Master Thesis, Department of Geosciences

Mapping of potential snow avalanche paths and infrastructure hazard analysis

A study of snow avalanches along Raumabanen railway

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Discipline: Environmental Geology and Geohazards

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Abstract

The country of Norway has a topography and climate that facilitates snow avalanche production, especially in its northern and western parts. There is a need for extended snow avalanche mapping in areas with known avalanche activity. Increasing the knowledge and understanding of snow avalanches is an important factor for a successful land-use planning in avalanche-prone areas. In addition, more snow avalanche expertise is a prerequisite for a more detailed snow avalanche warning service.

This study provides an analysis of the snow avalanche hazard along an avalanche-prone section of Raumabanen railway in Møre and Romsdal in Western Norway. The study area constitutes 57 kilometres of railway; from Bjorli in the East to Åndalsnes in the West. There are 20 known potential snow avalanche paths in the study area, of which nine are included in this study. Local snow avalanche history, topography and climate form the basis for this study, together with the use of the alpha-beta model, a statistical-topographic model used to evaluate maximum snow avalanche run-out distances.

The main results from the snow avalanche hazard analysis gave that the annual frequencies for a snow avalanche reaching the railway vary between 1/8 and 1/32 at the different avalanche paths. Probability analyses showed that the total probability for a snow avalanche reaching Raumabanen equals 0,319/year for the whole study area.

Keywords: *Snow avalanche, hazard analysis, avalanche mapping, the alpha-beta model, infrastructure*

Sammendrag

Det finnes mye skredutsatt infrastruktur i Norge, og det er et behov for kartlegging av skredbaner ved lokaliteter hvor man kjenner til at det regelmessig går skred. Dette både for bedre å kunne vurdere snøskredfaren i arealplanleggingen og for å gi en mer detaljert snøskredvarsling.

Denne masteroppgaven er en studie av snøskred langs Raumabanens rasutsatte parti; fra Bjorli i øst til Åndalsnes i vest, en totalstrekning på 57 km. På strekningen har det blitt identifisert 20 potensielle skredbaner, hvorav 9 av disse har blitt undersøkt nærmere i denne studien. For disse skredbanene ble det gjort en generell snøskredfarevurdering, basert på historisk skredinformasjon, topografiske og klimatiske undersøkelser, samt bruk av alfa-beta modellen; en statistisk-topografisk beregningsmodell for maksimale utløpslengder for snøskred.

Hovedresultatene fra farevurderingen viste at årlig frekvens for snøskred mot jernbane varierer mellom 1/8 til 1/32. Sannsynlighetsberegninger viste at total sannsynlighet for at et snøskred skal nå fram til Raumabanen er lik 0,319/år for hele strekningen.

Stikkord: *Snøskred, skredfarevurdering, skredregistrering, alfa-beta-modellen, infrastruktur.*

Acknowledgements

The biggest thanks goes to the best guy in the world; Hans Olav. Thank you for all the support and unconditional love, and for being so encouraging and endlessly patient the last weeks of my master studies – I could not have made it without you.

Lene Lundgren Kristensen

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1. Introduction

1.1 Motivation

Snow avalanches make up the deadliest geohazard in Norway. Throughout the last 150 years, snow avalanches have been responsible for more than 1500 fatalities [*Christian Jaedicke et al.*, 2008]. The regions of Northern and Western Norway are the most snow avalanche-prone areas in the country [*NGI*, 2011].

The study area is situated on the north-western part of Southern Norway. There has not yet been carried out any detailed snow avalanche mapping for Raumabanen, which means there is little systematic knowledge about the snow avalanche hazard in the area. It is of importance to know which smaller sections in the study area that are exposed to snow avalanche activity; both because of the health concern for passengers travelling by train or living in the vicinity of the railway, but also due to socio-economic considerations. For this reason, there is a demand for a better mapping and evaluation of snow avalanches in the area.

There is an on-going cooperation project between several institutions in Norway, which aims at improving the regional snow avalanche warning service [*Engeset et al.*, 2011]. In relation to this project, it is of great value to improve the quality of the avalanche database used in the warning service.

Also, with the society's increased focus on climate change and future climate scenarios, there is a need for knowledge about the link between climate and geohazards. The goal is to define avalanche-prone areas, to achieve a land-use as best as possible. In this context, mapping of potential snow avalanches throughout the country, together with an evaluation of the avalanche hazard, is of importance to the authorities.

1.2 My thesis

1.2.1 Objectives

The main purpose of this master thesis is to conduct a snow avalanche hazard analysis for a defined section of Raumabanen railway on the north-western coast of Norway. The study area includes the railway section between Bjorli and Åndalsnes. The focus will be on identifying snow avalanche paths that endanger the railway. There are other elements at risk as well, including the road E136 that runs through the valley, as well as a few houses and buildings. But the element at risk focused on in this thesis is the railway.

The identified snow avalanche paths are used to extract the locations along the railway that have a higher snow avalanche hazard than the surrounding areas. The result is an analysis on the snow avalanche hazard; both in terms of the individual hazard at single avalanche paths, as well as the total hazard for the whole study area.

The alpha-beta model, a statistical-topographic model, is used to evaluate the maximum avalanche reach at each identified snow avalanche path. Information on historical snow avalanches provided by the Norwegian National Rail Administration (NNRA) is used to decide return periods and annual nominal probabilities for avalanches reaching the railway.

The sections of the railway that run through each of the studied avalanche paths are implemented into the alpha-beta model as individual points. Each of these points is assigned an annual snow avalanche frequency on the basis of the registered avalanche events at that particular location. These results are further used to assess the snow avalanche probability for the railway.

This thesis is a result of a co-operation between the University of Oslo (UiO) and the Norwegian Geotechnical Institute (NGI), and is related to the InfraRisk project carried out at several research institutions in Norway. InfraRisk aims at gaining knowledge about how extreme weather events may influence the possibility of certain geohazards, such as avalanches. The project also aims at characterizing the risk that these geohazards pose to infrastructure, by quantifying the vulnerability and socio-economic value of infrastructure [*NGI*, 2010].

Raumabanen is one of the main focus areas in InfraRisk [*Dyrrdal et al.*, 2010], and the evaluation results in this thesis will be incorporated into the project.

In addition, the avalanche paths mapped along Raumabanen will be added to the avalanche database at NGI, so that they may be used for future snow avalanche warning services.

1.2.2   Structure of the thesis

In the following chapter, I will present the study area with its geology, climate, infrastructure and snow avalanche history.

Chapter 3 contains a presentation of the theoretical background on which this thesis is based. Included here are some basic theory about concepts used in hazard and risk analysis, considerations in land-use planning and some snow avalanche basics.

A thoroughly examination of the methodology for this master thesis is presented in chapter 4, with emphasis on the alpha-beta model and calculations of snow avalanche frequency and probability.

The last part of the thesis contains the results for the hazard analysis. I will also discuss several aspects of the evaluation, as well as providing conclusions and recommendations for future research on the topic.

The main work with this thesis, the GIS operations and the analysis part, was carried out at the Division for Natural Hazards at NGI.

An excursion in the study area was done 06.10.2010, together with two representatives from NGI, Christian Jaedicke and Frode Sandersen, and a representative from NNRA, Stig Arild Brenden. The goal was to identify the individual snow avalanche paths that pose a threat to the railway.

2. Study area

2.1 Topography and geology

Raumabanen railway is situated in the valley Romsdalen, on the north-western coast of southern Norway. The study area constitutes the northernmost part of the railway, from Bjorli to Åndalsnes (figure 1). It lies mainly within the county of Møre and Romsdal, as well as the North of Oppland. The northernmost part of the area, starting at Verma and continuing towards Åndalsnes, has a characteristic post-glacial landscape with high mountain peaks, steep mountain flanks, and relatively flat valley bottoms. The highest mountain along the railway is Breitinden, with its looming 1797 meters.
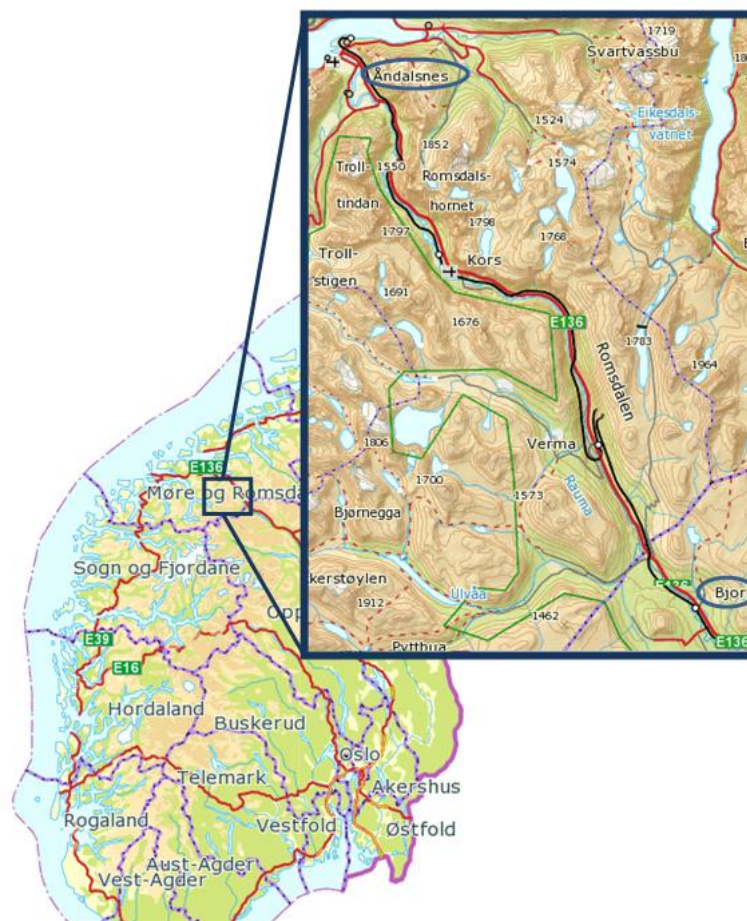
Figure 1: Topographic map showing the location of Raumabanen railway, with Bjorli in the lower right and Åndalsnes in the upper left corner of the map section. The railway is indicated with a black line, while the road E136 is shown in red [norgeskart.no].

This is the typical landscape for the western coast of Norway; a landscape that has been eroded and shaped by repeated glaciations throughout geological time. Glaciers have given Romsdalen the U-shape that is typical for Norwegian valleys [*Ramberg et al.*, 2006]. The last 10 000 years, rivers have eroded the valley bottom and, step by step, given the valley a more V-shaped look (figure 2) [*Ramberg et al.*, 2006].

Figure 2: Picture taken at Stavem, looking down towards the coast (Photo: L. L. Kristensen, 06.10.2010).

The southernmost part of the study area, from Bjorli to the county border of Møre and Romsdal, does not have this spectacular mountainous landscape, but a rather flat and round look.

As for Norway in general, the common land-use involves houses built close to the valley sides, in order to be able to use most of the arable land areas at the valley bottom. The result is houses located in avalanche-prone areas [*Hestnes and Lied*, 1980]. This also applies to the railway and the road E 136 through the valley.

2.2 Infrastructure

Raumabanen railway runs between the villages of Dombås and Åndalsnes, and makes up a total travelling distance of 114 kilometers [*nsb.no/raumabanen*]. I will focus on the

northernmost part, specifically the section from Bjorli to Åndalsnes, which makes up 57 kilometers (figure 1). This part of Romsdalen is especially steep, with a rapid decrease in altitude from 575 m.a.s.l. at Bjorli station to 4 m.a.s.l. at Åndalsnes station (figure 3) [*nsb.no/raumabanen*].
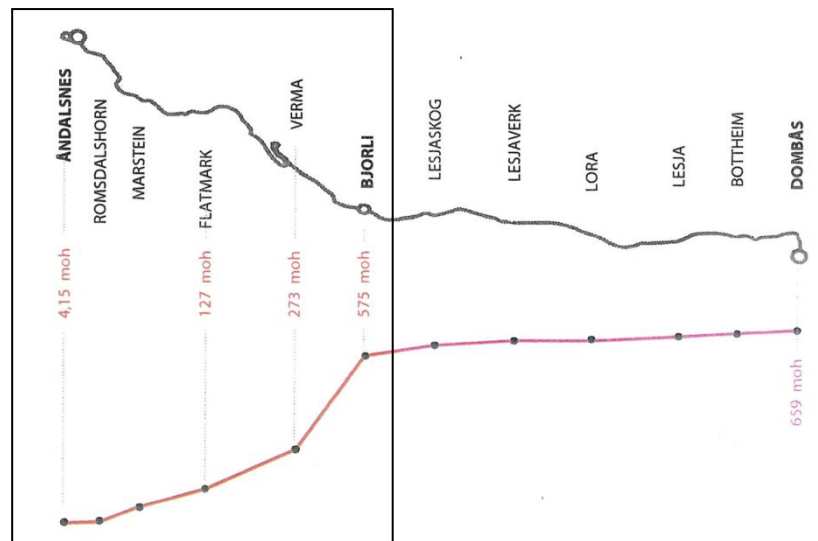
Figure 3: Sketch of the topography along Raumabanen. The study area is indicated by the rectangle [Emilsen, 2008].

The study area is scarcely populated. Åndalsnes has around 2800 inhabitants, Verma has 200 [*visitandalsnes.com*, 2011] and Medalen (constitutes Flatmark, Marstein and Horgheim) has about 100 [*romsdalsalpene.com*, 2007]. Only a minor part of these people live in the close vicinity of the railway.

Raumabanen is important for both the transport of goods and people; and it serves as an important communication route through the valley. Each day there are 10 trains running on the railway through the study area. Eight of these are passenger trains, and two are cargo trains [S.A. Brenden, personal communication, 2011]. A trip with the passenger train between Bjorli and Åndalsnes takes 42-45 minutes [*nsb.no*, 2011].

The road E136 runs through the valley, and follows much of the same route as the railway. The road between Bjorli and Åndalsnes make up 50 km, and the approximated driving time is 39 minutes [*gulesider.no*, 2011]. According to Bråthen et al., the daily traffic density on the road is 1650 transport units [2008].

According to NNRA, there were a total of 57 000 passengers travelling with Raumabanen in 2004 [*Jernbaneverket*, 2005]. Tourism make up a larger part of it, but the exact number of tourists is not clear. In 2005, the cargo transport made up almost 50 % of the total transport on the railway [*Jernbaneverket*, 2005].

A snow avalanche affecting the railway may result in several possible outcomes:

1) If a snow avalanche should block the railway while a train is on its way, the worst-case scenario would be that the avalanche hits the train directly, or that the train collides into the avalanche masses shortly after the avalanche event. Both alternatives could involve passenger fatalities and/or injuries, as well as large repairing costs for NNRA.

2) A more likely scenario is that the railway is blocked by a snow avalanche and closed for a period of time during clean-up work. This could imply great consequences to the passengers, as well as to the cargo transport. The passengers would have to use alternative transport. Also, the travelling time is likely to increase because the possible detours involve longer travel distances.

3) A third possible scenario is a closure to the railway due to an avalanche warning. This happened 15.-16.03.2010, when both the road and the railway were closed because the snow avalanche hazard was set to level 4, indicating a high snow avalanche hazard [*Siem*, 2010].

The possible consequences involved with snow avalanches are of social, economic and physical nature. For the transport industry, represented by CargoNet, a closure of the railway would imply great economic losses, and a reduction in the punctuality [*Hultgren and Bentzrød*, 2011]. Naturally, a closure to the railway would mean a remarkable reduction in the reliability of the cargo transport. The road between Dombås and Åndalsnes serves as part of the transportation route between Oslo and Ålesund. Should the road through Romsdalen be inaccessible, the alternative route via Lom would involve an extra cost; both in terms of extra time and distance.

"The national group for avalanche protection" (in norwegian: Nasjonal rassikringsgruppe) have taken the initiative to make an analysis of the socio-economic consequences of road closures due to avalanches on selected road sections throughout the country. The main goal with the study was to document the socio-economic value of implementing mitigation

measures along roads within potential avalanche terrain [*Bråthen et al.*, 2008]. The analysis is based on a network model that chooses the "cheapest" alternative road traffic route that can be driven in case of a closure along the preferred route [*Bråthen et al.*, 2008]. For the road E136 through Romsdalen, the study showed that a closure could affect a large area and involve great detours (figure 4) [*Bråthen et al.*, 2008]. Based on a daily traffic of 1650 *transport units*, such a closure would on average involve an extra driving distance of 80 kilometres for any vehicle.
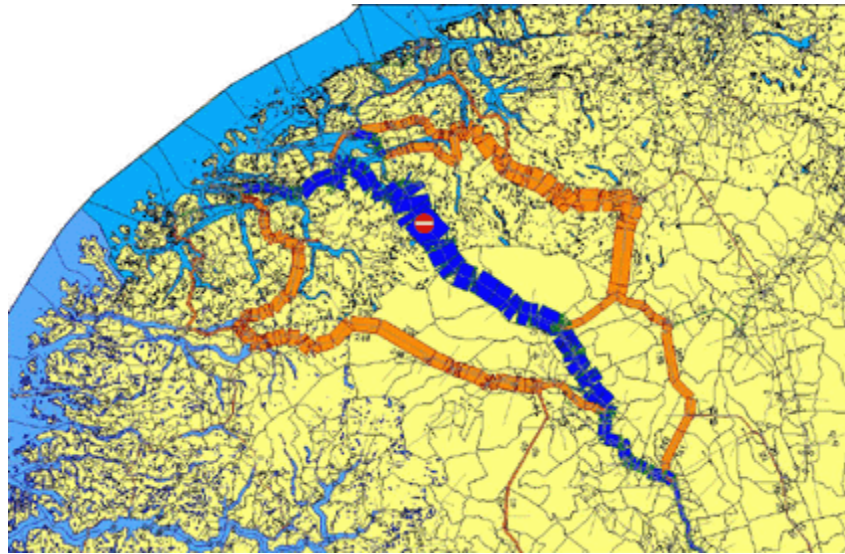
Figure 4: Map showing the consequences of a closure of E136 due to an avalanche on a specific location along the road. Road sections with increased traffic are shown in orange, while the affected road through Romsdalen is coloured blue, to symbolize a reduction in traffic [Bråthen et al., 2008].

NNRA has made an action plan for the period 2010 – 2019, which includes a plan for making the Norwegian railways safer and less exposed to different types of avalanches. For Raumabanen, this involves that 10 million NOK has been granted for the section Otta – Dombås – Åndalsnes for the period 2010 – 2013 [*Jernbaneverket*, 2009]. This plan is in line with the statements about the national transport made by the Parliament.

2.3 Climate

Western Norway typically receives quite a lot of precipitation, and the region as a whole is characterized by a mild and wet climate [*met.no*, 2011]. The precipitation pattern is

dominated by frontal and orographic precipitation, giving a concentrated belt of precipitation just within the coastal areas [*met.no*, 2011]. Typically, westerly weather systems make up the main precipitation source. The moist air is retained by the coastal mountains, so that the main portion of precipitation is concentrated on their westerly slopes. The air that continues eastward is quite dry, causing the lee areas to receive little precipitation. This process is the main reason for the two major climatic regimes in Norway; at the coast we have a maritime climate, while further inland, the climate gradually gets more and more continental [*met.no*, 2011].

The study area lies within the transitional zone between a maritime and continental climate, with Bjorli located just within the "precipitation shadow", while most of the study area has a maritime climate (figure 5). This has great implications on the snow avalanche hazard, since there must be sufficient snowfall for snow avalanches to occur. Naturally, areas that on average receive a lot of snow should be considered potential avalanche areas, provided the topography allows for mass movement. This is the case for the study area, especially the section from Verma and further north (figure 1).
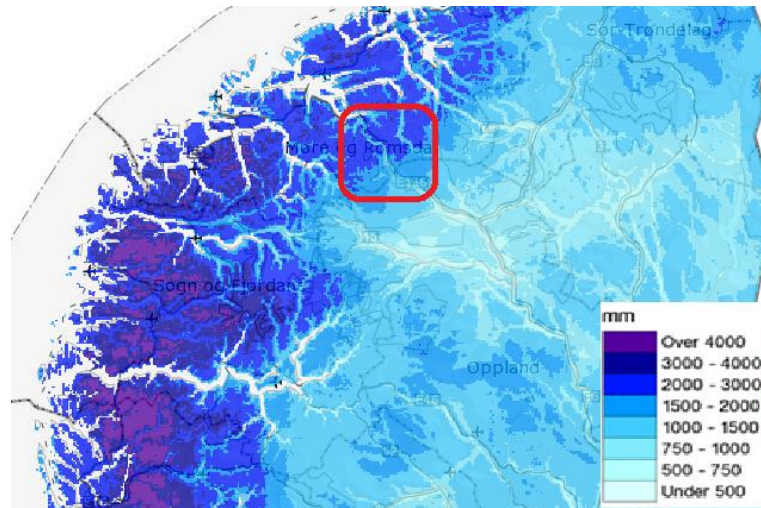
Figure 5: Map of the interpolated annual precipitation on the west coast of Norway. The study area (indicated with red square) lies in the transition zone between a maritime and a continental climate [nyforevar.senorge.no/, 2011].

Data on precipitation, wind direction, air temperature and snow depth was taken from The Norwegian Meteorological Institute's online database eKlima, put into NGI's climate database and utilized produce weather statistics. Data were taken from the following weather stations (figure 6):

- 62480 Ona II
- 61350 Åndalsnes
- 61550 Verma
- 61770 Lesjaskog

The stations were chosen to get a representative view of the climate in the region; all the way from the coast to the inland. Ona was used as a reference station for weather systems coming in from the Northern Sea. The station is wind exposed, so I assume that weather systems from all directions are registered in the data. The stations at Åndalsnes, Verma and Lesjaskog are used to obtain information about local variations in precipitation. Lesjaskog was used as a reference station for an area with relatively dry climate.
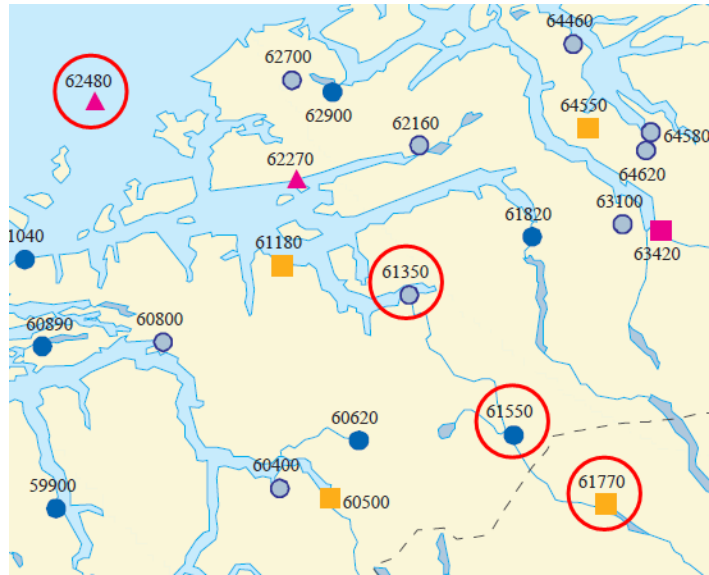
Figure 6: The weather stations used in the study indicated with red rings (background map taken from [met.no, 2007], 14.10.2011). The numbers correspond to the numbers given for each station in the text.

The annual amount of precipitation at Ona is 1792 mm, while at Åndalsnes it is 1263 mm [*eklima.met.no*]. For this reason, a large part of the precipitation hitting the western coast is likely to reach Åndalsnes at the innermost of Isfjorden. The annual precipitation at Verma is 541 mm, so most of the incoming precipitation is lost between Åndalsnes and Verma. A summary of the precipitation registrations in the study area is given in table 1.

The weather stations at Ona and Lesjaskog provide information about wind direction and wind velocity. For Lesjaskog station the data show a relatively stable wind orientation all through the year, showing a steady East – West, West – East wind pattern (figure 7). This stable wind regime is caused by the local topography, with Romsdalen acting as a wind channel, causing the wind to blow in either direction.
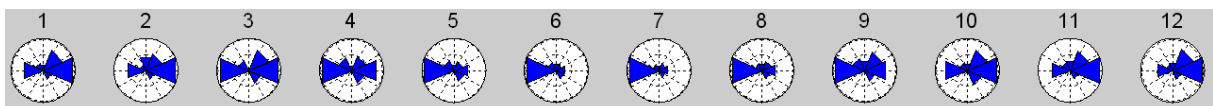
Figure 7: The average monthly wind orientation at Lesjaskog. The numbers above the wind roses indicate the months during a year; with 1 = January, 2 = February, etc. [C. Jaedicke, 2007].

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The wind data from Ona showed a more varying wind orientation. During winter, the wind is mainly southern, while in spring, summer and fall, there seem to be a tendency for North-Westerly ↔ South- Easterly winds. With the use of NGI's weather database, I was able to map the dominating wind directions during snowfall in the winter (figure 8).

Stasjonsnavn: 62480 ONA II
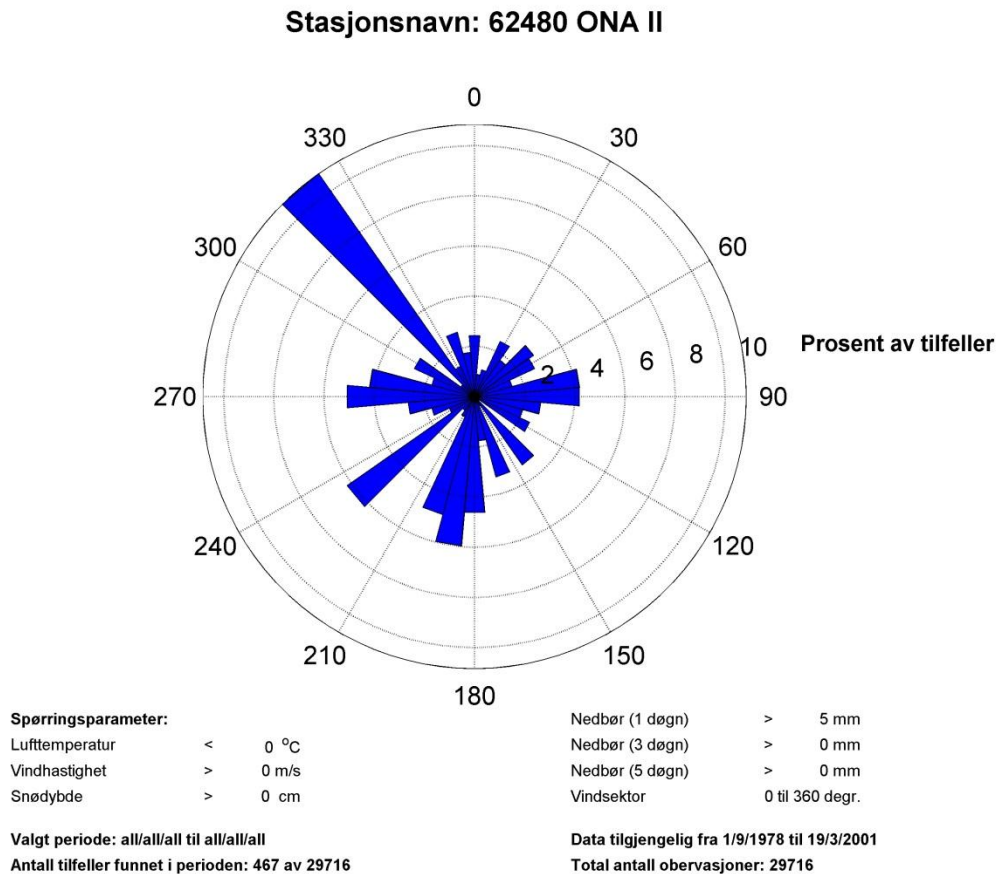
Figure 8: Wind rose for Ona II. The query was done for temperature < 0°C and precipitation > 5 mm. The result displays the wind orientation for 467 events that meet the given criteria [C. Jaedicke, 2007].

Figure 8 shows that there is no clear relation between wind and precipitation during winter. It seems like precipitation-carrying wind can come from any direction, but with the majority coming from westerly directions.

The snow height data from all four weather stations show that the winter season is slightly shorter at the coast than further inland. At Ona the winter on average lasts from November to April, whereas at Lesjaskog the winter is in the period September – May.

The weather stations at Åndalsnes and Verma do not have wind measurements, but it seems natural to assume that the dominating wind orientations at these locations are the same as the orientation of the valley. In the case of both Åndalsnes and Verma, the domination wind direction is then be North-West ↔ South-East.

The wind pattern high up in the mountain sides and on the top of the mountains can be totally different than the local wind pattern down at the valley floor. Since there is less sheltering effect or topographic barriers the higher up we get, these areas are wind exposed and the wind is likely to come from a range of orientations [C. Jaedicke, personal communication, 2011].

A summary of the topography, annual precipitation and average annual temperatures in Romsdalen is provided in figure 9. The profiles were developed with the use of map information from senorge.no that were analysed in GIS. The resulting three profiles are a result of interpolation of the original raster data along the line from A to B.

The plot shows that the precipitation decreases steadily as we move inland, while there are fluctuations in both the topography and temperature along the length of the line AB. In total, the average temperature decreases as we move from A to B.

Table 1: Summary of precipitation registrations in the study area [C. Jaedicke, 2007].

Station	Average precipitation (mm)			Maximum precipitation (mm)			Registration period	Average winter season
	Annual	Winter	Summer	1 day	3 days	5 days		
Ona II	1792	1118	674	127	170	214	01.09.1978 - 19.03.2001	October - April
Åndalsnes	1263	724	539	99	192	192	01.01.1957 - 31.12.2010	October - April/May
Verma	541	340	201	83	150	153	01.07.1895 - 31.12.1925, 01.01.1957 - 01.05.2009	October - April/May
Lesjaskog	533	314	219	51	83	88	01.09.1976 - 30.04.2003	Sept./Oct. - April/May
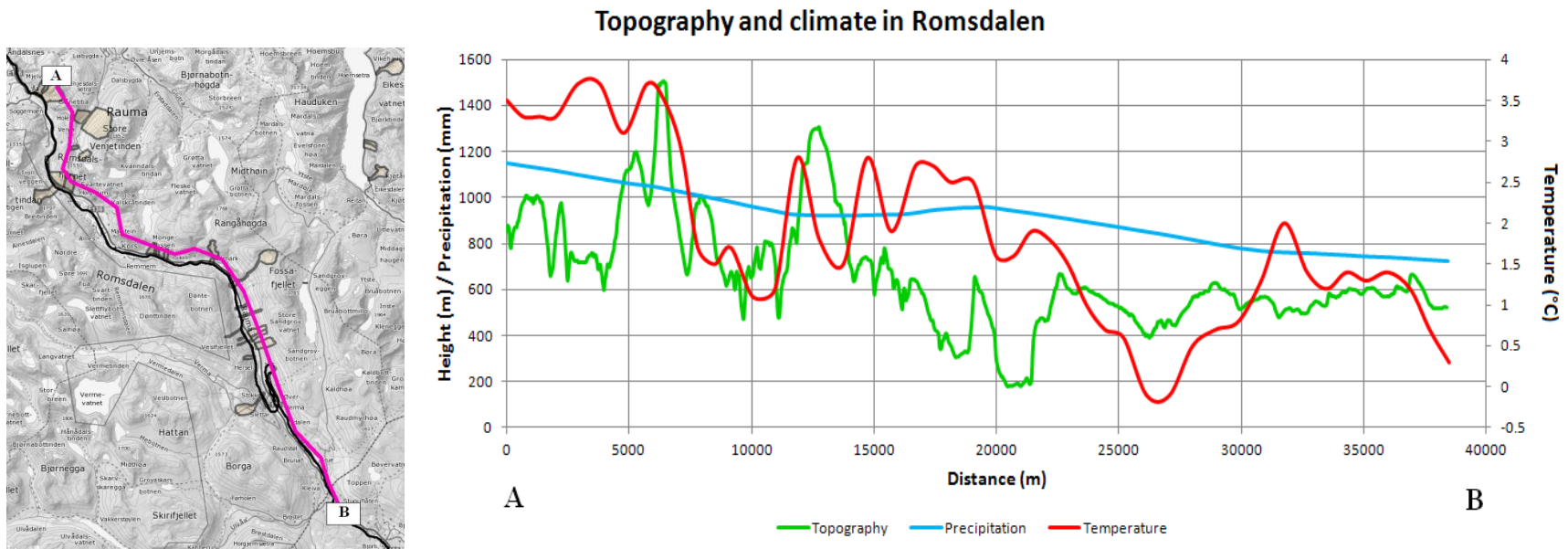
Figure 9: A summary of the topography, annual mean precipitation and annual mean temperature in Romsdalen along a line AB parallel to the railway in the study area.

2.4 Snow avalanche history

Knowledge about previous snow avalanches in the study area, including their timing, specific location and extent, is of crucial value for analysing the snow avalanche hazard. This type of information is utilized to achieve a good understanding of the nature and frequency of local avalanches. The more avalanche data available, the better is the ability to evaluate the hazard at individual snow avalanche paths.

NNRA has done some snow avalanche registrations along the railway. The registrations include avalanches occurring in the period between the opening of the railway in 1924 and the end of registrations on 10.10.1987. The information is limited to approximate locations and the year of the event. There is no further information about avalanche run-out distances, specific locations or timing of the events. A copy of the original map with these registrations is provided in appendix 1.

Also, the Norwegian Geological Survey (NGU) has collected information about historical snow avalanches for the road E 136, mainly prepared by Astor Furseth [*skrednett.no*]. The registrations go back to around 1750 and new events are still being registered. However, the uncertainties regarding time and location are relatively high for some of the registrations.

Figure 10 includes all the relevant snow avalanche registrations that I was able to locate on a standard topographic map. With "relevant" avalanche registrations, I mean registrations that contribute to the understanding of the snow avalanche hazard along the railway. The registrations are numbered and listed in tables 2 and 3.

Not all of the registrations from NGU could be localized on the map. Especially older registrations from the 1700s and 1800s were sometimes difficult to identify. The oldest events were typically registered using the family name of the people that lived in the area or the name of the farm. In recent times, the names for these locations might have changed, making it difficult to locate the events. Due to registration uncertainties, the locations are somewhat arbitrary, and should not be considered completely valid [*skrednett.no*].
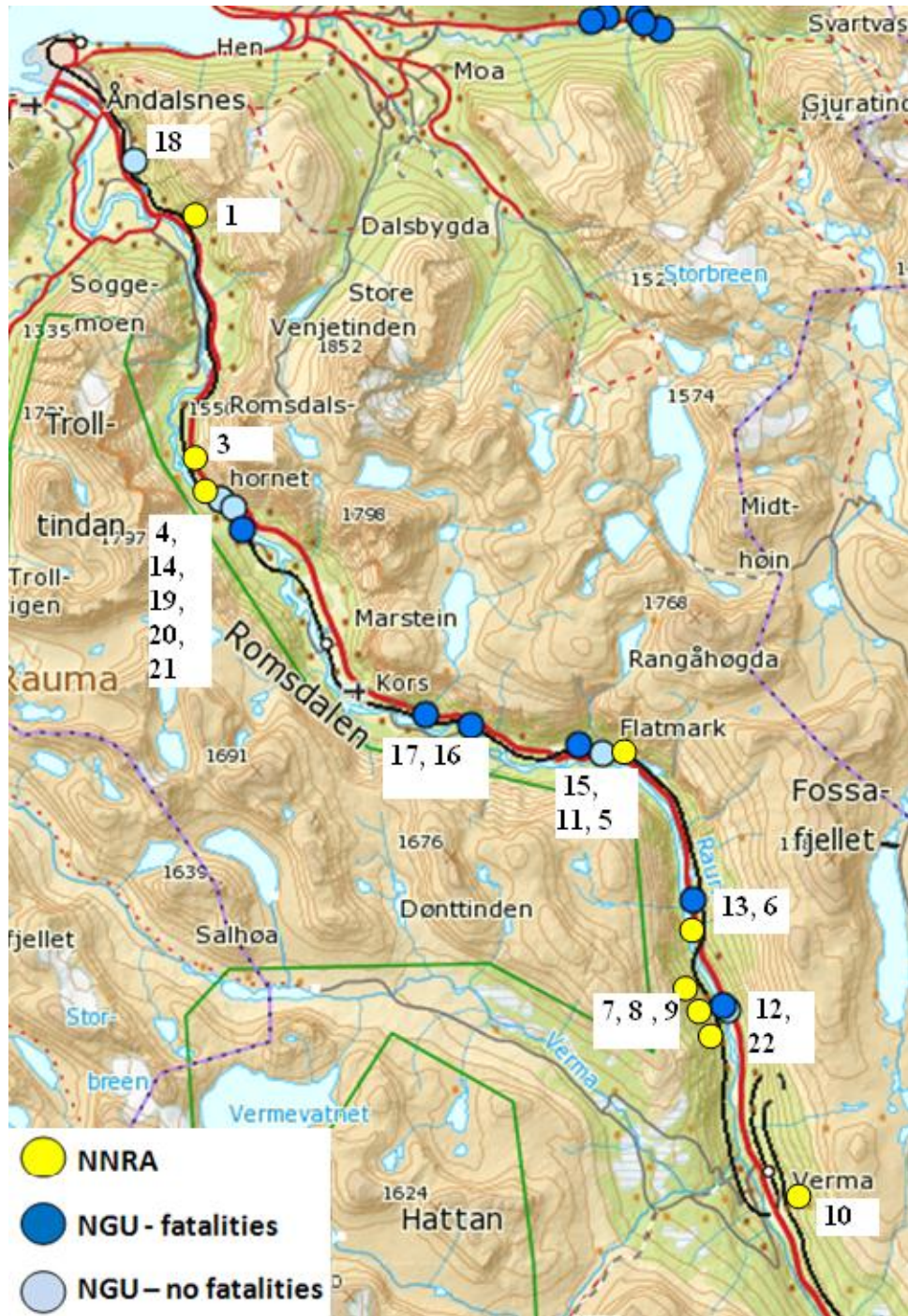
Figure 10: Summary of snow avalanche registrations in the study area for the period from around 1750 up to present. Yellow dots represent registrations made by NNRA, while blue dots represent registrations by NGU. Dark blue dots indicate events were people were killed, while light blue dots indicate events without fatalities. The numbers correspond to the ID numbers in tables 2 and 3 [formatted map from [skrednett.no]].

Table 2: Snow avalanche registrations along Raumabanen railway prepared by NNRA in the period 1924 – 10.10.1987 [M. B. P., 1987].

ID	Name of location or avalanche path	Km (from Dombås)	Years of snow avalanche events
1	Halsa	450,90	1976, 1981, 1982
2	Ødegård	450,65	1955, 1956, 1968, 1976, 1982
3	Hornet	446,70	1952, 1982
4	Joengfonna	443,75	1932, 1940, 1943, 1947, 1965, 1966, 1967, 1985
5	Grønfonna	430,90-431,10	1952, 1958, 1965, 1981
6	Gurifonna	426,25	1942, 1958
7	Fossagrovfonna	425,70	1940, 1942, 1952, 1955, 1987
8	Fossalia	425,20	1955, 1968, 1974
9	Kverngrova	424,10	1942, 1958, 1974
10	Styggfonna	412,59	Unknown

Table 3: Snow avalanche registrations along the main road prepared by NGU and The Norwegian Public Roads Administration (NPRA) in the period 1750 – 2011 [skrednett.no].

ID	Location	Date (time)	No. of fatalities	Accuracy	
				Time	Location
11	Flatmark N	XX.XX.1750	-	Uncertain[1]	-
12	Fossafjellet	13.03.1828	2	-	-
13	Gravdehaug	13.03.1828	2	-	-
14	Lyngheim	10.03.1829	1	-	-
15	Nordre Flatmark	12.04.1858	11	-	-
16	Rygg	12.04.1858	2	-	-
17	Mongemyra	10.02.1868	1	-	-
18	Mjelvafonna	12.04.1982	-	-	-
19	Unknown (Somewhere around Romsdalshorn)	18.12.1999	-	+/- 30 min	+/- 25 m
20	Unknown (Somewhere around Romsdalshorn)	20.12.1999	-	+/- 30 min	+/- 50 m
21	Fantebrauta	24.03.2002 (00:30:00)	-	Exact	+/- 50 m
22	Verma	14.03.2004 (00:15:00)	-	Exact	+/- 10 m

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[1] The actual timing of the snow avalanche is highly uncertain, but it happened sometime before 1773.

3. Theoretical background

3.1 Main concepts in hazard and risk analysis

Before going into the process of hazard and risk evaluation, it is of great importance to define the main terms used in these analyses.

3.1.1 Danger

A *danger* or a *threat* can be defined as a natural process or phenomenon that has the potential of causing damage to people and their goods [*ISSMGE*, 2004]. We characterize a danger according to its physical nature, geometry and mechanics.

It should be pointed out that there lies no forecast or quantification within the definition of a danger [*ISSMGE*, 2004].

In Romsdalen, snow avalanches constitute a danger to Raumabanen railway, in that snow avalanches are occasionally produced in avalanche paths located near the railway.

3.1.2 Hazard

The Technical Committee on Risk Assessment and Management (TCRAM) has made a glossary of risk assessment terms, which includes the following definition of "hazard": *Probability that a particular danger (threat) occurs within a given period of time* [*ISSMGE*, 2004].

Alternative definitions also exist. In their book "Environmental hazard − Assessing risk and reducing disaster", Smith and Petley view a hazard as a potential threat to humans and their surroundings [2009]. They define "hazard" as "…*a naturally occurring or human-induced process or event that have the potential to create loss.*"

In the case of Raumabanen railway, snow avalanches are potential geophysical extreme events that could lead to severe losses. The snow avalanche hazard therefore constitutes the probability that there will be a snow avalanche of a certain size, occurring in a given area

within a specified period of time. With "size", it is implied that the avalanche has a certain volume and impact pressure and produce a specific run-out distance.

3.1.3 Hazard analysis

Evaluating the snow avalanche *hazard*, involves using all the available background information about snow avalanches, topography and climate in the study area, to identify and estimate the extent of the snow avalanche hazard. There are several sources of background information. Some typical examples are: Snow avalanche records, written documents or drawings of avalanche accidents, geomorphologic and topographic maps, oral information from local people, visual observations in the field, as well as photos covering the study area [*Hestnes and Lied*, 1980].

The background information is utilized to obtain a fundamental understanding of the snow avalanche hazard in the area, and serves as the basis for further investigations and the making of avalanche hazard maps. The latter contains all known snow avalanche paths in the study area, their outline and reach, together with the year of each event (figure 11) [*Hestnes and Lied*, 1980].

An avalanche registration map is a way of visualizing the snow avalanche hazard in the area, and can be used as a guiding tool in the process of specifying the hazard for smaller areas, infrastructure, buildings or other types of installations [*Lied and Kristensen*, 2003]. NNRA's hand-drawn map of snow avalanche registrations along Raumabanen is kind of a registration map, but without the outline of the avalanches (appendix 1).
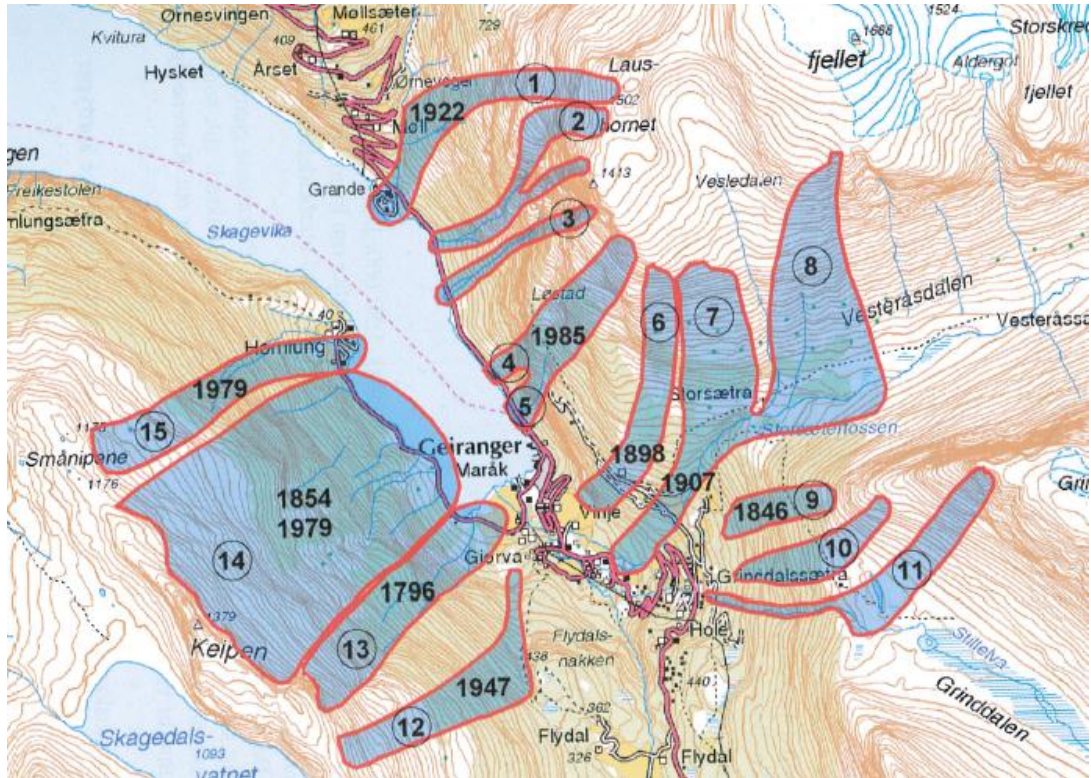
Figure 11: Snow avalanche registration map from Geiranger in Norway. Each avalanche event is numbered and identified with the year of the event [Lied and Kristensen, 2003].

3.1.4 Common hazard analysis terms

- *Frequency*

The concepts of frequency and probability are inter-related, but have distinct meanings. "Frequency" is often explained as *the number of occurrences of an event in a given time or in a given number of trials* [*ISSMGE*, 2004]. The frequency can be expressed as:

$$f = \frac{1}{T} \qquad (1)$$

Where f= frequency and T = return period. In other words, the frequency equals the inverse of the elapsed time between two similar events.

- *Probability*

Probability can be related to the certainty of something happening. TCRAM defines "probability" as *a measure of the degree of certainty* [*ISSMGE*, 2004]. Defined like this,

probability obtains a value between 0 and 1, corresponding to impossibility and certainty, respectively. The quantified probability is a measure of the likelihood that a specified event should happen; our degree of belief [*Kaplan and Garrick*, 1981].

In cases when avalanche consultants have enough avalanche registration data to establish a frequency for a certain event, the frequency is used to "calibrate" the probability for this particular event [*Kaplan and Garrick*, 1981].

In situations with a lack of historical avalanche registrations, there is either very little or no information about the frequency of a specific avalanche event. In such cases it is quite challenging to assess a probability. Still; we would often need to know something about the probability for having an avalanche. This is often the case for rural areas that the municipality wants to plan for housing [*Hestnes and Lied*, 1980]. Uninhabited areas normally lack avalanche registrations, something which naturally hampers the hazard evaluation.

- ***Run-out distance***

The run-out distance represents the horizontal distance covered by the avalanches; measured from the top of the release area to the maximum reach of the avalanche deposits [*McClung and Schaerer*, 2006]. "Maximum reach" implies the farthest stopping position of the avalanche masses.

- ***Return period***

In their book, *The avalanche handbook,* McClung and Schaerer defines "return period" as: *...the average interval of time within which the run-out distance is reached or exceeded at a given location* [*2006*]. The return period, T, is inter-related with the avalanche frequency, as shown in equation 1.

3.1.5 Risk

TCRAM has defined "risk" as *...measure of the probability and severity of an adverse effect to life, health, property, or the environment* [*ISSMGE*, 2004].

In other words, while a "hazard" has to do with the probability of a potential danger, the "risk" term in addition includes the possible consequences involved in the hazardous event.

Examples on such consequences are the number of fatalities, the vulnerability of people and their surroundings and economic losses due to damages to buildings and infrastructure.

"Risk" can be described with the following expression [F. Nadim, personal communication, 2010]:

$$Risk = Hazard \times Consequences \qquad (2)$$

The terms *danger*, *hazard* and *risk* are often mixed up, and in everyday life they may be used incorrectly. Knowing the scientific meaning of the different terms is of great importance, since, according to each of the definitions, the terms have quite distinct meanings.

3.1.6 Risk analysis

According to equation 2, the risk is equal to the hazard times the consequences. Therefore, when estimating the risk, it is common to use the hazard evaluation as a starting point. After having established an understanding of the hazard, the avalanche consultant can extend the analysis by adding information about potential consequences.

The process of risk analysis is illustrated in figure 12. The questions that need to be answered are: What are the potential hazards in this area, and how can they be quantified? If a hazardous event should happen, what are the probable consequences?

In the case of snow avalanches reaching Raumabanen, such consequences may be fatalities or injuries to people and damage to train and train tracks. Other, maybe not as obvious consequences, are loss of income and reputation for the train companies that use the railway, as well as loss of life quality and a general dissatisfaction among the public. The final result of the risk evaluation is an estimation of a particular risk; either in a qualitative or quantitative way [*ISSMGE*, 2004].
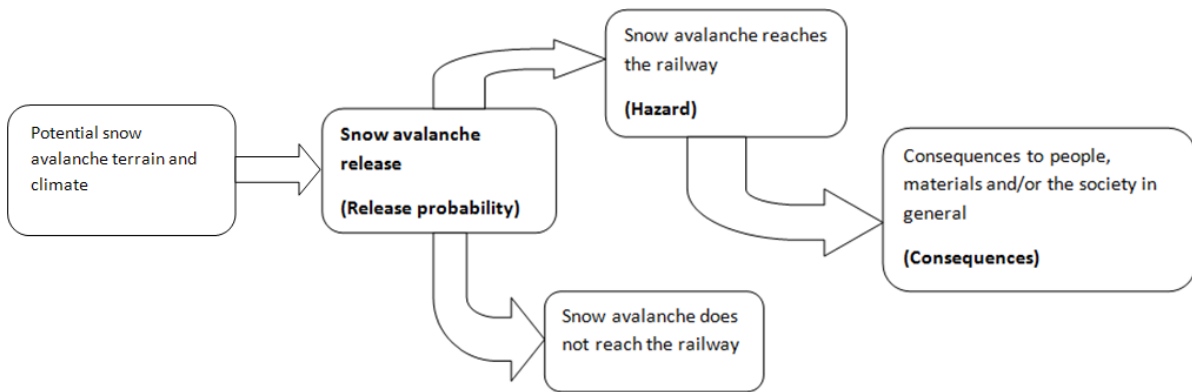
Figure 12: Sketch of the principals for snow avalanche risk analysis.

3.2 Snow avalanche basics

3.2.1 Types of snow avalanches

Snow avalanches are not easy to group, and different approaches with varying numbers of avalanche categories exist. One way of defining snow avalanches is by the free water content, which gives three main groups: Dry snow avalanches, wet snow avalanches and slush avalanches [C. Jaedicke, personal communication, 2011].

Another way of grouping snow avalanches is given by Lied and Kristensen [2003], and gives that there are two main types of snow avalanches: Slab avalanches and loose snow avalanches (figure 13) [*Lied and Kristensen*, 2003]. These two types are further divided into wet and dry slab avalanches and wet and dry loose snow avalanches. Slush avalanches are considered a third snow avalanche type. I will now give a short presentation of all three types:

Slab avalanches consist of one large, continuous slab of snow that breaks off as a result of increased shear and/or load to the snowpack. The most pronounced characteristics of this avalanche type are that all the snow is released at the same time and that it flows on top of a gliding layer. This gliding layer can either be a layer of underlying snow or the ground surface [*Lied and Kristensen*, 2003]. The main principle is that the sliding slab is hard packed and has a higher strength than the underlying snow layer, which allows for pressure

transmission throughout the slab layer. For this reason, slab avalanches can be widespread, affecting a large area [*Lied and Kristensen*, 2003].
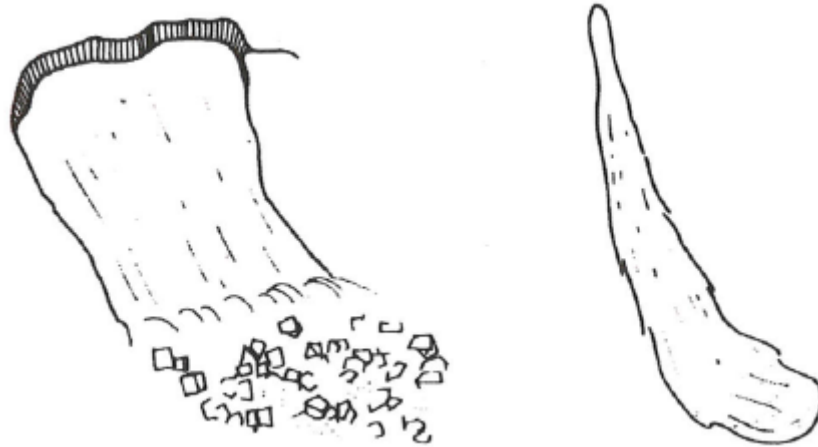
Figure 13: An illustration of slab avalanche (left) and loose snow avalanche (right) [Lied and Kristensen, 2003].

The deadliest and most damaging snow avalanches are almost always dry slab avalanches, due to their large volumes, high mobility and impact pressures [*Lied and Kristensen*, 2003]. It is known that large volumes generally give long run-out distances [*de Blasio*, 2011]. For this reason, they will be of major concern in this thesis.

Loose snow avalanches consist of loose, newly fallen snow or wet snow. These avalanches have a small point of origin from where a minor amount of snow is released. As the avalanche moves downward, it widens out and grows larger as more snow is added to the avalanche; a process called entrainment [*Lied and Kristensen*, 2003]. The movement starts when the cohesive and frictional forces within the snowpack are overcome by the driving forces; normally by the additional weight of new snow. Usually the terrain needs to be steeper than 45° for such avalanches to occur [*Lied and Kristensen*, 2003].

Normally, loose snow avalanches don't result in losses of lives or damage to infrastructure or property. For this reason, they will not be of major concern in this work.

Slush avalanches occur when the water content gets so high that the snowpack can no longer be kept in place [*Lied and Kristensen*, 2003]. This avalanche type typically occurs during the early winter season due to intense rainfall, or in spring time when there is intense snowmelt or rainfall, or a combination of both [*Lied and Kristensen*, 2003].

Normally, slush avalanches are produced in connection with river creeks and depressions with water flow [*Lied and Kristensen*, 2003]. Due to the high water content, the avalanches are often quite mobile, and are likely to produce long run-out distances [*Lied and Kristensen*, 2003]. The nature and size of slush avalanches vary, and depend largely on the topography in the area and the physical properties of the snowpack.

3.2.2 Factors affecting the snow avalanche hazard

There are several factors affecting the snow avalanche hazard. For a general hazard evaluation made for land-use planning the two main factors are topography and climate.

Topography

What does the concept of an "avalanche-prone area" mean? It generally means all areas where the topography may allow for snow avalanches to happen. The terrain needs to be steep enough to allow for snow movement. Snow avalanche terrain is typically in the range of 30°-60° [C. Jaedicke, personal communication, 2011]. The areas must also be potential for snow accumulation. Typical avalanche-prone terrain may therefore be valleys, depressions and ravines (figure 14) [*Lied and Kristensen*, 2003].

The starting zone

The starting zone serves as the accumulation zone for snow, and therefore it must have a shape that facilitates accumulation. The shape and the surrounding topography decide the maximum volume of snow that can accumulate before an avalanche releases. Five different categories of starting zones can be classified: Cirques, shallow depressions, scars, flat faces and convex slopes [*Lied and Bakkehøi*, 1980].

It has been shown that there is a strong relationship between the volume and run-out distance of an avalanche [*de Blasio*, 2011; *Lied and Kristensen*, 2003]. Thus, there is a tendency for large avalanche volumes to produce large run-out distances, provided the avalanche reach is not restricted by any topographic barriers or water basins [*Lied and Bakkehøi*, 1980].
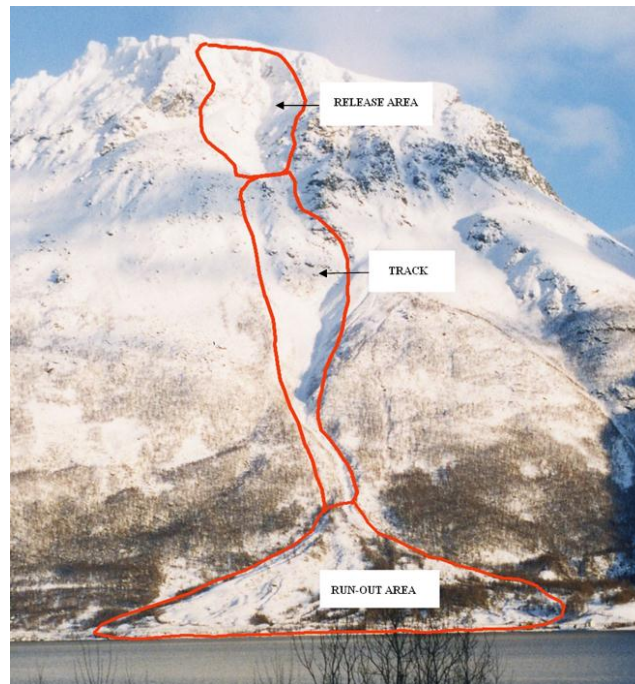
Figure 14: An example of avalanche terrain. The structure of the snow avalanche is indicated in the picture [Lied and Kristensen, 2003].

The starting zone of the avalanche must be steep enough for avalanches to occur, and for dry slab avalanches the "rule of thumb" is that the inclination should be 30° or steeper [*Lied and Kristensen*, 2003]. Statistics on the relationship between snow avalanche frequencies and terrain inclination show that most dry avalanches are produced in areas with an inclination of 35°- 45° (figure 15) [*Lied and Kristensen*, 2003]. Most terrains steeper than 45° are too steep for large amounts of snow to be accumulated. Instead of producing large snow avalanches, these areas often give many small avalanches during the winter, normally occurring shortly after a snowfall event [*Lied and Kristensen*, 2003].

On gentle slopes, a lot of snow accumulation is required for a snow avalanche to occur, often in combination with a high water content [*Lied and Kristensen*, 2003]. However, it needs to be pointed out that there is no lower limit for terrain inclinations that could produce a snow avalanche. In the end, whether there is an avalanche or not depends on several factors, including terrain inclination, snow cover stability, water content of the snow, snowfall intensity, forest density and the rate of snow drift [*DeWalle and Rango*, 2008; *Hestnes and Lied*, 1980; *Lied and Kristensen*, 2003].
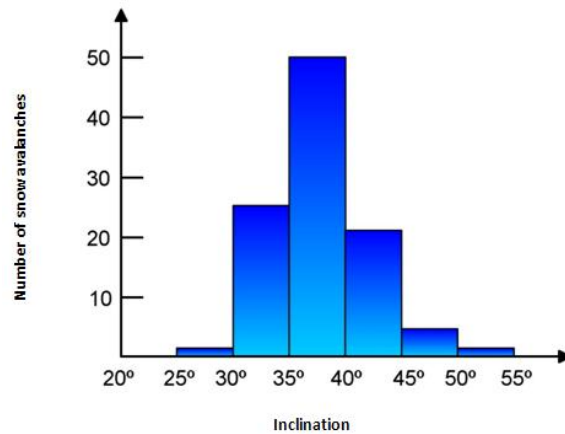
Figure 15: The relationship between the inclination and the number of large snow avalanches [modified after [Lied and Kristensen, 2003]].

Avalanche path characteristics

The shape of the avalanche terrain may not only affect the snow accumulation, but also the avalanche behaviour and reach [*Lied and Kristensen*, 2003]. Scientists agree that although there is no clear relationship, the terrain shape has some influence on the avalanche mechanics [*Bakkehøi et al.*, 1983; *McClung*, 2000].

In general, the view is that gentle, almost linear slopes and parabolic shaped slopes (figure 16, path 1 and 2, respectively) produce longer snow avalanches than steeper slopes with an abrupt change in inclination, so-called "hockey-stick profiles" (path 3, figure 16) [*Lied and Bakkehøi*, 1980; *Lied and Kristensen*, 2003].

(1) Linear (planar)   (2) Concave parabola   (3) Hockey-stick profile
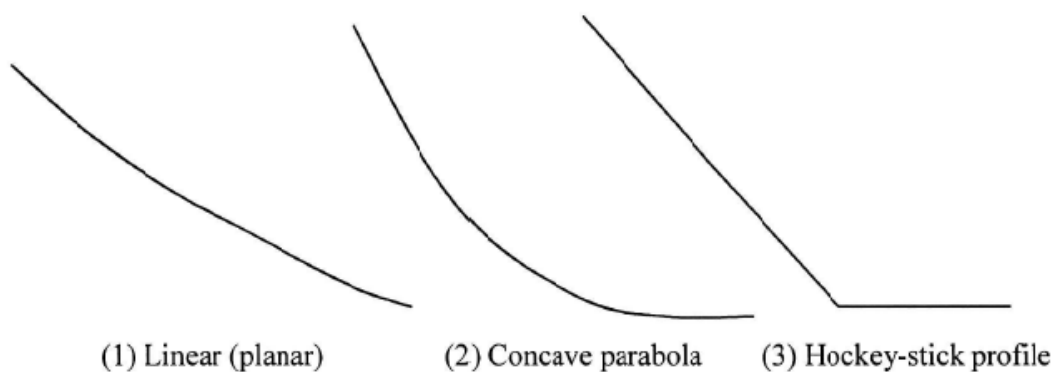
Figure 16: A comparison of some avalanche path shapes. 1) More or less linear avalanche path. 2) Concave parabolic path. 3) "Hockey-stick path" [Jones, 2002].

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Avalanche path 1 has an "ideal" terrain shape for the production of snow avalanches with long run-out distances. The terrain shape is close to linear, smooth and without drops or bumps. This gives maximum energy conservation within the avalanche masses, and minimum reduction in velocity [*Lied and Bakkehøi*, 1980]. Because of the smooth terrain, the radius of curvature, R, is large. The frictional forces acting on the avalanche masses depend on the velocity (v) and R:

$$F = \frac{v^2}{R}$$ (3)

Smooth avalanche paths with a large R, have smaller friction forces than steep paths, and hence; more energy conservation [*Lied and Kristensen*, 2003]. Studies performed by McClung support this finding, concluding that "linear" slopes obtain long run-out distances [*McClung*, 2000]. It should be mentioned, however, that too gentle "linear" paths will may restrict the avalanche movement [*Kronholm et al.*, Unpublished].

Avalanche path 2 makes up an intermediate path shape, with its relatively steep release area and gentle transition between avalanche track and run-out zone.

Avalanche path 3 has a steep terrain, and an abrupt change in the terrain shape at the bottom of the slope, producing a "head-on collision" when the avalanche hits the slope bottom [*de Blasio*, 2011]. In this impact, a lot of the movement energy is lost to the surroundings, and the snow avalanche is likely to come to a halt shortly thereafter [*Lied and Kristensen*, 2003].

Confinement has shown to be significant for the avalanche velocity [*Lied and Bakkehøi*, 1980], and therefore also for the run-out distance [*Jones*, 2002]. In highly confined avalanche paths, meaning paths with a high degree of channelizing, the avalanche masses are supported and conserved during the down-slope movement. This process restricts the dissipation of avalanche masses that occurs in areas without confinement, and has implications for the avalanche volume and the run-out distance. When avalanches are confined, the masses are concentrated together, which most likely results in higher avalanche velocities and longer reach [*Lied and Bakkehøi*, 1980; *Perla and Martinelli*, 1976].

Vegetative and morphologic clues of avalanche activity

In areas with recent snow avalanche activity, a visual inspection of the area can give valuable information about the location and extent of the most frequent avalanches. There are signs to look for in the terrain, such as missing or damaged vegetation. Bent trees may be an indication of avalanches, either from the avalanche masses themselves or from the pressure winds running in front of dry slab avalanches [*Lied and Kristensen*, 2003].

Sawed cross-sections of trees may reveal scars or other forms of breakage to the trees [*McClung and Schaerer*, 2006]. For damaged trees, counting of fresh tree rings can provide information about the timing of the avalanche event [*McClung and Schaerer*, 2006]. In areas where there recently has been an avalanche, the vegetation in the avalanche track and run-out zone will be dominated by pioneer species [*McClung and Schaerer*, 2006]. By mapping the extent of this vegetation, the scientist will get an overview of the area threatened by snow avalanches.

For snow avalanches occurring above the tree line, the scientist will have to look for traces of avalanche erosion and avalanche deposits like dirt and rocks along the edges of the path [*McClung and Schaerer*, 2006]. Other signs of snow avalanches may be large rocks or boulders that have been transported by avalanches from mountain areas and down into the valley.

Slush avalanches often have strong eroding power, and therefore often leave distinctive scars in the terrain [F. Sandersen, personal communication, 2010]. Since this avalanche type typically is connected to water networks, they often erode the established creeks and rivers, making these deeper and wider.

Climate

Climate is an important factor for the snow avalanche hazard, since it gives the average weather conditions in an area. Snowfall events may overload the snowpack if the amount of new snow is large enough, and the precipitation intensity controls the loading rate. Winds may redistribute the precipitated snow, and locally alter the snow avalanche hazard with time.

Recent and antecedent weather events

The most recent weather events have the greatest influence on the snow avalanche hazard [*Christian Jaedicke et al.*, 2008; *Kronholm et al.*, 2006]. This includes the weather on the actual avalanche day, as well as weather events a few days before, normally three to five days ahead of the avalanche day [*Christian Jaedicke et al.*, 2008]. When it comes to snow avalanche warning, it is necessary to include weather forecasts into the hazard evaluation. Imminent changes in weather are likely to alter the avalanche hazard in the nearest future, and must therefore be considered before an avalanche warning is issued.

However, long-term weather development also plays an important role for the avalanche hazard. In the case of snow avalanches, this implies that antecedent snowfall and weather events must be taken into account throughout the whole winter season [F. Sandersen, personal communication, 2011]. The variation of weather types and their duration will decide the snowpack properties throughout the winter, and therefore decide the snow avalanche hazard on a long-term basis [*Fitzharris and Bakkehøi*, 1986]. It is of interest to have knowledge about how these different weather patterns may influence the local snow avalanche hazard.

An example is the importance of the weather conditions in the beginning of the winter season. If the first winter months have little snowfall and sustained periods of frost, this facilitates the production of depth hoar at the bottom of the snowpack. This condition gives an unstable fundament for the snowpack [F. Sandersen, personal communication, 2011]. Unless there is melting of the snow or altering of the physical properties of the whole snowpack during the first coming weeks, the reduced stability could prevail for most of the winter season [F. Sandersen, personal communication, 2011].

Wind effects

Strong winds redistribute snow. The wind velocity required for snow transport varies with the age of the snow; meaning that newly fallen, light snow is easier to transport than older, hard-packed snow [*Tremper*, 2008]. Freshly fallen snow at low temperatures are likely to start drifting at wind velocities of about 5 m/s [*Lied and Kristensen*, 2003].

As a "rule of thumb" one can say that the amount of snowdrift increases with the wind velocity raised to the power of three [*Lied and Kristensen*, 2003]. This implies that if the wind velocity is doubled, the snowdrift is increased by a factor of eight [*Lied and Kristensen*,

2003]. Naturally, this has huge implications on the snow avalanche hazard. In practice this gives that when a storm is initiated, it won't take long until there has been enough snow accumulation on leeward slopes to raise the snow avalanche hazard remarkably. The combination of strong winds and large snowfall is what gives the highest snowdrift effect [C. Jaedicke, personal communication, 2011].

Knowledge about the general wind pattern in an area is therefore important. By mapping the dominating wind direction at each avalanche path, one is able to point out which individual paths that will face an increased avalanche hazard during weather events with particular wind patterns.

The main meteorological parameters regarding snow avalanches are precipitation, temperature and wind [*Christian Jaedicke et al.*, 2008]. Any additional parameters are outside the scope of this thesis, and will not be dealt with.

Meteorological triggers

A group of scientists have studied the link between climate patterns and the triggering of geohazards in Norway; a work revealing the statistically most important meteorological factors for snow avalanche triggering throughout the country [*Christian Jaedicke et al.*, 2008]. The results show that there are some regional differences. For western Norway, there is a tendency that precipitation is the main triggering factor. This includes snowfall both on the actual avalanche day, as well as precipitation fallen some days in advance, the so-called "3-day precipitation sum" and "5-day precipitation sum" (figure 17). For northern Norway, on the other hand, strong winds causing snow drift seems to be the most important release factor for snow avalanches [*Christian Jaedicke et al.*, 2008].

Although such studies give the regional picture of main triggering factors, and for that reason does not reflect local variations that well, this knowledge is still useful in a local perspective. The reason is that regional studies provide us with knowledge about the "typical" weather situations producing snow avalanches in that specific region. Next, it is up to us to use the regional findings as a starting point for further local studies.
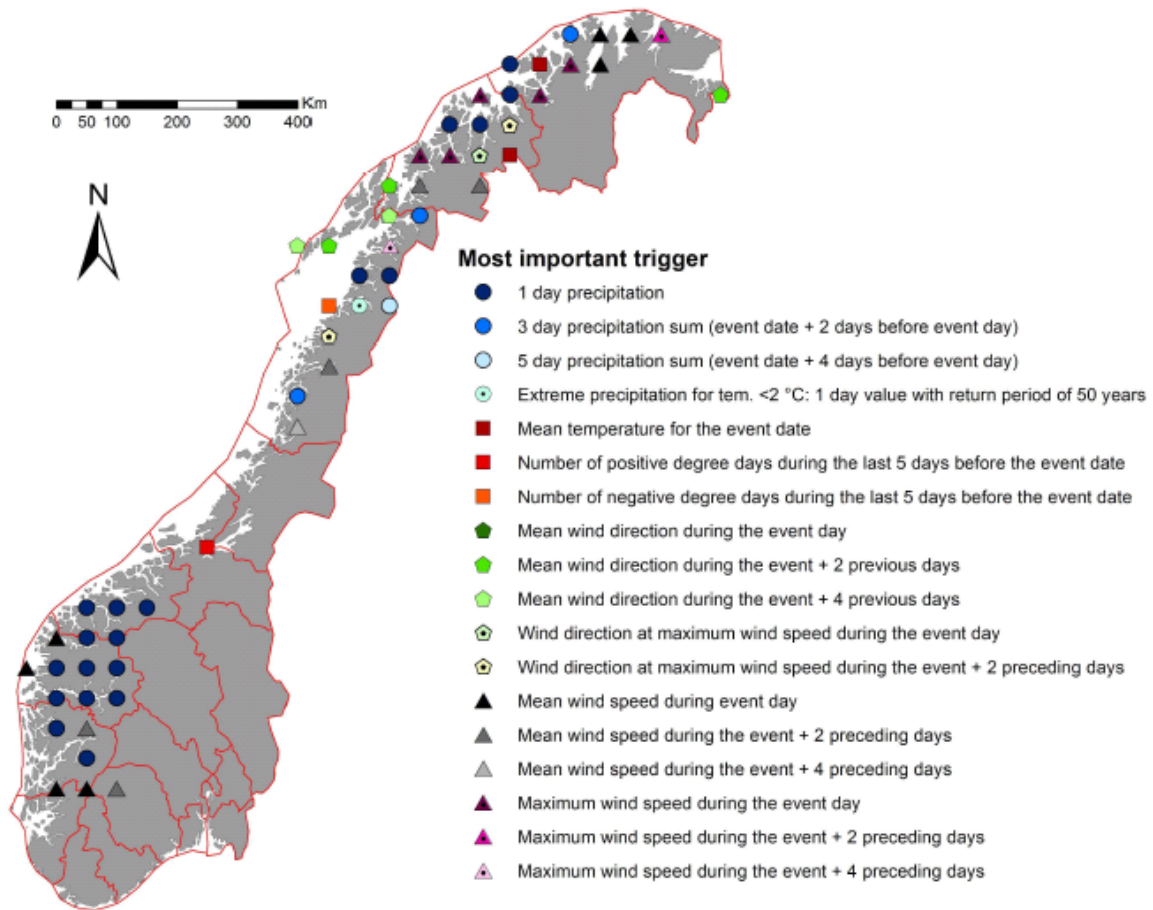
Figure 17: The main meteorological factors for snow avalanche trigger in Norway [Christian Jaedicke et al., 2008].

3.3 A short note on avalanche models

To be able to assess the snow avalanche danger and further evaluate the avalanche hazard at particular locations, scientists make use of several methods; both statistically and dynamically derived.

Statistical methods make use of terrain parameters and/or meteorological parameters to establish a run-out distance. Also, these methods are based on knowledge from past snow avalanche recordings.

Dynamical models are based on different physical variables, and give knowledge about the physical behaviour of the avalanche, for instance the velocity variations over the avalanche

path profile. Such models can be used to calculate impact pressures from snow avalanches [*Lied and Kristensen*, 2003].

Sometimes avalanche professionals may use a combination of statistical and dynamical methods. This is done to obtain more reliable results for the avalanche velocity and reach. Once the extreme run-out distance is decided with the help of a statistical method, the stopping position of the avalanche (the point along the profile where v = 0) can be identified. The end-position can be incorporated into the result of a dynamical model, tuning the model to give the velocity profile of the avalanche. The result can be used to calculate impact pressures at different locations in the run-out zone [C. Jaedicke, personal communication, 2011]. This knowledge is useful when dealing with dimensions for mitigation structures like stopping or deflecting dams.

The main advantage of statistical methods over more conventional dynamics methods, is that the uncertainty can be quantified using standard statistical terms, such as the standard deviation [*McClung and Mears*, 1991].

Since this thesis work aims at deciding run-out distances for a set of avalanche paths, and their corresponding avalanche frequencies and probabilities, the focus is on studying the snow avalanche history in the study area. Therefore, a statistical approach to the problem is the most natural.

Of the statistical methods, the alpha-beta method and the run-out ratio method are the ones commonly used for snow avalanche hazard and risk assessments and land-use planning [*Keylock*, 2005]. For this study, the alpha-beta model is used to study the relationship between snow avalanche reach and return period.

4. Methodology

The main goals for this thesis were to map potential snow avalanche paths, study the snow avalanche history of the area and make a general hazard analysis for the study area of Raumabanen. In this chapter I will present the methods and tools used to accomplish these goals.

4.1 The alpha-beta model

4.1.1 Basic concepts

The alpha-beta model is a statistical-topographic model used to estimate the maximum run-out distance for snow avalanches [*Bakkehøi et al.*, 1983]. It was developed by Bakkehøi and Lied [1980], based on a regression analysis of 206 individual avalanches in Norway. The study revealed that the run-out distance can be decided with the help of the relationship between the α-angle and the β-angle. The classical alpha-beta regression equation is:

$$\alpha \; = \; 0{,}96\beta - 1{,}4° \tag{4}$$

The correlation coefficient, R, equals 0,92 and the standard deviation, SD, equals 2,3° [*Bakkehøi et al.*, 1983]. The geometric principals for the model are shown in figure 18.

The *α-angle* equals the average gradient of the avalanche path between the top of the release area and the point of the maximum avalanche reach [*Lied and Bakkehøi*, 1980]. The *β-angle* is the average gradient between the top of the release area and the position along the track where the inclination reaches 10°, the so-called β-point. A parabola is fitted to the terrain profile, and both the α- and β-angles are determined as the angle between the tangent of this parabola and the horizontal [*Lied and Bakkehøi*, 1980]. The β-point serves as a reference point for the α-point, providing information about the path steepness in the transition between the avalanche track and the run-out zone [*Harbitz et al.*, 2001; *McClung and Schaerer*, 2006].
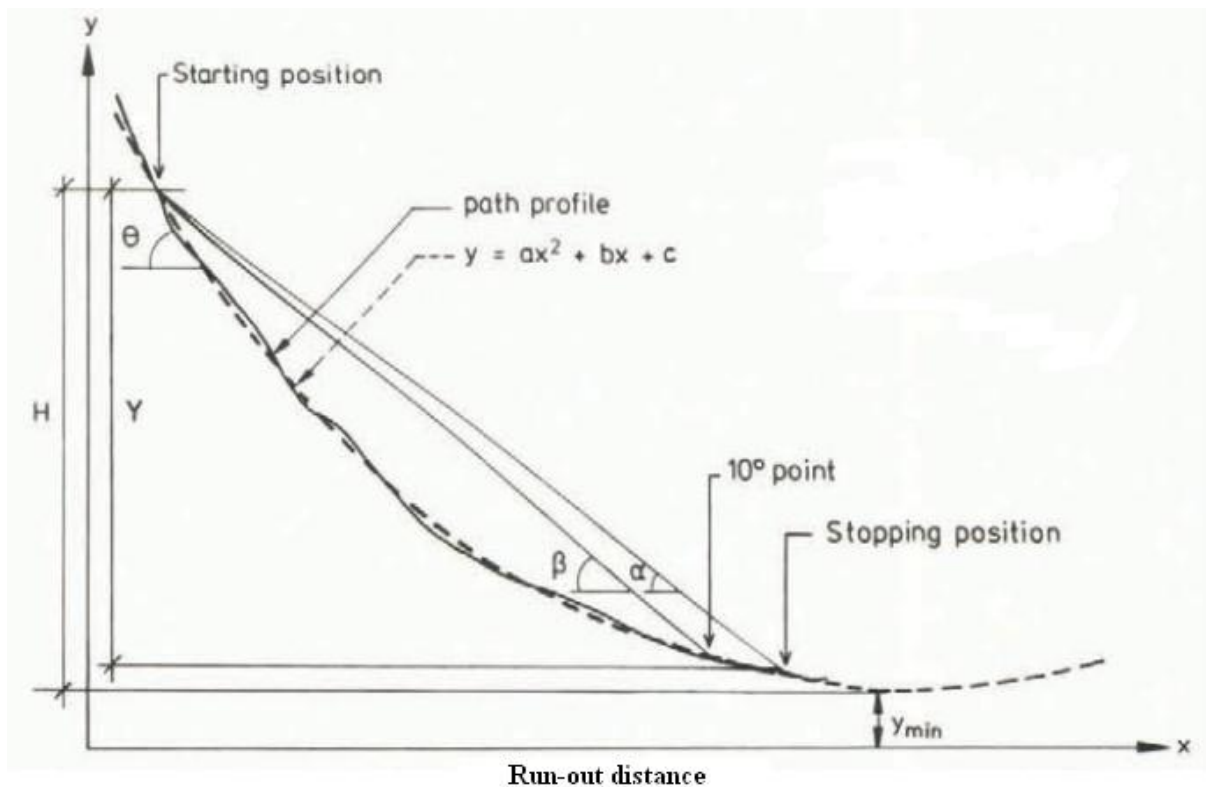
Figure 18: Illustration showing the main principles for the alpha-beta model [Bakkehøi et al., 1983].

The study performed by Lied and others showed that the β-point is the statistically significant topographic parameter for the location of the α-point, concluding that the two points are directly proportional to each other [*Lied and Bakkehøi*, 1980]. Several studies on statistical-topographic run-out methods have confirmed this finding [*Harbitz et al.*, 2001; *McClung and Schaerer*, 2006]. Experience has shown that when snow avalanches reach the β-point, they have a tendency to stop or start to slow down. This corresponds to a path steepness of about 10° [*Harbitz et al.*, 2001; *McClung and Schaerer*, 2006].

The snow avalanche paths analysed in the study were all taken from areas considered typical snow avalanche terrain, and all the paths had a well-documented snow avalanche history. The maximum registrations of avalanche run-out for each of the paths were extracted from the dataset and used to obtain equation 4. The anticipated return period for maximum avalanche reach vary locally, but is between 100 and 300 years [K. Lied, personal communication, 2011]. Naturally, in order to get representative results for run-out distances, the alpha-beta model should be used on avalanche terrain that corresponds to the avalanches examined in the study.

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4.1.2 Application of the alpha-beta model in GIS

The alpha-beta model can easily be incorporated into a Geographic Information System (GIS) by adding the model as a tool box. At the identified snow avalanche paths, avalanche profiles are drawn. An avalanche profile represents the most likely line for which the major parts of the avalanche masses travel along.

Some avalanche paths have a wide extent, and several avalanche profiles are possible. For confined paths there is usually only one alternative profile. This applies for instance to snow avalanches connected to river networks. The general rule for such paths is that they seem to follow more or less the same route downslope as the river [F. Sandersen, personal communication, 2011].

After an avalanche profile has been drawn, the alpha-beta model can be utilized to identify the points for α and β, as well as points for α with one or more standard deviations. Usually, this process is straight-forward, and the points are located automatically. However; sometimes there might be several options for the location of the β-point, due to an undulating or rough terrain profile. For such avalanche profiles there are several locations where the inclination varies around 10°. In such cases, the user is asked to choose one β-point among two or more possibilities. Since the location of the β-point is critical for the location of the α-point, this can sometimes be a tricky choice [*Kronholm et al.*, Unpublished], and may involve quite some difference in distance between the optional resulting α-points [P. Gauer, personal communication, 2011].

Choosing the uppermost optional β-point can be risky, because the resulting α might be too far upslope. On the other hand, choosing the lowermost optional β-point might be too conservative. In a land-use planning perspective, the latter might result in locking up a great portion of land areas that otherwise would have been utilized.

4.1.3 Implementing object points into the model

When applying the alpha-beta model to areas with infrastructure and buildings at risk, it is of interest to include points along the avalanche profiles to mark the location of objects at risk. I call these points "object points", and symbolize them with a Ω. In this thesis the relevant

object at risk is the railway line (figure 19). The object angle is the average angle of the line of sight between the top of the release area and the railway.
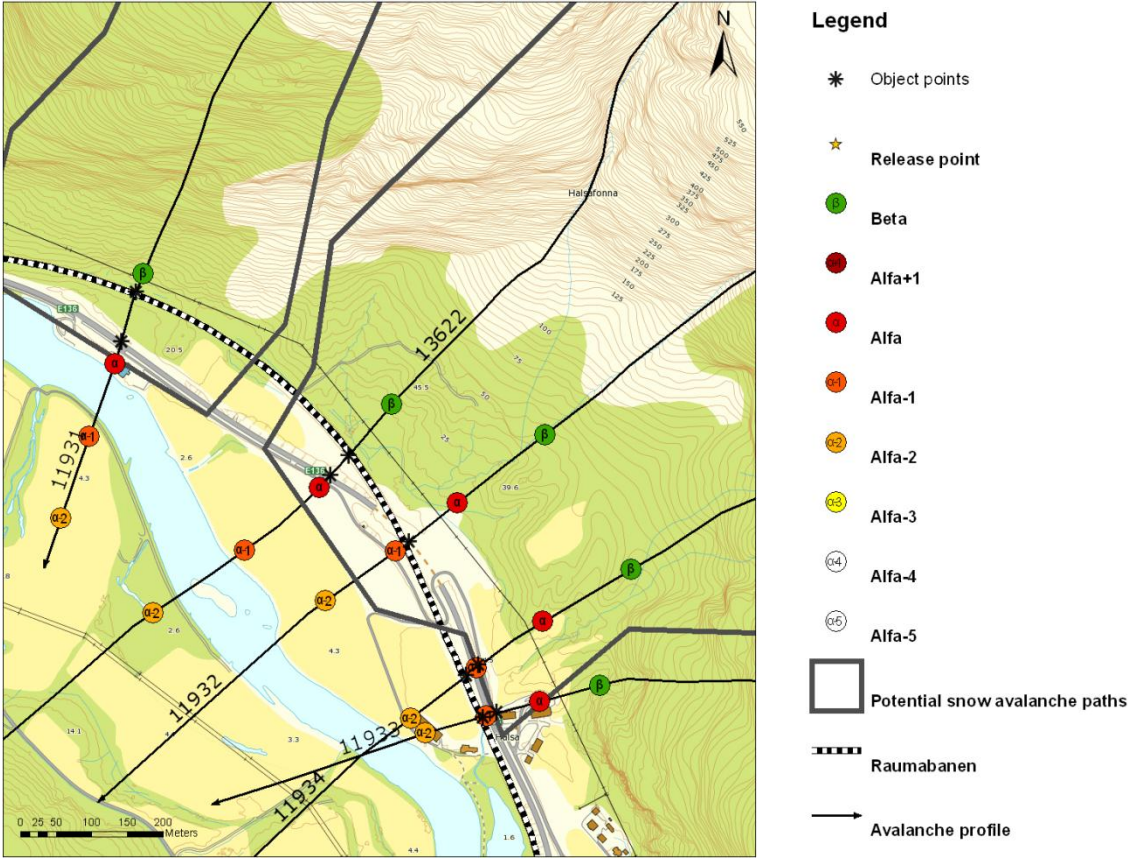
Figure 19: Close-up map from avalanche zone 1 at Halsa. The alpha-beta model has been run, and locations for the α- and β-points are shown with red and green circles, respectively. Object points indicating the locations where snow avalanches reach the railway are shown as black crystals. The avalanches have their origin at the upper right and descend at the lower left.

In the case of Raumabanen, object points were placed at every point where an avalanche profile crosses the railway.

4.2   Avalanche data included in the study

Of all the available registrations, the registrations made by NNRA were picked out and used in the following analyses of snow avalanche frequency and probability (figure 20, table 4). This implies that the analyses are based on a registration period of 63 years. Table 4 is almost

the same as table 2, except that registration 10 at Verma is removed. This registration lacks information about the year of the event, and could not be included in the frequency analysis.

The main reason for using only NNRA's avalanche registrations is that I consider these data to be of the best quality, and to be the most consistent data. All the NNRA registrations were collected by the same man until he retired [S.A. Brenden, personal communication, 2010]. The data from NGU, on the other hand, had a higher degree of uncertainty, because not all of the registrations contained the same amount and type of information. Also, there are "holes" in the avalanche history, for instance in the period from 1868 to 1982.

For these reasons, I considered the data from NNRA to be of the highest quality, and chose to make further analyses on these. The question on data selection is thoroughly discussed in chapter 6.
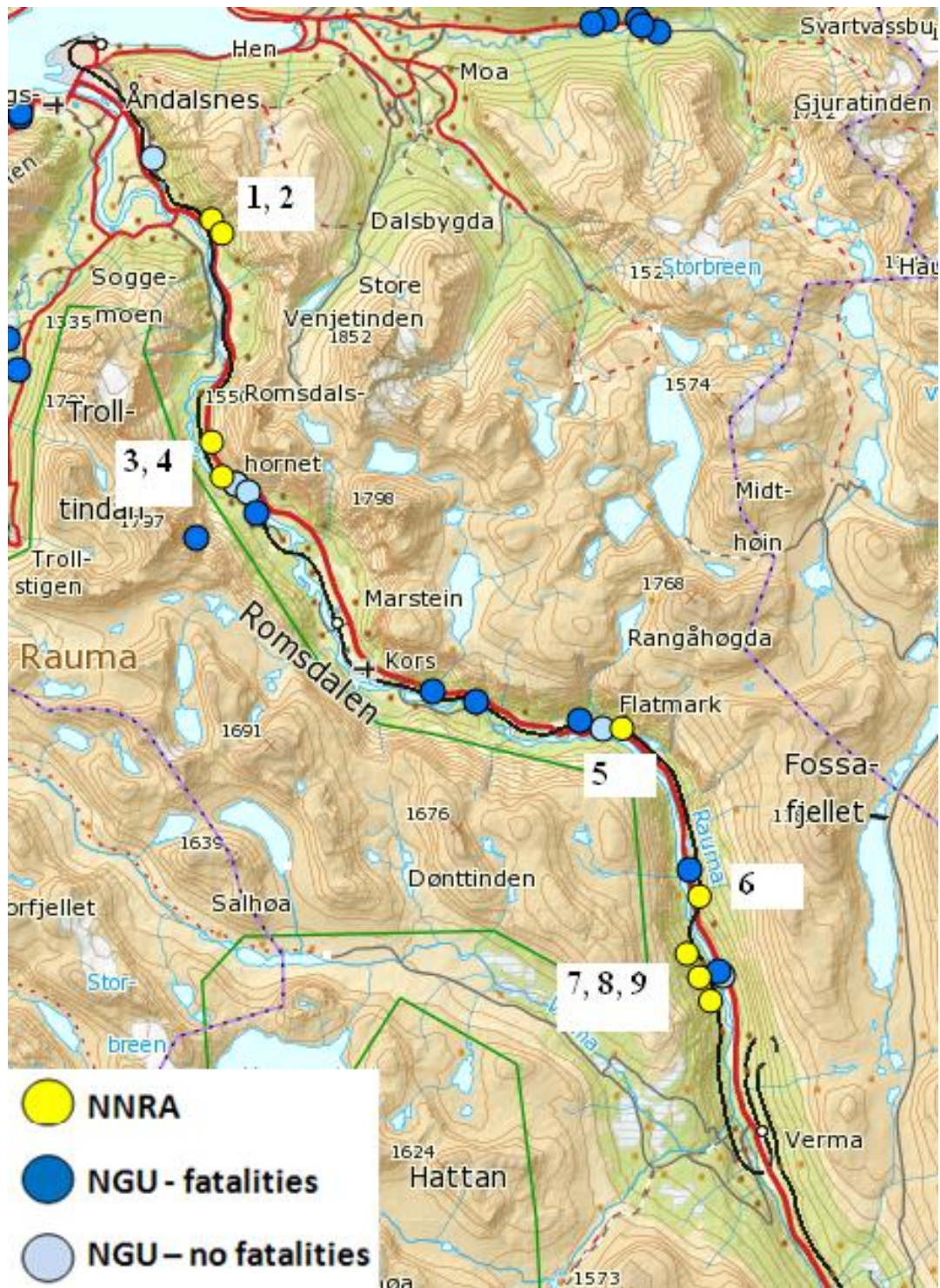
Figure 20: The selected snow avalanche registrations in the study area. The actual registrations are the ones from NNRA indicated with yellow dots. The numbers correspond to the ID numbers given in table 4. Map formatted from [skrednett.no].

Table 4: Snow avalanche registrations along Raumabanen railway prepared by NNRA in the period 1924 – 10.10.1987 [M. B. P., 1987].

ID	Name of location or avalanche path	Km (from Dombås)	Years of snow avalanche events
1	Halsa	450,90	1976, 1981, 1982
2	Ødegård	450,65	1955, 1956, 1968, 1976, 1982
3	Hornet	446,70	1952, 1982
4	Joengfonna	443,75	1932, 1940, 1943, 1947, 1965, 1966, 1967, 1985
5	Grønfonna	430,90-431,10	1952, 1958, 1965, 1981
6	Gurifonna	426,25	1942, 1958
7	Fossagrovfonna	425,70	1940, 1942, 1952, 1955, 1987
8	Fossalia	425,20	1955, 1968, 1974
9	Kverngrova	424,10	1942, 1958, 1974

4.3 Snow avalanche frequency and return period

Snow avalanche frequencies for the railway were decided on the basis of historical snow avalanches with the use of equation 1. The observation period, *T*, is 63 years, which constitutes the avalanche registration period from 1924 to 1987.

It is assumed that all the registered snow avalanches affected the railway; meaning all avalanches reached their respective Ω-points. Therefore, the avalanche history gives the snow avalanche frequency for the railway in each avalanche path. The Ω- frequencies is further utilized to obtain the probability that a snow avalanche will reach the railway at the individual paths.

The classical alpha-beta model can be extended into a model with an infinite number of points along the profile [C. Jaedicke, personal communication, 2011]. By doing so, it is possible to

calculate the avalanche frequency and probability for any point along the profile, with the use of the avalanche frequency from a known point [*Harbitz et al.*, 2001; *Kronholm et al.*, Unpublished]. In this study, the avalanche frequencies for the Ω-points were utilized to calculate the corresponding frequencies for the α-points. The method is derived from the on-going work with the extended alpha-beta model at NGI [*Harbitz et al.*, 2001; *Kronholm et al.*, Unpublished]. The procedure for calculating the α-frequencies follows two steps (equations 5 and 6):

For each avalanche path, the information about the Ω-point is utilized to calculate the return period for snow avalanche release, ΔT_r:

$$\Delta Tr = \frac{\Delta T\,\Omega}{e^{\left(\frac{-\pi(\Omega\,-0.96\beta+1.4°)}{6^{1/2}\cdot2.3°}\right)}}$$

(5)

Where Δt_Ω equals the return period for snow avalanches in the Ω-point along the avalanche profile, and Ω is equal to the assigned Ω-angle.

The return period of snow avalanche release is a constant factor for all points in that particular avalanche profile. Thus, it can be used to further calculate the return period for the α-point, ΔT_α, with the use of this formula:

$$\Delta T\alpha = \Delta Tr * e^{\left(\frac{-\pi(\alpha\,-0.96\beta+1.4°)}{6^{1/2}\cdot2.3°}\right)}$$

(6)

Where α is the α-angle. The snow avalanche return period at the α-points, T_α, is decided for each of the nine selected avalanche paths in the study area.

4.4 Snow avalanche probability

To be able to calculate the probability that a snow avalanche will block the railway, it is necessary to sort the avalanche registration data with relation to the year of the event. By doing this, we get an understanding of how many years that have in total 0, 1, 2 or more

registered snow avalanches. This knowledge can further be used to estimate the probability for a certain number of snow avalanches happening at any location along the railway within a year.

The probability calculations were made with the assumption that the snow avalanches can be characterized using a Poisson distribution. This type of distribution fits to situations were a certain event may happen anytime and anywhere in a given area in a given time interval [*Ang and Tang*, 1975]. In the case of Raumabanen, a snow avalanche may happen anytime and anywhere along the avalanche-prone sections of the railway during a winter season.

There is a set of assumptions that have to be made in order to use this distribution [*Ang and Tang*, 1975; *Innovation in Mathematics Teaching*]. Those are:

1) The events are independent of each other. In this context we need to assume that the occurrence of a snow avalanche is independent and unaffected by other avalanche events.

2) Each event occurs randomly. Snow avalanches occur randomly in time and space within the study area.

3) The expected number of events in an interval is directly proportional to the length of the interval. In this context, the expected number of snow avalanches reaching the railway is a constant number each year, corresponding to the Ω-frequency. The expected number of snow avalanches increases with increasing time interval.

4) The probability that two or more events happen at the same time is negligible. There cannot be two or more snow avalanches happening simultaneously. There can, however, be two or more snow avalanches occurring the same year.

In the following, I assume that all these requirements are fulfilled. The snow avalanche probability calculations were made with the use of the equation for the Poisson distribution [*Innovation in Mathematics Teaching*]:

$$P(X = x) = \frac{\lambda^x e^{-\lambda}}{x!} \quad (x = 0, 1, 2, \ldots)$$

(7)

Where λ is the mean number of occurrences of an event within the specified time interval; in this case the expected number of snow avalanches per year. x is the number of snow avalanches, meaning the expression P (X=x) is the probability that x snow avalanches will happen within a year [*Ang and Tang*, 1975].

The Poisson distribution is a one-parameter distribution, meaning we only need to identify λ to do the calculations. Equation 7 may be used in several applications; e.g. to study the occurrence of a certain type of extreme weather event [*Ang and Tang*, 1975], or to study the traffic density in transport corridors [*Innovation in Mathematics Teaching*].

The Poisson distribution is used to calculate both the snow avalanche probability at individual avalanche paths, as well as the total combined avalanche probability for the whole railway section from Bjorli to Åndalsnes. When combining several independent Poisson variables, the mean number of occurrences, λ_{tot}, is found simply by adding the individual λ-values [*Innovation in Mathematics Teaching*]:

New distribution J = [A+B+C+D+E+F+G+H+I]

$$\lambda J = \lambda tot = \lambda A + \lambda B + \lambda C + \lambda D + \lambda E + \lambda F + \lambda G + \lambda H + \lambda I \qquad (8)$$

In this context, it should be added that the probability that a snow avalanche hits the railway is the product of the probability of avalanche release and the probability that the avalanche actually reaches as far as the railway [*Harbitz et al.*, 2001]. The snow avalanche probabilities calculated in this study applies to the Ω-points, and must not be confused with the probability of snow avalanche release.

4.5 Snow avalanche exposure

The snow avalanche exposure time can be understood as the amount of time a train uses to drive through a snow avalanche run-out zone. The exposure should be viewed together with the avalanche probability to get a better idea of the snow avalanche hazard for the train traffic. The exposure time was estimated using the following equation:

$$E = \frac{(w + l)}{v} \tag{9}$$

Where w is the width of the avalanche path or avalanche area, l is the train length and v is the average velocity of the train.

Information needed to calculate the exposure times was provided by NNRA [S.A. Brenden, personal communication, 2011], and can be summarized as:

- Daily traffic density: 8 passenger trains, 2 cargo trains

- Length of passenger train: 60 m (standard length)

- Length of cargo trains: 20 m – 300 m (depends on the amount of cargo)

- Velocity for passenger trains: 70 km/h – 130 km/h

- Velocity for cargo trains: maximum 90 km/h

- Velocity for any train on days with snow avalanche hazard level 4: maximum 40 km/h

On days with high snow avalanche hazard (hazard level 4, appendix 2), there are two optional choices of action: 1. The allowed train velocity is reduced to maximum 40 km/h. The velocity must be so low that it is possible to slow down and stop the train on half of the sight distance in front of the train. 2. Both the road and railway are closed due to high snow avalanche hazard. Usually NNRA and NPRA work together to decide which solution to choose.

The information provided by NNRA was used together with measurements of the width of snow avalanche paths to estimate both the exposure time at individual avalanche paths as well as the total exposure time for the whole railway section Bjorli-Åndalsnes. The widths of individual snow avalanche paths were measured with a measuring tool in GIS.

4.6 Wind exposure

An analysis of exposition for the selected avalanche paths was undertaken, to determine which wind directions that account for most of the wind-related snow accumulation for each of the paths. This analysis was done by evaluating the avalanche terrain and surrounding topography with relation to snow drift and accumulation of snow in the release area. The assumed wind exposure is given a value between 0 and 1, for which 1 relates to wind

directions that are beneficial for snow accumulation in the release are. The value 0 is given for wind directions preventing snow accumulation, or even causing snow to blow out of the release areas.

5. Results

The evaluation of the snow avalanche hazard in the study area is a direct result of the findings in the analyses of snow avalanche frequency, probability and exposure. In addition, a general understanding of the topography and climate of the area forms the basis for the understanding of the variation in snow avalanche hazard along the railway.

Today, there are 20 known snow avalanche paths along the section Bjorli – Åndalsnes, out of which eight paths were either identified or confirmed on the day of the field excursion. An overview of all snow avalanche paths in the study area is given in figure 21.
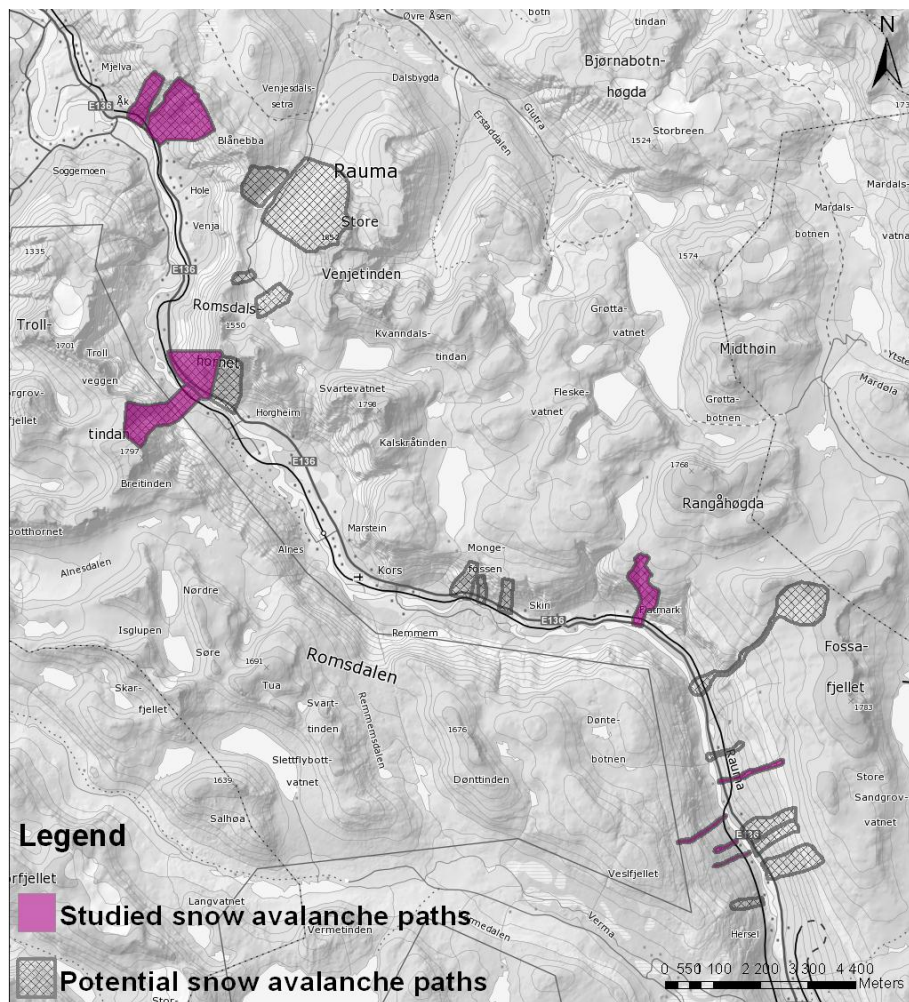
Figure 21: An overview of all snow avalanche paths in the study area. The studied paths are highlighted in purple.

5.1 Topography

The excursion was done when the area was snow-free, to discover any vegetative clues or other characteristics that could suggest recent snow avalanche activity. The observations were made by car along the road E 136; driving from Bjorli to Åndalsnes. We made several stops on the way, to make sure we got the terrain details at locations where avalanches were identified. Some avalanche paths were not that easy to study from the road, due to in part dense vegetation, but also lack of access from the road.

On the day of the inspection we saw several examples of avalanche paths with either missing or altered vegetation (figure 22). At some locations, there had been a re-growth of vegetation that could be distinguished from the original, surrounding vegetation by looking at the age, type and colouring of the trees.
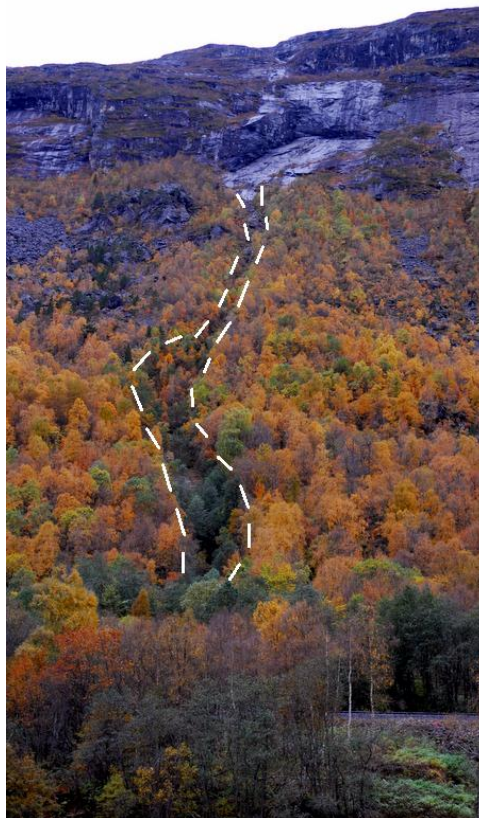
Figure 22: Example of how the post-avalanche vegetation can be distinguished from the surrounding vegetation. Fossagrovfonna next to Fossbrua. The avalanche path is indicated by white dotted lines. The railway can be seen in the lower right corner [Photo: C. Jaedicke, 06.10.2010].

The avalanche in figure 22 was recognised due to the distinct difference in vegetation. The trees covering the avalanche path are green, while the surrounding vegetation has typical autumn colours of yellow, orange, brown and red. It looks like the surrounding vegetation is dominated by deciduous trees, while the avalanche vegetation is mainly conifers. Norway spruce, *Picea abies*, has shown to be a common species in areas with both primary and secondary succession; meaning it is one of the first species that colonizes new areas [*Tjoelker et al.*, 2007]. Based on the sharp distinction in vegetation, it is reasonable to believe that there has been recent avalanche activity in this area.

Avalanche path 6, Gurifonna, is located just north of Fossbrua, in connection with a small stream. The end of the avalanche track is steep, 30-45°, and the profile flattens out only a few meters above the railway (figure 23).

Figure 23: Gurifonna. The white dotted line indicates the location of the railway [photo: L.L. Kristensen, 06.10.2010].

Slush avalanche scars were detected several places upslope of both the railway and the road (figure 24). Such avalanches can be distinguished from other avalanches because they tend to

erode away all the soil and vegetation, leaving the bedrock exposed [F. Sandersen, personal communication, 2010].

Figure 24: Slush avalanche scars along Raumabanen, in the area of Nyløvollen. The scars are indicated with rectangles. The railway is situated somewhere in the foreground of the picture [Photo: C. Jaedicke, 06.10.2010].

Along the road, at Foss, several relatively small avalanche paths were localized. Figure 25 shows a close-up of two of these.
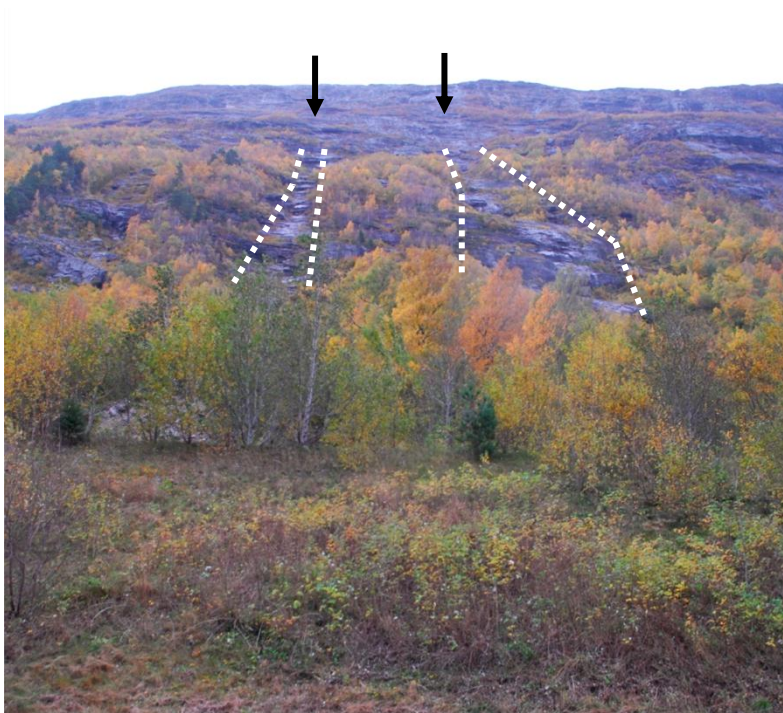
Figure 25: Avalanche scars at the "roadside" of the valley, approximately at Foss [Photo: C. Jaedicke, 06.10.2010].

Joengfonna is the most frequent avalanche in the valley, with eight registrations in 63 years. On the day of the excursion we were not able to see the top of the avalanche path, but the run-out zone could easily be defined because of the build-up of sediments in its lower part (figure 26).
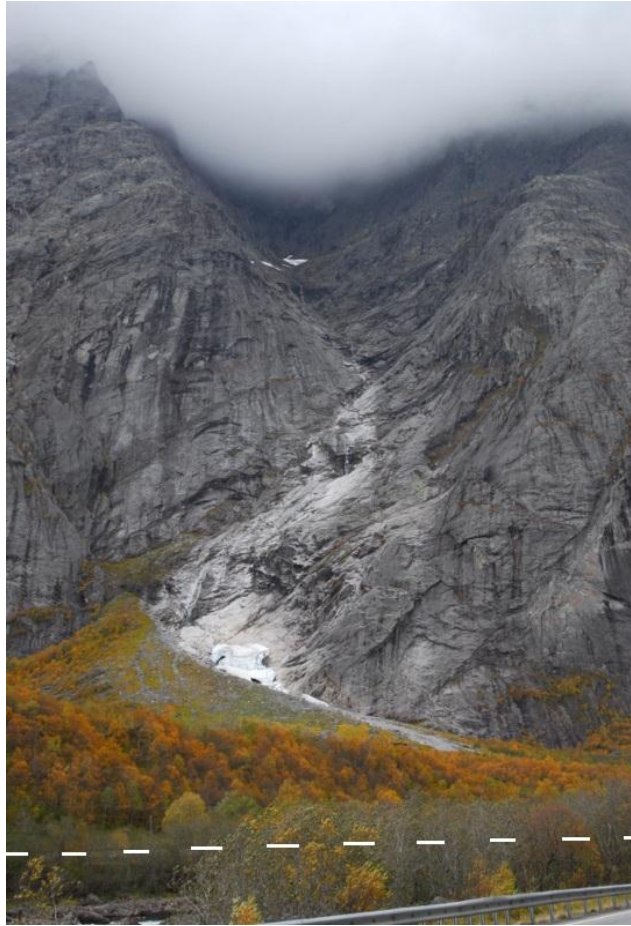
Figure 26: Joengfonna. The white dotted line indicates the location of the railway [photo: L.L. Kristensen, 06.10.2010].

The shape of the nine avalanche paths can be compared by plotting all avalanche profiles together (figure 27). Each profile was normalized with relation to its height, so that both the height and length are dimensionless.

The result shows that the ratio between the length and the height ranges from about 1:1 to 1:2. There are a range of profile shapes, and all the three main categories of profile shapes in figure 16 seem to be present. Joengfonna (4) and Ødegård (2) have parabola-shaped profiles. Fossalia (8) and Kvernagrova (9) are smooth and close to linear. Romsdalshorn (3) has the look of a hockey-stick.

Some of the avalanche profiles are not that easy to classify. Fossagrovfonna (7) and Gurifonna (6) have partly convex profiles, while Grønfonna (5) is uneven and "bumpy".
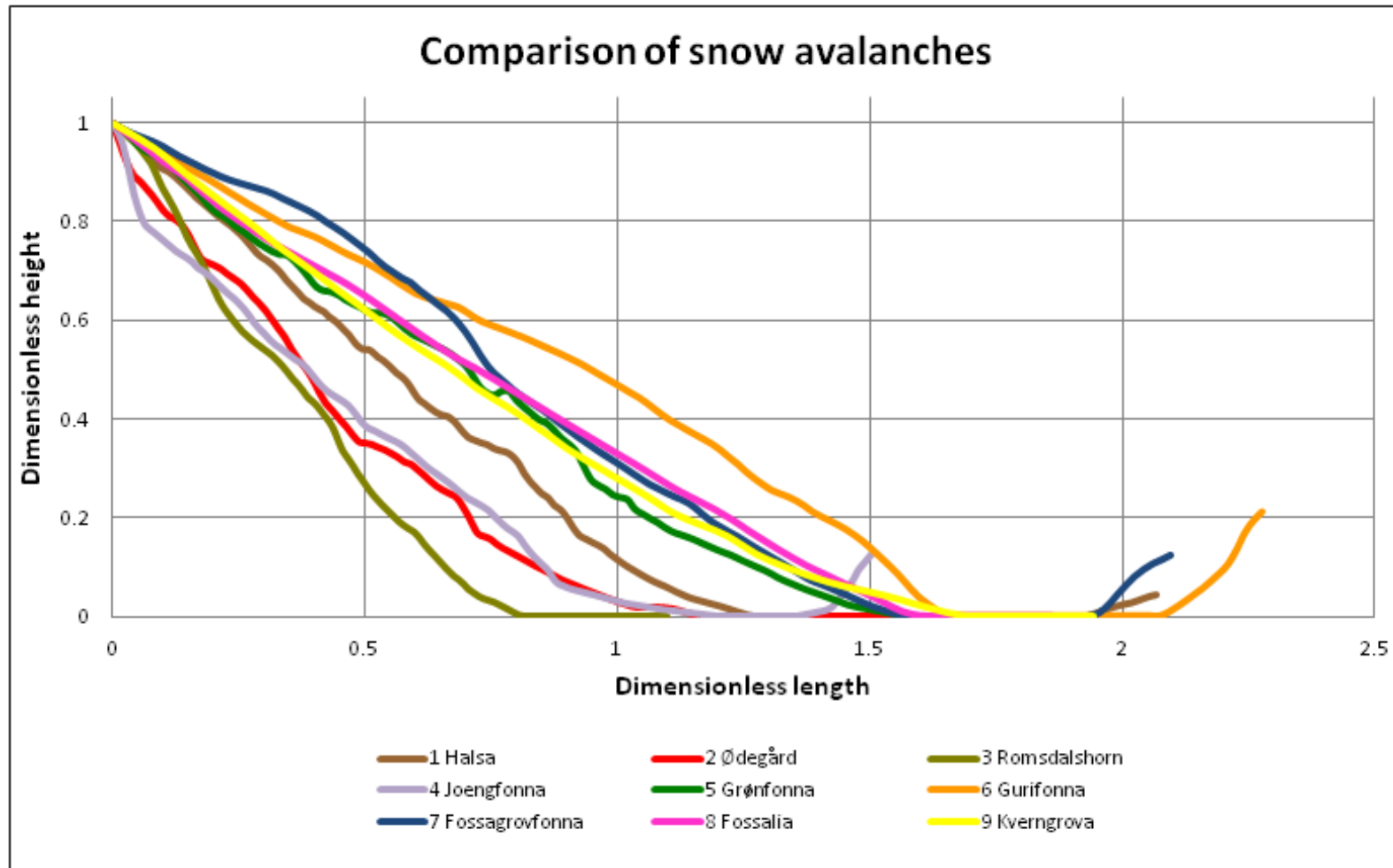
Figure 27: Comparison of the nine analyzed snow avalanche profiles. The profiles are normalized with respect to the height of each individual path, so that both length and height are dimensionless.

5.2 Snow avalanche return periods

The results for the analysis of snow avalanche return periods are given in table 6. All relevant information about each avalanche path is listed in table 5. The Ω-frequencies are purely a result of the snow avalanche history provided by NNRA. The related α-frequencies are calculated using the extended α-β model (equations 5 and 6).

A comparison of all the registrations shows that during the observation period of 63 years, there were 45 years with no registered avalanche activity. Eight years had one snow avalanche registration, while six and five years had two and three registrations, respectively. There were no years with more than three avalanche events. Figure 28 gives an overview of the studied avalanche paths and the snow avalanche return period in the Ω-points.

The results for T_α ranges from 4,3 years to 165,1 years. This variation is higher than the variation in T_Ω.

An unexpected error in the calculations of T_r appeared in the results. For some reason the return periods for snow avalanche release are higher than both T_Ω and T_α for almost all the avalanche paths. This finding will be discussed further in chapter 6.

Table 5: Topographic parameters from the alpha-beta model and snow avalanche registrations [M. B. P., 1987] .

ID	Name of avalanche path	Ω angle	β angle	α angle	Registrations
1	Halsa	36.4	38.2	35.3	1976, 1981, 1982
2	Ødegård	38.6	43.6	40.5	1955, 1956, 1968, 1976, 1982
3	Romsdalshorn	49	50.8	47.4	1952, 1982
4	Joengfonna	39.5	43.7	40.6	1932, 1940, 1943, 1947, 1965, 1966, 1967, 1985
5	Grønfonna	31.1	32.5	29.8	1952, 1958, 1965, 1981
6	Gurifonna	30.3	31.1	28.4	1942, 1958
7	Fossagrovfonna	32.1	32.6	29.9	1940, 1942, 1952, 1955, 1987
8	Fossalia	32.5	32	29.3	1955, 1968, 1974
9	Kverngrova	31.8	30.7	28.1	1942, 1958, 1974

Table 6: Calculated return periods (T) for all α- and Ω-points, as well as the return period for snow avalanche release, T, release.

ID	Ω angle	β angle	α angle	TΩ	T, release	Tα
1 Halsa	36.4	38.2	35.3	21.0	39.4	38.8
2 Ødegård	38.6	43.6	40.5	12.6	4.5	4.4
3 Romsdalshorn	49	50.8	47.4	31.5	78.2	76.8
4 Joengfonna	39.5	43.7	40.6	7.9	4.4	4.3
5 Grønfonna	31.1	32.5	29.8	15.8	32.5	32.5
6 Gurifonna	30.3	31.1	28.4	31.5	88.0	90.8
7 Fossagrovfonna	32.1	32.6	29.9	12.6	43.0	42.9
8 Fossalia	32.5	32	29.3	21.0	123.6	125.0
9 Kverngrova	31.8	30.7	28.1	21.0	167.7	165.1
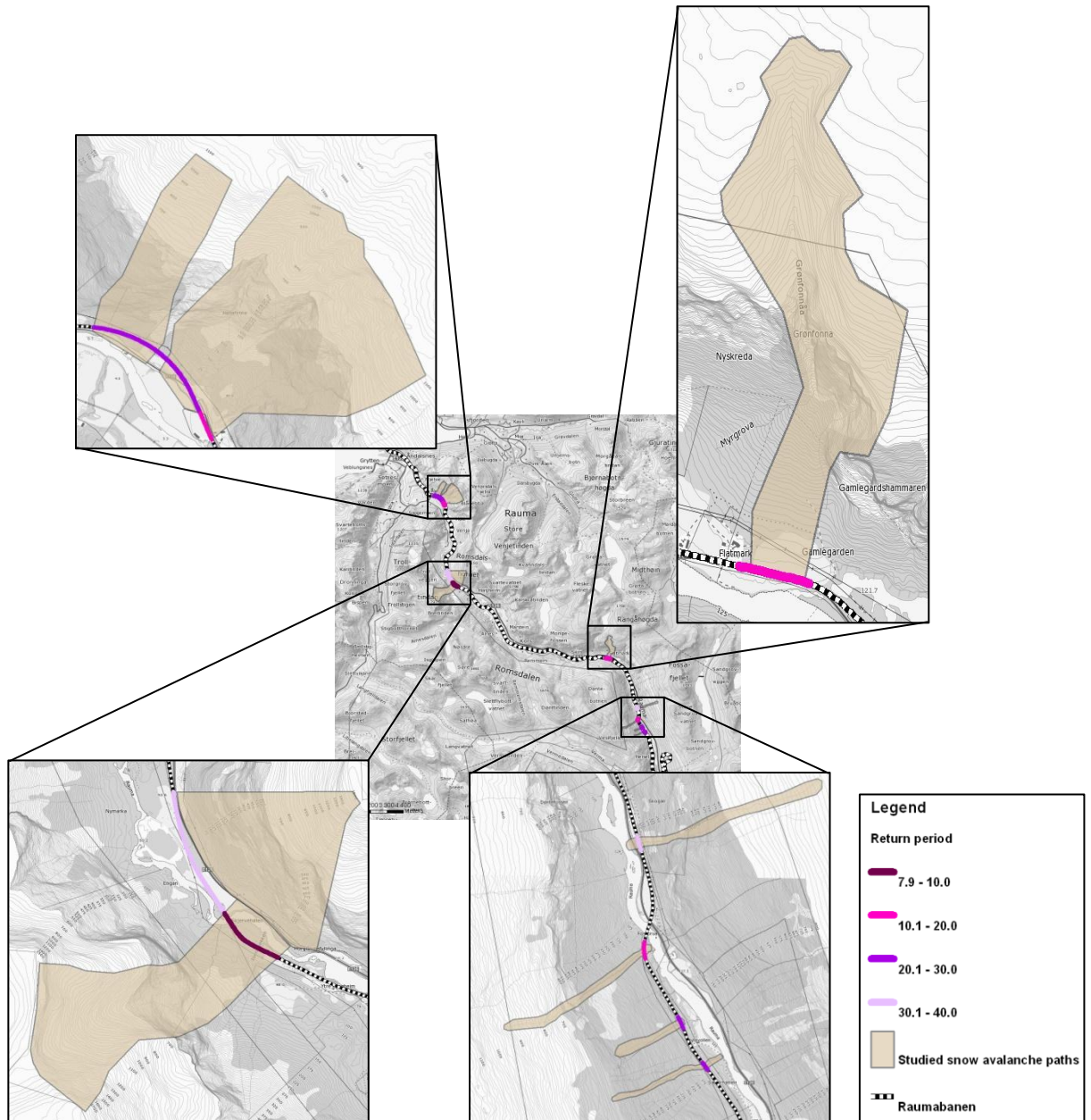
Figure 28: The nine analysed snow avalanche paths in the study area. The selected paths are highlighted and the return period for the Ω-points for individual paths is indicated according to the different colour classes.

5.3 Analyses of snow avalanche probability and exposure

5.3.1 Probability analysis

Individual snow avalanche probabilities were calculated for each of the nine avalanche paths in the area with the use of the Poisson distribution in equation 7. The calculations are summarized in table 7. The combined λ-value for the new distribution, J, represents the annually expected number of snow avalanches for the whole study area.

Table 7: Probability calculations for individual snow avalanche paths.

Snow avalanche path	New ID	λ	P(x=0)	P(x=1)
1 Halsa	A	0.048	0.953	0.046
2 Ødegård	B	0.079	0.924	0.073
3 Romsdalshorn	C	0.032	0.969	0.031
4 Joengfonna	D	0.127	0.881	0.112
5 Grønfonna	E	0.063	0.939	0.059
6 Gurifonna	F	0.032	0.969	0.031
7 Fossagrovfonna	G	0.079	0.924	0.073
8 Fossalia	H	0.048	0.953	0.046
9 Kverngrova	I	0.048	0.953	0.046
NEW DISTRIBUTION	J	0.556		

The total annual probabilities for snow avalanches on the railway section Bjorli – Åndalsnes were calculated using the combined λ, according to equation 8. The results are provided in table 8.

Table 8: Calculations of total probability for combined Poisson variables.

Total annual snow avalanche probability for the section Bjorli-Åndalsnes					
Annual number of events	0	1	2	3	4
Total probability	0.573	0.319	0.089	0.016	0.002

The total probability for having a snow avalanche anywhere along the railway section equals 0.319 / year.

5.3.2 Exposure analysis

The traffic information provided by NNRA given in part 4.5 was utilized to estimate the exposure times at various conditions. The results are listed in table 10. The term "E (passenger trains)" means the exposure time for standard passenger trains of 60 metres. The exposure time for cargo trains, "E (cargo trains)", is calculated with a train length of 200 metres. The exact length of such trains varies between 20 and 300 metres, so 200 metres was chosen to get a representative picture of the exposure.

The terms "E (hazard, p)" and "E (hazard, c)" refers to exposure times on days with high snow avalanche hazard for passenger trains and cargo trains, respectively. On these days, it is assumed that the trains have an average velocity of 30 km/h.

"Normal days" are defined as all days without a high snow avalanche hazard, and will account for the majority of days throughout a winter. The total exposure on normal days deviates a lot from the exposure on days with avalanche hazard level 4.

For passenger trains, the total exposure time for the whole railway section increases with (481,3 − 182,8) s = 298,5 s (~ 5 minutes) on days with a high snow avalanche hazard. The increase for cargo trains is (616,3 − 231) s = 385,3 s, This corresponds to an increase in exposure time of 6 minutes and 25 seconds.

Table 9: Exposure times at both individual avalanche paths and in total for the whole railway section, in seconds. For specifications of column headings, see text.

ID	Name of avalanche path	Velocity (m/s)	Width of avalanche path (m)	E (passenger train) (s)	E (cargo train) (s)	E (hazard, p) (s)	E (hazard, c) (s)
1	Halsa	22.2	1080	51.3	57.6	137.3	154.2
2	Ødegård	22.2	1080	51.4	57.7	137.3	154.2
3	Romsdalshorn	19.4	930	50.9	58.1	119.3	136.1
4	Joengfonna	19.4	500	28.8	36.0	67.5	84.3
5	Grønfonna	22.2	310	16.7	23.0	44.6	61.4
6	Gurifonna	33.3	195	7.7	11.9	30.7	47.6
7	Fossagrovfonna	27.8	165	8.1	13.1	27.1	44.0
8	Fossalia	25.0	165	9.0	14.6	27.1	44.0
9	Kverngrova	22.2	170	10.4	16.7	27.7	44.6
Total exposure time (s)				**182.8**	**231.0**	**481.3**	**616.3**

The probability for a direct hit between a random snow avalanche and train, $P_{\text{direct hit}}$, was calculated (table 10). The calculations of individual $P_{\text{direct hit}}$ at each snow avalanche path (table 7) form the basis for this calculation. Individual probabilities for direct hit are summed, and the total probability for direct hit for the whole study area is found.

As an example, here is the calculation procedure for avalanche path A (Halsa) for both normal days and days with a high snow avalanche hazard:

Situation 1: Days with normal traffic

1) The total daily exposure time for all trains passing avalanche path A is:

$$E_{\text{tot (normal days)}} = (E_{\text{passenger train}} * 8) + (E_{\text{cargo train}} * 2)$$

$$E_{\text{tot (normal days)}} = (51{,}3 \text{ s} * 8) + (57{,}6 \text{ s} * 2) = 525{,}6 \text{ s}$$

2) Assuming that there are no closures on the railway or no days with reduced traffic, the total fraction of exposure is:

$$E \text{ fraction } = \frac{E \text{ tot (normal days)}}{\text{day}} = \frac{525{,}6 \, s}{86400 \, s} = 0{,}0061 \, s$$

3) Applying the probability for snow avalanche at avalanche path A, the annual probability for a direct hit between a snow avalanche and a random train is:

$$P_{\text{direct hit}} = P(x{=}1) * E_{\text{fraction}} = 0{,}046 \text{ / year} * 0{,}0061 = 0{,}00028 \text{ / year} \approx 3*10^{-4}/\text{year}$$

This gives on average one direct hit every 3333 years at avalanche path A.

Situation 2: Days with a high snow avalanche hazard

The following findings are made with the assumption that the average velocity of the trains is reduced to 30 km/h. It is also assumed that the traffic density (number of trains per day) is the same as for other days.

1) The total daily exposure time for all trains passing avalanche path A is:

$$E_{\text{tot (high hazard)}} = (E_{\text{passenger train, high hazard}} * 8) + (E_{\text{cargo train, high hazard}} * 2)$$

$$E_{\text{tot (high hazard)}} = (137{,}3 \text{ s} * 8) + (154{,}2 \text{ s} * 2) = 1407{,}2 \text{ s}$$

2) The total fraction of exposure at avalanche path A is:

$$E_{\text{fraction, high hazard}} = E_{\text{tot (high hazard)}} / \text{day} = 1407{,}2 \text{ s} / 86400\text{s} = 0{,}0163 \text{ s}$$

3) Applying the probability for snow avalanche at avalanche path A, the annual probability for a direct hit between a snow avalanche and a random train on days with reduced train velocity is:

$$P_{\text{direct hit, high hazard}} = P(x=1) * E_{\text{fraction, high hazard}} = 0{,}046 / \text{year} * 0{,}0163 = 0{,}0007/\text{year}$$

This gives on average one direct hit every 1429 years at avalanche path A.

For avalanche path 1 the probability for direct hit is more than doubled on days with a high snow avalanche hazard. However; the calculations show that the probability for direct hit is low in both situations.

Table 10: Probability for direct hit between random snow avalanche and train for normal days and days with a high snow avalanche hazard.

Avalanche path	Normal days			Days with high hazard		
	E daily	E fraction	Pdirect hit	E daily	E fraction	Pdirect hit
A	525.6	0.0061	0.0003	1407.2	0.0163	0.0007
B	526.1	0.0061	0.0004	1407.2	0.0163	0.0012
C	523.5	0.0061	0.0002	1226.5	0.0142	0.0004
D	302.4	0.0035	0.0004	708.4	0.0082	0.0009
E	179.1	0.0021	0.0001	479.5	0.0055	0.0003
F	84.9	0.0010	0.0000	341.0	0.0039	0.0001
G	91.1	0.0011	0.0001	304.8	0.0035	0.0003
H	101.2	0.0012	0.0001	304.8	0.0035	0.0002
I	166.5	0.0019	0.0001	310.8	0.0036	0.0002
SUM (J)			**0.0017/yr**			**0.0043/yr**

The total $P_{\text{direct hit}}$ for the whole study area equals 0.0017/year and 0.0043/year on normal days and days with a high snow avalanche hazard, respectively.

5.4 Wind exposure

The results for the analysis of exposition and wind are illustrated in figures 29 and 30, and summarized in table 11. The main wind directions facilitating snow accumulation for each avalanche path is indicated with black arrows.
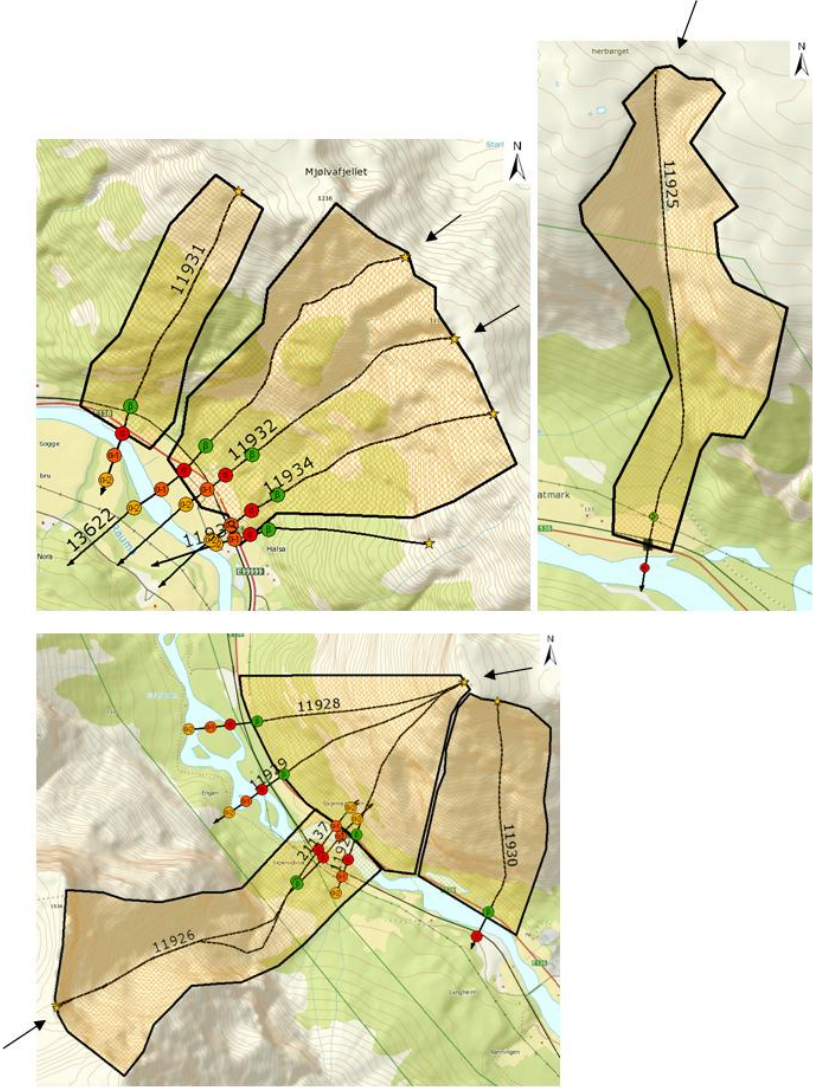
Figure 29: Wind exposure for the avalanche areas at Halsa and Ødegård (top left), Romsdalshorn and Joengfonna (bottom) and Grønfonna (top right).
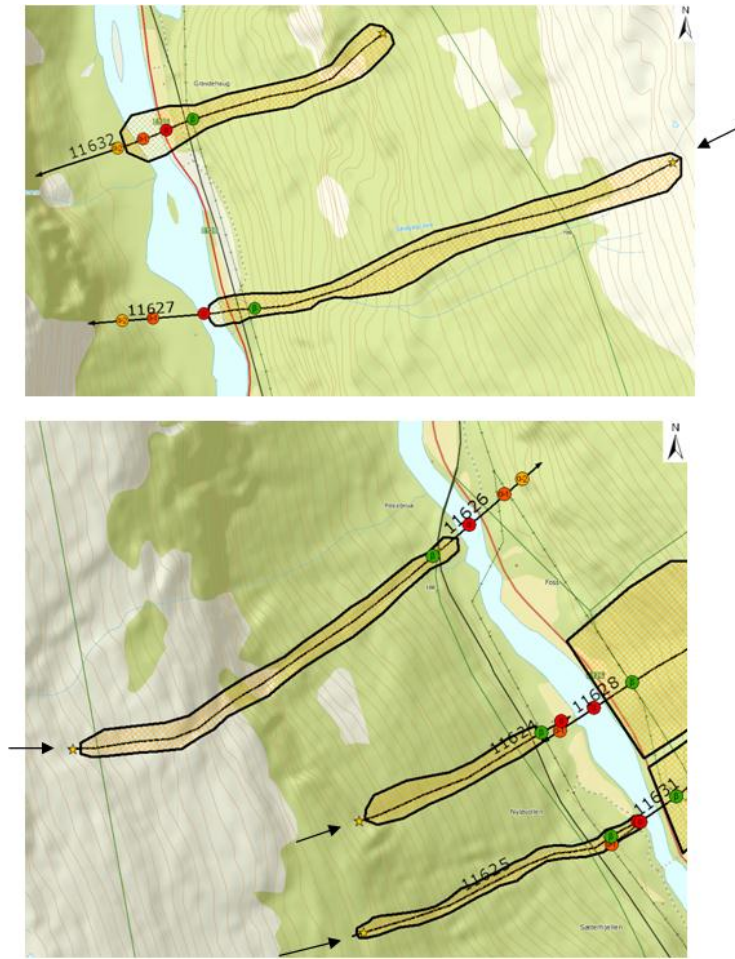
Figure 30: Wind exposure for the avalanche areas at Gurifonna (top) and Fossagrovfonna, Fossalia and Kverngrova (bottom).

The selected avalanche paths in the study area show some variation in wind exposure. The analysis results indicate that the main wind directions for snow accumulation are North-East ↔ East or South-West ↔ West, since these wind orientations most frequently get a value of 1 (table 11).

Table 11: Wind exposure analysis. The exposure values range from 0 to 1, with a value of 1 indicating the main wind direction for snow accumulation in each avalanche path.

Wind exposure	Halsa (profile 13622)	Ødegård (profile 11932)	Romsdalshorn (profile 11928)	Joengfonna (profile 11926)	Grønfonna (profile 11925)	Gurifonna (profile 11627)	Fossagrovfonna (profile 11626)	Fossalia (profile 11624)	Kverngrova (profile 11625)
N	0.7	0.7	0.2	0.5	0.9	0.3	0	0	0
N-E	1	1	0.6	0	1	1	0	0	0
E	0.6	0.6	1	0.4	0.7	0.7	0	0	0
S-E	0.3	0.3	0.5	0.4	0.1	0.2	0	0	0
S	0.1	0.1	0.2	0.7	0	0	0.3	0.3	0.3
S-W	0	0	0.1	1	0	0	0.7	1	1
W	0.6	0.6	0	0.8	0	0	1	0.7	0.7
N-W	0.7	0.7	0.2	0.2	0.2	0	0.2	0.2	0.2

6.   Discussion

In this chapter I will discuss the results presented in chapter 5. The findings will be related to the objectives of this study, presented in section 1.2.1. This comprises an evaluation of the snow avalanche hazard in the study area. I will comment on the results from the alpha-beta model, while considering both advantages and disadvantages with the chosen methodology. A discussion on model uncertainty is also provided, together with a socio-economic perspective on hazard and risk analysis.

6.1 Data selection

The procedure for the selection of avalanche registration data needs to be further explained. I did not use all the available background data for the avalanche history in the study area. I used the data from NNRA from the period 1924 to 1987 [*M. B. P.*, 1987]. These registrations are all included in appendix 1, and listed in table 4.

There were several reasons why I chose not to include the snow avalanche data from NGU into the hazard analysis. These were:

1) Some of the registrations lacked information about the year of the avalanche event.

2) Some registrations could not be localized on the background map used in GIS.

3) Some registrations contained additional information that suggested more extensive local avalanche activity than what were actually captured in each registration. For this reason, I am certain that not all known avalanches in the period from 1750 up until today have been registered.

4) The registration period seemed inconsistent, with longer periods without any registrations. An example: There are no registrations between 1868 and 1982, which suggests that there were no avalanche activity for more than 100 years. However, I know from NNRA's registrations that this suggestion does not hold.

5) There seems to be a focus on old avalanche events from the 18th and 19th century, rather than more recent events.

Generally, when evaluating the snow avalanche hazard in an area, it is preferred to have as much information about the snow avalanche history as possible. The longer the registration period, the more likely is it that extreme avalanche run-out distances at different paths have been registered. For this reason, it might seem a little strange to exclude some of the available data. However; it is never a good idea to analyse inconsistent data. Then the data situation becomes a question of trade-off between having a relatively short, consistent registration period or a longer, but less accurate data set.

In the situation of Raumabanen, I consider it more beneficial to use only the registrations from NNRA. I assume that all avalanches reaching the railway during the period from 1924 to 1987 were recorded. I therefore consider these registrations to be consistent and reliable.

In this context, whether the avalanche data contain avalanche registrations with maximum reach or not is really not that important, since the essential aspect is whether the railway was reached or not. The railway is the object at risk; it does not really matter whether the avalanche reached way past the railway, as long as it reached the railway.

6.2 Evaluation of the modelled and calculated results

Analysis of return periods

The results for the snow avalanche return period at individual Ω-points vary between approximately 8 and 32 years. The overall result for all avalanche paths is relatively consistent, meaning there are no large deviations in snow avalanche frequency for the railway in the avalanche areas.

The quality of the estimations of T_Ω is highly dependent on the quality of the snow avalanche registrations in the chosen observation period. The quality of the estimations also depends on my understanding of snow avalanches in the study area; in terms of choosing the most likely location for the snow avalanche profile at every avalanche path. Some of the avalanche paths are broad and contain several possible snow avalanche profiles. The choice

of profile is decisive for locations of the α-, β- and Ω- points, and therefore a source of uncertainty in the analysis of the return period.

The avalanche registrations do not contain exact information about the location of the events, so it is not possible to know for sure which profile that accounts for which of the different events. For each snow avalanche path, I have therefore chosen the profile that I assume is the most dangerous one with relation to snow avalanche activity. With "dangerous" I mean the profile that is assumed to represent the one with the most comprehensive consequences should there be an avalanche. Each profile was chosen somewhat arbitrary, according to known climatic conditions and as far as my knowledge on snow avalanche terrain goes.

The calculated return periods for the α-points showed a greater variation than those for the Ω-points, ranging from approximately 4 to 165 years. There is a logical relationship between the resulting T_α and T_Ω, giving that the lower the angle of the point, the higher the return period. This corresponds to the natural connection between long run-out distances and high return periods.

The resulting return periods for snow avalanche release, on the other hand, are somewhat surprising. For all nine avalanche paths, T_r has a high return period compared to both T_α and T_Ω. This result is obviously wrong, since both T_α and T_Ω are combined results of the snow avalanche release frequency and the frequency for having a snow avalanche reaching the locations for α and Ω, respectively. In other words; T_r make up T_α and T_Ω, and must always have the lowest value. There cannot be a higher number of snow avalanches reaching the α- and Ω-points than the total number of snow avalanches released.

I do not have a good explanation for this result, but it is obviously wrong. Although the extended alpha-beta model has given promising results for snow avalanches in other study areas, it gives erroneous results for the study area of Raumabanen. The methodology for the extended alpha-beta model is still not fully developed, and the set of formulas that equations 5 and 6 were derived from are likely to be modified before publication.

Probability analysis

The probabilities for snow avalanches reaching the railway at individual paths depend on the assigned snow avalanche frequencies for the Ω-points. For each avalanche path the Ω-frequency is included in the Poisson distribution as λ; the expected annual number of snow avalanches. All the individual snow avalanche probabilities are relatively high, with P(x=1) ranging from 0.112/year at Joengfonna to 0.031/year at Gurifonna and Romsdalshorn.

The overall result for the whole study area gives that the annual probability that a snow avalanche reaches the railway is quite high; P (x=1) = 0.319/year (table 8). At first glance, this might seem surprising. However; when considering that the total snow avalanche probability is a result of a combination of nine individual avalanche paths, the calculated probability seems credible.

The total snow avalanche activity in the area is likely higher than the avalanche registrations indicate. The registrations only apply to snow avalanches affecting the railway, and do not take into account snow avalanches with a shorter run-out. Snow avalanches that stopped upslope of the railway have most likely not been registered.

In this context it should be mentioned that one needs to be careful with viewing frequency and probability as something synonymous. This is especially true for non-stationary stochastic events like snow avalanches [*Kristensen et al.*, 2003]. In this study, the registered avalanche frequencies were used directly in the analysis of snow avalanche probability. Snow avalanche frequency is to a large extent dependent on the climate. The climate is dynamic, and in a long time perspective it is not recommended to use a constant snow avalanche frequency and probability. For this thesis work, however, the aim was to make a general hazard analysis of today's avalanche situation. Therefore, future climate change has not been considered in the analyses.

Exposure analysis

The evaluation of exposure times for trains shows that the exposure time varies a lot between individual avalanche paths, ranging from a few seconds up to almost a minute. The

variations in exposure time can be explained by the variations in avalanche path width and train velocities.

When comparing normal exposure times with the exposure on days with a high snow avalanche hazard, the result is, naturally, an increase in exposure times for all trains throughout the whole study area. Since cargo trains do not have a standard length, I made the calculations using an average length of 200 m. Naturally, the resulting exposure times for cargo trains are only guiding estimates. The actual exposure time for these trains will vary a lot, depending on their length.

NNRA's reason for reducing the train velocity on days with high snow avalanche hazard is that this measure is thought to prevent the trains from colliding into avalanche masses on the railway line [S.A. Brenden, personal communication, 2010]. The thought is that if the trains run much slower than normal, the driver has more time to react and stop the train whenever a snow avalanche is detected.

When reducing the maximum allowed train velocity to 40 km/h on days with a high snow avalanche hazard, the probability for collision between train and avalanche is most likely reduced. However, the probability of having an avalanche directly hitting the train is increased due to longer exposure times. The difference in probability for direct hit is quite large when comparing "normal" days with days with high avalanche hazard. The probability is increased from 0.0017/year to 0.0043/year, which gives an increase from 1 direct hit per 3333 years to 1 direct hit per 1429 years.

The calculations show that the probability of direct hit can be characterized as low, no matter what velocities the trains are running at. Even though the exposure times are more than doubled for all trains at all avalanche paths on days with a high snow avalanche hazard, the total fraction time of exposure is still small. Thus, the resulting probabilities for direct hit are low.

The probability of collision between random train and avalanche is not calculated here, because such calculations are complex and requires a lot of additional information. To be able to calculate the required braking distances at different locations along the railway, one

needs to know, for instance, the braking type and braking performance for different train types and the exact steepness of the terrain at the different locations. In addition, I would have had to make a lot of assumptions regarding the weather conditions; e.g. whether the tracks are wet or dry, and the driver's reaction time.

For this reason, I am not able to compare the reduction in collision probability and the increase in direct hit probability directly. However, experience has shown that when considering the total snow avalanche risk, the risk involved in a direct hit only accounts for a small part of the total risk for the railway [U. Eidsvig, personal communication, 2011]. Also, collisions between train and avalanche masses happen more frequently than direct hit events, and therefore constitute a greater risk to the railway [U. Eidsvig, personal communication, 2011].

Rather than focusing on the probability for a direct hit, NNRA are mainly concerned with avoiding collisions between train and avalanche, and subsequent derailment. It seems to me that focusing on reducing the collision probability is the right action, since the probability for collisions with snow avalanches in any case is likely to be higher than the direct hit probability. After all; the probability for direct hit on normal days is so low, that an increase in this probability on days with a high avalanche hazard can be accepted.

6.3 Advantages and disadvantages with the chosen methodology

The alpha-beta model is a well-established statistical model for extreme snow avalanche reach. It is internationally recognized and extensively used in many countries, e.g. Norway, Austria and Iceland [C. Jaedicke, personal communication, 2011].

There are both advantages and disadvantages regarding the use of the alpha-beta model for estimation of run-out distance. The simplicity of the model is one of its main advantages. It is purely topographic, and, according to the regression equation 4, we only need to define one parameter, the β-point, to calculate the α-point. The model does not require a lot of background data about snow avalanche history or the climate in the study area. The classical

alpha-beta model has its origin in Norwegian snow avalanches, and is supposed to represent the Norwegian topography and climate quite well [*Lied and Kristensen*, 2003].

However; one should bear in mind that the snow avalanches included in the development of the model were selected with the use of certain criteria; some of which are:

- The assumed return period for snow avalanches reaching the α-point is between 100 and 300 years [K. Lied, personal communication, 2011].

- The snow avalanche paths were thoroughly studied; both topographically and historically. For the majority of the avalanches, the registrations go more than 100 years back in time, sometimes as far back as the 17th century [*Lied and Bakkehøi*, 1980].

- One important assumption regarding climate was made: For all avalanche paths there were at least one episode throughout the documented avalanche period were "optimum snow conditions" for snow avalanches with extreme run-out distance occurred [*Lied and Bakkehøi*, 1980]. This implies that the scientists were quite sure that they had registered the maximum avalanche reach for every path.

- The avalanches are typically large with height differences greater than 500 meters. They also have relatively large release areas, and smooth, approximately parabola-shaped profiles.

Due to these criteria, the model will only represent well for similar snow avalanches as those used to develop it. As an example on such limitations, it has been shown that the model should not be applied to small avalanches, and/or avalanches with a small release area, since it has a tendency to overestimate the run-out distance for such paths [*Kronholm et al.*, Unpublished]. It has also been shown that the model has a tendency to overestimate the run-out distance for avalanches with steep run-out zones, resulting in too conservative avalanche reach [*McClung*, 2001].

Naturally, this leads to the knowledge that the model should not be utilized on avalanches that are not typical "alpha-beta avalanches". Careless use of the model can give misleading and unrealistic run-out distances [*Kronholm et al.*, Unpublished].

In the process of running the alpha-beta model in ArcGIS to calculate points for α and β, these points were usually located automatically when applying the model tool. But for some avalanche profiles, the β-point had several optional locations, due to variations in inclination around 10°. In such cases, the exact location of the β-point had to be chosen manually. This can be a little tricky, especially when there is large variation in the optional locations for β-points. Since the β-point is the only parameter controlling the location of the α-point, the selection of β is crucial for obtaining a realistic α [*Kronholm et al.*, Unpublished].

Whenever I encountered the problem of choosing between several optional β-points, I consequently chose the most conservative one; meaning the β-point furthest down-slope. The reason for that practice, is that I consider it as better to be a bit careful, than overoptimistic with regard to the maximum avalanche run-out in an area. However, for most of the avalanche profiles in the study area the model-tool could automatically assign the β-point and calculate α, so only minor subjective assessments of β were necessary.

6.4 Model uncertainties

All models are wrong, some are useful

(George E. P. Box, statistician)

Models are useful at helping scientists approach a problem, but should never be considered as the actual truth or reality. Models are only an approximation of reality, and therefore the result should always, as far as possible, be considered in combination with other methods, such as field work [*McClung and Schaerer*, 2006].

It should also be pointed out that it is never possible to model the exact maximum run-out distance at any location with any method [*Lied and Bakkehøi*, 1980]. The choice of method is then a question of the preferred solution among several options.

For the alpha-beta model it is important to bear in mind that the purpose of the model is to find the extreme run-out distances for snow avalanche paths. Thus, the model has some limitations when it comes to "non-ideal" avalanche paths that will never produce really long run-out distances, either due to the topographic conditions along the avalanche profile or because of topographic or hydrological barriers in the run-out zone.

The alpha-beta model has a standard deviation of 2,3°. This gives a variation in the location of the α-point. This variation represents a larger horizontal distance for the gentle parts of an avalanche profile, than for steeper parts. In other words, the closer to the mountainside the α-point is located, the lower is its uncertainty [C. Jaedicke, personal communication, 2011]. On very gentle and elongated slopes, this uncertainty gives vast differences in maximum horizontal reach.

Calculations for the maximum run-out distance in the alpha-beta model are done by fitting a parabola-shaped profile to the terrain profile. This practice leads to the question of whether the model can be used to a variety of avalanche profiles, or if the use should be restricted to more or less parabolic avalanche paths. The experience from several studies on alpha-beta accuracy, has shown that the model is relatively good at estimating run-out distance for several types of profile shapes; including smooth, almost linear profiles, parabolic profiles and hockey-stick profiles (figure 16) [P. Gauer, personal communication, 2011].

However, experience also indicates that there are certain profile shapes for which the model does not work that well. An example is avalanche profiles with a height difference less than 400 meters [P. Gauer, personal communication, 2011]. For such avalanche paths, the alpha-beta model seems to overestimate the maximum run-out distance. This finding is supported by Canadian scientists [*Jones*, 2002].

Elongated, gentle slopes also seem to be a problem for the alpha-beta model [P. Gauer, personal communication, 2011]. For such profiles, there is a long transition zone between the avalanche track and run-out zone, resulting in large horizontal differences in stopping position. The estimated α-point is therefore rather uncertain [P. Gauer, personal communication, 2011].

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The comparison of the different snow avalanche profiles in this study (figure 27) revealed that the avalanche paths have quite distinct shapes. There are several paths that cannot be characterized with a parabolic profile. Also, the avalanche paths at Fossalia and Kverngrova have a low height difference of approximately 400 and 500 metres, respectively. Thus, they are not "typical alpha-beta avalanche profiles". These are examples of possible sources of error in the modelled α-points.

In this thesis, the calculated Ω-frequencies are a direct result of the avalanche registrations in the area. Consequently; the return periods for the Ω-points solely depend on the quality of the avalanche registrations. 63 years of avalanche registrations does not provide us with detailed snow avalanche information; at least not from a statistical point of view. For that, the registration period is too short. However, it should be pointed out that compared to other avalanche-prone areas in Norway, the study area of Raumabanen actually has a well-known snow avalanche history. The normal situation for scientists assessing avalanche hazard around the country, is to have no or minor knowledge about the local avalanche history [C. Jaedicke, personal communication, 2011].

6.5 Socio-economic aspects

When evaluating the snow avalanche hazard and risk in an area, there are several non-technical aspects that should be considered. Some examples of such aspects are the society's perception of risk, the possible societal, economic and environmental consequences of avalanches and different political aspects. I will give a short discussion on some of these aspects.

Risk perception can be explained as the intuitive evaluation or judgement of risk made by individuals [*Slovic*, 1987]. In other words, risk perception can be said to be our understanding of a risk situation. People's perception of risk has shown to be highly dependent on personal experience and the ability to rank different risks against each other, and, hence, put a particular risk in perspective [*Kletz*, 1980]. This implies that scientific persons, laymen and the authorities may all have different views on different kinds of risks [*Slovic et al.*, 2004].

In the case of snow avalanche risk along Raumabanen, this risk is perceived differently by NNRA than by the Government. The Government has focused on avalanche protection to infrastructure, and has allocated money for this purpose, with the argument that they need to ensure people's safety and reduce the number of avalanche accidents [*regjeringen.no*, 2010]. The State provides 1 billion NOK annually for avalanche protection to roads [*regjeringen.no*, 2010]. NNRA, on the other hand, argues that there are other infrastructure-related risks that are higher than the snow avalanche risk. As an example, NNRA would rather prioritize removing train track crossings than building avalanche protection measures [P.A. Fevang, personal communication, 2011]. The reason is that such track crossings are considered a greater risk than snow avalanches, since they are responsible for a far greater number of fatalities than collisions with snow avalanches.

It is common to divide risk into voluntary and involuntary risk. In general, the public seem to have a greater tolerance for voluntary risks, than for involuntary risks [*Smith and Petley*, 2009]. As an example, there seems to be a greater acceptance for the risk implied by smoking, than for the risk implied by aviation. In a study about risk perception, it was revealed that, according to the public, the greatest risks in the society are activities or technologies like nuclear power and fire-fighting [*Slovic*, 1987]. This perception can be explained as a common fear for the unknown. Although experts on nuclear power plants may conclude that the risk implied by a nuclear power reactor is very low, the public often hold the opinion that together with this technology comes a great risk of radioactive disaster [*Slovic*, 1987]. The conclusion is that we seem to fear the uncontrollable, involuntary and complex threats, rather than the controllable, individual, voluntary and comprehensible.

There are indications that the society's acceptance of risk has changed over the last years. The acceptance for involuntary risks, like snow avalanches damaging infrastructure, has been reduced, while the acceptance for voluntary risks, like off-piste skiing, has increased [C. Jaedicke, personal communication, 2011]. This could perhaps explain why the State invests a lot of money in avalanche protection to infrastructure rather than other security measures.

It is difficult to quantify the value of infrastructure or estimate its vulnerability to snow avalanches. The possible losses involved with snow avalanches could be of social, economic, physical and environmental nature, depending on the situation. What is Raumabanen, together with all the passengers and goods, actually worth? That is a timely, but ever so difficult question to answer. According to a cost-benefit analysis made by the Transport-Economic Institute (tøi), the costs related to avalanche protection of infrastructure in Norway are large compared to the benefits that comes with it [T.C. Askildsen, personal communication, 2011].

Political decision-making in risk matters is a direct result of the current legislation and the society's acceptance of risk. The Planning and Building Act gives the acceptance criteria for avalanche risk for buildings. For infrastructure, however, there are no similar regulatory statements. Roads and railways are the State's responsibility, but there are no specified regulations or defined security classes controlling the planning of these types of infrastructure. Instead, the different infrastructure authorities will have to make their own safety regulations for how to deal with the avalanche danger. Often a great portion of discretion will have to be added to the evaluations, and different evaluations have to be made for different regions [H. Bjordal, personal communication, 02.11.2011]. I find it somewhat thought-provoking that the State imposes regulations on the municipalities regarding land-use planning, while there are no specified regulations defined for the State itself.

7. Conclusions and recommendations

In this chapter I will summarize the most important results and their explanations. Recommendations for future work on the area of snow avalanche hazard evaluation are presented briefly.

7.1 Overall conclusions

The results for the snow avalanche mapping and hazard analysis at the study area of Raumabanen can be summarized with the following conclusions:

1) The topography and climate of the study area allows for snow avalanches, and, generally speaking, most of the railway lies within potential snow avalanche run-out areas. Within the study area, there are 20 identified snow avalanche paths that endanger the railway. This study provides a hazard evaluation for nine of these paths.

2) The registration data from NNRA gives that, for each of the nine avalanche paths studied, the snow avalanche return period is relatively low, ranging from approximately eight to 32 years. The most frequent snow avalanche path studied is Joengfonna with eight registered snow avalanche events in 63 years.

3) The probability calculations show that the total snow avalanche probability for the study area as a whole is relatively high.

4) The extended alpha-beta model can possibly be utilized to calculate snow avalanche frequencies for the α-points in the studied avalanche paths, based on the known frequencies for the corresponding Ω-points for each path. However, this study shows that the current method needs to be modified, to be able to calculate realistic return periods for the snow avalanche release.

7.2 Recommendations for future work

Together with the society's aim for a better infrastructure security, there is a need for a more thoroughly and intensified registration of snow avalanches in Norway. This study of the snow avalanche hazard along Raumabanen has shown how vital it is to make systematic and consistent registrations of avalanches. Without these registrations, it would not have been possible to come up with any exact results for the snow avalanche frequency or probability for the railway.

In the future, one should strive to accomplish a registration system for snow avalanches that is both user-friendly, easy accessible and that holds the required amount of information about the avalanche events to be used for a hazard analysis. The goal should be to obtain as much information about each avalanche event as possible, including the time and location of the event, as well as the avalanche extent and reach.

Also, with more systematic avalanche registrations, avalanche frequency information from an object location in an avalanche profile can be used to obtain information about the avalanche frequency for the corresponding α-location, according to the methodology of the extended alpha-beta model. This could lead to a better knowledge about the frequency of different snow avalanches, and make it easier to relate run-out distance to frequency. This in turn could make a successful planning of infrastructure easier.

Snow avalanches are a direct product of mainly topography, snowpack stability and climate. Therefore, it is of importance to gain as much knowledge about the climate in a snow avalanche-prone area as possible. Establishing more weather stations in avalanche-prone areas would be useful for two main reasons: 1: In a short-term perspective and on a daily basis, these data would be useful for snow avalanche warning purposes. 2: In a long-term perspective, it is essential to have consistent climate data for avalanche-prone areas, to be able to evaluate the snow avalanche hazard. The climate information can further be utilized together with snow avalanche registrations to achieve a better understanding about climatic conditions "typical" for snow avalanche production in an area.

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Appendix 1

Snow avalanche registration map for the study area provided by NNRA
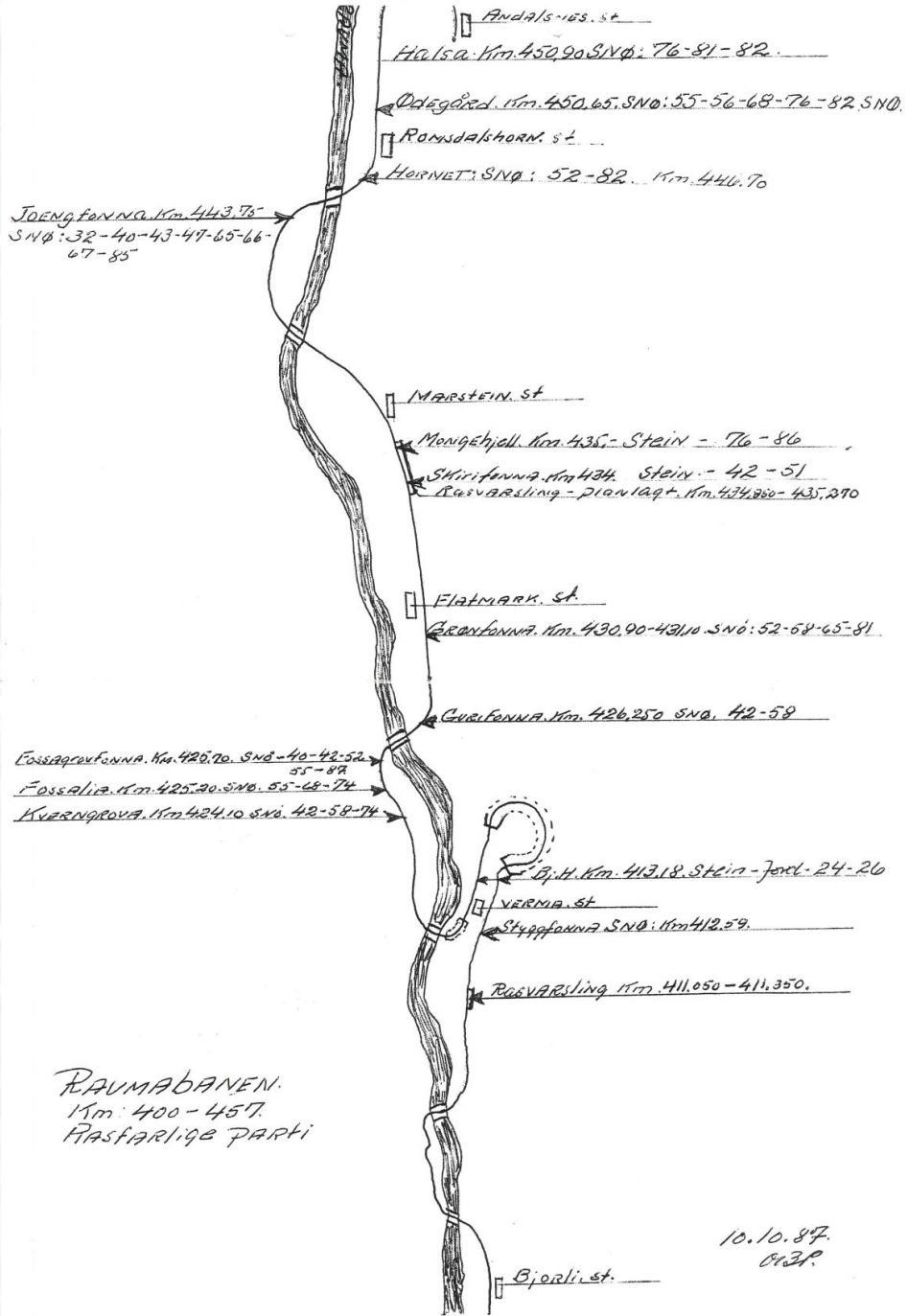
Appendix 2

The European Avalanche Hazard Scale used for avalanche warning.

Danger level	Icon	Snowpack stability	Avalanche triggering probability
5 - Very high		The snowpack is poorly bonded and largely unstable in general.	Numerous large-sized and often very large-sized natural avalanches can be expected, even in moderately steep terrain.
4 - High		The snowpack is poorly bonded on most steep slopes.	Triggering is likely even from low additional loads** on many steep slopes. In some cases, numerous medium-sized and often large-sized natural avalanches can be expected.
3 - Considerable		The snowpack is moderately to poorly bonded on many steep slopes*.	Triggering is possible, even from low additional loads** particularly on the indicated steep slopes*. In some cases medium-sized, in isolated cases large-sized natural avalanches are possible.
2 - Moderate		The snowpack is only moderately well bonded on some steep slopes*, otherwise well bonded in general.	Triggering is possible primarily from high additional loads**, particularly on the indicated steep slopes*. Large-sized natural avalanches are unlikely.
1 - Low		The snowpack is well bonded and stable in general.	Triggering is generally possible only from high additional loads** in isolated areas of very steep, extreme terrain. Only sluffs and small-sized natural avalanches are possible.