better understanding and handling of the uncertainty in the avalanche forecasting process can possibly contribute to improve the product, but also lay the groundwork for a systematic way for forecasters to account for uncertainty in the forecasting process.

1.2 Former research

As the focus on uncertainty has increased in the risk science field the last years, it has also gotten some attention in the avalanche forecasting field. The handling of uncertainty is an issue given focus on in the research project about governing climate-systemic risk in the Arctic (ARCT-RISK). Here the focus has primarily been on how to communicate uncertainty in the local avalanche forecast and systematic ways to describe it (NTNU, 2022), however they have identified sources of uncertainty in all five steps of the risk governance framework, which lies the groundwork for a checklist that has the purpose to visualise uncertainty better (Øien et al., 2022). Research from the ARCT-RISK project also shows that there is no standard way to communicate uncertainty and some choose to do it, other do not (Øien et al., 2022).

Even though forecasting, in general, is uncertain and does not necessarily represent a correct presentation of the future, studies have found that people can have higher confidence in forecasts than they should. A study on how winter recreationalist use weather forecasts and how it formed their perception showed that the users had higher confidence in parts of the forecast related to a variable they could not quickly assess themselves and validate the presence of (Rutty & Andrey, 2014). This shows that it could be crucial to communicate what is uncertain in the avalanche forecast, especially related to non-observable parameters, like the presence of weak layers in the snow or the depth down to the weak layer.

1.3 Goal and research problem

This thesis aims to contribute to the ongoing focus on uncertainty in avalanche forecasting. I'm searching for answers to which situations involves uncertainty, where this uncertainty is found and how the forecasters can meet these situations. To meet this goal, I followed the Norwegian Avalanche Warning Service for some time and examined what they assessed as uncertain, why is was, and how they dealt with it. This study is done from the avalanche forecasters perspective. Therefor the research problem I will examine is:

What are ways to reduce uncertainty in regional avalanche forecasting?

To find the answer to what the different ways to reduce uncertainty in regional avalanche forecasting, the study first needs to identify when the forecast is uncertain, where the uncertainty comes from. Therefore, I have defined a research question for each of the steps. The following questions are:

- *What are the situations that have higher uncertainty?*
- *What are the sources of uncertainty in the situations with higher uncertainty?*
- *How is uncertainty dealt with in the situations with higher uncertainty and what information is important for the forecasters?*

Until now, there has not been a systematic way for the forecaster to identify and document sources of uncertainty in the forecasting-process. With the study, a "tracking" of sources of uncertainty is introduced in the preparation of the forecasts. This will help to identify the most common sources of uncertainty and can be used to see a connection with different danger levels and avalanche problems.

1.4 Limitations

This thesis takes a closer look at the uncertainty that exists in the process of making the avalanche forecasts and the object of study is the regional avalanche forecasting in Norway. Uncertainty can be found in every step of a risk management process, from framing of the problem to treating the risk, but in this thesis, I focus on the uncertainty in the assessment part of the risk management process, very particularly on the steps, data collection and risk assessment. The data collection is limited to the avalanche forecasters assessment of uncertainty that goes into their process of making the regional forecasts and how they have managed the uncertainty.

1.5 Structure

This thesis is divided into seven chapters. Chapter 2 presents some background knowledge for the thesis, like what avalanches are and how they are forecasted in Norway. Chapter 3 presents the theoretical framework for the thesis. This includes theories about risk and uncertainty, as well as some theories about different categorisations of information. Chapter 4 will describe the research method used for collecting data for the study and discuss its strengths and weaknesses. Chapter 5 will present the empirical data collected through the Norwegian Avalanche Warning Service survey. In Chapter 6, the empirical data will be discussed considering the theoretical framework presented in Chapter 3. Lastly, in Chapter 7, the study will be summed up, and I will present further research problems on the topic of uncertainty in avalanche forecasting that can be explored.

2 Avalanche forecasting

In this chapter, I will describe concepts and terminology relevant to avalanche forecasting and give some background information on the objective of the study. I begin with the concepts of avalanches and release mechanisms; thereafter I will provide a short introduction to how avalanche danger is forecasted.

2.1 Snow avalanches

Snow avalanches is a mass of snow moving downslope doe to gravity, and the total volume needs to exceed 100m3 and be longer than 50 meters (EAWS, n.d.-b). Avalanches could be divided into *loose-snow avalanches* and *slab avalanches*, whereas the latter is more dangerous and responsible for most fatal accidents (McClung & Schaerer, 2022; NVE, n.d.-b). Loose-snow avalanches, which can be wet or dry, is surface snow or near-surface snow that starts at a single point, moving downslope due to loss of cohesion in the snow, and drags more snow with it as goes. Slab avalanches, which can also be wet and dry, is a cohesive block of snow that cracks up and glides downslope because of a failure of a weak layer in the snowpack doe to a trigger (natural or human). For a slab to glide and become an avalanche the slope need to be steeper than 27-30 degrees (McClung & Schaerer, 2022). There are other types of natural hazards related to snow avalanches or avalanches, such as cornice falls, ice avalanches, slush avalanches, roof avalanches and glide avalanches (McClung & Schaerer, 2022). However, this thesis only discusses loose-snow and slab avalanches, as these are the avalanche types forecasted in the research period.

Avalanche terrain is the area that can be affected by avalanches. It is where an avalanche can release, run, and get deposited. Avalanche terrain and areas can be defined into *avalanche paths* with their *starting, track,* and *runout zones* (McClung & Schaerer, 2022). The starting zone is where an avalanche can initiate and start to move; the track is where it runs and connects the starting zone with the runout zone. The avalanche stops in the runout zone, and most debris is deposited there.

2.2 Avalanche forecasting

Avalanche forecasting is all about predicting the instability of the snow cover over a period and for specific areas. This is often given by how easy it will be to trigger an avalanche in an area at a given time(McClung & Schaerer, 2022). Avalanche forecasting seeks to handle the dynamic problem with variation and interaction of human influence through the avalanche forecaster and natural systems through the temporal and spatial variation of the instability of the snow cover.

2.2.1 The avalanche danger scale

Avalanche danger is described trough a danger level scale. The European Avalanche Warning Services uses a 5-level scale to describe the avalanche danger. The danger level follows the conceptual model of avalanche hazard (Statham et al., 2017) and are a function of the snowpack stability, the frequency distribution of the snowpack stability and the expected avalanche size in a given area and time (EAWS, n.d.-a).

The avalanche danger scale is exponentially increasing between the different levels.

1. Danger level 1 is associated with generally stable conditions, triggering is generally hard and only small and medium natural avalanches are possible.
2. Danger level 2 is associated with heighten avalanche danger on specific terrain features. Triggering avalanches are possible, usually from high load, and very large natural avalanches are unlikely.
3. Danger level 3 is associated with dangerous avalanche conditions, triggering is possible, even with low additional load, some large and very large natural avalanches are possible.
4. Danger level 4 is associated with very dangerous avalanche conditions, triggering is likely with low additional load, and numerous large and very large natural avalanches are expected.
5. Danger level 5 is associated with extraordinary avalanche conditions, numerous very large and extremely large natural avalanches are expected, even in moderately steep terrain.

(EAWS, n.d.-a)

2.2.2 Avalanche problems

Avalanche hazard is given by the avalanche danger scale, but it uses avalanche problems to describe and define the avalanche danger. Avalanche problems are a way for avalanche professionals to describe typical situations of snow instability. The avalanche problems involves different factors that make up the avalanche hazard. Statham et al. (2017) has further shown in Figure 1 how assessing avalanche hazard is about (1) identifying which avalanche problem is present, (2) where in the terrain the problem is located (elevation zone and aspect), (3) how likely it is that an avalanche will occur (spatial distribution and sensitivity to triggering), and (4) how large will an avalanche become. This approach is called the conceptual model of avalanche hazard (CMAH) (Statham et al., 2017).

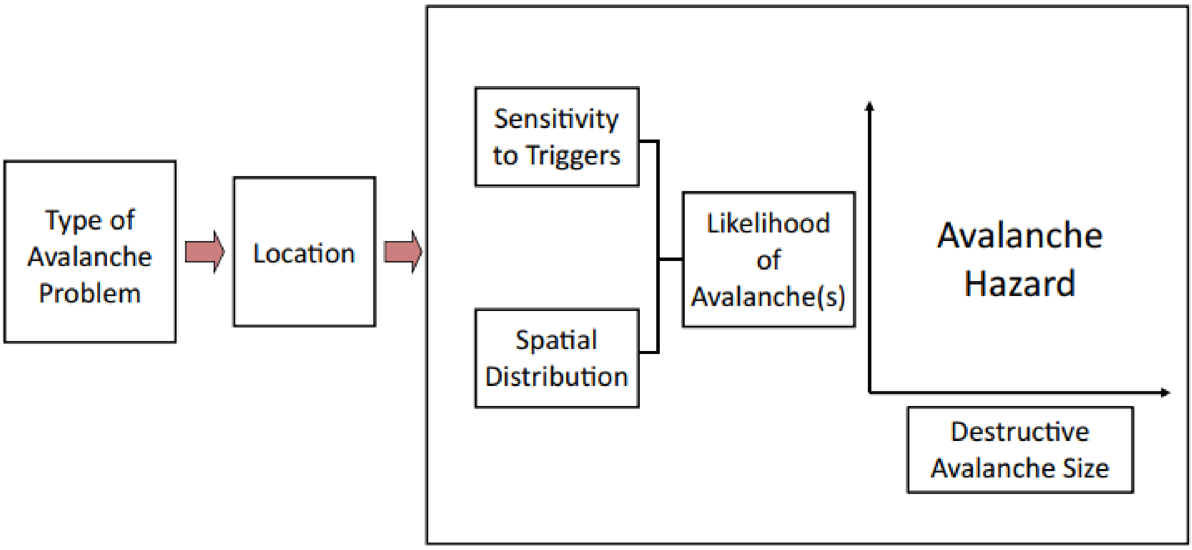

Figure 1 - Structure for assessing avalanche hazard based on an avalanche problems type, location, likelihood and size (Statham et al., 2017).

In the organisation European Avalanche Warning Services (hereafter: EAWS), which is an umbrella organisation for all the avalanche warning services in Europe, there are defined seven different avalanche problems, five of them mandatory for all warning services in their avalanche hazard assessments. I have only included the five mandatory problems in this research project because these are the ones Norway uses. In the following list, I will present the five avalanche problems.

- *New snow* is related to an ongoing or fresh snowfall. The main factor for this problem is the amount of new snow onto the existing snowpack and if it reaches a critical amount of load. It can result in both dry loose snow avalanches and dry-snow slab avalanches.
- *Wind slab*. It occurs when new or old loose snow near the surface is transported and deposited by the wind. It is only related to slab avalanches.
- *Persistent weak layers*. This problem is related to weak layers in the old snowpack which does not stabilise at the same rate as the other problems, therefor the word persistent. The weak layers are normally consisting of faceted crystals, surface hoar or depth hoar. This avalanche problem results in slab avalanches.
- *Wet snow*. It is a result of liquid water because of rain or melting that enters the snowpack and weakening it. This problem can both result in wet-snow slab avalanches or wet loose snow avalanches.
- *Gliding snow*. This is the entire snowpack gliding on the ground, typically on a smooth surface of any kind. There problem is often related to thick snowpacks with non or few weak layers but are not dependent on a wet or dry snowpack. The problem results in what is called glide-snow avalanches.

(EAWS, n.d.-d)

An important distinction to be aware of is the difference in danger indicators under conditions with persistent weak layers. The danger indicators related to persistent weak layers are mostly hidden and occur rarely. For many users the only "danger indicator" of this problem is the avalanche forecast (Ruetz, 2018). Compared to the other avalanche problems, where the indicators are highly visible (new snow, snow drift etc.), it is harder to assess the danger of avalanches because of persistent weak layers because of its lack of indicators. The accident statistics which show that over 50 % of the recent avalanche fatalities is because of avalanches released on persistent weak layers support this conclusion (NVE, n.d.-b).

Every avalanche problem is then made up of some components, were most of them are linked to the conceptual model of avalanche hazard. Each avalanche problem is given a value for spatial distribution, show sensitive it is to trigger an avalanche and the probable size of the avalanche. In the assessment of avalanche problems, the forecasters also must choose which weak layer slab avalanches are likely to release on and where in the terrain (elevation zone and slope aspect) the avalanche problem are likely found.

2.2.3 The Norwegian Avalanche Warning Service

In 2009 the Norwegian government gave the Norwegian Water Resource and Energy Directorate (NVE) the overall responsibility for preventing damages from floods and avalanches (Olje- og energidiepartementet, 2012). As part of this responsibility, NVE was to create an avalanche warning service for Norway. This service became operational in 2013 under the Norwegian Avalanche Warning Service (NAWS) and was available on the webpage varsom.no (Engeset et al., 2018). NAWS issues daily regional avalanche forecasts[1] for 24 pre-defined regions on mainland Norway and Svalbard from the 1st of December to 31st of May every winter. If conditions are assessed to be severe enough NAWS will publish forecasts outside of the main season and the 24 pre-defined regions.

2.2.4 How is the forecast made?

Four avalanche forecasters are usually on duty during the warning season, making bulletins for the 24 pre-defined regions. The forecasters work from different parts of the country, and there is always one lead forecaster and one meteorologist. The other two vary but could compromise of avalanche specialists from

[1] Avalanche forecast is an assessment of the avalanche danger for the next 2-3 days forward in time.

the Norwegian Road Administration, the Norwegian Water Resources and Energy Directorate or the avalanche observer corps.

The forecasting process starts with looking back in time. How has the weather been lately, and how is the snow cover? Based on this, the forecaster gets a picture on how the current conditions are, what is called a nowcast. The next step is to combine the current conditions with how they will evolve in the following days based on weather forecasts and analyse how the weather will influence the snow cover, resulting in an avalanche forecast for “day 1” and “day 2”.

Making the avalanche bulletins is an individual process. However, during the day, they have coordination talks among each other where they discuss the strategy for choosing avalanche problems in their regions, if there are places with expected high avalanche danger (danger level 4 or 5), and what is uncertain and how to account for it. Later in the day, the forecasters meet up and discuss if some new challenges have arisen. Lastly, before publishing the bulletins, the forecasters do quality control of each other’s bulletins (Snøskredvarslingen, 2022).

The avalanche bulletins are made in a digital tool created by NVE, RegVarsel. This tool is custom made to forecast avalanche danger after the standards provided by EAWS.

2.2.5 The avalanche bulletins

The avalanche bulletins from NAWS is presented according to the standard provided by EAWS (NVE, n.d.-d). The standard provided by EAWS defines what the bulletins should include, how they should be presented and how the workflow in assessing the avalanche danger should be. The bulletins are built up of six parts, danger level, avalanche-prone location, avalanche problem, danger description, other information (snowpack, weather) and measured values (unchecked raw data) (EAWS, n.d.-c). The Norwegian bulletins is to a large degree built with the same principles.

The bulletins provided by NAWS begin with a danger level and a main message at the top. Then a more detailed description of the avalanche danger is presented, followed by the avalanche problems and the avalanche-prone location. After that, travel advice is adapted to the avalanche problem through custom-made figures (only available online). Next follow a snow cover description which gives the user an overview of relevant details about the snow cover and relevant observations done in the last few days. The last part of the bulletin is the mountain weather forecast made by the meteorologist on duty (NVE, n.d.-c). In the bottom of the web-version of the bulletin, there is a map and list of observations registered through the natural hazard observation platform Varsom Regobs during the last three days. An example of a printed-out Norwegian avalanche bulletin containing all the information is provided in Appendix 1 – An example of a printed avalanche bulletin from NAWS.

3 Theory

In this chapter I will present the theoretical framework for the thesis, and what I will use in my discussion about what is uncertain, and how it is handled. As described in the introduction for the thesis, uncertainty plays a significant role in risk analysis, and as avalanche forecasting is an analysis of the avalanche risk, uncertainty plays a vital part there. Since the aim of the thesis is to get a better understanding of the uncertainty and ways to deal with it, the theoretical framework revolves around ways to describe and categorise uncertainty and how to deal with it.

Risk can be characterised to present threats, their consequences and probability. However this characterisation, as (Aven, 2017) points to does not reflect the knowledge aspect of risk. Viewing risk as having two components; the consequences in relation to some values, and not knowing what the consequences will be, it is uncertainty, captures most aspects of risk as a concept. This thesis seeks to give tools to handle the uncertainty aspect of risk in avalanche forecasting.

3.1 Uncertainty

As the different definitions of risk opens to elaborating uncertainty in it, some of them even goes as far as defining uncertainty (Goerlandt & Reniers, 2016), while some are more open (Aven, 2017). What all the definitions have in common is the focus on a lack of something. ISO (International Organization of Standardization, 2009) defines uncertainty as "the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequences, or likelihood", while (Schmitt & Klein, 1996) defines uncertainty as "what we do not know or understand about a given situation".

It's not uncommon to confuse and mix uncertainty and probability. There is however an important distinction. While uncertainty is what we don't know (Adams, 1995), probability is an attempt to predict and measure something quantitatively based on what we do know or believe (Flage et al., 2014).

As Aven (2017) defines risk as *consequences of the activity and related uncertainties*, uncertainty plays a vital role in his broad view of risk. And the approach to characterise uncertainty in risk assessments is considering the strength of knowledge in the judgements. The knowledge in judgements is conceptualised as justified beliefs that makes the foundation of the risk assessment. Recognising that knowledge can be flawed, Aven (2017) underlines the importance of examining the knowledge in the judgments to reduce the chance of unexpected outcomes. This focus on examining the knowledge and understanding how the strength of knowledge affects the risk assessment process is a way to managing uncertainty and keeping decision makers informed.

3.1.1 Types of uncertainty

There has been introduces several ways to categorise uncertainty (Burgman, 2016; Flage et al., 2014; Goerlandt & Reniers, 2016; Kiureghian & Ditlevsen, 2009), however one that is repeatedly presented is the distinction between aleatoric (natural variation), epistemic (knowledge) (Goerlandt & Reniers, 2016; Kiureghian & Ditlevsen, 2009), and linguistic (language based) uncertainty (Burgman, 2016).

Aleatoric uncertainty can be viewed as natural variation or the randomness of the outcome of events (Goerlandt & Reniers, 2016; Kiureghian & Ditlevsen, 2009). This is an uncertainty that is not reducible by collecting more data about the event (Burgman, 2016). Examples of natural variations may be the forecasted temperature in the air, amount of new snow and the exact direction of the wind. By collecting more data, it is possible to get a better understanding of a phenomena and make better estimates, but ultimately the uncertainty is not reduced (Burgman, 2016).

Epistemic uncertainty comes from a lack of knowledge or data, and can be reduced by collecting more and better data (Kiureghian & Ditlevsen, 2009). Examples of this lack of knowledge in avalanche forecasting can missing information about the presence of weak layers deep in the snowpack, the amount of new snow over a period. This type of uncertainty is also called evidence based uncertainty because it is a poor evidence base for making statements (Goerlandt & Reniers, 2016).

Linguistic uncertainty is a type of uncertainty that comes from the imprecision of the natural language we use (Burgman, 2016). Words can often have more than one meaning and we interpret them differently. When we talk about probability and use terms like, likely or often, firstly it is imprecise measures of how likely it is for something will happen, and secondly the words can have different meanings to the transmitter and the receiver of the message. In avalanche forecasting words are often used to describe different things rather than numerical values, therefore it is highly likely that it exists degrees of linguistic uncertainty in this field.

3.1.2 Sources of uncertainty

As there are different types of uncertainty, they can also have different sources. In a study on battlefield uncertainty, Schmitt and Klein (1996) identified four sources of uncertainty: missing information, unreliable information, ambiguous and conflicting information, and complex information. Jamieson et al. (2015) have provided an example of a dividing of sources of uncertainty in avalanche hazard and risk assessment.

Missing information could be crucial information needed to make accurate assessment about the current situation, and it has not been collected or is not found when needed. Examples of this source could be missing information about the amount of new snow in an area or the crystallisation processes ongoing in the snowpack.

Unreliable information has lower credibility because the source or correctness of the information provided is questioned. It is possible that the information provided is correct, but because of the credibility of the source, it is not trusted. An example of this source could be that assessment about the snowpack over a large area is done by someone who is not qualified to make such assessment, or that the receiver does not trust the source.

Ambiguous and conflicting information is possible to interpret in different ways or different information opens to different interpretations. Examples of this could be using sound readings to monitor avalanche activity close to a highway or two field observations telling two different stories about how the snow cover was affected by a storm. The common assumption is that the most normal source of uncertainty is missing information, but the study conducted by Schmitt and Klein (1996) showed that 50 percent of the sources of uncertainty they identified were ambiguous or conflicting information. This shows that judgements do not automatically improve by collecting more information, it could be just as important to improve the clarity of the information already gathered.

The last source of uncertainty Schmitt and Klein (1996) pointed to was complex information. This source of uncertainty is when the data is hard to interpret and understand the meaning of. Weather data combined with snow profiles data could be examples of this. Complex information affects different people differently. For an experienced avalanche forecaster, some combination of information could be easy to interpret, while for an unexperienced forecaster, the information could be complex and increase uncertainty.

3.1.3 Levels of uncertainty

Whereas we find that there are different kinds of uncertainty and that the sources can be categorised, it's also possible to divide uncertainty into different levels. The levels are uncertainty about the data, the second is uncertainty about how we interpret the data, aka. our knowledge. The last level is uncertainty which arise with the explanations or diagnosis of events and projections of the future we make on the basis of the data and our understanding of what they mean (Schmitt & Klein, 1996). Below is a list of the different levels in the context of avalanche forecasting.

- Level of data: *How much new snow is it? How much wind is it and what direction does it come from? What is the temperature in the mountains?*
- Level of knowledge: *Based on the amount of new snow, wind-strength, and wind-direction, have it formed wind-slabs in southern exposed slopes?*
- Level of understanding: *Is it likely for a skier to trigger a slab avalanche if skiing on freshly formed wind-slabs? Will wind-slabs release naturally if it rains tomorrow?*

The uncertainty often increases exponentially when moving from data to understanding (Schmitt & Klein, 1996). It is possible to get almost certain data on how much new snow there is, the wind strength and direction and the temperature in the mountain. Based on the data it is possible to make estimates of the formations of wind-slabs in some exposures, but this estimates in made with increasing uncertainty. And then based on the estimates about the wind slabs trying to understand the likelihood for ski-triggered avalanches or naturally released avalanches in slopes is nothing more than pure speculations.

Observation from a study conducted by Schmitt and Klein (1996) points to that successful military commanders generally focuses on the level of knowledge and projections, rather than spending time focusing on the details in the data-level. If this also would be the case in avalanche forecasting, one should not get hung up in how much new snow there is or the amount of wind and be limited by this. Rather spending more time focus on that some new snow and wind probably means that there is formed fresh wind-slabs and try to understand how unstable this avalanche problem will be, and how it will be affected by incoming weather.

Data is important as the basis for knowledge, but one should not be hung up in this level and use time and energy gathering and sorting out facts/data. Rather spend time trying to interpret what the data could mean and make projections based on that.

3.2 Specific for avalanche forecasting

3.2.1 Sources of uncertainty in avalanche risk

Jamieson et al. (2015) divided the uncertainty in avalanche hazard and risk assessment. Avalanche risk is a result of the combined effect of *weather and climate*, *terrain*, *snowpack*, and *people*, and they have roughly divided these as different sources of uncertainty in avalanche hazard and risk assessment.

Avalanche terrain is one of the key elements that need to be present to create avalanche danger. However, regional avalanche forecasting covers such large areas and specific terrain and the variability of it is usually not taken in consideration. But for the end user out there considering avalanche danger for specific slopes they must consider terrain as it is the interplay between terrain, snowpack and weather that make up avalanche danger.

Weather is one of the significant elements in avalanche forecasting and it includes uncertainty and it increases with greater spatial and temporal distance (Jamieson et al., 2015). When forecasting weather for the next three days and for an area of 10 000 km^2, which is not an unusual size for an avalanche forecasting region, the uncertainty and variation of the accuracy weather forecast will be greater than if the forecast was for one day forward in time and only for a ski resort or a town. Following this logic there will be greater uncertainty about weather in regional avalanche forecasting compared to local avalanche forecasting.

One of the other key elements in avalanche forecasting is how the snowpack is built up. This can vary with terrain and over spatial distances (Jamieson et al., 2015). Snowpack structure and properties is influenced by the interplay between previous weather and the terrain. Terrain influences how snow is deposited, and it can therefore be large differences in the snowpack over a short distance. For example, a ridge can have little snow and the distance to a weak layer can be 20 centimetres down in the snowpack, while 5 meters to the side of the ridge the distance to the weak layer is 120 centimetres because a lot more snow is deposited there by the wind. This differences is essential for how easy it is to trigger an avalanche (Jamieson et al., 2015), and make up a big source of uncertainty when assessing the ease of triggering avalanches. With regions with a size of 10 000 km^2 these differences in snowpack can be significant, and this makes up a lot of the uncertainty regarding the snowpack uncertainty.

The last source of uncertainty in avalanche forecasting identified by Jamieson et al. (2015) is people and their perception. The nowcast is in large extent based on observations provided by other humans and their interpretations of the weather and snowpack. These observations can come from both qualified and non-qualified personnel, and it generates uncertainty when the forecasters are forced to assess the avalanche danger without knowing the quality and usefulness of the data provided.

3.2.2 Information types

While forecasting avalanches there are primarily two types of information used. S*ingular information* which is specific data to the case one is studying (McClung & Schaerer, 2006). This information is collected to get an overview of the situation at hand and gives an idea of the instability of the snow cover. An example of this sort of data is what McClung and Schaerer (2006) divides into three classes of instability-factors which I will present further down.

The other type of information is *distributional information*, which is knowledge about how different situations in the past has led to different outcomes (McClung & Schaerer, 2006). One way to view distributional information can be so called general rules of thumb, like if there is more than 10 centimetres of new snow and it blows approximately 10 meters per second, size 2 wind slabs will form over the course of a few hours. This type of information is strongly linked to experience with the phenomena one is assessing, leading to inexperienced people might have limited access to distributional information, making the need for singular information even greater (McClung & Schaerer, 2006).

When making an avalanche forecast, singular information is collected to get an overview of the situation at hand and is then combined with distributional information to make predictions on how the future situation will look (McClung & Schaerer, 2006).

3.2.3 Classes of instability-factors in avalanche danger assessment

Forecasting avalanche hazard is about assessing the instability of the snowpack; how much additional load the snow can support without failing. The evaluation of the instability is through a combination of factors, and McClung and Schaerer (2022) has classified different factors related to snow instability based on their ease of interpretations and relevance for assessing snow instability. The higher number the class has, it includes more uncertainty in interpretation, and it is harder to directly relate it to snow instability.

Class 1: Instability factors – This class contains the factors that can be directly linked to snow instability (McClung & Schaerer, 2022). For example, occurrence of avalanches, fracture propagation and cracking of the snow cover is a direct evidence of snow instability. This class is also referred to as danger signs.

Class 2: Snowpack factors – This class deals with factors that are related to the presence, strength, and loading of weak layers in the snowpack. Information about this is sought from within the snowpack (McClung & Schaerer, 2022). This information is relevant, but not directly related to snow-instability, although it provides information that is relevant for analysis of snow-instability. Examples of snowpack factors is depth and structure of the snowpack, temperature gradient in the snow, or surface penetration with ski or boots.

Class 3: Meteorological factors – This class deals with indirect evidence of snow stability, either currently or in the future. The type of information is collected above or on the surface of the snowpack and is connected to the weather. Either it is the amount of new snow, wind speed and direction, or solar radiation. These factors relationship and correlation with snow stability is developed through empirical data (McClung & Schaerer, 2022).

In this chapter I have introduced many aspects of uncertainty and some ways to classify information in forecasting. These will be used to categorise the results from the survey and understand how sources of uncertainty is connected and can be dealt with as the purpose of this thesis is to provide additional understanding of uncertainty in regional avalanche forecasting and give some pointers on ways to deal with uncertainty for the warning service.

4 Method

In this chapter I will present the research method I have used to investigate the topic of uncertainty in avalanche forecasting. Further, I will present the choices taken to collect the data and how it was analysed. Lastly, I will discuss the quality of the research project, through the elements of reliability and validity, as well as ethical considerations around conducting research in an organisation which I have a strong connection to.

As this project seeks to examine variables of uncertainty in avalanche forecasting, and the forecasters assessment and handling of it, the choice of method was open. It would be possible to take a in depth examination of the topic to get a deeper understanding of uncertainty in avalanche forecasting, but that would limit the possibility to get a broader picture, supported by data, of which situations in regional avalanche forecasting is uncertain and why it is so. A quantitative approach based on numerical data (Ringdal, 2018) was chosen as it gave me the possibility to follow the avalanche warning service over a period of time and collect data on the assessment and handling of uncertainty in different situations encountered in the research period. I ended up on collecting empirical data through a survey that ran for 43 days during parts of January, February, and March in 2023 and combining this with output data from the published avalanche forecasts.

Uncertainty is a complex subject and can have many dimensions, so in order to examine this subject there is a need to break the subject down to measurable variables and values through operationalisation (Johannessen et al., 2010). This is done by breaking it down into different questions about where and why some things in the forecast and in the forecasting-process is uncertain in the survey.

4.1 Sampling

As the goal of the research is to identify what in the avalanche forecast is uncertain and where the uncertainty comes from it is natural to gather data from those who has this information, the ones who are assessing and using various kinds of data while making avalanche forecasts. Therefor a strategic selection of respondents are utilised (Thagaard, 2018), and the avalanche forecasters on duty have the answers to the questions I want answered. The selection was therefore all the avalanche forecasters who made the regional avalanche forecast during the research period (23rd of January to 6th of March).

During the period I ended up on 102 complete responses, out of 172 possible responses, this ending up on a 59 % response rate. A response rate of 50 % is consider good (Johannessen et al., 2010). The higher the response rate the better it would have been regarding being able to generalise the finding of the survey. I believe that transparency about the project and a collaboration with the lead forecasters in promoting the survey towards the end of the forecasting-days is essential reasons the survey ended up with a good response rate.

The forecasting group each day consist of four people. One lead forecaster, who has the overall responsibility and deals with external communication, two regular avalanche forecasters and one meteorologist specialised in avalanches (Snøskredvarslingen, 2022). Therefor the supposed distribution of responses should be lead forecaster stands for 25 %, regular forecaster stands for 50 %, and meteorologist stands for 25 % Looking at the distribution of the respondents, the lead forecaster stands for 34 %, the regular forecasters stand for 43 % and the meteorologist stands for 23 %. Even if the distribution of different forecasters is a bit skewed, and that sometimes make the results non-generalising (Johannessen et al., 2010), I consider this to be of minor importance for this study and still consider the results generalising.

The avalanche forecasting regions are divided into four areas, North-North, North-South, Western Norway and Eastern Norway + Svalbard (Snøskredvarslingen, 2022). The regional distribution of the respondent shows an even distribution, with 24,5 % respondents from each of the regions, North-North, North-South and Eastern Norway + Svalbard, and 26 % respondents from the regions Western Norway. The survey was intended to take approximately 3-5 minutes, and data shows the mean response time was 3 minutes and 3 seconds.

4.1.1 The research period

The research period lasted from late January (23rd of January) to early March (6th of March), ending up on a total of 43 days. To find out if this period is representative as "normal avalanche forecasting period" I compared what has been forecasted in this period compared to what has been forecasted in from the start of the avalanche forecasting season ,1st of December until 24th of March.

Firstly, what are the normal conditions in the forecasting regions? The data spanning large part of the season show that the two danger levels that's often forecasted is moderate (55 % of all forecasts) and considerable avalanche danger (30 % of all forecasts). This is followed by low avalanche danger (14 % of all forecasts), and high avalanche danger rarely forecasted (1 % of all forecasts). The highest danger level, 5-extreme avalanche danger is not forecasted in this period. If compared with what is forecasted in the research period from January to march one can see that the distribution of different forecasted danger level follows the "season normal" with very little difference (Table 1).

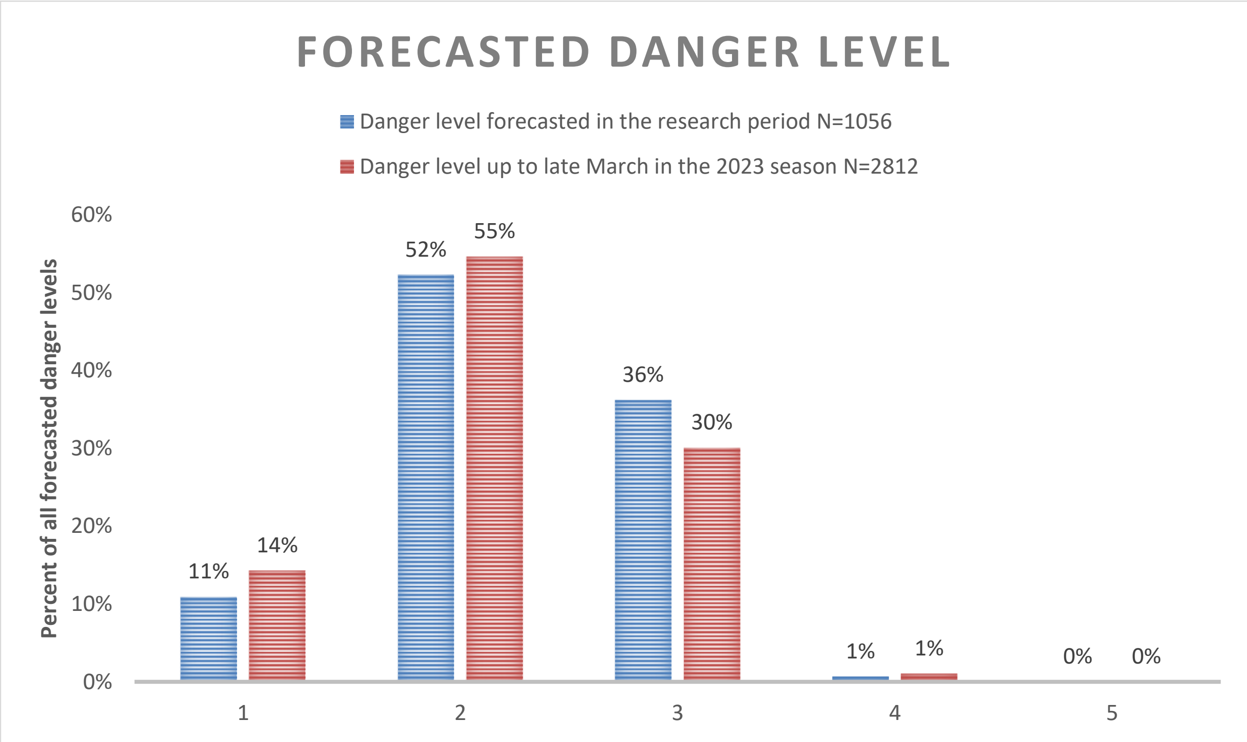

Table 1 - Forecasted avalanche danger in the season and the research period.

Forecasted avalanche danger is not the only indicator if the research period is representative for what is a normal avalanche forecasting period in Norway. The forecasted avalanche problems can also say something about what is normal. Therefore, I have done the same with the avalanche problems as done with the avalanche danger level. The result from the analysis shows that wind slab and persistent weak layers are the most common avalanche problems forecasted for the 2023 season in Norway with respectively 44 % and 36 % of all forecasted problems being them. Followed by avalanche problems related to wet snow (3 and 9 %) and new snow (6 and 1 %) (Table 2). The distribution of forecasted avalanche problem in the research period mostly follows the season normal, but with 10% fewer forecasts including persistent weak layer, and an increase in wet snow avalanche problems. This is naturally connected to weather during this period. Warmer weather often destroys persistent weak layers and increases the chance of wet snow avalanche problems.

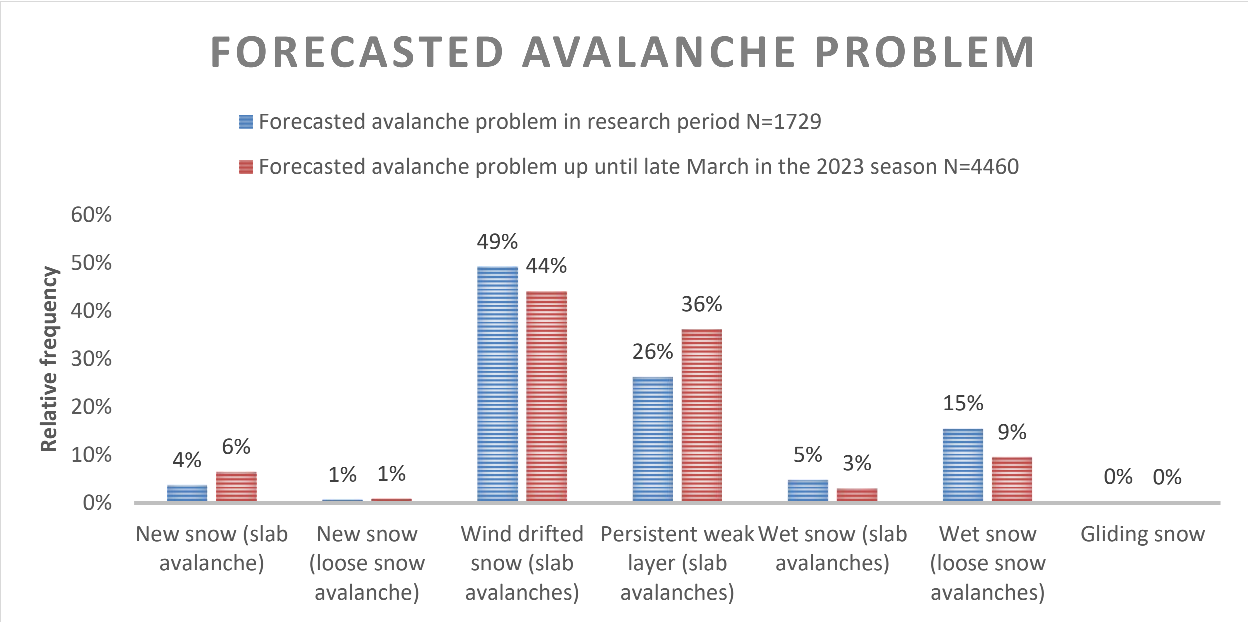

Table 2 - Forecasted avalanche problems in the season and the research period.

Looking at the forecasted avalanche danger level and avalanche problems the research period seems to fall within what is reasonable to call normal. It was probably a bit warmer and wetter period that usual because of the decrease in forecasted persistent weak layers and new snow problematic and an increase in forecasted wet snow problematic.

4.2 Survey on assessed uncertainty for avalanche forecasters

To gather data on how avalanche forecasters assessed and handled uncertainty I conducted a survey about uncertainty in the avalanche forecast. The survey assumes that for every avalanche bulletin produced, there is an element of uncertainty and that the forecasters is aware of this. At the end of every forecasting day, they were encouraged to answer the survey on uncertainty that was made available to them through the forecasting tool, RegVarsel, and the Microsoft Teams-channel for the forecasters on duty.

In the survey the forecasters were to choose the forecasting region they assessed had the most uncertainty in the avalanche forecast for the next day. After that followed multiple questions about the uncertainty and how they choose to handle it. The flow of the survey with the different parts it consisted of is shown in Figure 2.

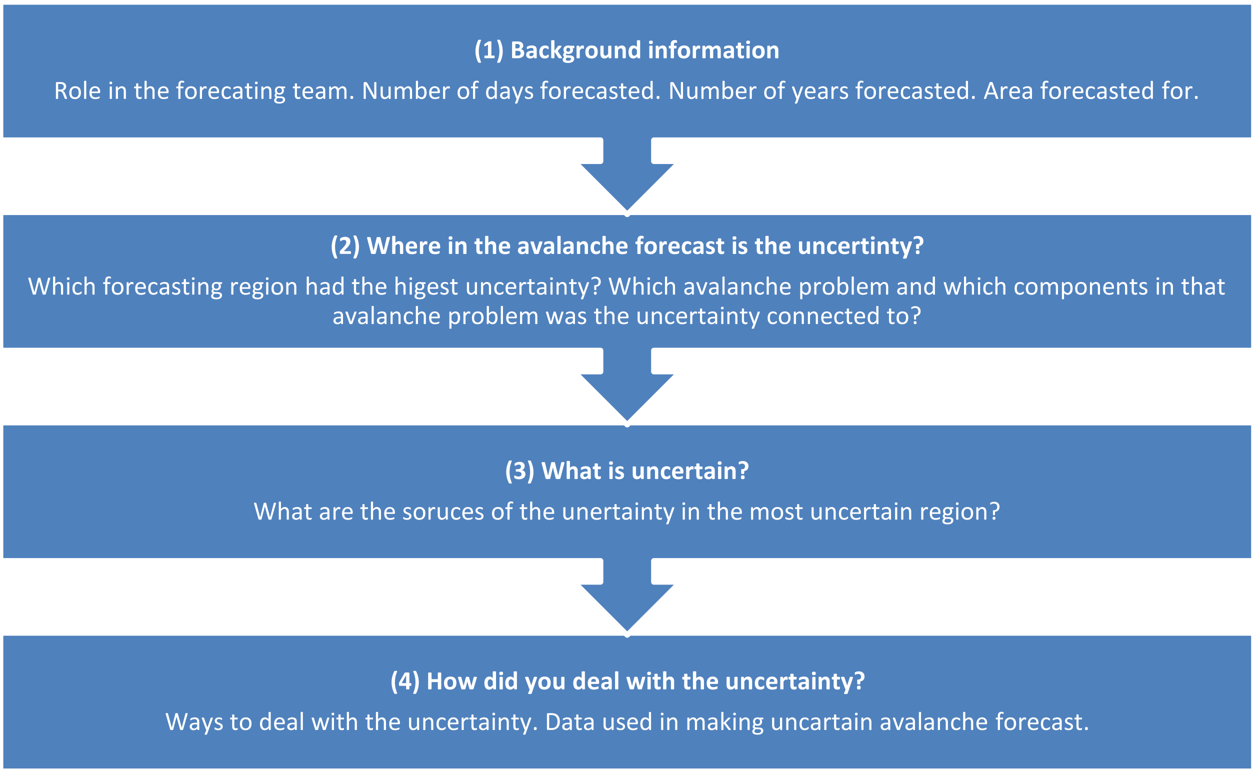

Figure 2 - The flow of the survey

The survey has four main parts as displayed in Figure 2. The first part gives me data about the avalanche forecaster and which area they forecasted for. The second part gives me data about where the most uncertainty is found (forecasting region and avalanche problem). The third part gives data about why it is uncertain, where does the uncertainty comes from. And the fourth and last part of the survey provides data about how the forecasters deals with uncertainty and which data is the most important when working with uncertain avalanche danger situations.

To ensure that the survey gave me data on what it was supposed and that it had the questions and answer options needed to measure the different variables of uncertainty I was interested in, I conducted several expert reviews, which served to strengthen the validity of the study (Johannessen et al., 2010). Through meetings with different lead forecasters, we discussed the questions and answer options and made revisions if we found that something was missing. As a last quality test of the survey, before the final version was published, I conducted a pre-study where the forecasting team on duty tested the survey as it was intended used, to see how it worked out and if they felt it made sense.

After I got thumbs up on the pre-study, the survey was distributed to the forecasters on duty through the forecasting platform, RegVarsel on the 23rd of January and was available to the 6th of March. A link to the survey was placed in the bottom of the forecasting platform (Figure 3), so that the forecasters where constantly reminded about the survey throughout the day.

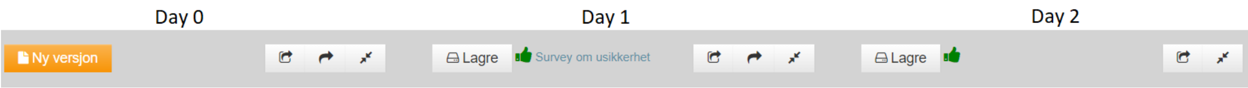

Figure 3 - Placement of link to the survey in the forecasting platform.

The results from the survey were combined with data extracted from the most uncertain avalanche forecasts. This extra dataset includes data about the forecasted avalanche danger level, avalanche problems, avalanche danger description, snow cover description and uncertainty chosen in the forecasting tool. Combining this data with data gathered from the avalanche forecasts I'm able to connect the most uncertain regions to what was forecasted.

4.2.1 Item generation and validation

To measure a theoretical concept such as uncertainty it must be broken down to measurable values. This is the process of item generation that should strengthen the reliability of the study (Ringdal, 2018). The item generation was limited to part 3 of the study, as this is where uncertainty was sought to be measured. The item generation consisted of two steps. Firstly, a literary review was conducted to identify sources of uncertainty in avalanche forecasting. The second part consisted of using subject matter experts to review and validate the items. Before the survey was published a pre-survey was also done.

The Canadian Avalanche Association have looked at factors that influence certainty, or uncertainty, and divided them into two main categories (CAAs Industry Information Exchange, 2015). First are factors that influence the forecasters certainty about the current conditions (nowcast), and that is related to different of data. The second are factors that influence the forecasters certainty about forecasted conditions, which is related to the weather forecast (CAAs Industry Information Exchange, 2015). The other part of the literature review considered the work on uncertainty through the ARCT-RISK project in Longyearbyen, Svalbard. During the project they have identified sources of uncertainty related to the five stages of avalanche risk management. The different sources of uncertainty is found in all stages from framing of the problem to the treatment of the risk (Øien & Alberchtsen, 2022). However, sources of uncertainty relevant for this thesis is limited to the stages framing, data collection and risk assessment.

Based on the literary review a draft of the survey with the variables and values was created. This draft was then sent out to three lead avalanche forecasters, subject matter experts, to review. Following the reviews of the experts, the final draft of the survey was prepared. The last part of the preparation of the survey was to conduct a pre-study to make sure the survey worked in practise with the forecaster's workflow.

4.3 Analysis

As the main part of the project is to describe aspects of uncertainty in avalanche forecasting, I mostly use the data to show the occurrences of different values and how different variables are connected.

In the first part of the survey, where I want to examine if some specific situations are connected to the most uncertain avalanche forecasts, I conducted chi square tests of the modern version (Ringdal, 2018). This is a statistical hypothesis tests, which tells if the values in two categorical variables are independent in influencing each other. In the modern version of the chi square test the statistical hypothesis is implied and not formulated (Ringdal, 2018). This meaning I will be able to tell if the most uncertain avalanche bulletins are connected to specific danger levels and avalanche problems. The rest of the study focuses on descriptive statistics to show different aspects of uncertainty and its handling. The different sides of the survey have different values, so to make sure it is easy to compare I have chosen to present everything in percentages of a total. That either being all responses in total or the total of a certain value in a variable.

4.4 Quality of the research project

The quality of the research is crucial in the case of getting reliable and valid results, and to ensure trustworthy results. I will review the quality of this research project considering the terms, reliability, and validity. Reliability meaning how replicable the method data collection is, and validity is how well the research answers the questions asked (Johannessen et al., 2010; Ringdal, 2018).

4.4.1 Quality of the survey

Reliability is another measure of a study's quality, it says something about if the way the study is conducted and if it has credibility (Thagaard, 2018). To ensure credibility in the study I have focused on transparency in how the survey was created and conducted. The survey is added as an appendix so that it is possible to see how it looked like for the respondents and test the questionnaire (Johannessen et al., 2010). Something that can reduce the reliability of the questionnaire is the respondents answer. In some subjects the respondents might not want to answer honestly because it could put them in a bad light, or they are giving away information they do not wish to give. To counter this, the respondents was anonymous, and the data was handled confidentially by the researcher, and not possible to trace back to the respondent. And there will always be measurement errors when conducting surveys, but having more respondents smooth it and.

I have decided to view the study's validity in term of its internal and external validity. The internal validity is about my interpretation of the results and if it is valid in relation to the phenomenon I have studied (Thagaard, 2018). As I will elaborate a bit more on in the next section, I have a connection to the environment I've studied. This can be reflected both positively and negatively on the validity of the results and play a role in how I view and interpret the results. Having an acquired understanding of the subject from within makes me predefined to lean toward an understanding of the phenomenon than can make me less open to "new perspectives" and less critical to my findings (Thagaard, 2018). On the other hand, already having acquired an understanding makes it easier to pick up on and understand patterns, as is a big part of this study. And the close collaboration with lead forecasters and using expert reviews in the process of designing and implementation the questionnaire ensured that the survey made sense in the eyes of the respondents and that it was perceived as relevant to the respondents.

Another thing that challenges the internal validity is using closed questions in the survey. This attempt to operationalize a phenomenon does not always pick up every possible answer alternative. To counter this I introduced an option to choose open answer so that, if needed, the respondents could provide an additional answer (Ringdal, 2018), rather than giving a wrong one. As well as not all the pre-defined answers not always covering the situations, there could be situations where there was not much uncertainty for the forecasters. In these cases, to not get invalid answers about the source of uncertainty, a “low uncertainty”-option was introduced into the survey.

External validity is about the transferability of the results, if can they apply to other “populations” or different time-periods (Johannessen et al., 2010). This study focused on the forecasters in the regional Norwegian Avalanche Warning Service, and as regional avalanche forecasting faces some different challenges than site-specific avalanche forecasting, how the forecasters in the different forecasting-types view uncertainty might change. There are other aspects in site-specific forecasting that one does not find in regional forecasting, like the aspect of a specific avalanche path or exactly how much snow is in one specific release area. But there are also many similarities. Regardless of the type of forecasting, weather and snow cover plays a very important part in the avalanche danger. The study is also limited to a period, and mostly focus on uncertainty in a period which where it is normally less warm weather and sun radiation does not play an equally large role in the avalanche danger. This is important to keep in mind when view the results and make them less generalizable to uncertainty in avalanche forecasting in general.

4.4.2 Ethical considerations and conducting research on my own organisation

Since 2015 to the summer of 2023, I have been involved with the Norwegian Avalanche Warning Service (NAWS) doing fieldwork, where I’ve been collecting data about the snow cover and avalanche danger. And during the summer of 2021 to the summer of 2023, I have worked part-time as a department engineer at the Norwegian Water Resource and Energy Directorate and worked closely with many of the lead forecasters in NAWS with various tasks related to the warning service. This has resulted in me meeting and getting to know most of the avalanche forecasters in NAWS, and them knowing me. From a research point of view this has compromised me to the field I’m studying. This is one of the reasons I chose a quantitative approach, so that I did not have to be “close and personal” with the subjects I am studying. This also opened the possibility to get data from the forecasters while they stay completely anonymous and making sure I would not be able to connect the answers in the survey to any of the forecasters.

This involvement with the object I’ve studied can be viewed as both positive and negative. On one hand I am compromised and formed in my opinion and views by the NAWS. Most of my knowledge about avalanches and avalanche danger comes from either my own research or through courses, seminars or conversations with people working in NAWS. Since I have such a close relation to NAWS and the people working there, it is not possible to ensure complete objectivity in my role as researcher. The relation to the warning service can, proven or unproven, influence how I choose to present or emphasize aspects of the results in a more favourable way than the data base should indicate. This is discussed in the prior section as a challenge to the study's validity. On the positive side, due to my past working-relationship, it grants me access to a lot of data and computer systems which is used in avalanche forecasting, and I got access to people which is skilled in the field. This has helped me in creating a questionnaire with high credibility and implementing it in the daily routine to the forecasters.

5 Results

Here I will present the results from the survey the avalanche forecasters answered after every forecasting day, combined with data gathered from the published forecasts. The project seeks to answer three questions. (1) what are situations that involve uncertainty? (2) what are the sources of uncertainty in these situations? (3) how are these situations dealt with, and how can they be dealt with in the future?

5.1 Situations in the avalanche forecasts when uncertainty is repeatedly found

I have chosen two ways to view the avalanche danger situation. It is through the forecasted danger level and the forecasted avalanche problem. During the survey on uncertainty, the forecasters chose the forecasting region with the most uncertainty associated with it. When doing so, I connected the region they chose to the forecasted avalanche danger level and the forecasted avalanche problems. This way I can see if there is a connection between what is forecasted and the most uncertain regions.

5.1.1 Danger level

To correct for forecasted danger levels during the research period I added all the forecasted danger levels to then see if the uncertain danger levels followed the overall forecasted danger levels or if the danger level in the most uncertain regions was more connected to some specific danger levels.

The table shows that both the most often forecasted danger level and the most uncertain danger level (DL) is DL2 – moderate avalanche danger, followed by DL3 – considerable avalanche danger. Later followed by DL1 – low and DL4 – high. DL1 (11 % forecasted – 7 % uncertain) and DL2 (52 % forecasted – 49 % uncertain) was forecasted relatively more often than it was chosen to have the most uncertainty, while DL3 (36 % forecasted - 42 % uncertain) and DL4 (1 % forecasted – 2 % uncertain) was forecasted relatively less that it was chosen to have the most uncertainty (Table 3). This indicates that the higher danger levels with generally more unstable conditions have a higher degree of uncertainty connected to it. To test if this indication is statistically significant a chi-square test was conducted to assess the relationship between the forecasted danger levels and the danger levels in the uncertain regions. The relationship was not significant, X^2 (3, N = 1158) = 4.54, p = .20, meaning that there is no statistical connection between forecasted avalanche danger level and the most uncertain regions, and that it is not possible to say that higher danger levels generally consist of higher uncertainty.

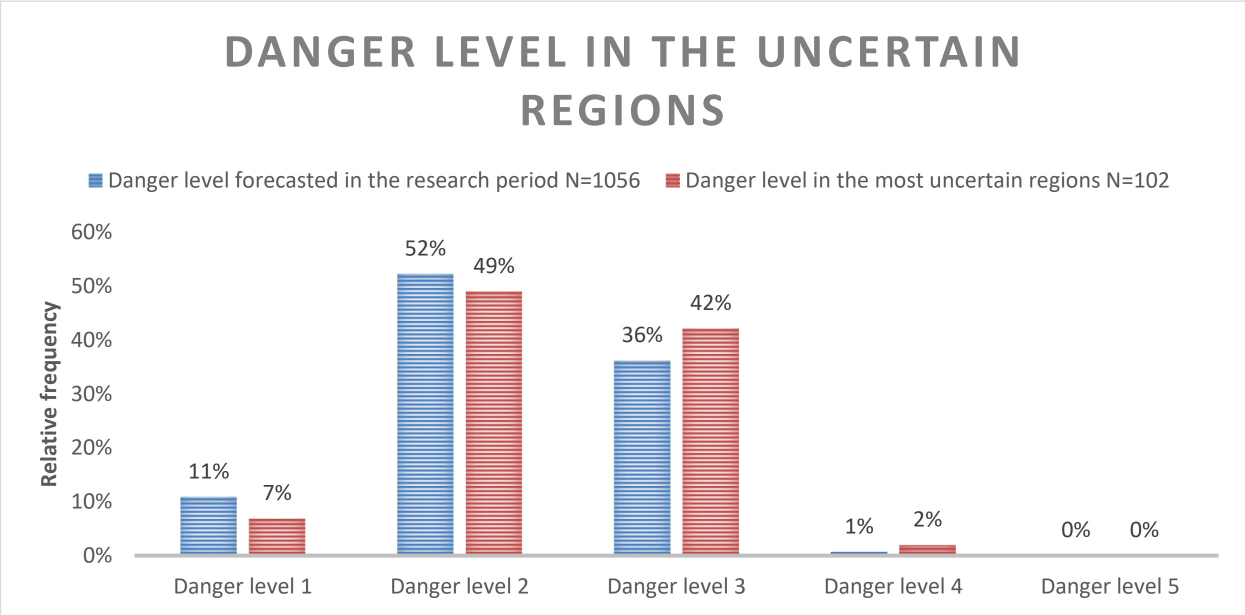

Table 3 - Forecasted danger level in the research period and forecasted danger level for the regions with the highest uncertainty.

5.1.2 Avalanche problems

As for avalanche problems, the only problems that was chosen as uncertain more often that it was forecasted was persistent weak layer (26 % forecasted – 49 % uncertain) and wet snow slab avalanches (5 % forecasted and 7 % uncertain). All the other avalanche problems were forecasted more often than it was uncertain. However, wind slab still holds as the position as the second most uncertain avalanche problem as it was chosen 33 % of the time (Table 4). An explanation of this could be that this was the only avalanche problem forecasted that day, and therefore it had to be chosen as the uncertain one.

The questions follows if the uncertain avalanche problems are connected to the general picture, or if there are some that sticks out. To get assess this this I did another chi-square test on the relationship between all the forecasted avalanche problems and the uncertain avalanche problems in the most uncertain regions. The relationship between the two variables were significant, X^2 (4, n = 1838) = 32.75, p = < 0.00001, shows that there is a connection between the forecasted avalanche problems and the most uncertain regions.

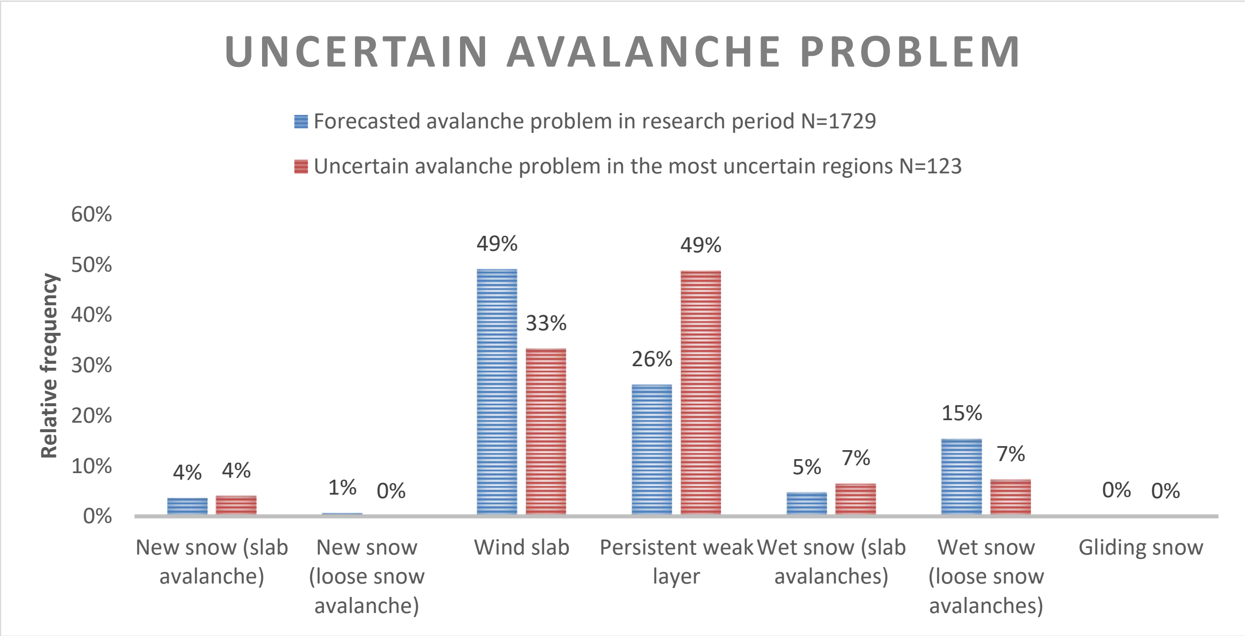

Table 4 - Forecasted avalanche problem and the avalanche problems chosen as uncertain in the research period.

Avalanche problems does not necessarily occur alone and are not mutually exclusive. Of the 2812 forecasts in the season, and the 1056 forecasts produced in the research period, 585 of the forecasts contained two or more avalanche problem. A review of the forecasts of the most uncertain forecasting regions chosen in the survey shows that 70 % of the forecasts contains two or more avalanche problems. Using a chi-square test it gives a significant result, X^2 (1, n = 1158) = 7.65, p = .0057. The low p-value tells us that there is a statistical connection between the amount of forecasted avalanche problems and the most uncertain regions.

5.1.3 What is it about persistent weak layers and wind slab?

I have defined a critical value if I have enough data to take a deeper examination of the uncertain avalanche problem. This value is 10 observations. Looking back at Table 4 we can see that the avalanche problems persistent weak layers and wind slab are the ones that are most often chosen, and they both exceeds the critical value number of 10, therefor I will examine them closer further in this thesis.

Avalanche problems are made up of six components as described in chapter 2.2.2. In the survey the avalanche forecasters had the opportunity to choose which component in the avalanche problems uncertainty was related to. This can give an indication on what in the problems that uncertainty is often related to.

Persistent weak layers are an avalanche problem that persist over time and is not directly related to the ongoing or previous weather. The problem arises through processes ongoing in the snowpack. The highest uncertainty about this problem is how easy it is to trigger avalanches on this problem (44 of n=60) and the spatial distribution of the problem (47 observations of n=60). However, the other components also occur a reasonable amount of time. Uncertainty about which weak layer in the avalanche problem occurs 13 times, uncertainty about the possible avalanche size occurs 16 times, and uncertainty about the exposition and hight occurs 9 and 14 times.

Wind slab as an avalanche problem is much more related to the previous weather and very dependent on the forecasted weather regarding its development over time. The components which is most uncertain is how easy it is to trigger avalanches on this problem (26 of n=41), the spatial distribution of the problem (23 of n=41), and the possible size of the avalanches (24 of n=41). The rest of the components does not occur as often, but uncertainty about the hight of the problem occurs 8 time, whereas uncertainty about exposition and which weak layer in the avalanche problem occurs 3 and 4 times.

To summarise this section, I have identified that the most uncertain regions does not seems to be connected to specific danger levels. However, there is a connection between these regions and the forecasted avalanche problems. Persistent weak layers occur as an uncertain avalanche problem almost double the amount of time than it is forecasted. This pointing to that there is usually more uncertainty connected to it than the other problems. There can be other avalanche problems where this also it the case, but the data on these problems are so few that I've chosen not to look at it.

5.2 Why is the avalanche forecast uncertain?

Now that we have established which situations that seems to be more uncertain that others it is time to look at why these situations are uncertain. Avalanche forecasting, being a prediction of a future situation, is uncertain to some degree no matter how you view it. However, one of the things that is interesting is why the forecasts are uncertain. In this chapter I will look at the sources of uncertainty at a generic level and then related to the avalanche problems persistent weak layers and wind slab.

5.2.1 General sources of uncertainty

In the following table I'll present the sources of uncertainty on a generic level. In the main categories of the different sources of uncertainty is view, and it is possible to see how often they occurred during the season up until the 24th of March, how often they occurred at the time of the survey and how often they were chosen in the survey.

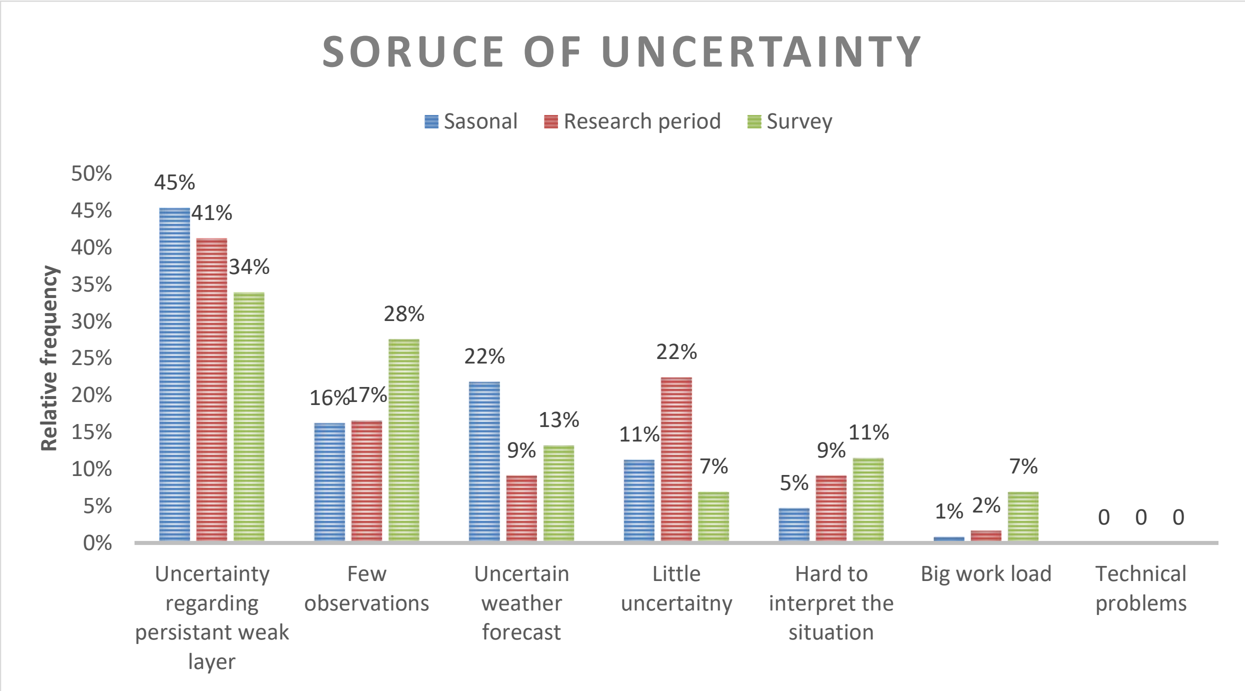

Table 5 - The overall categories of uncertainty during the season, in the research period, and from the survey.

As Figure 5 shows the most common source of uncertainty is the inherent one in persistent weak layers (120 % of 300), followed by uncertainty due to few observations (61 % of 300) and an uncertain weather forecast (44 % of 300). There are some big differences in the data that points to some sources have occurred more often, either in the research period or throughout the season in total. The data points to uncertainty coming from the weather forecast is higher in the season than in the research period (22 % in the season to 9 % in the research period).

The data that is not collected through the survey, but through the forecasting tool, RegVarsel, has a look of information missing. The number of forecasts that do not have a value for source of uncertainty is for the research period 739, and for the season in its entirety 2161. Therefor this data is not necessarily a good representation of the reality.

5.2.2 Sources of uncertainty under persistent weak layers and wind slab

Since situations with persistent weak layers is one of the situations that occurs often as the uncertain it is interesting to take a closer look at why this is the most uncertain avalanche problem. The first thing that sticks out is the uncertainty related to persistent weak layers is the highest source of the uncertainty (53% relative frequency) followed by a lack of observations (27% relative frequency). The other sources of uncertainty occur a few times, but it does not reach the critical value of 10 occurrences.

When the avalanche danger situations are related to the problem wind slab the pictures is somewhat different. Few observations are the dominant source of uncertainty with 35% relative frequency, followed by uncertain weather forecast (21% relative frequency) and little uncertainty (17% relative frequency). As with the persistent weak layers, the other sources do not reach the critical value of 10 occurrences. The reason I've included little uncertainty is because it shows that this also is one of the avalanche problems that there sometimes are little uncertainty related to.

		Source of uncertainty					
		Little uncertainty	Uncertain weather forecast	Hard to interpret situation	Few observations	Uncertainty related to PWL	Big workload
Avalanche Problem	Persistent weak layers N=60	2 %	5 %	8 %	27 %	53 %	4 %
	Wind slab N=41	17 %	21 %	10 %	35 %	10 %	8 %

Table 6 - Table that shows the relative frequency of each source of uncertainty for the avalanche problems persistent weak layers and wind slab.

There are some occasions that both avalanche problems have been chosen as uncertain in the same observation (N=10), and then the source of that uncertainty are connected to both. As a result of this there is a 10 % relative frequency of uncertainty regarding persistent weak layers connected to the avalanche problem wind slab. Avalanche danger is a complex natural phenomenon, and it is not given that situations come alone or that having one excludes having another. Technical problems were also included as a source that could result in uncertainty, but it never occurred, therefor it is not included in the analysis.

To summarize this, the general results show that the most prominent source of uncertainty is in the persistent weak layers, followed by few observations and the weather forecast. About the avalanche problems persistent weak layer and wind slabs the uncertainty follows the problem. With persistent weak layer the uncertainty lies within itself, while with wind slabs it is often few observations or weather forecast that is the source of the uncertainty.

5.3 How does avalanche forecasters handle the uncertainty they meet?

Now that I've identified the situations with the most uncertainty and the reason behind this uncertainty it is time to take a closer look at how the forecasters deal with this uncertainty.

As established in previous chapters and as the data shows, there is most of the time some kind of uncertainty involved in forecasting. Uncertainty needs to be dealt with in some way, and the data collected shows that it most of the time is dealt with in some way or another.

5.3.1 Generic handling of uncertainty

Avalanche forecasters deal with uncertainty in different ways depending on the reason behind the uncertainty. Looking at it generically, there are two ways that sticks out. The forecasters discuss with colleagues (34 % of the time), meaning other avalanche forecasters on duty, and they describe the uncertainty in the forecast (32 % of the time). Following is sending out e-mails and calling the snow observers (12 % and 10 % of the time). Sometimes they also discuss the weather forecast with the meteorologist on duty (9 % of the time). It rarely happens that they do nothing to deal with the uncertainty (3% of the time).

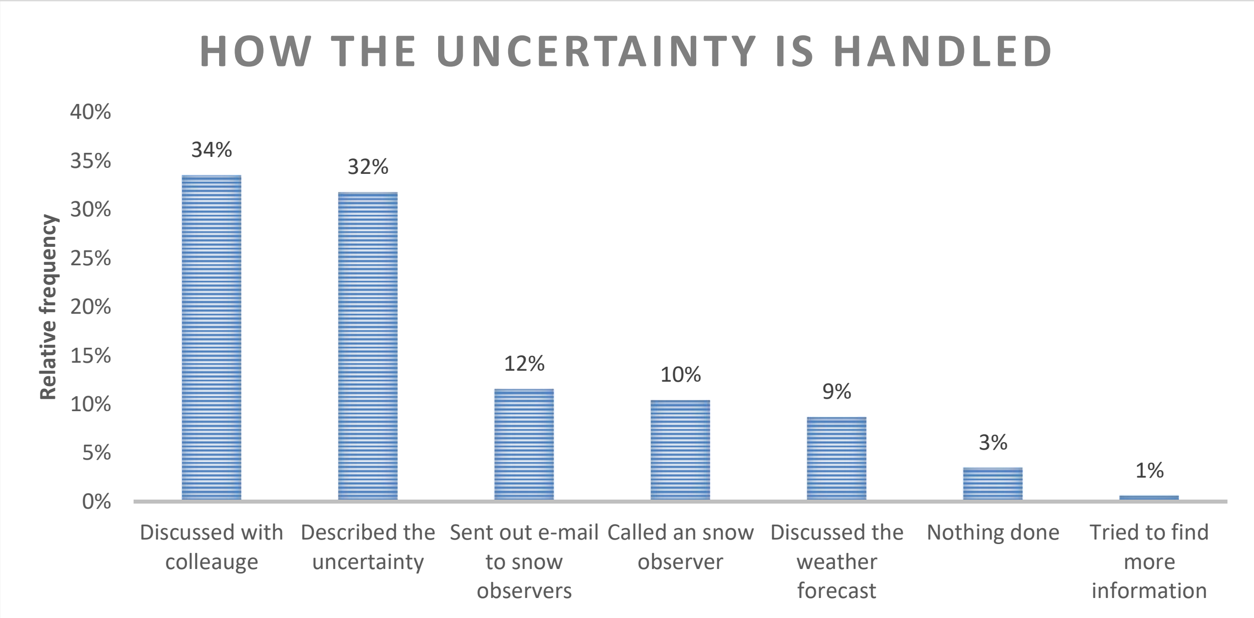

Table 7 - Generic ways used to handle uncertainty in regional avalanche forecasting.

Since the second most common way to deal with uncertainty is to describe it in the forecast it is interesting to see where it is communicated and how it changes with the different source of uncertainty. In Table 8 this is illustrated. Uncertainty is usually described in the avalanche danger assessment, followed by snow cover description. The only time the uncertainty was described in mountain weather forecast was when the weather forecast was uncertain, however it seems to be rarely used to describe uncertainty.

	Main message	Avalanche danger assessment	Snow cover description	Mountain weather
Generic	11 %	57 %	31 %	1 %
Uncertain weather forecast	10 %	60 %	20 %	10 %
Hard to interpret the situation	0 %	58 %	42 %	0 %
Few observations	13 %	58 %	29 %	0 %
Uncertainty regarding PWL	8 %	56 %	36 %	0 %

Table 8 - Relative frequency of where in the avalanche forecast uncertainty in communicated.

5.3.2 Is there any difference in how avalanche forecasters deal with uncertainty under different sources of uncertainty?

The way uncertainty is dealt with by forecasters is dependent on its source. As shown in Diagram 1 the most normal ways to deal with uncertainty is through discussing with colleagues and to describing it, and when the weather forecast is uncertain you also discuss that with the meteorologist on duty. The only time nothing is done to handle the uncertainty is when the forecasters find it hard to interpret the situation (10 % of the time). When using observers to handle the uncertainty, either by calling them or sending them e-mails with questions, is when the observers can provide something new or additional thoughts on the matter. If Diagram 1 shows the real picture the forecasters do not use observers to deal with uncertainty related to the weather forecast.

There is one more source of uncertainty, “Big workload”, but I have chosen to exclude this source in the diagram because it only had 6 occurrences, and the answer did not necessarily present a representative image of how forecasters deal with that situation.

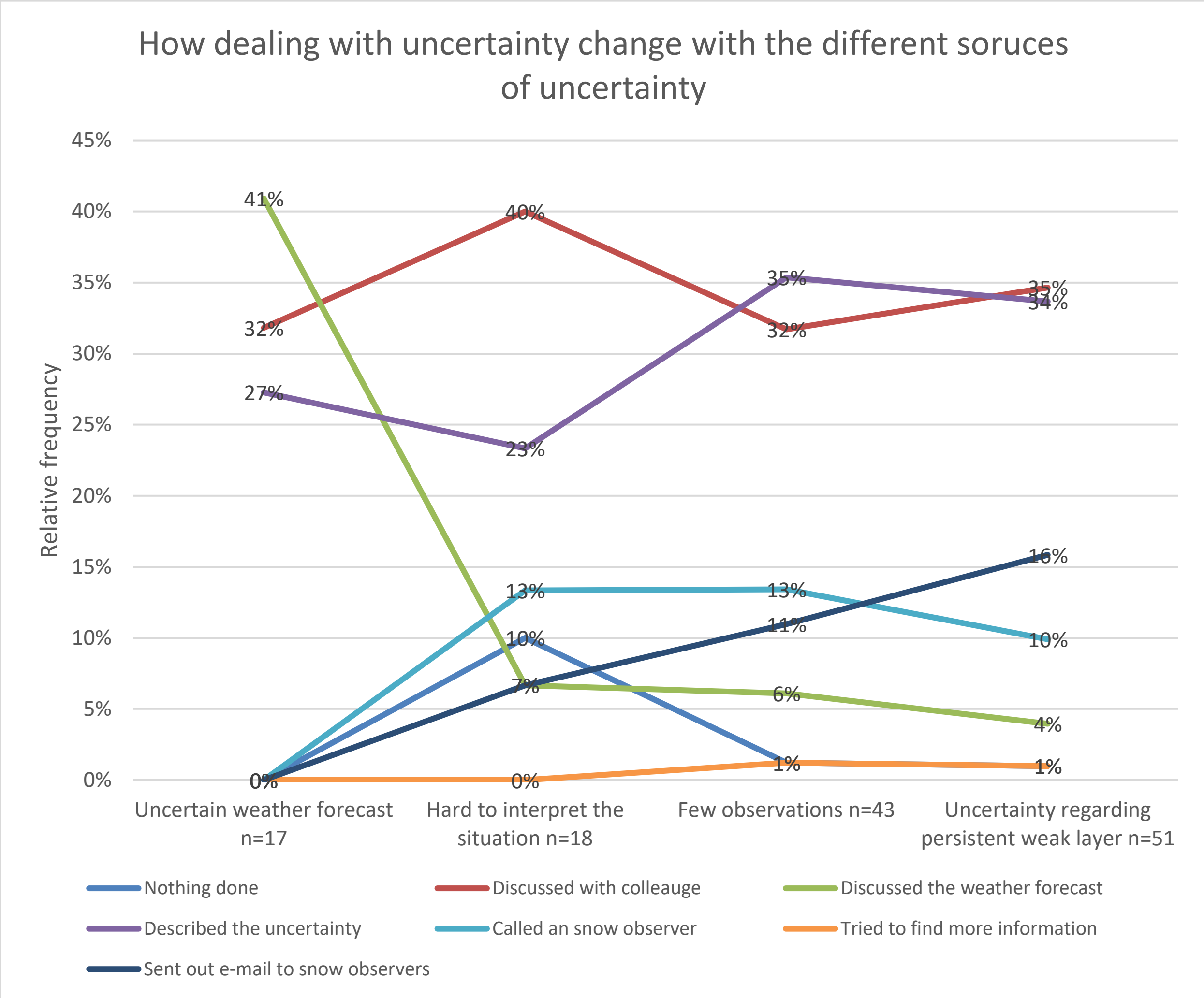

Diagram 1- A line diagram showing how the different ways to handle uncertainty changes with the different sources of uncertainty. The selected source of uncertainty is placed on the horizontal axes and the coloured lines are the different ways to deal with uncertainty. The percentage is connected to how often the different sources of uncertainty is handled in one way.

This section focused on how the forecasters handle the uncertainty. And what is clear from the results is that forecasters take active measures to deal with the uncertainty and try to ensure quality in the warnings. The most common ways to deal with uncertainty is either discussing with another forecaster or describing the uncertainty in the forecast. Except when it is an uncertain weather forecast, the ways to deal with uncertainty does not change much.

5.4 Which data sources is important for forecasters in times of uncertain forecast?

Now that we know what situations are uncertain, why these are uncertain, and which measures the forecasters take to handle the uncertainty, which data sources is important to make good warning?

When avalanche forecasters make the forecasts, they have access to data sources from different sources. How they use and prioritise these data is interesting in terms of which data should be prioritised under the different situations that are uncertain. In the last part of the survey the forecasters choose and prioritised the importance of the five most important data sources they had used in making the forecast. In this chapter, as the chapter before, I will take a closer look at which data is prioritised in general and under the avalanche problems, persistent weak layer and wind slab.

5.4.1 In general

Avalanche forecasting is based on a combination of individual data, and under separate situations, e.g., avalanche problems, there are different need for distinctive kinds of data. In general, there are however some data that seems to be more important than other. An overview of all the data sources used in making the most uncertain avalanche forecasts in general is presented in Table 9. This shows which data source is most used and its ranking from the most important (1) to the fifth most important (5).

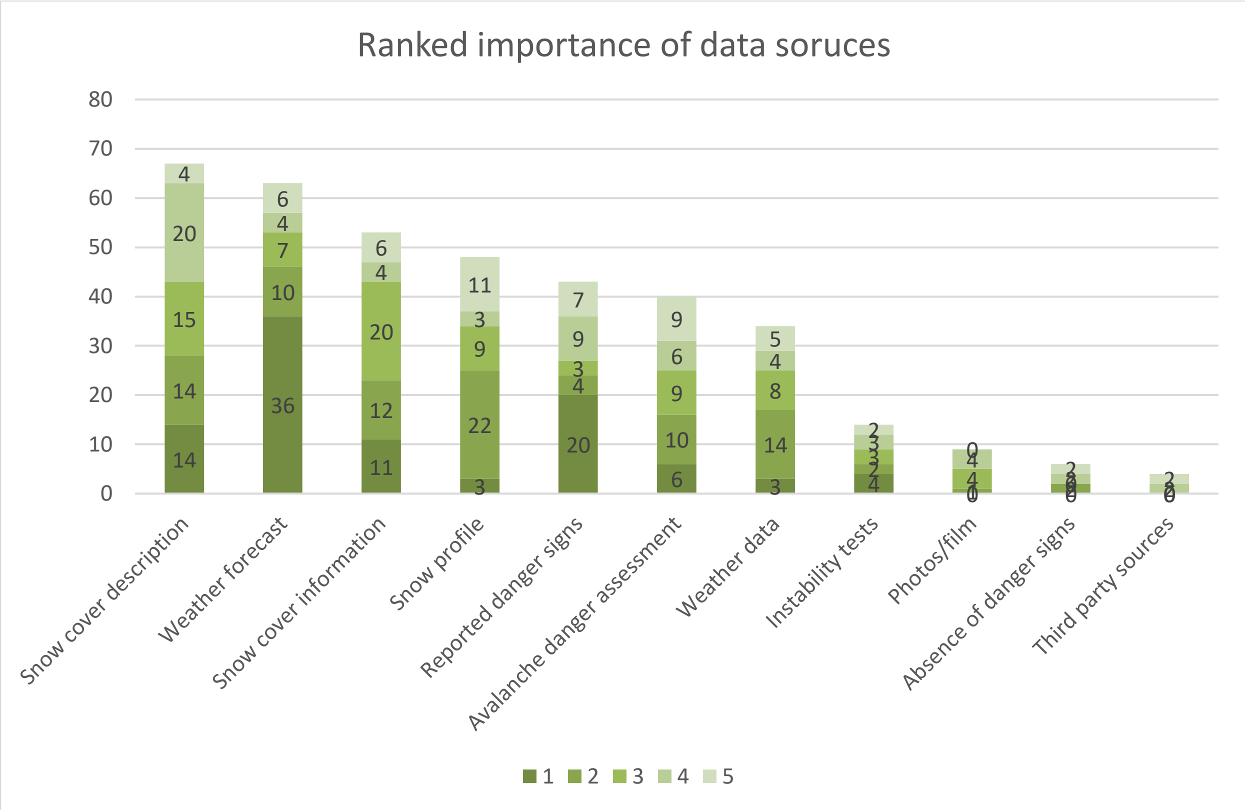

Table 9 - All the data sources used in the making of the most uncertain forecasts and their ranking from most important to fifth most important.

To figure the average importance of each data source I will look at both how many times they were chosen and their average score. In Table 10 the most important data sources are presented with number of times it was one of the five most important data and average score. The higher the score, the higher the crucial the data is. In Table 10 I have taken a closer look at the five most common data source and looked at their average score to see their importance.

Data name	*How many times chosen*	*Average score*
Snow cover description	67	2.791
Weather forecast	63	2.016
Snow cover information	53	2.648
Snow profile	48	2.938
Reported danger sign	43	2.512

Table 10- The most important data sources when making the avalanche forecasts in general.

Following the same pattern as the rest of the chapter I will further present the findings when the avalanche problems has been persistent weak layers and wind slab.

5.4.2 Persistant weak layer and wind slab

Different situations demand different kinds of data to make assessment of the current and future avalanche danger. To illustrate how the different sources of data is distributed between the avalanche problems persistent weak layers and wind slab I have put them into the table listed below (Table 11).

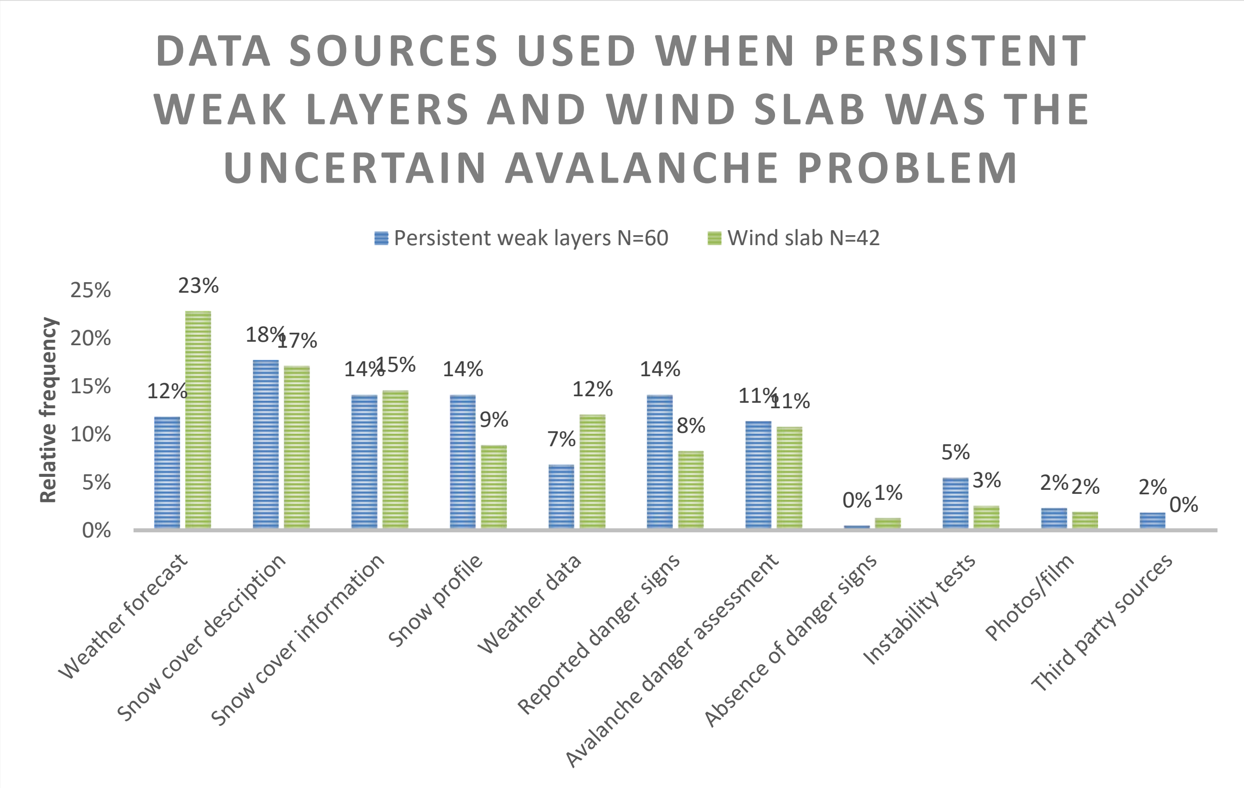

Table 11 - Data sources and their relative distribution under the avalanche problems persistent weak layers and wind slab.

In the table above it is visual that weather forecast, and weather data plays a much more important role in forecasting wind slabs (23 % and 12 % versus to 12 % and 7 %). And snow profiles and reported danger signs play a larger role when forecasting persistent weak layers (14 % and 14 % versus to 9 % and 8 %). In Table 11 it seems that there are some data sources that seems to be equally important in during the different situations, that is snow cover description, snow cover information, and avalanche danger description from the field.

To summarize this, the importance of different data sources mostly changes depending on the avalanche problem situation. Snow profiles and danger signs are more important during situations with persistent weak layer, while weather forecast, and weather data are more important during situations with wind slabs. This section shows that focusing on the right kind of data during different situations is highly important to give the forecaster a good basis for making the warnings.

Overall, the results show that there clearly are some situations that are generally more uncertain than others, and it is possible to connect that uncertainty to certain sources. Based on this the forecasters take active measures to reduce the uncertainty, and it is mostly the same techniques regardless of the situation. To help the forecasters make good warnings under uncertainty it is important to give them the right kind of data, and that changes based on the situation. In the next chapter I will discuss these findings in the context of different aspects of uncertainty.

6 Discussion

This study has three goals. The first (1) is to identify the situations with higher uncertainty than the "usual" uncertainty when making predictions. (2) When you can point to the situation and know the sources of uncertainty, can you do something to reduce this uncertainty (understanding how some sources of uncertainty can be reduced and collecting the right kind of data, and (3) given an uncertainty that cannot be reduced, shall we just give up and ignore it or are there ways to handle those situations.

This chapter seeks to use the situations and sources of uncertainty identified and to see them considering the different aspects of uncertainty described in chapter 3.

6.1 The uncertainty – can we reduce it?

To deal with a problem, you need to accept there is one and understand the reason behind the it. This study, even with its weaknesses, identified some situations that correlated with higher uncertainty. This made it possible to take a close look at these situations and find data that pointed to why they were assessed to be more uncertain.

If you divide the sources of uncertainty into two main categories, reducible (epistemic) and non-reducible (aleatoric), it's interesting to look at the different sources of uncertainty (Burgman, 2016)**.** In general, as the data points to, the most common sources that the regional avalanche forecast is uncertain is uncertainty regarding the persistent weak layer, few observations, and an uncertain weather forecast. So, what types of uncertainty are these sources?

Much of the uncertainty the avalanche forecasters face is because there is a lack of knowledge connected to data, or the strength of knowledge is weak (Aven, 2017). They are simply pointing to missing information as the reason for the uncertainty in the forecast. The uncertainty regarding persistent weak layers, is either about a lack of knowledge about the presence of, the characteristics of, or if it is an active weak layer. This is information found in the snowpack and can also therefore be categorised as snowpack-uncertainty (Jamieson et al., 2015). This is an uncertainty that can be reduced by collecting more and better data, strengthening the knowledge (Aven, 2017). And another source of uncertainty that can be connected to this is the source of uncertainty that is few observations. The avalanche forecasters are dependent on, especially in some situations, field observations to make good assessments of the situation and how it will evolve over time. The forecasting regions are stretch over a large geographical area, and to be able to give a representative picture of the situations they need observations that is representative for a larger area. Here as well, more and better observations are a key for reducing the uncertainty. To summarise, the key to dealing with epistemic uncertainty is to understand what affects the strength of knowledge that forecasters make their assessments on (Aven, 2017).

The other main category of uncertainty is aleatoric, that is not easily reducible and is connected to the natural variation of randomness of outcomes (Burgman, 2016). In this study the only source of uncertainty that can be directly linked to this type is the uncertainty in the weather forecast as the forecasters points out, this also corresponds with Jamieson et al. (2015) idea that weather is one of the main sources of uncertainty in avalanche risk. Uncertain weather forecasts did not occur that often in the research period (accounting for only 13 % of the sources of uncertainty in the survey). However, it is the third largest source of uncertainty in general and when it comes to the avalanche problem wind slabs. This is dimed very natural as wind slabs are directly correlated with weather conditions, wind direction, wind strength, temperature and new snow. Even though this is ultimately dimed as controlled by natural variation and cannot be reduced, collecting more data, getting a better understanding of the phenomena can help giving more accurate weather forecasts in the future, then resulting in reduced uncertainty form this source.

6.1.1 Levels and sources of uncertainty that forecasters meet

But what is it about these sources of uncertainty? Schmitt and Klein (1996) pointed out that there are levels and sources of uncertainty that can help us understand them.

As the previous section explained a lot of the uncertainty in avalanche forecasting comes from having to little or weak knowledge about what is happening with the snow, they feel they have to few observations to support their assessment on and do not have the required information about aspect about weak layers and what is happening in the snowpack. The lack of this information and knowledge is what Schmitt and Klein (1996) identified as the "missing information" source of uncertainty.

The forecasters also must deal with unreliable information as a source of uncertainty (Schmitt & Klein, 1996). Weather forecast can play a big role in deciding how the avalanche danger plays out. And sometimes the weather is harder to forecast than other times or is more unpredictable. This makes the avalanche forecasters questioning the correctness of the information provided from the weather forecast.

The previous section has pointed out that the uncertainty comes from missing information. However, it is important that the forecasters have an active idea about what level of uncertainty the source is. As Schmitt and Klein (1996) points out, it might be better to focus on the level of knowledge and understanding as Aven (2017) also points to, rather than focusing on getting more data. Even if the forecasters feel they are missing information to be more certain about the forecast, they should also consider if its more effective spending resources on interpreting the data they already have available. And lastly making projections on future based on the data and their understanding of it.

There is a source of uncertainty that is not addressed in the survey and in the discussion. It is probably also a source of uncertainty that is not in the mind of everyone. A lot of the data the forecasters use is written words provided by snow observers and other people out in the mountain which are posted on the digital platform, Varsom Regobs. As Burgman (2016) pointes out there is a third type of uncertainty that comes from the natural language we use, and with no standardise form/language for sharing information, there is introduced a source of uncertainty that is not addressed.

6.2 Dealing with uncertainty

A big part of the uncertainty identified is of a type that makes it reducible. But there is also a part that cannot be reduced, and you'll always end up with residual uncertainty when trying to make projections on the future. As mentioned in the section above, one way the forecasters might be able to reduce uncertainty is focusing of making sense of the data they have available and making projection thereafter. But sometimes gathering more information is the only way, and then it is important that the snow observers know what to provide.

6.2.1 Asking the right questions – Which information is highly valued?

Since much of the uncertainty comes from missing information, asking for the right information from the snow observers is one of the easiest ways to meet this problem. As (McClung & Schaerer, 2022) does, there are information classes that can say something about the instability of the snowpack and therefore likelihood of avalanches.

Not surprisingly, weather forecast was the data source that the most important for the forecasters with the highest average score and occurred second most times. This is information is available to the forecasters through meteorological projections and meeting with a meteorologist, and not something the snow observers can add to. Even though weather forecasts is the least direct sign of instability (McClung & Schaerer, 2022) it plays such a vital role in forecasting due to it being one of the main parameters of the development of the avalanche danger over the next few days.

The next most important data was reported danger signs, but the fifth most occurring data source. This source is the most direct sign of instability (McClung & Schaerer, 2022) and is clear information for the avalanche forecaster that the snowpack is not stable. Danger signs does not occur under every condition, and this is probably why it does not occur more often in the survey. But the low average score points to it being one of the most important data sources for indicating instability for the avalanche forecasters.

The other three data sources of the top 5 most occurring in the survey are class 2 information (snowpack factors). The data sources *description of the snow cover by a snow observer*, *information about the snow* cover and *snow profile* was the first, third and fourth most occurring data source and shows the importance of giving the forecasters eyes on the situation out in the mountain. This information does not directly indicate avalanche danger but is related to snow instability (McClung & Schaerer, 2022).

To summarize this, even when uncertainty is high, and the weather forecast might even be a source of the uncertainty, the weather forecast provides vital information that the forecasters rely on. And danger signs, maybe especially when uncertainty is high, is a clear indicator of snow instability and can help the forecasters be more certain in their assessments. Information about the snowpack is always important, but when uncertainty is high and the forecasters feel their missing information, the information provided about the snowpack is highly valued.

6.2.2 Dealing with unreducible uncertainty

If the uncertainty is not easily or practically reducible, it must be dealt with in other ways. One third of the ways forecasters handled uncertainty in the research period was to describe it in the avalanche bulletin. This is good in the perspective of making the users informed about the uncertainty in the assessments they use as decision-support tool, but it also brings another aspect of uncertainty into the equation. As Burgman (2016) points out, the natural language we use is imprecise and words can often have more than one meaning. Therefore, even though describing uncertainty in free-text as it is done today, it brings another element of uncertainty into the decision-support tool that the bulletins should be, and one that cannot be illuminated as easily as the other types of uncertainty.

Other ways forecasters deal with the uncertainty follows its source. When it's the weather forecast that is uncertain, they discuss it with the meteorologist on duty, and in general the forecasters discuss the uncertainty between them. This is, in general, viewed as a good way to deal with uncertainty as more eyes on a problem adds extra perspective and you might end up with a better picture of the situation.

6.2.3 The days you should be most conservative – if that is the best way to deal with uncertainty

There might be situations where one cannot reduce uncertainty, or it is a hard thing to do. As the study identified the avalanche problems persistent weak layers and wet snow slab avalanches are especially difficult to forecast and involves more uncertainty than other avalanche problems. And the sources of uncertainty in these avalanche problems are not always easily reducible for the forecasters.

Not many fatalities happen under wet snow conditions. A speculation is that wet slab avalanche problems correlate with bad weather (NVE, n.d.-b), and when it's bad weather, the amount of people in the mountains are lower than usual. In addition, avalanche accident and fatality statistics from the Norwegian Avalanche Warning Service (NVE, n.d.-b) shows that most fatal accident happens on conditions with persistent weak layer in the snowpack. Given the data collected in the study, persistent weak layers are the avalanche problem that is highest correlated with uncertain forecasts. Given Atkins (2014) approach to avalanche danger in the backcountry, it is especially under these types of conditions that skiers and other backcountry users should show moderation and be conservative when in and close to avalanche terrain.

As the results of the study shows, some of the sources of uncertainty are reducible by collecting more data. Even if Schmitt and Klein (1996) point to the data processing-stage as the stage where you can have the highest effect on reducing uncertainty, if the source of uncertainty is a lack of situational awareness or a question on presence or stability of a weak layer, taking the time to collect more data so that the pool of data is enlarged could give positive effect in reducing the uncertainty and making it possible to say with higher certainty if you should “open” or “close” terrain as given by Atkins (2014).

7 Concluding remarks

This thesis sought to take a closer look at uncertainty in regional avalanche forecasting from the forecaster's perspective. It was aimed to identify, understand, and address sources of uncertainty faced in regional avalanche forecasting. The defining research problem is *What are ways to reduce uncertainty in regional avalanche forecasting?* To answer this question, I needed to further spit up the questions.

The first was to identify which situations that had higher uncertainty and operationalised different situations into avalanche problems forecasted and avalanche danger level forecasted. The results did not show that there was any clear correlation between forecasted avalanche danger level and uncertainty, however, the avalanche problem persistent weak layer was the only one that correlated with high uncertainty. This showed that, as far as generalising uncertain situations goes, persistent weak layers can be said to be an avalanche problem with more uncertainty that the other avalanche problem.

The next step in finding ways to reduce uncertainty, is to understand the uncertainty, where it came from. Uncertainty was mainly divided into two categories in this study, reducible (epistemic) and non-reducible (aleatoric) uncertain. The study identified three sources of uncertainty that was the most occurring during the research period. In the column of reducible uncertain was a lack of knowledge about characteristics of the persistent weak layer in the snowpack and few field observations to make the assessment for a region. These sources of uncertainty could be reduced mainly by collecting more and better data, strengthening the strength of knowledge the forecasters make their assessments on. In the other column, unreducible uncertainty, was an uncertain weather forecast. As avalanche forecasting is about the situation ahead in time, it is very dependent on how the weather plays out. While not the biggest source of uncertainty under the avalanche problem persistent weak layer, it was much more correlated with wind slabs, as it is an avalanche problem highly connected to weather. Even though it is not easily reducible, a continuing focus on collecting more data and enhancing the understanding can lead to more accurate weather forecasts in the future.

And finally, on how to address the uncertainty we now know where and why some part of the avalanche forecast is uncertain. Based on the study we know that forecasters mean they are missing data, and that is a big part of the where the uncertainty comes from, but rather than just collecting more data the forecasters would have to interpret, it is worth noting that often it is more efficient emphasizing the importance of good interpretations of the data that already exists. That does not mean the warning service should look at ways to collect more and better data. The study found that five sources of data was generally more important for the forecasters, and improving these data is a step towards reducing the uncertainty for the forecasters. But as the study also found, not every source of uncertainty the forecasters face is reducible, and then it should be addressed in other ways. Communicating the uncertainty to decision-makers is a key way of letting the users make better informed decisions, but also recognizing the inherit imprecisions in the natural language as a new uncertainty. And as the forecasters communicate uncertainty, they also have the opportunity to point out which days the users should exercise more caution as the situation is more uncertain.

To summarize, forecasters deal with both reducible and non-reducible uncertainty while forecasting. Understanding what kind of uncertainty they deal with is a step towards know whether they should spend energy reducing it and knowing which kind of data they should prioritise. When dealing with non-reducible uncertainty, forecasters should use the possibility to inform the readers of the forecasts about the uncertainty, so that informed decisions could be taken by the users. And an informed decision can be to just be extra cautious in and around avalanche terrain because the situation is more uncertain than usually.

7.1 Future research

This thesis has done a lot to identify areas and give an introductory understanding of the uncertainty faced in regional avalanche forecasting and was thought of as a starting point for further research. This thesis did not provide a thorough understanding why some situations was related to higher uncertainty and more depth about the sources of uncertainty. Therefor I have some suggestions for further research in the list below:

- As my survey was limited to the months January – March, it would be interesting to do the same survey throughout an entire winter season to see if and how it varies through the winter.
- Taking a deeper look at the mechanism behind the different sources of uncertainty and how it leads to uncertain outputs.
- Examine how forecasters handles uncertainty through the mechanism they utilise today.
- What tactics work best to reduce or handle uncertainty under different situations.
- Given forecasters predicting probability of outcomes, measuring the strength of knowledge in their subjective probabilities would be interesting to characterize the uncertainties.

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Appendix 1 – An example of a printed avalanche bulletin from NAWS

2
Moderat

Snøskredvarsel for Tromsø fredag 28. april 2023

Publisert: 27. apr. 2023, 15:33:36

Fremdeles varme temperaturer og mulighet for sol gjør at snøen er myk og fuktig. Det kan være lett å løse ut skred og enkelte skred kan løsne av seg selv.

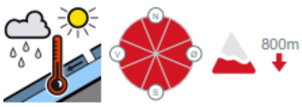
Skredfarevurdering

Fortsatt høye temperaturer, manglende nattefrost enkelte steder og sol vil øke vanninnholdet i snøen. Det vil være lett for en skikjører å løse ut skred i den fuktige snøen. Det er ikke utenkelig at det kan gå naturlig utløste flakskred i takt med at svake lag i snødekket fuktes opp, men omfanget er usikkert. Skavler vil svekkes av varmen og det er økt fare for skavlbrudd. Unngå opphold under glidesprekker.

Skredproblem

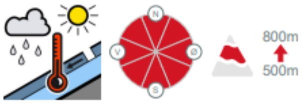
Våt snø (løssnøskred)

Du kan lett løse ut skred i noen bratte heng. Skred kan bli store nok til å begrave og ta livet av deg (str 2).



Våt snø (flakskred)

Skred kan løsne av seg selv i noen få bratte heng. Skred kan bli store nok til å begrave og ta livet av deg (str 2).



Snødekkehistorikk

Snødekket påvirkes av mildværet og selv i nordsider høyt til fjells fuktes snøen i overflaten opp i takt med at temperaturen øker. Før mildværet var det løs og ubunden snø i lune terrengformasjoner, vindpåvirket snø i fjellet og solskare i sørvendt terreng. I lavlandet er det gamle snødekket gjennomfuktet med en tynn skare mellom den siste snøen og det gamle.
Under snøen fra sist har det dannet seg et vedvarende svakt lag av kantkorn. Hvor lett det er å løse ut skred på dette varierer med hvordan flaket over er. Gamle kantkornlag er nå avrundet i lavlandet av regnet, mens de fortsatt kan være intakt enkelte steder i høyden. Generelt er disse vanskelige å påvirke.

Fjellvær

0-3 mm nedbør i døgnet. Nedbør som regn. Frisk bris fra sørøst. -2 °C til 6 °C på 700 moh. Delvis skyet. Nedbør bare lengst i sør.

Varselet er et hjelpemiddel, ikke en fasit. Gjør alltid egne vurderinger.
Vil du være helt skredtrygg, unngå alt skredterreng.

Sjekk oppdaterte varsel på varsom.no

En tjeneste fra

Appendix 2 – The survey on assessing uncertainty for NAWS

Intro til undersøkelsen

Usikkerhet i snøskredvarsling

Denne undersøkelsen skal gi svar på:
- Hvor ligger usikkerheten i dagens utarbeidelsen av snøskredvarsel for dag 1
- Hva er kildene til usikkerheten
- Hvordan blir usikkerheten håndtert av den som lager varslene
- Hvordan vurderer du som snøskredvarsler datakildene som var viktige i utarbeidelsen av varselet

Ved å gå videre og svare på denne undersøkelsen godtar du at data om deg som snøskredvarsler samles inn. Det som er interessant er hvordan du vurderer og håndterer usikkerheten i varslingsprosessen.

Innledende info

Hvilken rolle har du på vakt i dag?

- ◯ Skredmeteorolog
- ◯ Vaktleder
- ◯ Varsler

Hvor mange dager har du varslet i denne vaktperioden

	1	2	3	4	5
Antall dager varslet i denne perioden					

Hvor mange sesonger før denne har du vært snøskredvarsler for Varsom?

	0	1	2	3	4	5	6	7	8	9	10	11	12
Har varslet i antall sesonger													

Hvilket område varsler du for denne vaktperioden?

- ◯ Nord-Nord
- ◯ Nord-Sør
- ◯ Vestlandet
- ◯ Østlandet + Svalbard

I hvilken varslingsregion vurderer du usikkerheten i snøskredvarslet for dag 1 til å være størst

- ◯ Finnmarkskysten

- ◯ Vest-Finnmark
- ◯ Nord-Troms
- ◯ Lyngen
- ◯ Tromsø
- ◯ Indre Troms
- ◯ Sør-Troms
- ◯ Annen (f.eks. B-regioner)

I hvilken varslingsregion vurderer du usikkerheten i snøskredvarslet for dag 1 til å være størst

- ◯ Indre Troms
- ◯ Sør-Troms
- ◯ Ofoten
- ◯ Lofoten og Vesterålen
- ◯ Salten
- ◯ Svartisen
- ◯ Helgeland
- ◯ Heiane
- ◯ Hardanger
- ◯ Annen (f.eks. B-regioner)

I hvilken varslingsregion vurderer du usikkerheten i snøskredvarslet for dag 1 til å være størst

- ◯ Trollheimen
- ◯ Romsdalen
- ◯ Sunnmøre
- ◯ Indre Fjordane
- ◯ Voss
- ◯ Hardanger
- ◯ Heiane
- ◯ Annen (f.eks. B-regioner)

I hvilken varslingsregion vurderer du usikkerheten i snøskredvarslet for dag 1 til å være størst

- ◯ Jotunheimen
- ◯ Indre Sogn
- ◯ Hallingdal
- ◯ Vest-Telemark
- ◯ Nordenskiöld Land
- ◯ Heiane
- ◯ Hardanger
- ◯ Helgeland
- ◯ Svartisen

- ○ Annen (f.eks. B-regioner)

Hvor ligger usikkerheten?

Hvilket skredproblem er usikkerheten knyttet til? (flere valg mulig)

- ☐ Nysnø (løssnøskred)
- ☐ Nysnø (flakskred)
- ☐ Fokksnø (flakskred)
- ☐ Vedvarende svakt lag (flakskred)
- ☐ Våt snø (løssnøskred)
- ☐ Våt snø (flakskred)
- ☐ Glideskred

Velg hvilke komponenter i skredproblemet nysnø (løssnøskred) det er mest usikkerhet knyttet til (flere valg mulig)

- ☐ Hvilket svakt lag
- ☐ Utløsbarhet
- ☐ Utbredelse
- ☐ Skredstørrelse
- ☐ Himmelretning
- ☐ Høyde

Velg hvilke komponenter i skredproblemet nysnø (flakskred) det er mest usikkerhet knyttet til (flere valg mulig)

- ☐ Hvilket svakt lag
- ☐ Utløsbarhet
- ☐ Utbredelse
- ☐ Skredstørrelse
- ☐ Himmelretning
- ☐ Høyde

Velg hvilke komponenter i skredproblemet fokksnø (flakskred) det er mest usikkerhet knyttet til (flere valg mulig)

- ☐ Hvilket svakt lag
- ☐ Utløsbarhet
- ☐ Utbredelse
- ☐ Skredstørrelse
- ☐ Himmelretning
- ☐ Høyde

Velg hvilke komponenter i skredproblemet vedvarende svakt lag (flakskred) det er mest usikkerhet knyttet til (flere valg mulig)

- [ ] Hvilket svakt lag
- [ ] Utløsbarhet
- [ ] Utbredelse
- [ ] Skredstørrelse
- [ ] Himmelretning
- [ ] Høyde

Velg hvilke komponenter i skredproblemet våt snø (løssnøskred) det er mest usikkerhet knyttet til (flere valg mulig)

- [ ] Hvilket svakt lag
- [ ] Utløsbarhet
- [ ] Utbredelse
- [ ] Skredstørrelse
- [ ] Himmelretning
- [ ] Høyde

Velg hvilke komponenter i skredproblemet våt snø (flakskred) det er mest usikkerhet knyttet til (flere valg mulig)

- [ ] Hvilket svakt lag
- [ ] Utløsbarhet
- [ ] Utbredelse
- [ ] Skredstørrelse
- [ ] Himmelretning
- [ ] Høyde

Velg hvilke komponenter i skredproblemet glideskred det er mest usikkerhet knyttet til (flere valg mulig)

- [ ] Hvilket svakt lag
- [ ] Utløsbarhet
- [ ] Utbredelse
- [ ] Skredstørrelse
- [ ] Himmelretning
- [ ] Høyde

Hva er kildene til usikkerhet?

Hva er kildene til usikkerhet? (flere valg mulig)

- [ ] Det er et godt varsel / liten usikkerhet
- [ ] Usikker / stor variasjon i værprognose
- [ ] Vanskelig å forstå/forutsi situasjonen med min erfaring og tilgjengelig info / "Jeg sliter med å forstå/forutsi situasjonen basert på tilgjengelig informasjonen med min erfaring / faglige kunnskap"
- [ ] Usikkert / manglende observasjonsgrunnlag
- [ ] Usikkerhet knyttet til VSL

- [ ] Redusert kapasitet eller stor belastning / "Jeg fikk ikke tid til å se over all tilgjengelig informasjon eller tenke ut alle tankerekker"
- [ ] Tekniske problemer
- [ ] Annet

Hva i værprognosen var usikkert? (flere valg mulig)

- [ ] Nedbørsmengde
- [ ] Skydekke
- [ ] Nysnøgrense/nullisoterm
- [ ] Vindstyrke
- [ ] Vindretning
- [ ] Usikkerhet i lavtrykksbane (hvor være "treffer")
- [ ] Usikkerhet knyttet til tidspunkt for endring i været løpet av varslingsdøgnet (når været "treffer")
- [ ] Annet

Hvorfor var det vanskelig å forstå/forutsi situasjonen med informasjon du hadde tilgjengelig? (flere valg mulig)

- [ ] Jeg er usikker på prosessene som foregår i snøen
- [ ] Jeg er usikker på hvordan været vil samspille med nåværende snødekke
- [ ] Det er motstridende data om situasjonen
- [ ] Jeg er usikker på oppbyggingen av nåværende snødekke
- [ ] Det var for lite data tilgjengelig
- [ ] Annet

Utdyp usikkert / manglende observasjonsgrunnlag (flere valg mulig)

- [ ] Det finnes ingen feltobservasjoner for å vurdere nå-situasjonen
- [ ] Feltobservasjonene er ikke relevante pga. tid
- [ ] Feltobservasjonene er ikke relevante pga. plassering
- [ ] Det er for få feltobservasjoner til å få oversikt over snødekket i regionen
- [ ] Observasjonene som er tilgjengelig har ikke nok informasjon til å få oversikt over snødekket i regionen
- [ ] Det var for lite data tilgjengelig
- [ ] Annet

Utdyp usikkerhet knyttet til vedvarende svakt lag (flere valg mulig)

- [ ] Usikker på om laget finnes
- [ ] Usikker på utbredelsen
- [ ] Usikker på om det er et relevant / aktivt lag
- [ ] Usikker knyttet til det overliggende flaket
- [ ] Egenskapene til det svake laget

- [ ] Annet

Hvorfor var det redusert kapasitet som økte usikkerheten i utarbeidelsen av varselet? (flere valg mulig)

- [ ] Sykdom / fravær
- [ ] Andre oppgaver tok oppmerksomheten bort fra varslingen
- [ ] Det var for mye informasjon å få oversikt over med den tiden jeg hadde til rådighet
- [ ] Komplekst snødekke og mye informasjon å fordøye
- [ ] Annet

Hvilken tekniske problemer økte usikkerheten? (flere valg mulig)

- [ ] Bortfall av modeller (xgeo, værpakken o.l.)
- [ ] Problemer med varslingsverktøyet / varsom som skapte ekstraarbeid (redusert kapasitet)
- [ ] Annet

Hvordan ble usikkerheten håndtert?

Hvordan ble usikkerheten håndtert? (flere valg mulig)

- [ ] Ringte en observatør
- [ ] Sende ut observatørmelding
- [ ] Beskrev usikkerheten i varselet
- [ ] Diskuterte værprognosene med meteorolog
- [ ] Diskuterte med kollega / annen varsler
- [ ] Oppsøkte informasjon fra alternative kanaler (facebook, instragram, nyheter o.l.)
- [ ] Annet
- [ ] Ingenting gjort for å håndtere usikkerheten

Hvor i varselet kommuniserte du usikkerheten? (flere valg mulig)

- [ ] Hovedbudskapet
- [ ] Skredfarevurderingen
- [ ] Snødekkehistorikk
- [ ] Fjellværet
- [ ] Annet (nyhetssak, pressemelding e.l.)

Rangering av data som var viktig i utarbeidelsen av varselet

Velg og ranger de 5 viktigste datakildene som hadde betydning i din utarbeidelsen av det mest usikre snøskredvarslet for dag 1

Dra dataene til boksen til høyre, og deretter flytt dem opp eller ned for å ranger dem utfra viktighet, hvor 1 er viktigst.

Items	Data brukt og som hadde betydning i utarbeidelsen av varselet
Innrapporterte faretegn	
Innrapportert fravær av faretegn	
Nåværende eller tidligere værdata (stasjoner, vær-historikk o.l.)	
Værprognoser	
Test-resultater	
Snøprofiler	
Snødekke-informasjon	
Snødekkebeskrivelse fra felt	
Skredfarevurdering fra felt	
Bilder/filmer	
Informasjon hentet fra tredjeparts-kilder (aviser, facebook osv.)	
Annet	