ROCKSLIDES IN A CHANGING CLIMATE:
ESTABLISHING RELATIONSHIPS BETWEEN METEOROLOGICAL CONDITIONS
AND ROCKSLIDES IN SOUTHWESTERN NORWAY FOR THE PURPOSES OF
DEVELOPING A HAZARD FORECAST SYSTEM

by

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Abstract

The steep, mountainous terrain of southwestern Norway is prone to a high frequency of rockslides. It is known that many of these rockslides are triggered by meteorological conditions, yet there have been few studies dedicated to quantifying the link between rockslides and the runoff conditions and freeze/thaw processes that trigger failure. With recent climate research indicating that southwestern Norway will experience warmer temperatures and increased precipitation, it has become apparent that a better understanding of this link is required to help prepare for future events.

Rockslides in Norway lead to road closures, property damage and fatalities every year, and one of the biggest challenges for Norwegian authorities is to react to rockslides as they happen and to reopen roads as soon as possible. This is especially true when several rockslides occur on the same day in multiple locations. As a result, authorities wish to implement a hazard mapping system that uses a weather forecast to predict when and where geohazards are likely to occur. To this end, this thesis is aimed at providing a rockslide forecast map that changes every day based on the weather forecast.

By comparing a rockslide database to historic weather records, the work carried out for this thesis has indicated that extreme runoff during winter storms is responsible for triggering the majority of rockslides in the region. Using this knowledge as a basis, two potential hazard mapping systems are proposed, one based on trigger threshold exceedance and the other based on weights-of-evidence susceptibility mapping. Both of these methods operate by mapping areas experiencing extreme runoff conditions. Several runoff parameters were tested for possible inclusion, and it was found that 48-hr
antecedent runoff, normalized by mean monthly precipitation had the best correlation with rockslide occurrence. Verification of these methods indicates that both approaches are successful in predicting days with extreme conditions, thereby alerting authorities that a high frequency of rockslides is likely.

Due to the complex nature of rockslide triggering, it is not fully understood how climate change will affect future rockslide activity; however, this thesis attempts to answer these questions and to provide a basis for future studies.
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List of Abbreviations

AOGCM – Atmospheric Ocean Couples General Circulation Model
BCCR – Bjerknes Centre for Climate Research (BCCR)
CICERO – Centre for International Climate and Environmental Research at the University of Oslo
DEM – Digital Elevation Model
DMI – Danish Meteorological Institute
GIS – Geographic Information System
IPCC – Intergovernmental Panel on Climate Change
Met.no – Norwegian Meteorological Institute
NGI – Norwegian Geotechnical Institute
NGU – Geological Survey of Norway
NPRA – Norwegian Public Road Administration
NVE - Norwegian Water Resources Directorate
RCM – Regional Climate Model
TIN – Triangular Irregular Network
QTT – Local runoff from rainfall + snowmelt
Q – Cumulative runoff from all upstream cells
SD – Snow Depth
WofE – Weights of Evidence
Chapter 1
Introduction

1.1 Background

1.1.1 General

Rockslides are a frequent and significant hazard to the coastal, mountainous areas of southwestern Norway. Between 1963 and 2005, transportation authorities in the counties of Sogn og Fjordane and Hordaland have recorded a total of 3,595 rockslides. The most common consequence is a temporary road closing; however, property damage and casualties also occur every year. Two examples of Norwegian rockslides are shown in Figure 1-1. Both events resulted in road closure for an extended period of time and the larger event on the right caused property damage as it demolished a garage. Fortunately, the house was untouched and no casualties occurred.

Figure 1-1: Examples of rockslides causing road closure and property damage (courtesy of the Norwegian Public Road Administration)
The focus of this research is to gain a better understanding of the meteorological conditions that trigger rockslides, and to apply these new relationships to a weather-dependent hazard forecasting system. This type of system is of interest to the Norwegian Public Road Administration (NPRA), because sufficient warning will allow maintenance crews to prepare for extreme events. In addition, with recent climate research suggesting significant climate change in northern regions, it has become apparent that a better understanding of the link between meteorological conditions and geohazards is required to help prepare for future events.

1.1.2 Geohazards in a Norwegian Context

Geohazards such as landslides, debris flows and snow avalanche are a frequent occurrence in southwestern Norway. Historically, the Norwegian attitude towards geohazards is one of annoyance and frustration; however, due to the long-standing history with these events, a culture of tolerance has developed and geohazards are accepted as part of everyday life. This is not to say that geohazards are inconsequential; hazards often result in road closures, sometimes leaving communities completely stranded until maintenance crews can remove debris. In addition, geohazards are estimated to have caused more than 2,000 casualties during the past 150 years.

While geohazards are still an expected part of life, in recent decades Norwegians have begun to question whether the government is prepared for the next catastrophic event. In addition, extended road closures lasting days or weeks are becoming increasingly less tolerated. The increased public pressure has alerted authorities like the NPRA, the Norwegian Geotechnical Institute (NGI) and the Geological Survey of
Norway (NGU) to research geohazards more thoroughly; to understand their mechanics, how they are triggered, and how to predict when they will occur in the future.

1.1.3 Climate Change

Recent climate studies have suggested that southwestern Norway will experience significant changes over the next century, including increased temperatures, increased precipitation levels, and more frequent ‘extreme’ precipitation events. While warmer temperatures are generally welcomed among the Norwegian population, climate change has the potential to bring more frequent and more severe geohazards; especially those triggered by increased precipitation, including landslides, debris flows and floods. Whether the effects of climate change are regarded as positive or negative, a certain degree of adaptation will be required by the government and the general population. Therefore, it is desirable to research the effects of meteorological conditions on historical geohazards, so that climate change studies can be applied to future scenarios.

1.1.4 Previous Studies

In order to research the effects of climate change on geohazards, Norwegian authorities initiated an interdisciplinary research project, called “GeoExtreme”. The objective of GeoExtreme was to study the meteorological conditions of historic geohazards in order to establish relationships between meteorological factors and geohazards. In addition, GeoExtreme used state-of-the-art climate change projection models to assess the socio-economic consequences of future geohazards.
As part of the GeoExtreme project, NGI and the Norwegian Meteorological Institute (met.no) created a geohazard database, using data provided by the Road and Rail Authorities, which includes the meteorological conditions of the day and days preceding each event. Factors such as antecedent precipitation, mean annual precipitation, return periods, cold periods, frost interval, degree days and mean temperatures were included for research purposes. Methods such as classification trees have been applied by GeoExtreme researchers in Norway, and results are discussed further in Chapter 4.

In the cases of snow avalanches and debris flows, GeoExtreme was successful in establishing general links between geohazards and meteorological triggers. Unfortunately, the study did not find a strong correlation with rockslides. This result is counter-intuitive because rockslides are known to occur during extreme precipitation events. In order to shed some light on this topic, the research conducted for this thesis aims to build on the GeoExtreme work by establishing meteorological relationships specific to rockslides.
1.2 Research Objectives

1.2.1 Determining the Effects of Climate Change

The issue of climate change has become an important topic in recent years. With recent studies predicting a 20% increase in precipitation for western Norway, it is important to assess if this change will affect the occurrence of geohazards, including rockslides. When research for this thesis began, the assessment of future climate effects was a key objective; however, there are few studies dedicated to quantifying meteorological trigger thresholds for present-day rockslides. Without this background knowledge, it is difficult to scientifically apply future climate scenarios to a rockslide trigger model. Therefore, this research is more focused on the preparation of background knowledge; that is, establishing links between meteorological conditions and rockslides, so that others can make a more concerted effort to ascertain the effects of climate change. Nonetheless, climate change projection scenarios have been researched as part of this study, and some general comments on climate effects, in regard to rockslides, are made in the concluding chapter.

1.2.2 Forecasting Rockslides to Optimize Road Maintenance

One of the biggest challenges for the NPRA is to react to rockslides as they happen and to reopen the roads as soon as possible. This is especially true when several rockslides occur on the same day in multiple locations. In order to prepare for these events, the NPRA would like to use a dynamic rockslide susceptibility map that indicates where and when rockslides are likely to occur.
To this end, the research described here is aimed at providing a rockslide forecasting system that changes day-to-day based on the weather forecast. Two potential systems, one based on trigger threshold exceedance and the other based on weights-of-evidence susceptibility mapping, are discussed in Chapters 4 and 5, respectively. Both of the proposed methods required a detailed analysis of how weather conditions triggered rockslides in the past, so that relationships can be linked to future weather scenarios.

While rockslides can be triggered by a number of factors, it was found that runoff contributed to 76% of all winter-time slides. In addition, it was found that extreme days with multiple rockslides were caused exclusively by winter storms bringing severe runoff conditions. Since these extreme days are of most importance to the NPRA, the proposed rockslide forecasting systems are focused on identifying severe runoff conditions. The maps make no attempt to predict if rockslides will be triggered by frost wedging or other non-runoff related factors. Since the majority of rockslides occur in the winter, research is focused specifically on winter weather conditions.

The purpose of the rockslide forecasting systems is to provide authorities with a 24-hr warning that severe rockslide conditions are approaching. Both proposed systems provide a colour-coded rockslide susceptibility map for ‘tomorrow’ based on the weather forecast. This will alert maintenance crews of an impending heavy workload, as well as indicate where slides are most likely to occur.
1.3 Methodology

1.3.1 Meteorological Trigger Thresholds

There have been several studies related to the establishment of meteorological trigger thresholds for geohazards. The majority of these efforts are related to antecedent rainfall intensity-duration thresholds for shallow soil landslides or debris flows. All of these studies are focused on areas where rainfall is responsible for triggering the majority of events. Unfortunately, there have been few studies dedicated to quantifying meteorological trigger thresholds specific to rockslides. This is because the majority of rockslide prone areas are subject to triggers in addition to rainfall, including: runoff from snowmelt, frost wedging, seismic activity, erosion, root wedging and human activity. If a statistical approach were applied to a rockslide database containing all of these possible triggers, the result would surely be erroneous and unreliable.

In order to overcome this difficulty, a runoff trigger threshold has been established using a database that only includes runoff-triggered rockslides. During the study, it was found that rockslides are more likely to occur when runoff levels significantly exceed normal conditions, whether the area is wet or dry in general. Therefore, the runoff threshold has been normalized by mean monthly precipitation to account for normal conditions at each rockslide location, both spatially and seasonally. A detailed discussion on the proposed runoff trigger threshold is provided in Chapter 4.

In terms of rockslide forecast mapping, it is proposed that the normalized runoff trigger threshold can be used to indicate where runoff levels are exceeding the threshold. The map is colour-coded and changes every day with the forecast. The procedure for creating a threshold exceedance map is shown in Figure 1-2.
Data:
- Weather stations & weather maps
- Rockslide Database
- Digital elevation map & geological map

Research:
- Meteorological trigger analysis
- Weights-of-evidence analysis

Results:
- Frost wedging
- Runoff
- Normalized 48-hr runoff

Mapping:
- Trigger threshold exceedance
- Weather dependent weights-of-evidence

Figure 1-2: Research methodology flow chart
1.3.2 Rockslide Susceptibility Mapping

The threshold exceedance mapping system described above is an effective method for identifying areas that are likely to fail based on the weather. However, threshold exceedance fails to account for geomorphologic conditioning factors that are known to affect rockslide susceptibility, such as slope angle, slope aspect and rock type. A separate rockslide forecasting system, based on weights-of-evidence susceptibility mapping is proposed to identify specific slopes that are likely to fail based on the incoming weather, as shown in the methodology flow chart, Figure 1-2.

The weights-of-evidence approach is a bivariate statistical method based on Bayesian probability. It uses the characteristics of historical rockslides to predict areas that are susceptible to slides in the future. The method is popular among geoscientists for the purposes of hazard identification; however, other studies are based purely on static terrain factors such as slope angle, slope aspect, rock type, etc. The result is a susceptibility map that remains constant; that is, it provides an indication of where slides will occur, but not when they will occur. This study differs in that it takes into account a dynamic weather factor, normalized runoff, which changes day-to-day with the weather forecast. The result is a new susceptibility map produced every 24-hr, colour-coded to indicate the most hazardous areas. A more detailed discussion of the dynamic, weights-of-evidence approach is provided in Chapter 5.
1.3.3 Modeling of Thaw-induced Rockslope Failures

A literature review of thaw-induced rockslope failures has revealed that thawing of ice-filled fractures leads to a rapid loss of shear strength. In fact, an ice-filled joint that is near thawing (approximately -0.5°C) has significantly lower strength than if the joint had no ice at all. To visualize the effect of progressive thawing, finite-element modeling software, Phase², has been used to determine the slope’s factor of safety under several hypothetical slope conditions, including diurnal and permafrost thawing. An example of one of the permafrost models is shown in Figure 1-3. Such a study is helpful in establishing why rockslides are more likely to occur during winter thaw cycles than any other conditions that occur during the year. The full discussion of the finite-element modeling is provided in Chapter 6.

Figure 1-3: Example of modeled slope subjected to permafrost thawing in Phase²
1.4 Description of Study Area: Southwestern Norway

1.4.1 General

The study area encompasses two counties in southwestern Norway, Sogn og Fjordane and Hordaland, as shown in Figure 1-4. These counties were chosen because they have the highest frequency of rockslides and they share a similar maritime climate.

Figure 1-4: Map of study area
Together, the two counties accounted for 56% of all rockslides recorded in Norway between 2000 and 2005, as shown in Figure 1-5. The only other county with a significant amount of rockslides in the database is Nordland. However, it should be noted that Figure 1-5 is not indicative of the actual amount of rockslides that occur in each county; rather, it shows which counties keep comprehensive databases of the rockslides that occur. Other mountainous counties such as Møre og Romsdal, located immediately north of Sogn og Fjordane, also experience a high frequency of slides, but the rockslide database of this county lacks the proper detail for further analysis.

Figure 1-5: Map of Norway showing the number of rockslides per county
1.4.2 Physiography and Geology

The counties of Sogn og Fjordane and Hordaland are characterized by coastal islands and fjord valleys with very steep terrain. In terms of rockslides, the vast majority occur in the mainland valleys. In addition to having very steep slopes, the terrain is naturally susceptible to rockslides due to extensive areas of heavily fractured, exposed bedrock. A complete description of the geology of the region is provided in Chapter 2.

1.4.3 Weather and Climate

Southwestern Norway experiences a maritime climate that is wetter and milder than other areas of the country. Summer temperatures typically range from 6°C to 16°C and winter temperatures typically range from -5°C to 2°C, depending on altitude and distance-to-coast. The region experiences several freeze/thaw cycles in the winter due to the frequent exchange of high and low pressure systems, which bring cold and warm temperatures, respectively. Extreme runoff events are most frequent during the winter when low pressure systems bring heavy rainfall over previously frozen land with a significant snowpack. Research of the rockslide data indicates that these extreme runoff events are responsible for the majority of rockslides recorded in the region. A more detailed description of the study area’s climate and weather patterns is provided in Chapter 3.
1.4.4 Sandane Sub-study Area

Some of the analyses carried out for this research were impractical to perform on the entire rockslide database of the two counties. For this reason, a 2000 km$^2$ area around the Village of Sandane in northern Sogn og Fjordane was chosen as a sub-study region, as shown in Figure 1-6. This area was chosen because it has a high frequency of rockslides and it has a reliable, long-operating weather station.

The 98 rockslides recorded in this area between 2000 and 2005 were used for a meteorological trigger analysis, as described in Chapter 4. In addition, the slides were used to correct for location error, as described in Chapter 5, in order to obtain accurate slope angle values for the weights-of-evidence analysis.

![Figure 1-6: Map of Sandane sub-study area](image-url)
1.5 Data Sources

1.5.1 Rockslide Database

At present, the NGU maintains a national database of all geohazards recorded in Norway. The types of events include: rockslides, soil slides, sub-aqueous slides, debris flows, snow avalanches and ice falls. The database is mapped using Geographic Information Systems (GIS), and can be viewed publicly on the web at “www.skrednett.no” (in Norwegian only). The majority of registered geohazards have been recorded by the NPRA, which records all types of events that encroach on public roads. Secondary sources include NGI and NGU.

As mentioned in Section 1.1.4, as part of the GeoExtreme project, ‘met.no’ has used historical weather maps to append the Norwegian geohazard database with a set of derived weather variables. These variables include: antecedent precipitation, mean annual precipitation, return periods, cold periods, frost interval, degree days and mean temperatures. The GeoExtreme version of the geohazard database was made available for this research by NGI.

For the purposes of the work presented here, rockslides recorded in the counties of Hordaland and Sogn og Fjordane have been extracted from the larger database. The refined database includes 3,595 rockslides, dating between 1963 and the end of 2004. Historical slides older than 1961 have been excluded from the database due to a lack of weather information. A map of the rockslide locations is given in Figure 1-4.
1.5.2 Weather Maps and Weather Station Data

‘Met.no’ maintains a database of gridded weather maps that cover the entire country with 1 km x 1 km spatial resolution. Maps are available for each day dating back to 1961, with each day represented by different weather/climate themes (ex. precipitation, temperature, snow depth, snow melt, etc.). Maps can be viewed publicly at “www.senorge.no”. An example from January 14th, 2003 is shown in Figure 1-7.

![Example of weather maps from www.senorge.no (Jan. 14th, 2003)](image)

Figure 1-7: Example of weather maps from www.senorge.no (Jan. 14th, 2003)
The temperature and precipitation maps from this database represent raw data that has been statistically interpolated from local weather stations, and remaining themes are derived from the temperature and precipitation grids by mathematical algorithms.

Regrettably, the raw raster data of the weather map database is not available publicly, making it difficult to carry out analyses with GIS. Fortunately, the Norwegian Water Resources Directorate (NVE), which is in charge of maintaining “www.senorge.no”, agreed to supply a limited number of raw weather maps for this research. Since the majority of slides occur during extreme winter storms, data of the five most extreme storms was requested and provided for. The five storms are defined as follows:

[1] February 11\textsuperscript{th} to 20\textsuperscript{th}, 2001 (10 days)
[2] January 10\textsuperscript{th} to 17\textsuperscript{th}, 2002 (8 days)
[3] January 13\textsuperscript{th} to 16\textsuperscript{th}, 2003 (4 days)
[4] March 7\textsuperscript{th} to 12\textsuperscript{th}, 2003 (6 days)
[5] February 3\textsuperscript{rd} to 8\textsuperscript{th}, 2004 (6 days)

In addition to weather maps, observations from local weather stations were used for parts of this research. The raw data for every weather station in the country, including those that are not longer in operation, is maintained by ‘met.no’, and is available to the public at the eKlima web portal (access via ‘eklima.met.no’). The portal also provides free access to statistical analysis of weather extremes and trends.
1.5.3 Geological Data

Geological data made available for this research includes a digital 1:50,000 scale bedrock map of Norway. The level of detail on this map is relatively basic, but does give a sense of the rock type and its period of deposition. In addition to the bedrock map, NGU provided a lineament map, which gives the location of all known faults within the study area. Supplementary geological information was attained through literature review, and is discussed in further in Chapter 2.
1.6 Structure of Thesis

Following the introduction, the remainder of the thesis is divided into six chapters, as shown in Figure 1-8.

**Introduction:**
- Chapter 1: Introduction

**Background Information:**
- Chapter 2: Geology & Rockslope Failures
- Chapter 3: Weather and Climate

**Rockslide Forecasting Systems:**
- Chapter 4: Meteorological Trigger Thresholds
- Chapter 5: Weather-dependent Susceptibility Mapping

**Numerical Modeling:**
- Chapter 6: Finite-element Modeling of Thaw-induced Rockslope Failure

**Conclusion:**
- Chapter 7: Conclusions and Recommendations

Figure 1-8: Structure of thesis
Chapter 2, “Geology and Rock Slope Failures in Southwestern Norway” and Chapter 3, “The Weather and Climate of Southwestern Norway” are primarily literature review, and are meant to give background information for the technical work described in the subsequent chapters. Chapter 4 and Chapter 5, which represent the bulk of the research work carried out for thesis, discuss the two proposed rockslide forecasting systems: meteorological trigger thresholds and dynamic, weather-dependent susceptibility mapping.

Chapter 6 represents work carried out for GEOL 873, a numerical modeling graduate course in geological engineering. The literature review completed for this project and the subsequent simulations of thaw-induced rockslope failures provided valuable insights into why the majority of rockslides in Norway are triggered during thawing periods. For this reason, the results from this project are included as a supplementary chapter in the thesis. Lastly, the concluding chapter provides a discussion of the two rockslide forecast systems, the possible effects of climate change, and a summary of recommendations for future work.
Chapter 2
Geology and Rock Slope Failures in Southwestern Norway

2.1 Introduction

Based on the steepness of southwestern Norway’s terrain (see Figure 2-1), it is not surprising that the region experiences a high frequency of rockslides. In addition to being steep, the terrain is naturally susceptible to rockslides due to extensive areas of heavily fractured, exposed bedrock. In order to better understand the origin of rockslides in the region, this chapter reviews the rocks and geological history of southwestern Norway. In addition, rock slope failure types and mechanisms will be discussed to establish a basis for subsequent studies.

Figure 2-1: View from Slogen Summit in western Norway
2.2 Rock Slope Failure Types

2.2.1 General

Rock slope failures are often classified based on magnitude and transport mechanism. The most common terms are: rockfall, rockslide, and rock avalanche. The volume of rockfalls and rockslides are not predefined; however, the term ‘rock avalanche’ is usually reserved for very large events. The rockslide database used in this study does not contain volume information; however, the Norwegian Public Road Administration has indicated that the majority of rockslides are less than 10 m³; therefore, rock avalanches, while they do pose a threat to the Norwegian landscape, are not studied further here.

The difference between a rockfall and rockslide is usually identified by whether the rock was airborne at some point during its descent from the source zone (rockfall), or not (rockslide). Typically, rockfalls occur on slopes with a steep gradient, (i.e. >60°), and rockslides occur on moderate slopes, (i.e. <45°) (Braathen et. al., 2004). The rockslide database provides no indication whether the failure should be considered a ‘rockfall’ or ‘rockslide’, so for simplicity, the term ‘rockslides’ has been applied to all rock slope failures in the database. Of more importance from an engineering point-of-view is the failure mode of the rockslide, whether it is by toppling or sliding, as these modes can be triggered by different factors. While information about the failure mode is not included in the database, it may be inferred from a review of particular failure cases, or suggested based on the lithology and structural geology of the area.
2.2.2 Toppling

Toppling is a failure mode that involves rotation of columns or blocks of rock about a fixed base (Wyllie and Mah, 2004). There are two basic types of toppling failure: [1] block toppling and [2] flexural toppling. Block toppling occurs when columns of rock are formed by a set of discontinuities that dip steeply into the slope face, with a secondary set of orthogonal discontinuities defining the column height, as shown in Figure 2-2. Block toppling failure is typical of rock types with orthogonal jointing, such as sandstone or columnar basalt.

![Figure 2-2: Example of toppling failures: (left) block; (right) flexural](from Wyllie and Mah, 2004)

Flexural toppling is similar to block toppling, in that the rock is separated by discontinuities dipping steeply into the slope face. The difference is that flexural toppling failures lack an orthogonal set of discontinuities to define a basal plane. Without this basal plane, the rock breaks in flexure as it bends forward, as shown in Figure 2-2. Lithologies [sic] in which this type of failure may occur include thinly bedded shale and slate in which orthogonal jointing is not well developed (Wyllie and Mah, 2004).

In terms of triggering mechanisms, toppling is likely heavily influenced by freeze/thaw activity. The volumetric expansion of ice in a vertical joint effectively...
‘wedges’ the two rocks apart, increasing the likelihood of detachment. In addition, successive freeze/thaw events continually widen joints, increasing the likelihood of toppling over time. In addition to ice, water pressure from runoff has the potential to trigger ultimate failure.

In total, rock types typically subject to toppling (sandstone, limestone and shale) make up just 2.2% of the study area, so toppling is considered less likely than the sliding failure mode discussed below. However, there is a 55 km stretch of road (Hwy 614) that runs through the Hornelen Sedimentary Basin in northwestern Sogn og Fjordane (Sogn) that is particularly susceptible to rockfalls. Slopes in this region are primarily sandstone, and more than 40 rockslides have been recorded on this stretch of road since 1963. The southern boundary of the basin in particular is subject to several slides. In this case, it is possible that a high proportion of the events are toppling failures.

2.2.3 Sliding

Sliding is a failure mode that occurs when driving forces (gravity and water pressure) of a rock block exceed the shear strength of its basal sliding plane, provided that the sliding plane “daylights” out of the slope face (the dip of the plane is less than the dip of the slope). The geometry of the rock block defines whether the failure is classified as a "plane" failure or a "wedge" failure.

Plane failure is a simple two-dimensional problem, where the sliding plane is defined by a single discontinuity. Release surfaces may be defined by other discontinuities or tension cracks; however, these surfaces provide no resistance to sliding. This type of failure is possible as long as the sliding plane strikes near parallel
(±20°) to the slope face, and the dip of the sliding plane is greater than its angle of friction (Wyllie and Mah, 2004). An example of planar failure is shown in Figure 2-3.

![Figure 2-3: Geometry of a slope exhibiting planar failure](from Wyllie and Mah, 2004)

On the other hand, wedge failure is a three-dimensional sliding problem, which is defined by two sliding planes, that occurs when two obliquely striking discontinuities intersect, as shown in Figure 2-4. This type of failure is possible when the line of intersection “daylights” in the slope face and dips steeper than the angle of friction.

![Figure 2-4: Geometry of a slope exhibiting wedge failure](from Wyllie and Mah, 2004)
2.2.3.1 Role of Water Pressure on Stability

Water pressure has a significant effect on rock slope stability. Considering a block on an inclined sliding plane, shown in Figure 2-5, water penetrates the tension crack, creating maximum water pressure at the base of the tension crack. The water then enters the sliding surface and flows out of the slope face at atmospheric pressure. The water pressure profile in the tension crack, \( V \), effectively "drives" the block downslope, and thus reduces slope stability. In addition, the water pressure profile on the sliding plane, \( U \), is an uplift force that reduces normal stress, which also reduces slope stability.

![Figure 2-5: Schematic of a planar sliding problem with water pressure](from Hoek and Bray, 1981)

The pressure distribution shown in Figure 2-5 is probably very much simpler than that which occurs in an actual slope; however, since the actual pressure distribution is unknown, this assumed distribution is as reasonable as any other which could be made (Hoek and Bray, 1981). A more dangerous condition may occur in the winter when ice at the slope face prevents drainage. Such conditions would mean that the full head of water in the slope is applied to the entire sliding plane, reducing stability significantly.
2.3 Geology

2.3.1 Setting

The study area is divided into three geological settings: [1] Precambrian basement rocks, [2] Caledonian Mountain nappes that strike southwest-northeast, and [3] the Devonian sedimentary basins located on the coast of Sogn, as shown in Figure 2-6.

Figure 2-6: Simplified geological map of southwestern Norway
The large area of Precambrian rocks located northwest of the Caledonian Mountain chain is colloquially called The Western Gneiss Region. The landscape here varies between high mountains with remains of palaeic land surfaces dissected by peaks, knife-edge ridges, more rounded edges, precipitous cliffs, valleys and long, deep fjords (Nordgulen and Andresen, 2008). The region is dominated by granitic gneisses and migmatites formed approximately 1.5 billion years ago. The northeastern part of the region consists of younger plutonic rocks, primarily granite and monzonite, which were formed approximately 1.0 billion years ago. In structural terms, the Western Gneiss Region is a large, elongate dome mainly generated by post-Caledonian extension. There are also some areas of Precambrian plutonic rocks located south of the Hardanger Fjord that were unaffected by the Caledonian orogeny (Nordgulen and Andresen, 2008).

The Caledonian Mountain chain was formed when the Laurentia and Baltica continents collided over 400 million years ago during the Ordovician and Silurian time periods. There is now consensus that the Caledonian orogenic belt consists of many thrust sheets, some of which were detached from the Precambrian basement and the late Precambrian to Ordovician deposits on Baltica, while others derive from the Iapetus Ocean and perhaps even further northwest (Fossen, et. al., 2008a). In the case of southwestern Norway, Caledonian rocks are of the Middle Allochthon, which are basement nappes of the Baltic continent. The primary nappe in the region is called the “Jotun Nappe”, which primarily consists of mangerites and anorthosites. Immediately north of Hardanger Fjord, parts of the Jotun Nappe have been eroded to reveal the Lower Allochthon, which is characterized primarily by phyllite and mica schist. These
rocks are the metamorphosed remains of clay and mud deposited over the entire Baltic Shield during the Cambrian. An example of the anorthosite slopes of the Jotun nappe are shown in Figure 2-7.

![Figure 2-7: Anorthosite slope in Nærødalen, part of the Jotun nappe (from Fossen, et. al., 2008a)](image)

The conglomerates and sandstones of the Devonian sedimentary basins on the west coast of Sogn were deposited in large alluvial fans as the young Caledonian Mountains were eroded approximately 360 million years ago (Fossen et. al., 2008b). Only
remnants of the original basins are preserved, and include the following present-day deposits: Solund Basin, Kvamshesten Basin, Håsteinen Basin and Hornelen Basin. Of these, Hornelen Basin is by far the largest, as shown on Figure 2-6. Major units in the Hornelen Basin are 100 to 200 m thick, which gives rise to the marked, staircase-like topography, as shown in Figure 2-8. Since the Devonian, the basins have been folded due to shortening in a north-south direction. There is no consensus on the explanation for this shortening; however, it has been suggested that it may be due to interference between sinistral movements along the Møre-Trøndelag fault zone and the westward transition of the Caledonian nappes in southern Norway (Fossen, et. al., 2008a).

Figure 2-8: Tilted beds of sandstone in the Hornelen Basin (from Fossen et. al., 2008b)
2.3.2 Glaciation

The present-day topography of southwestern Norway is due primarily to the glaciers of the last ice age, known as the Weichselian, which reached its last maximum approximately 11,500 years ago. During the ice age, glaciation could be described by one of the following three scenarios, as described by Vorren and Mangerud (2008):

[1] *Interglacial periods with local glaciers restricted to mountains, during which climatic conditions were similar to the present-day.*

[2] *Periods during which the Scandinavian Ice Sheet extended to the Norwegian coast, dominant between 2.6 and 0.7 million years ago.*

[3] *Periods during which the ice advanced across Sweden and Finland, and reached as far as southern Germany.*

The landforms that dominate southwestern Norway are the glacial fjords. These large, U-shaped valleys were likely first established by rivers during Cenozoic continental uplift, prior to glaciation. At the onset of glaciation, local glaciers advanced from cirques at high altitude and “flowed” downstream through the pre-shaped river valleys. The erosive power of the glaciers reshaped the valleys, creating steeper valley slopes and basins in the valley floors. Successive glaciations over-deepened the glacial valleys, creating the fjords as we know them today. The major fjords of the study area, from south to north, are: Hardangerfjorden, Sognefjorden and Nordfjorden, as shown in Figure 2-6. Sognefjorden is the largest fjord in Norway and one of the largest in the world. It is 205 km long, 1,308 m deep at its deepest point, and it is estimated that glacial erosion has removed 7,610 km³ of rock from its channel (Vorren and Mangerud, 2008). Many of the
fjord slopes are extremely steep, such as those shown in Figure 2-1. This is the primary reason why the landscape of southwestern Norway is prone to a high frequency of rockslides. To compound matters, the majority of roads in the region follow the water level at the base of these slopes, making rockslides a significant hazard to motorists.

Following glaciation, global temperatures and sea levels began to rise, which generally would have the effect of flooding the fjords; however, Scandinavia has been subjected to isostatic uplift at a rate faster than sea-level rise, resulting in an emergent shoreline. Today, southwestern Norway continues to experience uplift at a rate of approximately 0.5 to 2 mm per year (Vorren et. al., 2008).
2.4 Engineering Considerations

2.4.1 Rock Type and Fracturing

Given the bedrock information described above, it is important to understand its influence on rock slope instability. With the exception of the Devonian sedimentary basins, all of the rocks in the region have been tectonized in at least two orogenic events, and are heavily fractured (Saintot, A., NGU, personal communication, 2009). Review of the rockslide locations in the database reveals a diverse variation in rock type, from the migmatites and gneisses of the Western Gneiss Region, the mangerites and phyllites of the Caledonian nappes, and the sandstone of the sedimentary basins. The only rock types that have a low incidence of rockslides are the plutonic rocks of the Precambrian basement. This wide range of occurrence indicates that rock type alone is not a good indicator of rockslide susceptibility. The effect of other factors has been studied further as part of the weights-of-evidence susceptibility mapping discussed in Chapter 5.

2.4.2 Seismic Activity

Earthquakes are a significant triggering mechanism for rockslides around the world. However, earthquakes larger than magnitude 5.5 are rare in Norway, and there are only a few examples of rockslides triggered by earthquakes (Braathen, et. al., 2004). For the purposes of this study, all of the rockslides are assumed to be triggered by a mechanism other than seismic activity.
2.4.3 Glacial De-buttressing

As discussed in section 2.3.2, the fjords in southwestern Norway were carved by glaciers. During glaciation, the loading under the weight of the overlying ice induced high internal stresses both on the valley floor and the valley slopes. Release of elastic strain energy during periods of ice down-wasting (de-buttressing) results in propagation of internal fracture networks, which may cause rock-slope failures (Braathen, et. al., 2004). The time dependency of glacial unloading is unknown, but it seems unlikely that this effect alone is responsible for present-day rockslides. However, the fracturing caused by de-buttressing likely increases a slope’s susceptibility to rockslides, and helps to explain the high occurrence of rockslides along the fjord slopes in the region.

2.4.4 Shear Strength of Discontinuities

In order to trigger a rockslide, the total driving forces acting on the basal sliding surface have to overcome the shear strength of the same surface. Two common mechanisms for reducing shear strength, acting either isolated, or in harmony, are: [1] increased water pressure along the shear surface, and [2] weathering and/or abrasion of rocks and clasts/fragments along the shear surface (Braathen, et. al., 2004). Increased water pressure reduces the normal stress on the shear surface, thereby reducing shear resistance. Water pressure can increase rapidly, in the order of hours or days, by an influx of runoff from rainfall or snowmelt. This is considered the predominant trigger mechanism in the study area, and is discussed further in subsequent chapters.

On the other hand, strength reduction by weathering and abrasion is a process that occurs slowly over many years. This may include mechanical or chemical
decomposition of small obstacles, resulting in a smoother surface, or the chemical alteration of minerals into clay particles. Both of these processes may result in a shear strength that decreases over time. Eventually, the driving forces will overcome the shear strength, and failure will occur. However, ultimate failure is still likely to be triggered by a high runoff event, due to the relatively sudden increase in water pressure.
2.5 References


Chapter 3

The Weather and Climate of Southwestern Norway

3.1 Introduction

3.1.1 General

Norway has a ‘climate culture’, where people are accustomed to harsh or bad weather (O’Brien et. al., 2004). Conditions vary throughout the country, from long, frigid winters in the north, to the mild and rainy climate on the western coast. With recent climate research suggesting significant climate change in northern regions, it has become apparent that Norway requires a multi-scale assessment of climate change impacts. At the local level, many Norwegians view global warming as a positive, due to the projected warmer and dryer summers and the prospect of increased agricultural productivity. Regardless of whether impacts related to climate change are seen as challenges or opportunities, they will presumably by met by adaptation, or adjustments that minimize negative effects and take advantage of positive effects (Sygna et. al., 2004).

Part of this multi-scale assessment involves looking at natural hazards and how they will be affected by future climate change. However, there must first be a clear understanding of how today’s weather triggers natural hazards. Once this has been accomplished, climate change studies can be studied to determine the effect on hazard triggering. To this end, Chapter 3 will describe both the weather and climate of western Norway. This background study allows specific weather triggers to be established, and also helps to develop the forecast mapping systems described in Chapters 4 and 5.
3.1.2 Significance to Rock Slope Detachment

In order for a rock slope to fail, gravitational force must exceed the frictional resisting force, as discussed in Chapter 2. This most often occurs when frictional forces are reduced by elevated water pressure within the rock mass. For this reason, the study of weather in relation to rainfall and snowmelt levels is conducted in an effort to detect and define runoff trigger thresholds. In addition to runoff, rockslides can be triggered by a number of other factors, including: frost wedging, erosion, seismic activity, root wedging, and human activity. In order to establish links between runoff and rockslide triggering, it is important to determine the proportion of rockslides triggered by runoff, and also to be able to recognize when rockslides are triggered by a non-weather factor.
3.2 Weather Patterns

3.2.1 High and Low Pressure Systems

The majority of rockslides in the region occur during the winter months (Chapter 4). Specifically, the most hazardous conditions exist during extreme winter storms, when Atlantic low-pressure systems bring warm temperatures and heavy rainfall over previously frozen land. When using the hazard maps described in Chapters 5 and 6, it is equally beneficial to study daily weather maps in order to determine the location of pressure systems and warm/cold fronts.

High-pressure systems are characterized by cold air converging in the upper atmosphere, which then spirals clockwise downwards towards the ground surface, as shown in Figure 3-1. Due to the high density of cold air, the atmospheric pressure at the surface is “high”. This type of system often results in clear skies, with extreme hot temperatures in the summer and extreme cold temperatures in the winter. Natural hazards triggered by the weather do not generally occur under this type of system.

Figure 3-1: Schematics of pressure systems in the northern hemisphere (from www.phys.port.ac.uk)
Low-pressure systems form when two air masses at different temperatures interact (Buckley et. al., 2008). Atmospheric pressure is “low” because warm air at the ground surface spirals upwards towards the centre of the system in a counter-clockwise direction (northern hemisphere), as shown in Figure 3-1. The rising of warm air assists in cloud development, and consequently increased precipitation. These low-pressure systems are characterized by both warm and cold fronts, as shown in Figure 3-2. Initially, warm air begins to spiral upward over cold air, creating a warm front. As the warm front advances, an area of low pressure is left behind, resulting in the development of a cold front. These two fronts spin around the low-pressure system to create the famous spiral cloud formations, as shown in Figure 3-3 on the following page. Since cold air is denser than warm air, the cold front advances more quickly, and eventually catches up to the warm front, creating an occluded front, resulting in windy and unsettled weather (Buckley et. al., 2008). Weather maps represent warm fronts with red lines, cold fronts with blue lines and occluded fronts with purple lines, as shown in Figure 3-3. The circles (warm front) and triangles (cold front) on the lines represent the direction of air movement.

Figure 3-2: Schematic cross-section of a warm and cold front (from www.physicalgeography.net)
3.2.2 Extreme Runoff Events

In terms of rockslide triggering, the most extreme conditions occur in the winter and are preceded by the development of a low-pressure system over the Atlantic. As the system moves north through the ocean, warm air brought from the south begins to interact with cold air from the north. Under the right conditions, a low-pressure system’s intensity will pick up south of Greenland and begin to travel east between Iceland and Great Britain.

A low-pressure system will usually make first contact with Norway with its warm front. During the winter, this is often preceded by cold conditions and the presence of a pre-existing snowpack. The temperature difference associated with the warm front is significant enough to raise temperatures above 0°C, resulting in snowmelt. In addition, the warm front often brings heavy rainfall, resulting in extreme runoff conditions. Extreme runoff may last up to three or four days as the low-pressure system moves inland; however, precipitation and runoff usually peak on the first or second day.
Weather maps of the most extreme storm in the database, January 13th to 16th, 2003, are provided in Figure 3-4. In this case, the warm front made landfall on Jan. 13th, and rockslide triggering peaked on January 14th.

Figure 3-4: Weather maps for extreme low-pressure system (Jan. 13th to 16th, 2003) (courtesy of met.no)
3.3 Present and Past Climate

3.3.1 Seasonal Conditions – Temperature and Precipitation

The southwestern counties of Sogn og Fjordane and Hordaland experience a maritime climate that is wetter and milder than other areas of Norway. Mean summer temperatures are highly dependent on elevation, but generally range from 6-8°C in high mountain areas while some coastal areas normally experience temperatures of 14-16°C (Engen-Skaugen et. al., 2007). The mean winter temperature is in the range of 0-2°C on the coast and below freezing (-5 to 0°C) in the fjord valleys. However, even the coastal regions experience temperatures below freezing, usually in the presence of a high pressure system that lasts about a week at a time. To illustrate the spatial variation in temperature, a map of mean annual temperature (MAT) is provided in Figure 3-5.

![Figure 3-5: Mean annual temperature and precipitation for the study area](image-url)
The region experiences varying levels of precipitation depending on elevation and distance-to-coast. Overall, mean annual precipitation is about 1700 mm, but can be as high as 3800 mm, or as low as 250 mm, depending on the location. To illustrate the spatial differences in precipitation, a map of mean annual precipitation (MAP) is provided in Figure 3-5. Typically, the wettest time of year is autumn, when long stretches of rainy days are common, and the driest time of year is late spring. The winter months of December, January and February are characterized by intermittent periods of rain and snow at the lower elevations. Snow will generally accumulate for about a week or so while temperatures are below freezing, but will melt as soon as low pressure systems bring warmer temperatures. At higher elevations, snow will accumulate all winter long, which generally begins to melt during the month of March.

The mean monthly temperature and precipitation values for the study area are shown in Figure 3-6. This chart was generated by considering monthly observations from thirty-seven, spatially distributed weather stations in the region.

![Data from eKlima](image)

**Figure 3-6:** Mean monthly temperature and precipitation for the study area
3.3.2 Climate Trends of the 20th Century

The climate of any region varies periodically due to natural factors such as solar radiation and volcanic activity, as well as anthropogenic factors such as greenhouse gasses and land use change. To visualize historic trends, graphs of deviation from normal temperature (MATA) and percentage of normal precipitation (RRA) have been provided by eKlima, the online weather and climate database of the Norwegian Meteorological Institute (met.no). Graphs are shown in Figure 3-7, and represent a period between 1900 and 2007 for all of western Norway.

![Figure 3-7: Temperature and precipitation trends of Western Norway (1900-2007)](image-url)
During the 20th century, western Norway experienced three general trends: a warming period culminating in the 1930’s, a cooling period between the 1930’s and 1960’s, and a warming period that has persisted since the 1970’s. One of the warmest periods was the 1930’s, when MAT peaked at 1.4°C in 1934. On the other hand, the 1960’s were cool, when MAT dropped to -0.9°C in 1966. The most significant observation is that temperatures have been on a steep upward warming trend since the late 1970’s, which is likely due to anthropogenic forcings (IPCC, 2007). Considering the entire century, the overall trend for the annual mean temperature in western Norway is an increase of 0.08°C per decade, with the greatest warming occurring in the winter (0.11°C/dec) and the lowest warming occurring in the summer (0.06°C) (Hanssen-Bauer, 2005).

The graphs in Figure 3-7 indicate that precipitation oscillates at the same general interval as temperature, but does not follow a regular pattern. For instance, during the first half of the century, precipitation increased during cool periods and decreased during warm periods; however, the opposite relationship is true for the 1950’s onward, when precipitation increased with temperature and vice versa. Overall, the trend for precipitation shows a gradual increase in precipitation from 1900 to present. Hanssen-Bauer (2005) states that western Norway has experienced an increase in precipitation of 1.2% during this time, with the highest increase occurring during the spring (2.1%), and the lowest increase occurring in the winter (0.7%).
3.4 Future Climate Change

3.4.1 General

The concept of global warming and climate change began to draw the attention of the general public when the Intergovernmental Panel on Climate Change (IPCC) released their first assessment report in 1990. This report stated that atmospheric concentrations of greenhouse gases were substantially higher than pre-industrial times, and that the global mean temperature would rise 0.2°C to 0.5°C per decade during the 21st century (IPCC, 2007). However, the report also stated that there were many uncertainties in climate modeling due to an incomplete understanding of climatic forces. Since that time, climate scientists and meteorological institutions have been developing increasingly accurate climatic models as research in the field progresses.

3.4.2 Climate Modeling

3.4.2.1 Global Climate Models

The most common global climate models used today are atmosphere-ocean coupled general circulation models (AOGCM). These models aim to calculate the full three-dimensional character of the atmosphere and ocean by solving the following fundamental equations: conservation of energy, conservation of momentum, conservation of mass, and the ideal gas law (McGuffie and Henderson-Sellers, 2005). The earliest models were “Cartesian grid models”, which discretized the atmosphere by dividing three-dimensional space with a matrix of “boxes”, spaced evenly horizontally (latitude and longitude) and with a prespecified number of vertical layers that decreased
in resolution away from the ground surface (higher resolution is required at the surface to properly model boundary layer fluxes). Models are then run by calculating variables for each “box” at specified time-steps. The six basic model variables are: temperature, moisture, surface pressure, two horizontal wind components, and geopotential height. Sub-models of atmosphere, ocean, land and sea ice are then combined with a coupler program that transfers fluxes between the model components, as shown in Figure 3-8. A model is validated by observing if it can successfully replicate a control run of past climate (typically the 1961-1990 control period). If validated, the model is allowed to run into the future, and climate change projections are inferred.

Figure 3-8: Structure of a coupled atmosphere-ocean global climate model (from McGuffie and Henderson-Sellers, 2005)
Global climate models are constantly evolving. It is estimated that a fully-coupled AOGCM takes about 25-30 person-years to code, and the code requires continual updating as new ideas are implemented and as advances in computer science are accommodated (McGuffie and Henderson-Sellers, 2005). New advances include: spectral models, geodesic grids, finite-volume methods and finite-element methods. Today, AOGCMs most commonly used for Northern Europe are the ECHAM4/OPYC3 model developed by the Max-Plank Institute of Meteorology (MPI) in Hamburg and the HadCM3 model developed by the Hadley centre in the United Kingdom.

The accuracy of AOGCM’s is limited by computational power. For instance, the HadCM3 model runs at a grid spacing of 2.5° in latitude and 3.75° in latitude (Gordon et. al., 2000). As computer science advances, both spatial and temporal resolution will improve; however, for the time being, the resolution of HadCM3 is considered sufficiently accurate on a global scale. The disadvantage is that it does not fully capture regional differences in exposure to climate change for a country such as Norway (Sygna et. al., 2004). For a country as far north as Norway, this equates to about 250 km x 200 km grid spacing. This resolution is too coarse to properly study the regional impacts of climate change, and thus methods of regional downscaling have been developed to produce climate scenarios at small scales.

3.4.2.2 Downscaled Norwegian Models

Research to date includes two types of regional downscaling: dynamical (regional) downscaling and empirical-statistical downscaling. Empirical models are based on statistical relationships between local climate variations and large-scale climate
anomalies (Benestad, 2002). On the other hand, regional climate models (RCM) increase resolution of global models by using lateral boundary forcings.

The first coordinated effort to develop a Norwegian RCM was the Regional Climate Development under Global Warming (RegClim) project. Launched in 1997, RegClim’s goals during the first two phases (1997-2002) were to prepare for impact studies of climate change by downscaling global climate scenarios; and to reduce the uncertainty in the region’s climate development by investigating the role of the Nordic Seas and the significance of forcing patterns brought about by pollutants with regional contrasts (Iversen, 2003). The primary contributor to this project was the Norwegian Meteorological Institute (met.no), with additional research coming later from the Bjerknes Centre for Climate Research (BCCR) and the Centre for International Climate and Environmental Research at the University of Oslo (CICERO). The result of this project is a model for dynamical downscaling known as HIRHAM-Oslo. This is a revision of the HIRHAM regional climate model, originally developed for northern Europe by MPI and the Danish Meteorological Institute (DMI), and is based on the dynamics of the weather forecast model HIRLAM and the physics of the ECHAM4/OPYC2 global model.

3.4.2.3 Limitations of Climate Modeling

Climate modeling in general is subject to a wide range of uncertainties. Sorteberg and Andersen (2008) identify the two greatest uncertainties as: [1] Uncertainties related to future changes in external forcings, and [2] uncertainties related to model formulations and physical understanding. The first uncertainty has to do with the fact that changes in natural forcings like solar radiation and volcanic activity are unknown. Likewise, future
greenhouse gas emissions are unknown. Several emission level “scenarios” have been suggested by the IPCC for possible use in climate change studies. The “A2” scenario represents a worst-case emission scenario, where growth continues unabated and technological advances are slow. Due to its conservative nature, the A2 scenario is most often used in climate studies.

The second group of uncertainties has to do with the physical understanding of climate and how researchers develop models to solve future scenarios in the form of mathematical equations. Each research group has different knowledge and their own method for developing a model. The result is several different models that each give their own result, given identical input. To reduce uncertainty, most climate studies use an “ensemble” of models. This approach averages out the results from the entire ensemble to give an overall finding.

An additional limitation specific to western Norway is that the resolution of the HIRHAM regional climate model (55 km x 55 km) is too coarse to account for steep, mountainous terrain (Engen-Skaugen et. al., 2005). This resolution tends to misidentify altitudes and consequently gives inaccurate climate predictions. A method of reducing this error is provided by Engen-Skaugen (2007), who uses empirical refinement of the modeled results to adjust the precipitation and temperature predictions to realistic levels.

### 3.4.3 Climate Projections

There have been several climate change projection studies completed for Norway, including, but not limited to: Benestad, (2002); Benestad, (2005); Benestad, (2007a); Engen-Skaugen et. al., (2007); Engen-Skaugen et. al., (2008); and Sorteberg and
Andersen (2008). All of these studies give similar findings, but only the results of Sorteberg and Andersen (2008) will be presented here because it is the only study that uses an ensemble of several different regional climate models, as well as covering both temperature and precipitation simulations. The ensemble used by Sorteberg includes eight different European regional climate models, including the HIRHAM-Oslo model developed by RegClim. In this study, climate projections are for the year 2025, with future emissions modeled using the A2 SRES emissions scenario given by the IPCC.

3.4.3.1 Temperature

The Sorteberg study indicated that winter temperatures in Norway will rise by 1.5 to 2.2°C, with the greatest change occurring in the north, as shown in Figure 3-9.

![Temperature Rise in Winter and Precipitation Change in Winter](image)

**Figure 3-9**: Projected winter climate change for the year 2025 using A2 scenario (from Sorteberg and Andersen, 2008)
Western Norway will have the lowest rise in temperature due to the large thermal inertia of the ocean. The different models in the ensemble show good agreement, with lowest result giving a rise in temperature of 1.1°C, and the highest rise giving a rise of 1.9°C. The temperature rise in western Norway for the other seasons are: spring (1.6°C), summer (1.4°C) and autumn (1.7°C).

3.4.3.2 Precipitation

The change in precipitation is highly dependent on season. For the mid-western coast, winter precipitation will increase by 8.1%, as shown in Figure 3-9. Spring and autumn precipitation will also increase, by 13.5% and 6.8% respectively. Summer on the other hand will experience a decrease in precipitation by 0.2%. Unfortunately, the models within the ensemble do not agree well with each other. For summer, the models range from -5.2% to 8.3%, so the projection is actually inconclusive. For the other seasons, the range between high and low remains significantly large; however most of the models indicate an increase in precipitation. Spring is the only season where all the models agreed on an increase in precipitation. For winter, the models ranged from -0.5% to 25.0%, so it appears that an increase in precipitation is very likely, but the amount still remains in question.

3.4.3.3 Runoff

Sorterberg and Andersen (2008) do not specifically address the issue of runoff; however, the RegClim study used dynamically downscaled models and hydrological models to
show that runoff in parts of western Norway will increase by more than 200 mm/yr from the period 1980-99 to 2030-49 (Iversen, 2003). In addition, the Norwegian Water Resources Directorate (NVE) has completed hydrological modeling on a HIRHAM simulation for the period 2071-2100 using the IPCC SRES B2 emissions scenario (B2 is a more conservative emissions estimate that assumes moderate population growth and environmental protection at the regional level). These models indicate that western Norway will experience an increase in winter runoff by more than 250 mm, which is more than a 100% increase from current levels. In contrast, summer will experience a reduction in runoff by 20-75%, as shown in Figure 3-10.

![Figure 3-10: Projected change in runoff for 2071-2100 using B2 scenario (from NVE, 2009)](image)
3.4.3.4 Extreme Events

Most climate projection studies focus on overall changes in temperature and precipitation; however, hazardous conditions in the form of rockslides, flooding, drought, etc. usually occur during extreme weather events. These natural hazards are not captured in climate studies. In the case of precipitation, the studies agree that western Norway will likely experience wetter weather, but the question is whether these changes will be averaged out over the entire year, or will it be represented by more severe storms that occur at a higher frequency. This issue has been addressed by Benestad (2003) and Benestad (2007b), who uses statistical methods to infer the future probability of extreme precipitation events.

Benestad (2003) does not specifically address extreme events in terms of climate change, but rather how often we can expect record events to occur based on historical data. The record event of interest is the monthly-maximum 24h precipitation; that is, a record amount of precipitation for a 24hr period in a specific month. The study found that Norway should expect approximately 5 record events in a 100 year period, or about one every 20 years. The study attempted to ascertain whether record setting events had become more severe during the 20th century; however, results were inconclusive.

Benestad (2007) set out to establish the effects of climate change on extreme rainfall events over Northern Europe, and found that there is an increased probability for 24 hr precipitation in western coastal areas to exceed the present-day 95th percentile in 2050. The magnitude of this increase is highly sensitive to the choice of predictors used to map the results, but estimates are that the probability of exceeding the present 95th percentile may increase by up to 30%. In other words, the scenarios indicate that daily
rainfalls that are considered extreme today will be more common in the future (Førland, et. al., 2007). For example, if a present-day storm has a 20-year return period, a storm of the same magnitude in 2050 will have a lower return period, perhaps as low as 15 years.

3.4.4 Application to Rockslide Studies

Climate projection scenarios allow researchers to assess the effects of climate change to a wide range of applications, including natural hazards. For instance, a projected increase in runoff may result in a higher frequency of rockslides. Certainly, any assessment of this sort requires a thorough analysis of all contributing factors, including: temperature, freeze/thaw activity, elevation differences, snowfall, rainfall, extreme events, and permafrost. Each of these factors is considered in a general discussion of possible climate change effects on rockslides in Chapter 7. In the future, it would be interesting to introduce climate projection scenarios into a GIS-based model. This should make it possible to scientifically assess the implications of climate change.
3.5 References


Chapter 4  
Establishing Rockslide Meteorological Trigger Thresholds  
in Southwestern Norway

4.1 Introduction

4.1.1 The GeoExtreme Project

Meteorological conditions such as rainfall and temperature often play an important role in the triggering of geohazards, such as landslides, rockfalls and snow avalanches. This is especially true in the coastal mountainous areas of western Norway. In the last 150 years, geohazards have resulted in over 2,000 casualties in Norway, making it an important area of study. With recent climate research suggesting significant climate change in northern regions, it has become apparent that a better understanding of the link between meteorological conditions and geohazards is required to help prepare for future events.

To this end, Norwegian authorities initiated an interdisciplinary research project, called “GeoExtreme”. By studying the weather conditions at the time of historic geohazards, GeoExtreme has worked to establish relationships between meteorological factors and geohazards. In addition, GeoExtreme forecasted geohazard scenarios using state-of-the-art climate change projection models and assessed the socio-economic consequences of future geohazards (Jaedicke et. al., 2008).
4.1.2 Scope of Work

The work presented here is focused specifically on establishing links between meteorological factors and the triggering of rockslides. This includes the analysis of the two primary rockslide triggers in the area, extreme runoff from rainfall and snowmelt and freeze/thaw processes (frost wedging). The purpose of establishing meteorological triggers is to aid in the prediction and monitoring of present-day rockslides, as well as to establish a baseline for studying the effects of climate change on future rockslides.

A study of historic rockslides and weather conditions has been completed for two counties in western Norway, Hordaland and Sogn og Fjordane, which have been chosen for the high frequency of rockslides recorded in the region. The basis of the study is a database of rockslides provided by the Norwegian Geotechnical Institute (NGI), which includes 3,595 rockslides that have been recorded in the area since 1963.

In order to help study the effects of weather on these historic slides, the Norwegian Meteorological Institute ('met.no') has provided a set of weather variables for each slide event, which include the weather conditions on the day and days preceding each slide. Furthermore, weather data from Norwegian weather stations and Norway’s weather map database, “www.senorge.no” have been used to establish specific meteorological triggers.
4.1.3 Methodology

4.1.3.1 Background and Related Studies

It is well known that extreme meteorological conditions have the ability to trigger geohazards. To date, there have been several studies dedicated to the establishment of trigger thresholds for shallow soil landslides and debris flows (Guzzetti et. al., 2007; Corominas and Moya, 1999; Glade et. al., 2000). The majority of these efforts are related to antecedent rainfall intensity-duration thresholds, and are focused on areas where rainfall is the primary triggering factor. Unfortunately, there have been few studies dedicated to quantifying meteorological trigger thresholds for rockslides.

4.1.3.2 Application of Meteorological Triggers to Rockslides

The majority of rockslide prone areas are subjected to meteorological triggers in addition to rainfall. These include: runoff from snowmelt, frost wedging assisted by supply and migration of water, and increased water pressure due to ice-blocked drainage routes (Braathen et. al., 2004; Sandersen et. al., 1996). Non-meteorological triggers must also be considered, including: seismic activity, erosion, root wedging and human activity.

The reason why meteorological thresholds have not yet been established for rockslides is that statistical analysis of a database containing all possible triggers produces mixed and erroneous results. In order to overcome this difficulty, it is proposed in this thesis that a rockslide database can be separated into categories of different triggers, which are then analyzed separately.
4.1.3.3 Meteorological Trigger Analysis

The separation of meteorological triggers within a database is accomplished by studying weather data of the days preceding each slide, and then identifying the most probable trigger. In cases where no meteorological trigger is discernible, the slide is attributed to a non-meteorological factor, and removed from further analysis. This process has been applied to 98 winter-time rockslides in a 2000 km$^2$ area around the Village of Sandane in Sogn og Fjordane, and is discussed in Sections 4.4.6 and 4.4.7. With the database separated into events associated with different triggers, it is then possible to establish thresholds for each group. As discussed in the following sections, runoff was found to be the primary trigger for winter rockslides in the study area. Based on this work, a preliminary normalized runoff threshold has been established, and is further discussed in Section 4.6. In addition, thresholds have been evaluated in terms of a weights-of-evidence mapping approach, which is further discussed in Section 0 and Chapter 5. Both of these methods are applied to rockslides that are triggered by runoff only.

4.1.3.4 Mapping

The chosen output of this analysis is a dynamic, weather-dependent susceptibility map that changes day-to-day based on the weather forecast. A general methodology for creating such a map is given as a flowchart in Figure 4-1, shown on the following page. This methodology is intended as a starting point for any weather-dependent susceptibility map, which can be applied to any study area and to any natural hazard that is triggered by weather conditions (ex. debris flows, snow avalanche, etc.).
The advantage of a weather-dependent susceptibility map is that it can serve as a prediction or monitoring tool for rockslides (both spatially and temporally) by indicating hazardous areas based on the weather forecast. Furthermore, it can provide an effective means for studying the effects of climate change on rockslides.
Referring to Figure 4-1, the dynamic susceptibility map consists of two components: a susceptibility map based on physical characteristics (i.e. slope angle, slope aspect, rock type, etc.), and a dynamic trigger map that changes based on weather input. This thesis considers two types of trigger maps, one based on threshold exceedance levels (discussed in this chapter), and the other based on a weights-of-evidence approach, which is further discussed in Chapter 5. The advantage of the weights-of-evidence approach is that it produces a single map that takes weather and physical terrain into account automatically. On the other hand, the threshold exceedance map has to be physically overlain on the physical hazard map to indicate susceptible slopes; however, it has the advantage of providing a clearer picture of the definition of severe weather conditions.

Regardless of which trigger map is chosen, the idea behind this methodology is that a trigger map, which indicates hazardous areas based on the weather, can be added to a physical-factor susceptibility map to highlight specific areas which are in danger of failing due to a meteorological trigger. In this case, mapping indicates hazardous areas that are in danger of failing due to runoff only; however, the same approach can also be applied to other trigger mechanisms, such as freeze/thaw processes. For various reasons, some of the items listed in the flowchart were not used in this particular study. A complete description of the mapping process used in this study is given in Chapter 5.
4.2 Rockslide Database

Norwegian institutions have kept their own registers of geohazards for the past 30 years (Jaedicke et. al, 2006). These include all types of geohazards, including: icefalls, snow avalanches, rockslides, debris slides and sub-aqueous slides. The majority of registered geohazards have been recorded by the Public Road Administration, which records all types of events that encroach on public roads. Secondary sources of information include NGI and The Geological Survey of Norway (NGU). At present, the NGU maintains a national database of all recorded geohazards by all partnering institutions. This database has been mapped using Geographic Information Systems (GIS), and can be viewed publicly on the web at “www.skrednett.no” (in Norwegian only).

For the purposes of the work presented here, rockslides recorded in the counties of Hordaland and Sogn og Fjordane have been extracted from the larger database. The refined database includes 3,595 rockslides, dating between 1963 and the end of 2004. Historical slides older than 1961 have been excluded from the database due to a lack of weather information.

Each slide in the database includes the following information: location in UTM coordinates (of where the slide impacted a road), recorded slide date (year, month, day), and slide date accuracy. Slides with poor date accuracy have been excluded from this analysis. Raw data is provided in APPENDIX D. A map of the rockslide locations is given in Figure 4-2, as shown on the following page.
Figure 4-2: Map of rockslides in Sogn of Fjordane (north) and Hordaland (south)
4.2.1 Limitations of Data

4.2.1.1 Spatial Discontinuity

Nearly all rockslides in the database were recorded because they collided with a road. Rockslides that occur away from the road network are rarely recorded, and hence the dataset contains substantial spatial discontinuity. An additional source of spatial discontinuity exists due to the location error associated with each recorded rockslide. Coordinates given in the database indicate a position where a rockslide collided with a road, not the source zone from which it originated. Since the actual distance between these two points is relatively small (usually less than a kilometre); weather conditions between the points are relatively similar, and analyses of meteorological triggers is unaffected. However, this error has a negative effect on certain aspects of statistically determined susceptibility mapping.

The physical rockslide susceptibility map on the right-hand side of Figure 4-1 has been completed using a Bayesian probability, weights-of-evidence approach, as discussed in Chapter 5. This method uses a historical slide inventory to assign weights to certain parameters (ex. slope angle, slope aspect, rock type, etc.) according to the physical characteristics of the slide source zone (Soeters and Van Westen, 1996). As certain parameters vary significantly between the source zone and the recorded location, particularly slope angle, a statistical approach based on the given rockslide inventory will produce erroneous results. Therefore, a separate source zone inventory has been created in order to acquire a statistically prepared susceptibility map. A procedure for this is proposed in Section 5.3.
4.2.1.2 Temporal Discontinuity

The county of Sogn og Fjordane has been recording rockslides semi-frequently since the 1970’s, but there has been a distinct increase in reported rockslide occurrence since 1997, as recording procedures became more detailed and comprehensive. Similarly, the county of Hordaland recorded rockslides very infrequently prior to 2000, but since then has kept a very detailed rockslide inventory. The lack of comprehensive data prior to these dates makes it difficult to assess meteorological triggers; therefore, only events following the year 2000 are considered.

4.2.1.3 Slide Volume Information Deficiency

For the purposes of the database, the term “rockslides” refers to both small-scale rockfalls and large-scale rockslides. The database contains a column for volume information; however, only about 2% of the total rockslides have a value given for this parameter (either <100 m$^3$ or >10,000 m$^3$). Unfortunately, the volumes for the remaining 98% are unknown.

The lack of volume information is unfortunate because different sized slides are expected to require different meteorological conditions to trigger failure. For instance, very large rockslides may be affected by long-term antecedent precipitation, in the order of months, whereas small rockfalls are more likely to be affected by short-term antecedent conditions (i.e. less than a week). Nonetheless, since the majority of slides are expected to be of a relatively small volume, meteorological trigger thresholds that are applicable to most rockslides can be established.
4.2.2 Weather Database

‘Met.no’ maintains a database of gridded weather maps that cover the entire country with 1 km x 1 km spatial resolution. Maps are available for each day dating back to 1961, with each day represented by several different weather/climate themes (ex. precipitation, temperature, snow depth, snow melt, etc.). These maps can be viewed publicly at “www.senorge.no”. The temperature and precipitation maps from this database represent raw data that has been statistically interpolated from local weather stations. The procedure for generating these grids is described in Tveito and Førland (1999) and Mohr (2008). The remaining themes are derived from the temperature and precipitation grids by mathematical algorithms. The most important additional theme is the snow map, which is used to calculate snowmelt. A description of how the snow map is derived and validated is given by Engeset et. al. (2004a; 2004b).

In conjunction with the GeoExtreme project, ‘met.no’ has appended the geohazard database with a set of derived weather variables. Each event is mapped on the temperature and precipitation grids for the event day, which allowed the following variables to be computed:

- Precipitation sum for ‘n’ antecedent days (n=1, 3, 5, 7, 10, 13, 30, 60 and 90),

- Mean annual precipitation (using the standard normal period 1961-1990),

- Extreme precipitation for 1, 3 and 5 day(s) with return period of 50 and 100 years,
- Number of cold periods (an event of 5 consecutive precipitation-free days with temperature below -5°C) from the start of the year,

- Frost interval (number of freeze-thaw events from January 1, each year),

- Positive and negative degree days (the sum of air temperatures above and below 0°C) from the start of the year and during the past 5 days,

- Mean temperatures for the slide date and the last 7 days and last 30 days before the slide.

A complete description of each variable and how it was derived is described in Vikhamar-Schuler and Isaksen (2006). Unfortunately, no measure of snowmelt, and therefore runoff, was included in the GeoExtreme database. To help overcome this difficulty, the Norwegian Water Resources and Energy Directorate (NVE) has provided snowmelt and runoff weather maps for days that fall within the five most extreme winter storms between the years 2000 and 2005.
4.3 Previous GeoExtreme Analyses

4.3.1 Classification Trees

The purpose of the combined geohazard-weather database was to establish links between the derived weather variables and the triggering of geohazards. Applying statistical analyses only, Kronholm et. al. (2006) described how classification trees can be used to determine the critical meteorological conditions required for hazard triggering. This process proved successful for snow avalanches; however, the same process showed little correlation between rockslides and the derived weather variables.

The negative result from the classification tree process is counter-intuitive because rockslides are known to occur during intense storm events. Consequently, it is evident that further research is required to establish the relationships between meteorological conditions and rockslide triggering.

4.3.2 Hypothesis for Negative Result

In regards to the rockslide analysis, the classification tree approach was unsuccessful because the weather variables were chosen mainly with a focus on snow avalanches, which do not share the same trigger mechanisms as rockslides. In terms of geomechanical processes, weather conditions can initiate rockslides by either increasing water pressure in the form of runoff, or by physical movement generated by freeze-thaw processes (Sandersen et. al., 1996). Therefore, the key factors to consider are:

[1] runoff (rainfall + snowmelt), and

[2] temperature changes across 0°C during preceding days.
For this research, runoff is defined hereafter as the sum of rainfall and snowmelt at each location of interest. This definition has been chosen to take advantage of the data available, and it is believed to be a reasonable analog for judging water levels within discontinuities in a rockmass. Rainfall data from Norwegian weather stations is typically given as a 24-hour cumulative sum for each day; therefore, runoff in this thesis is given in antecedent increments of 24 hours (i.e. 24-hr, 48-hr, 72-hr, etc.).

Unfortunately, the GeoExtreme database provided no measure of runoff due to a lack of snow depth information. Also, the 7-day mean temperature and degree-day variables only give a general measure of temperature conditions during preceding days. In addition, the freeze/thaw variable provided by ‘met.no’ was poorly defined, making it difficult to establish a freeze/thaw trigger threshold. This factor, called frost interval, was defined as the number of times the daily air temperature rose above or dropped below 0°C between January 1st of the slide year and the slide date (refer to Figure 4-3).

Figure 4-3: Graph of derived frost interval variable
This graph plots the frost interval of each slide against its elapsed time from January 1\textsuperscript{st} (for whichever year the slide occurred). Two issues with this variable make it difficult to establish a specific trigger threshold. Firstly, it resets every January 1\textsuperscript{st}, thereby ignoring December freeze/thaw events that may have affected January rockslides. Secondly, it is questionable if rockslides that occur late in the year should have a frost interval that includes the freeze/thaw events from the previous winter.

Despite this drawback, the frost interval chart does give a clear indication of the times of year when frost is a factor. Beginning on January 1\textsuperscript{st}, frost interval rises steadily until approximately April 10\textsuperscript{th}; levels off during the summer period, and then begins to rise again by about October 15\textsuperscript{th}. In addition, when frost interval is compared to cumulative rockslide count, it is evident that the rate of rockslide incidences decreases sharply in mid-April, about the same time that frost ceases to be a factor. This may suggest that frost is a triggering factor; however, it may be coincidental with the occurrence of rain-on-snow events, which are believed to trigger the majority of winter rockslides, as discussed in the following sections of Chapter 4.
4.4 Meteorological Trigger Analysis

4.4.1 Objective

The fundamental goal of this work is to create a weather-dependent susceptibility map that highlights areas where there is danger of the weather triggering a rockslide. Two methods of trigger mapping are considered, one based on threshold exceedance levels (discussed in Section 4.6), and the other based on a weights-of-evidence approach, (discussed in Chapter 5). In order for either map to work effectively, there must be a clear understanding of the weather conditions that trigger rockslides. Research describing the establishment of this understanding is given in the sections below.

4.4.2 Monthly Trends

The first step in analyzing meteorological triggers was to compare average monthly climate conditions with a monthly rockslide histogram (see Figure 4-4 on the following page). The mean monthly temperature and precipitation represent the average conditions for the entire study area, which were obtained by taking the statistical mean of monthly observations from thirty-seven, spatially distributed weather stations.

The first observation from Figure 4-4 is the high frequency of rockslides during the months of January, February and March. This is most likely due to regular thaw events that occur when Atlantic low-pressure systems bring warm temperatures and heavy rainfall over previously frozen land, as described in Section 4.4.4. The resulting rain-on-snow produces extreme runoff that triggers a high frequency of rockslides. This observation correlates well with previous research by Sandersen et. al. (1996).
The effect of runoff is evident by observing the rockslide count in April, when monthly precipitation is low, yet the rockslide count remains relatively high, presumably due to continued snowmelt at higher elevations. The remaining months, which experience little to no snowmelt, exhibit a much lower incidence of rockslides. Even the wettest months in autumn have little effect on rockslide triggering. This observation suggests that runoff due to snowmelt, coupled with rainfall, is a factor that triggers more rockslides than rainfall alone.
4.4.3 Daily Rockslide Count

To further examine rockslide trends, a histogram of daily rockslide count between 2000 and 2005 was generated for the two southwestern counties, as shown in Figure 4-5.

![Histogram of daily rockslide count between 2000 and 2005](image)

**Figure 4-5: Number of rockslides recorded each day in Sogn og Fjordane and Hordaland between 2000 and 2005**

This figure reveals that days with a high incidence of rockslides usually occur during winter or early spring, when days of 5 or more rockslides are relatively common. In addition, the five most extreme days, highlighted in Figure 4-5, all occur during these months. In contrast, there are generally no more than one or two rockslides during any given day in summer and autumn. The significance of extreme events is observed by noting that days with five or more rockslides occurred only 107 times between 2000 and 2005 (6% of total days), yet they account for about 36% of all recorded rockslides.
4.4.4 Rockslides Triggered During Extreme Winter Storms

The high incidence of rockslides in the winter can be attributed to Atlantic low-pressure systems, which bring warm temperatures and heavy rainfall over previously frozen land. The resulting extreme runoff from rainfall and snowmelt is believed to be the primary meteorological trigger in the study area. An example of a low-pressure system hitting the coast is shown in Figure 4-6. This weather map represents conditions at noon on January 13th, 2003, a day when 15 rockslides were recorded. The following day, January 14th, represents the most extreme day in the database, when 37 rockslides were recorded.

Figure 4-6: Weather map for January 13th, 2003 (courtesy of met.no)
From the Figure 4-6, it can be seen that Norway was previously located behind a cold front. The temperatures in Norway were below 0°C, and there was a significant snowpack in most regions (confirmed by weather station observations). The low-pressure system, and the corresponding warm front made landfall sometime in the afternoon on January 13th. This system elevated temperatures above freezing, which initiated snowpack thawing. In addition, the low-pressure brought heavy rainfall. Further evidence of these conditions is shown in Figure 4-9, which shows daily weather observations from the Sandane weather station during this period.

In general, the majority of slides were observed to occur within four days of a low-pressure system making landfall. This is likely because rainfall and snowmelt is concentrated during this period, and subsides afterward. Another possible contributing factor is the melting of ice within rock joints. For instance, it is possible that a shear surface was recently developed due to freeze/thaw action. Once the rock joint(s) extends sufficiently, and the shear surface has developed, failure can occur when the ice melts and elevated water pressures are introduced to the slope.

Another consideration, suggested by the research of Davies et. al. (2000; 2001) and Günzel (2007), is that shear strength of an ice-filled joint can decrease to a minimum during warming, specifically as the ice temperature approaches -0.5°C. In fact, this condition has a shear strength less than if a joint is completely thawed with no ice. Therefore, risk of detachment is increased during a thawing period, and might contribute to the high incidence of rockslides observed during a low-pressure system thaw. This phenomenon is described in more detail in Chapter 6.
4.4.5 Slope Aspect

Slope aspect (i.e. the direction the slope faces: north, south, east, west) is commonly used to assess rockslide susceptibility because certain slope aspects are more prone to sliding than others, usually due to meteorological differences. In terms of geohazards, the analysis of slope aspect distribution is a useful analog for evaluating weather triggers. With that in mind, each rockslide in the database was assigned its appropriate slope aspect, as determined from a 25 m resolution digital elevation model (DEM) and the slope aspect function in ArcGIS. Figure 4-7 shows the rockslide distribution, by slope aspect, in the form of a radar plot.

![Radar plot showing rockslide distribution by slope aspect](image).

Figure 4-7: Radar plot showing rockslide distribution by slope aspect
Figure 4-7 clearly shows that southwest facing slopes are the most prone to rockslides, and northeast facing slopes are the least prone, especially during the winter and spring, when most slides are triggered. This effect is less pronounced during the summer and autumn; however, western slopes still exhibit a slightly higher frequency of slides.

There are two possible considerations for this phenomenon; [1] solar radiation, i.e. differences in freeze/thaw activity, and [2] increased precipitation from prevailing winds. In the case of western Norway, prevailing winds from the west are the primary reason for more rockslides occurring on west-facing slopes, as indicated by Benestad (2005), who states that “east-facing slopes tend to be in the ‘rain shadow’” and Sandersen et. al. (1996), who describes the effect of slope aspect in Norway as follows:

*Slope aspect plays an important role in the distribution of precipitation. The high relief in the west-coast area leads to large differences in precipitation, even over small distances. As a result, precipitation is largest on the windward sides of the mountains, that is on slopes facing southwest and west.*

During the winter months, the region experiences very short days, with minimal sunlight, so the effect of solar radiation is reduced significantly. It is also clear that the majority of slides occur when low-pressure systems from the Atlantic make landfall, as discussed in the previous section. By observing weather maps, it appears that the path of these storms is typically southwest to northeast. Therefore, when these storms makes landfall, the wind will deposit the most rainfall on southwest facing slopes, and the least on northeast facing slopes. It is also important to note that the rate of snowmelt depends largely on wind speed (Sandersen et. al., 1996); and therefore high wind speeds on southwest facing slopes result in faster rates of snowmelt. In addition, it is probable that
southwest facing slopes have thicker snowpacks due to western winds during snowfall. Ultimately, it is believed that southwest facing slopes experience a higher frequency of rockslides due to elevated levels of runoff brought upon by the weather.

4.4.6 Analysis of Study Area – Village of Sandane

A sub-study area contained within a 25 km radius around the Village of Sandane in Sogn og Fjordane, shown in Figure 4-8, was chosen for a meteorological trigger analysis.

![Figure 4-8: Sandane Study Area](image)
The Sandane site was chosen because it has a high frequency of rockslides, as well as consistent and complete weather data from the Sandane weather station. In total, there are 98 winter rockslides used in this analysis.

The purpose of this study is to separate rockslides into groups based on different meteorological triggers, which is accomplished by studying daily weather data from the Sandane weather station (example shown Figure 4-9).

Figure 4-9: Comparison of Sandane weather data with rockslide activity
(Top) Example of daily weather data from Sandane weather station
(Middle) Precipitation and snow depth
(Bottom) Daily rockslide Count
To account for possible meteorological differences between the Sandane station and the rockslide locations, weather data has been cross-referenced with daily weather maps from “www.senorge.no”. By combining these two data sources, a probable trigger has been assigned to each of the 98 rockslides. During this process, it became evident that a number of slides in the database occurred on unsupported road-cuts. Since this study is more interested in rockslides on natural slopes, the 98 rockslides in this study were separated into categories of “cut slopes” and “natural slopes”.

4.4.7 Results

Of the 98 rockslides in the Sandane trigger analysis, 67 occurred on natural slopes and 31 occurred on cut slopes. Of the 67 natural slope slides, 51 were triggered by runoff and 10 were triggered by frost wedging. The remaining six rockslides did not have a discernible meteorological trigger. Table 4-1 on the following page contains complete results of the Sandane meteorological trigger analysis.
<table>
<thead>
<tr>
<th>Meteorological Conditions</th>
<th>Condition Occurrence (days)</th>
<th># Slides</th>
<th>Number of Slides per Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cut Slopes</td>
<td>Natural Slopes</td>
<td>Runoff</td>
</tr>
<tr>
<td>Above 0°C with recent thaw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry or light rain</td>
<td>84</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Light rain on snow</td>
<td>23</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Heavy rain on bare ground</td>
<td>13</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Heavy rain on snow</td>
<td>10</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Sustained heavy rain on snow</td>
<td>6</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Above 0°C sustained</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light rain on snow</td>
<td>18</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Heavy rain on bare ground</td>
<td>57</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Heavy rain on snow</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Sustained heavy rain on bare ground</td>
<td>20</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sustained heavy rain on snow</td>
<td>11</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Below 0°C freezing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After light runoff</td>
<td>25</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>After heavy runoff</td>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>After sustained heavy runoff</td>
<td>7</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Dry</td>
<td>45</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Unspecified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry or light rain</td>
<td>279</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>596</td>
<td>31</td>
<td>67</td>
</tr>
</tbody>
</table>

1 maximum and minimum temperatures have risen above 0°C at some point within the last 4 days
2 heavy rain defined as 10 mm or more accumulated on the slide date
3 sustained heavy rain defined as 60 mm or more accumulated during the 3 last days before slide

Table 4-1: Results from the Sandane Meteorological Trigger Analysis
4.5 Discussion of Rockslide Triggering Mechanisms

4.5.1 Shear Strength Reduction

4.5.1.1 Increasing Water Pressure from High Runoff Events

Taking a closer look at the natural slope rockslides triggered by runoff, it is evident that the majority (76%) occurred after a recent thaw (i.e. the maximum and minimum temperatures had risen above 0°C within the last four days). Braathen et. al. (2004) state that frozen ground is a vital factor in the stability of mountain slopes since, in most cases, thawing of ice-filled fractures leads to a rapid loss of shear strength. In addition, stability can be affected by an increase in water pressure due to blocked drainage, either from an unmelted ice layer along the shear plane (Braathen et. al. 2004), or an ice slab at the rock face (Hoek and Bray, 1981).

Moreover, it is important to note that a melting snowpack greatly increases the likelihood of a slide due to the rapid and sustained delivery of water. Thirty-seven of the 59 runoff-triggered slides (63%) occurred during rain-on-snow conditions, even though runoff periods were characterized by rain-on-snow only 30% of the time. A general trend observed was that rockslides could be triggered by rain-on-snow up to four days after melting begins. This is likely due to the snowpack’s capacity to absorb rain in available void space (Singh et. al, 1997). After a few days, the snowpack becomes fully saturated and snowmelt accelerates to a point where runoff is sufficient to trigger rockslides.

Overall, the most hazardous conditions from a meteorological point-of-view are when a large snowpack is rained on heavily for a sustained period of three days or more. It was observed that a 72-hr antecedent rainfall of 60 mm was required to trigger the
majority of the winter rockslides recorded in the database. Overall, these extreme runoff conditions only occurred on 17 of the 596 days (3%) studied, yet resulted in 26 of the 67 natural slope slides (39%).

4.5.1.2 Temperature Variation in Ice-filled Discontinuities

Recent research by Davies et. al. (2000; 2001) and Günzel (2008) suggests that the shear strength of ice-filled discontinuities is a function of ice temperature and normal stress. Of particular importance is the notion that as ice temperature rises close to -0.5°C, the shear strength of an ice-filled joint drops below the strength of the same thawed joint. Theoretical simulations of this type of rockslope failure have been carried out using finite-element modeling software, Phase², and are described in Chapter 6.

Results of these simulations suggest that permafrost slopes are particularly at risk of failing due to this phenomenon. To a lesser extent, non-permafrost slopes, such as those in the southwestern Norway, are also affected by ice strength reduction. Simulations showed that the factor of safety (FoS) of a non-permafrost slope can reduce by as much has 17%. Therefore, slopes with an unfrozen FoS of 1.0 to 1.2, which are otherwise stable, may become unstable as ice within the joints warms close to -0.5°C.

It is also important to note that the Phase² simulations demonstrated that water pressure due to runoff also has a significant impact in creating instability. In fact, for non-permafrost slopes, it appears that water pressure has the potential to reduce shear strength more than ice warming alone. In all likelihood, these two forces act together to create instability within a slope. This may help to explain why the majority of slides occur immediately after a slope begins to thaw.
4.5.2 Rockslides Triggered by Frost Wedging

Of the ten natural slope rockslides triggered by frost wedging, only one occurred during dry conditions. The remaining nine slides were accompanied by the supply of water. In each of these nine cases, the slide occurred within two days of the temperature dropping below 0°C, and runoff conditions existed prior to freezing.

According to Matsuoka (2001), there are two mechanisms for rock failure by frost action: [1] hydro-fracturing due to the 9% volumetric expansion of the water-to-ice phase change, and [2] ice growth due to continual migration of water to the ice front by adsorptive forces (ice segregation). Volumetric expansion is facilitated by a large supply of water subjected to rapid freezing, whereas ice segregation is a slow freezing process maintained by a steady supply of migrating water. Since the majority of slides in the Sandane study occurred immediately after a sudden drop below 0°C, it is assumed that volumetric expansion is the primary triggering force; however, ice segregation may still play a role in this process, and may contribute to the triggering of rockslides where no meteorological trigger was apparent.
4.6 Establishment of Meteorological Trigger Thresholds

4.6.1 Procedure

The trigger analysis work carried out on the Sandane study area revealed that the majority of rockslides are triggered by elevated water pressure due to runoff. Therefore, threshold levels for runoff are sought to facilitate a rockslide forecast system. This system will provide warning for rockslides triggered by runoff only, as it does not take into account temperature change or non-meteorological factors.

Runoff values have been assigned to rockslides that occurred during the five most extreme winter storms using runoff maps from Norway’s weather map database. Regrettably, the raw raster data of Norway’s weather map database is not available publicly; however, the Norwegian Water Resources Directorate (NVE) agreed to supply a limited number of raw weather maps for the most extreme storms. While the limited data makes it difficult to establish a robust mapping system, it still represents an inventory of 195 rockslides triggered specifically by runoff, and provides a good first-step towards establishing effective threshold levels. In addition, it will provide a good indication of whether or not the threshold captures extreme runoff conditions, which is of primary importance to the study. Supplementary runoff data is available for summer months from the GeoExtreme database, which contains antecedent precipitation data. Since the summer months do not experience snowmelt, the precipitation value is assumed to represent a runoff value.

It is important to note that this research does not aim to establish thresholds for an absolute value of runoff; rather, the threshold will represent a normalized runoff value, which takes into account the climate of each rockslide location. This is important
because regions with high annual rainfall tolerate higher precipitation intensities than slopes situated in a drier area (Sandsersen et. al., 1996). In other words, a slope is more susceptible to rockslides when runoff increases significantly from normal conditions, whether the area is wet or dry or wet in general.

Sandsersen et. al. (1996) established a normalized runoff threshold for debris flows by expressing each runoff value as a percentage of the mean annual precipitation at the corresponding debris slide location. This routine was effective for the Sandsersen study; however, the work presented here aims to take this concept further by normalizing the runoff value by the mean monthly precipitation. This not only takes into account the spatial variation of precipitation, but also temporal variation. If a slope in a dry region requires less runoff for failure than a slope in a wet region, then it stands to reason that a slope within the same region will require less runoff to fail during a drier time of year than during a wetter time of year. Under perfect circumstances, the runoff value would be normalized by the mean runoff for a period of ‘x’ number of days before the slide to ‘x’ number of days after the slide; however, only mean precipitation for each month is available, and it is believed that this provides a reasonable proxy for the ideal case.
4.6.2 Results

4.6.2.1 Winter – Runoff from Rainfall and Snowmelt

From the Sandane trigger analysis, it was observed that the majority of slides occurred if 24-hr runoff was greater than 10 mm and/or 72-hr runoff was greater than 60 mm. Using this as a basis, an antecedent runoff threshold was established with the equation:

\[ R = 27 \cdot \log_e(D) - 80 \]

where, \( R \) = normalized runoff as a percent of mean monthly precipitation
\( D \) = antecedent duration (i.e. time since rockslide occurred), in hours

An example of the proposed threshold is given in Figure 4-10, as shown on the following page. The upper graph plots antecedent normalized runoff for all rockslides that occurred between January 13\(^{th}\) to 16\(^{th}\), 2003, when an intense Atlantic, low-pressure system made landfall. Likewise, the lower graph plots rockslides during a similar storm between February 3\(^{rd}\) and 6\(^{th}\), 2004. Graphs of the three other winter storms are provided in APPENDIX A.
Figure 4-10: Proposed antecedent normalized runoff threshold

Dots represent normalized runoff for each rockslide

(Top) Rockslides between January 13th and 16th, 2003
(Bottom) Rockslides between February 3rd and 6th, 2004
Considering all five storms, the threshold successfully captures 171 of the 195 slides (88% success rate), within a 96-hour window, as shown in Table 4-2. For comparison, the lower thresholds, 0.75-R and 0.5-R, captured 92% and 96% of all the slides, respectively. The only storm in which the set of thresholds did not have a very high success rate is the March 2003 storm.

Table 4-2: Success rate of threshold levels for each winter storm

<table>
<thead>
<tr>
<th>Storm</th>
<th>Success Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
</tr>
<tr>
<td>February 2001</td>
<td>100</td>
</tr>
<tr>
<td>January 2002</td>
<td>69</td>
</tr>
<tr>
<td>January 2003</td>
<td>97</td>
</tr>
<tr>
<td>March 2003</td>
<td>54</td>
</tr>
<tr>
<td>February 2004</td>
<td>100</td>
</tr>
<tr>
<td><strong>All five combined</strong></td>
<td><strong>88</strong></td>
</tr>
</tbody>
</table>

*The threshold is considered successful if it captures normalized runoff at least once in a 96-hr window*

By observing the graphs in Figure 4-10, it may appear that there are more rockslides below the threshold; however, the normalized runoff only needs to exceed the threshold once during the 96-hour window for failure to occur. For rockslides that fell below the threshold levels, it is possible that runoff was not the primary triggering factor.

As another visualization tool, the threshold level has been plotted against daily weather data from Sandane weather station. Results for winter 2003 are shown in Figure 4-11 on the following page. Results of other winters are given in APPENDIX A.
Figure 4-11: Threshold levels plotted with daily weather data from Sandane station
These charts show the 48-hr normalized runoff and the maximum/minimum daily temperatures measured at Sandane station. In this case, 48-hr antecedent runoff was used in favour of 24, 72, or 96-hr antecedent runoffs because it was found to have the best correlation with rockslides during the weights-of-evidence analysis discussed in Chapter 5.

Referring to Figure 4-11, the magenta triangles on the graph indicate days when one or more rockslides were triggered by runoff within 25 km of Sandane station, and the black dots represent the 48-hr normalized runoff at every recorded rockslide in Sogn og Fjordane and Hordaland (note that only data from the five most extreme storms is available; two of these storms are shown in Figure 4-11).

Overall, both of these graphs indicate that the proposed threshold is sufficiently accurate to predict a high occurrence of rockslides due to a severe winter storm. In addition, the 0.75·R and 0.5·R thresholds can be used to indicate areas that are at a lower risk, or areas that may become at risk in the near future. For future work, it would be beneficial to plot all runoff-triggered rockslides on the antecedent charts shown in Figure 4-10. This would allow for the development of a more robust set of thresholds.

4.6.2.2 Summer – Runoff from Rainfall Only

Although runoff data was not made available outside the five most extreme winter storms, the GeoExtreme database does provide antecedent precipitation for ‘n’ antecedent days (n=1, 3, 5, 7, 10, 13, 30, 60 and 90). Since snowmelt is not a factor during summer (June, July and August), this value strictly represents rainfall, and can be
used as a runoff value for analysis. The normalized runoff for all June rockslides in the 
database is plotted in Figure 4-12.

![Normalized Runoff vs. Time](image)

**Figure 4-12: Antecedent normalized runoff threshold for all June rockslides**

At first glance, the threshold does appear to capture the majority of rockslides. For 
example, only 51% of June slides fall above the threshold, with the 0.75·R and 0.5·R 
thresholds capturing 60% and 70%, respectively. However, this chart includes all 
rockslides, not just those triggered by runoff. As part of the Sandane trigger analysis, it 
was found that approximately 9% of slides are not related to meteorological factors. 
Similarly, it was observed that 13 of the 149 rockslides (9%) during June were evidently 
not related to runoff (i.e. there was little to no rainfall). If these slides are removed from
the database, the threshold improves slightly, capturing 56% of slides, with the 0.75-R and 0.5-R thresholds capturing 66% and 77%, respectively. This success rate suggests that this threshold is more applicable to winter conditions; however, it still is successful in determining the most extreme summer conditions, when slides are most likely to occur. For future studies, it would be beneficial to study meteorological triggers specifically focused on summer conditions. This would provide valuable insight for developing a more accurate threshold level for summer. For the time being, the runoff threshold based on the normalization of mean monthly precipitation is only suitable for the winter months.

4.6.3 Mapping Daily Threshold Exceedance

The purpose of a weather-dependent trigger map is to highlight areas that are susceptible to rockslides due to the weather. This map can act as either a prediction tool if using a weather forecast, or as a monitoring tool if using real-time recorded weather data. In this case, the weather map will be a raster grid with 1 km² cells, which is generated with GIS by calculating the 48-hr antecedent, normalized runoff for each cell on the map, and then colour-coded to indicate the level of threshold exceedance. The procedure for generating a threshold exceedance forecast map is as follows:

[1] The runoff map for “tomorrow” is added to the runoff map for “today” to give a forecasted 48-hr antecedent runoff map.
[2] The 48-hr antecedent runoff map is divided by the mean monthly precipitation (expressed in percent) to give the 48-hr antecedent, normalized runoff map.

[3] Each cell on the 48-hr antecedent, normalized runoff map is assigned a colour based on its exceedance level (R = red; 0.75·R = orange; 0.5·R = yellow) to create the threshold exceedance forecast map.

[4] The procedure is repeated each day, so that the map changes with the weather.

Threshold exceedance maps for the period of January 10th to 14th, 2003 are shown in Figure 4-13 on the following page. Since the map is based on a 1 km resolution, it is most effective at a regional county scale. By examining the progression of threshold exceedance day-to-day, it is clear that the likelihood for rockslide triggering increases each day between January 10th and 14th 2003. This observation is validated by the number of slides recorded each day, as outlined in Table 4-3.

Table 4-3: Rockslides and threshold exceedance for January 10th to 14th, 2003

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of slides</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>15</td>
<td>37</td>
</tr>
<tr>
<td>% area &gt; threshold R</td>
<td>0.8</td>
<td>30</td>
<td>45</td>
<td>54</td>
<td>72</td>
</tr>
</tbody>
</table>
Figure 4-13: Threshold exceedance hazard maps for January 10\textsuperscript{th} to 16\textsuperscript{th}, 2003
The main disadvantage of this type of trigger map is that it does not take into account physical rockslide conditioning factors (i.e. slope angle). Therefore, certain areas that are relatively flat, and thus not prone to rockslides, will nonetheless appear red in the exceedance map if runoff conditions are sufficiently high. By omitting these physical factors, there is potential for the map to appear more severe than actual conditions. In order to overcome this shortfall, it is recommended to use a weights-of-evidence mapping system, as discussed in Chapter 5. This type of mapping takes both physical terrain and runoff into account, and therefore presents a more accurate indication of rockslide risk. Despite the drawback of threshold exceedance mapping, it does give a distinct indication when runoff conditions are most severe. For the Norwegian Public Road Administration, this is of primary importance, so that highway crews can be prepared to clear the roads as quickly and efficiently as possible (Humstad, T., NPRA, personal communication, 2009). For this reason, a threshold mapping system can be valuable, and further studies regarding their use are recommended.
4.7 Conclusions and Recommendations

Comparing a rockslide inventory with weather data has given valuable insight as to how rockslides are triggered in southwestern Norway. Firstly, it became clear that the majority of slides occur during the winter, especially during thawing periods. Historic weather maps were also studied, and it was discovered that intense low-pressure systems from the Atlantic bring severe runoff conditions, which increases water pressure within rockmasses, and consequently triggers a high frequency of rockslides. The slope aspect study also revealed that southwest facing slopes are the most prone to rockslides, due to the southwest to northeast path that the low-pressure systems typically follow.

Overall, it was found that extreme runoff, from rainfall and snowmelt, triggers approximately 76% of the slides in the region. The other meteorological trigger, frost wedging accounted for 15% of the slides, and the remaining 9% did not have a discernible meteorological trigger. The high frequency of runoff triggered slides prompted the study of a runoff related trigger threshold, which could then be used to map threshold exceedance for hazard monitoring. The principle that dryer slopes require less runoff to fail than wetter slopes was used by normalizing the runoff threshold to the mean monthly precipitation at each rockslide location. This method effectively accounted for the spatial and temporal variation of precipitation, and ultimately provided a threshold that is successful in predicting extreme winter runoff conditions. In terms of summer, the threshold managed to identify extreme conditions, but only captured about half of summer rockslides. Therefore, a more in-depth study of how meteorological conditions trigger rockslides in the summer would be beneficial in future studies. In
addition, if runoff data is made available, a more complete study could be applied to winter conditions, allowing the development of more robust threshold levels.

The trigger threshold exceedance maps were effective at highlighting severe runoff conditions at a regional county scale. In its current form, the trigger map would allow authorities to predict days when a high frequency of slides is likely. In addition, the map has a practical advantage, in that it is easy to use and gives obvious indications of impending danger, thereby alerting authorities to take proper action. On the other hand, the weights-of-evidence mapping discussed in Chapter 5 may appear ambiguous and difficult to judge without proper training. For this reason, a threshold mapping system can be valuable, and further studies regarding its use are recommended.

The downside of threshold exceedance mapping is that it does not account for physical rockslide conditioning factors. Therefore, certain areas that are relatively flat, and thus not prone to rockslides, will nonetheless appear red in the hazard map if runoff conditions are sufficiently high. By omitting these physical factors, there is potential for the map to appear more severe than actual conditions. Consequently, it is a less robust system than the weights-of-evidence approach, and is not favoured from a scientific point of view.
4.8 References


Chapter 5

5.1 Introduction

5.1.1 General
The primary research objective identified in Chapter 4 was to create a dynamic, weather-dependent susceptibility map (see methodology flow chart, Figure 4-1). Susceptibility maps are increasing in popularity among geohazard researchers and government authorities due to advances in Geographic Information System (GIS) technology, and its ability to quantitatively assess the risk of hazards with easily obtained information, particularly geomorphologic data in the form of Digital Elevation Models (DEM). These maps are represented as a grid of cells (raster) and are colour-coded to separate terrain into susceptibility classes (ex. high, moderate, low). The advantage of this type of system is that it allows users to easily identify areas that are in danger of experiencing natural hazards.

A bivariate statistical method called Weights-of-Evidence (WoE) has been chosen for creating the proposed susceptibility maps. This mapping system includes commonly used spatially-dependent terrain variables: slope angle, slope aspect and rock type, but differs from other WoE maps by using a temporally dependent, weather variable, normalized runoff. The addition of a dynamic weather factor to susceptibility mapping is a new step forward, as most other susceptibility studies are forced to exclude
it due to a lack of data. At best, some studies try to include weather by using analogous spatial variables, such as mean annual precipitation, elevation, or distance-to-coast. In this case, the availability of daily weather maps from the Norwegian Meteorological Institute provides a rare opportunity to incorporate a runoff-trigger factor that changes day-to-day to indicate where and when rockslides are likely to occur.

During the course of this work, it became evident that the majority (76%) of rockslides in southwestern Norway are triggered by runoff, so this trigger has been specifically chosen for mapping. Due to a short supply of data, only events that occurred during the five most extreme winter storms between 2000 and 2005 have been used for analysis. It is important to note that all of these events are triggered by runoff, and the produced susceptibility maps are only valid for runoff related failures. If a susceptibility map for frost wedging failures is sought, then a separate analysis must be performed. Also, analysis was limited to the southwestern counties of Sogn og Fjordane and Hordaland, so the produced maps are only valid for these two counties.

5.1.2 Definition of Susceptibility Mapping

Susceptibility maps, often confused with hazard maps, are defined as the division of territory into classes based on their relative proneness to produce landslides (Corominas, et. al., 2003). Hazard maps on the other hand are required, by definition, to establish the probability of occurrence within a specific period of time and within a given area (Varnes, 1984). In a sense, the proposed dynamic mapping system provides a qualitative measure of probability by using a daily weather variable that changes with the weather forecast; however, it makes no attempt to specifically identify the probability of
failure. Therefore, the mapping described herein should be considered a susceptibility map that changes daily, as opposed to a hazard mapping system.

5.1.3 Principles of Susceptibility Mapping

The past and present are the keys to the future (Varnes, 1984). In other words, the characteristics of past and present slides are the best indicators of where and when future rockslides are likely to occur. Therefore, a reliable landslide inventory defining the type and activity of all landslides, as well as their spatial distribution, is essential before any analysis of the occurrence of landslides and their relationship to environmental conditions is undertaken (Soeters and van Westen, 1996). In this respect, the GeoExtreme database described in Section 4.2 is extremely valuable because it differentiates between hazard types (rockslide, debris flow, avalanche, etc.) and the weather conditions that triggered failure.

5.1.4 Methodology

A flow-chart showing the methodology of the WofE susceptibility map is given in Figure 5-1 on the following page. This chart is based on the general methodology given in Chapter 4 (Figure 4-1); however, modifications have been made to customize the map to study area conditions and the data available. A complete discussion of the factors chosen for this approach is provided in Section 5.5.
Figure 5-1: Weights-of-evidence susceptibility mapping flowchart
5.2 Description of the Weights-of-Evidence Approach

5.2.1 General

There are several methods for creating landslide susceptibility maps, each with advantages and disadvantages based on the purpose of the map and the data available. Generally, there are three methods to consider: heuristic, deterministic and statistical. Soeters and van Weston (1996) provide a detailed breakdown of each of the methods.

The heuristic method is described as a qualitative approach that relies heavily on expert opinion and a detailed geomorphic analysis. Without a detailed site visit, this approach is not suitable for the research described here. Conversely, deterministic modeling typically uses GIS to carry out slope stability calculations in order to map factor-of-safety values. The main disadvantage of this approach is that it often oversimplifies problems, and it is most often used for soil slides, not rockslides.

The remaining options are statistical methods, one of which is the WofE approach. Statistical methods take advantage of a large landslide database and provide a quantitative prediction of landslide areas based on characteristics of historic slides. There are different approaches to statistical mapping, including different types of bivariate and multivariate methods. The WofE method described here is a bivariate statistical approach, which uses Bayesian probability. The main advantage of bivariate statistical procedures is that the determination of parameters or parameter combinations used in the assessment is determined by the professional, which enables the introduction of expert opinion into the process (van Westen, 2000). The main disadvantage is that the method assumes conditional independence amongst the chosen parameters (described further in Section 5.2.6).
5.2.2 Geographic Information Systems

A geographic information system, or simply GIS, is a computer system for managing spatial data (Bonham-Carter, 1994). GIS software, such as ArcGIS, provides support for making decisions based on spatial data by allowing users to organize and visualize data in a meaningful way. One of the most powerful advantages of GIS is its ability to query spatial data, which allows users to answer questions that are not readily answered by visualization alone. For instance, it might be useful to know which rockslides in a database occur on slopes steeper than 45°. Further to this, a second query can be performed on the “steep rockslides” to include only those slides which occurred on a day with heavy runoff. In terms of research, multiple querying is an extremely powerful tool, and is only limited by the quality of data and the imagination of the user.

One of the main purposes of GIS is to aid in the prediction of a specified feature. For instance, GIS is often used by urban-planners to determine the best location for certain developments, such as a landfill. Factors such as distance-to-road, zoning, and soil type can be used to create a favourability function, which is then computed by GIS to give optimal areas for development. In the case of geohazard research, the interest is in predicting areas that are susceptible to rockslides. Factors like slope angle, slope aspect, rock type, and normalized runoff have been compared to a historical rockslide inventory to determine a weighting function. The different weight classes are then colour-coded and mapped to help the user visualize where the terrain is susceptible to rockslides. In addition, the proposed mapping system produces a different susceptibility map each day, as determined by the weather forecast. This gives the user a general sense of when the terrain is susceptible to rockslides.
5.2.3 Bayesian *Prior* and *Posterior* Probability

The WofE approach is a Bayesian method, which combines datasets using a probability framework. To determine the “weight” of a particular factor, the user must first understand the concept of *prior* and *posterior* probability. The prior probability is defined as the probability of a rockslide occurrence given no further information (Bonham-Carter et. al., 1989). Using the example shown in Figure 5-2, if a rockslide inventory contains 100 rockslides within an area of 10,000 cells, the prior probability would be: 

\[ P(R) = \frac{100}{10,000} = 0.01 \]

This initial estimate can be improved by considering other forms of information. For example, it is well known that rockslides are more likely to occur on steep slopes; so, a posterior probability can be calculated by multiplying the prior probability by a slope angle factor: 

\[ P(R | A) = P(R) \times \text{slope angle factor} \]

---

**Figure 5-2:** Hypothetical example to demonstrate prior and posterior probability
There are two posterior probabilities that can be expressed: [1] the probability of a rockslide occurring given the *presence* of a steep slope, and [2] the probability of a rockslide occurring given the *absence* of a steep slope. From Bonham-Carter (1994), the posterior probability given the *presence* of a steep slope is expressed as:

\[
P\{ R \mid A \} = \frac{P\{ R \} \cdot P\{ A \mid R \}}{P\{ A \}}
\]

where,
- \( P\{ R\mid A \} \) = the probability (P) of a rockslide (R) if a steep slope (A) is present
- \( P\{ R \} \) = the prior probability of encountering a rockslide
- \( P\{ A\mid R \} \) = the probability of having a steep slope if a rockslide is present
- \( P\{ A \} \) = the prior probability of encountering a steep slope

Using the same example as earlier, if 1,500 of the 10,000 cells are classified as "steep", and if 95 of the 100 rockslides occur on a steep slope, then:

\[
P\{ R \mid A \} = 0.01 \cdot \frac{(95/100)}{(1500/10000)} = 0.063
\]

On the other hand, the probability of a rockslide occurring given the *absence* of a steep slope is given as:

\[
P\{ R \mid \bar{A} \} = \frac{P\{ R \} \cdot P\{ \bar{A} \mid R \}}{P\{ \bar{A} \}} = 0.01 \cdot \frac{(5/100)}{(10000-1500)/10000) = 0.0006
\]

In this example, it can be readily seen that slope angle has a significant effect on the probability of encountering a rockslide. The probability of a rockslide occurring given the *presence* of a steep slope is 0.063, which is higher than if the slope angle was not known, 0.01, and significantly higher than if a steep slope is known to be absent, 0.0006.
5.2.4 Positive and Negative Weights

For WofE mapping, each themed parameter, such as slope angle and rock type, are divided into categories (classes), and each class is assigned a positive weight ($W^+$) and a negative weight ($W^-$) based on conditional probabilities. The positive weight indicates the likelihood of encountering a rockslide when the specific factor is present, and the negative weight is an indication of the likelihood when the specific factor is absent (Quinn, 2009).

It is also important to note that both $W^+$ and $W^-$ can be greater than or less than zero. A weight greater than zero indicates conditions that are more susceptible to slides than average, whereas a value below zero indicates that conditions are less susceptible than average. For example, a steep slope angle will have a $W^+$ above zero because the odds of encountering a slide are greater than average when a steep slope is present. Furthermore, a steep slope will have a $W^-$ below zero because the odds of encountering a slide are less than average when a steep slope is absent. On the other hand, a factor may have the exact opposite relationship. For instance, a strong, massive rockmass may have a $W^+$ below zero because the odds of encountering a slide are less than average when this rock type is present. In some cases, a factor will have weights close to or equal to zero, which indicates that the factor does not have a significant correlation to rockslide occurrence. Consequently, a positive or negative weight that is significantly higher or lower than zero is a good indicator of rockslide susceptibility.

The model for calculating weights is based on odds formulation, similar to that used in horse racing. The key difference is that WofE uses the natural logarithm of
odds, known as log odds, or *logits* (Bonham-Carter, 2004). The positive weight and negative weight are defined as follows:

\[
W^+ = \log_e \frac{P\{F \mid R\}}{P\{F \mid R \}} \\
W^- = \log_e \frac{P\{\bar{F} \mid R\}}{P\{F \mid R \}}
\]

where, \(F\) = presence of a rockslide conditioning factor
\(\bar{F}\) = absence of a rockslide conditioning factor
\(R\) = presence of a rockslide
\(\bar{R}\) = absence of a rockslide

Considering that these calculations are carried out on raster grid, the values for \(F\) and \(\bar{F}\) are simply the number of cells with and without the factor, respectively. Likewise, \(R\) and \(\bar{R}\) are the number of cells with and without a rockslide.

Another value worth calculating is the contrast factor, \(C_W\). This value is defined by Bonham-Carter (1994) as:

\[
C_W = W^+ - W^-
\]

The contrast value is zero when the patterns overlap only by the expected amount due to chance, is positive for positive associations and negative for negative associations. The key to keep in mind is that factors with the highest (positive) or lowest (negative) contrasts are the best factors used for predicting rockslide susceptibility.
5.2.5 Final Weights and Combining Weighted Factors

The positive and negative weights described in the previous section do not represent the final weight used for mapping. In the case of multi-class maps, containing several factors (classes), the presence of one factor (e.g. one specific geomorphological unit) implies the absence of the other factors of the same map (e.g. geomorphological map). Therefore, in order to obtain the final weight of each factor, the positive weight of the factor itself should be added to the negative weight of the other factors in the same map (van Westen, 2002).

Once the final weight for each class has been calculated, adding the thematic maps together will produce the final susceptibility map. In the case of this research, the thematic maps include: slope angle, slope aspect, rock type and normalized 48-hr runoff. The first step to adding the WofE parameters together is to reclassify each thematic map using GIS. Using slope angle as an example, this function converts each raster cell from a slope angle in degrees to its slope angle final weight, as determined from the WofE analysis. The second step is to simply add each of the reclassified thematic maps together to give the overall susceptibility map. Finally, the map is given a colour scheme to help the user visualize spatial patterns.

5.2.6 Conditional Independence

Conditional independence (CI) is assumed to exist when combining two or more maps with the Bayesian method (Bonham-Carter, 1994). If two factors are in fact not independent, then the map will produce erroneous results. For example, a 24-hr antecedent runoff factor cannot be used with a 48-hr runoff factor because the two maps
are not independent (i.e. the 48-hr value is dependent on the 24-hr value). The effect of using both of these factors would be a susceptibility map with values that are excessively high. Therefore, the factor that has the best correlation with rockslides should be chosen for the WofE mapping (in this case the 48-hr value), and the other factor should be excluded entirely. In some cases, two or more dependent factors can be arithmetically combined to create an index factor that has correlation with rockslides; however, this requires careful analysis by a qualified expert.

In terms of rockslide mapping, there will always be some degree of CI violation. For example, slope angle has some correlation with rock type. The question then becomes: Is this violation significant enough to distort the results? The most popular method for evaluating CI is the use of contingency tables and the chi-squared test. This test is run for each pairing of mapped factors, and involves the comparison of the observed vs. the predicted number of rockslides for each combination of classes. For example, if both of the two factors are binary (i.e. two classes: “yes” and “no”), a contingency table would look like the one shown in Table 5-1.

Table 5-1: Example contingency table for conditional independence

<table>
<thead>
<tr>
<th></th>
<th>N(F₁)</th>
<th>N(F₂)</th>
<th>Sum x²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
<td>x²</td>
</tr>
<tr>
<td>a</td>
<td>b</td>
<td>e</td>
<td>f</td>
</tr>
<tr>
<td>N(F₁)</td>
<td>(a-b)² / b</td>
<td>(e-f)² / f</td>
<td>Ex²</td>
</tr>
</tbody>
</table>

120
In the case of Table 5-1, the degrees of freedom equals one. The summed $x^2$ is then compared to a tabled critical $x^2$ value to see if the null hypothesis is true. If a 99% probability level is assumed, the critical $x^2$ value is 6.63, so if the contingency table reveals a $x^2$ value greater than 6.63, the null hypothesis is rejected, and the factors are deemed to be dependent, and therefore unsuitable to be used together in WofE mapping.

In the case of “multi-classed” maps, the contingency table must include a $x^2$ value for every combination of classes given by the two factors. For instance, if a 6-class map is tested with a 4-class map, the number of $x^2$ values will be 24, and the degrees of freedom would be $(6-1)*(4-1)=15$. At 99% probability level, the tabled critical $x^2$ is 30.58, so the contingency table would have to indicate a $x^2$ value less than 30.58 in order for the two multi-classed maps to be considered conditionally independent.

For this research, each combination of parameters (slope angle, slope aspect, rock type and normalized 48-hr runoff) was tested for conditional independence. In the case of slope aspect vs. normalized runoff, a minor violation of independence was found, but it was not great enough to warrant the exclusion of slope aspect as a parameter (discussed further in Section 5.5.2.2). All other combinations were found to be conditionally independent. During the first phase of this work, other weather factors were tested for inclusion in the WofE mapping, particularly daily change in runoff; however, this parameter failed the conditional independence test when compared to runoff; therefore, it was excluded from the mapping system. These results are further discussed in Section 5.4.1.2. All contingency tables used in these analyses are provided in APPENDIX B.
5.3 Data Sources

Statistical susceptibility mapping works on the basic principle that future rockslides can be predicted based on observed conditioning factors of past rockslides. Therefore, there must be a sizable rockslide inventory, as well as knowledge of the conditioning factors that led to failure. The following data sources were available for this analysis.

5.3.1 Rockslide Database

5.3.1.1 General

As described in Section 4.2, a database of 3,595 rockslides recorded in the counties of Hordaland and Sogn og Fjordane, dating between 1963 and 2004 (inclusive) has been extracted from a national database of geohazards. Each slide in the database includes: location in UTM coordinates (of where the slide impacted a road), recorded slide date (year, month, day), and slide date accuracy. Slides with poor date accuracy have been excluded from this analysis. A map of rockslide locations is given in Figure 4-2.

5.3.1.2 Limitations of Data and Sandane Sub-study Area

There are both spatial and temporal discontinuities in the rockslide database, as described in Section 4.2. Firstly, the temporal discontinuity exists because of a change in recording procedures. Only after the year 2000 have the counties of Sogn og Fjordane and Hordaland recorded every rockslide that encroached on a public road, regardless of magnitude or damage caused. Since WofE analysis is only valid for a comprehensive database, only events following the year 2000 are considered in this
analysis. Secondly, a spatial discontinuity exists because only rockslides that impact a road are included in the database. Therefore, the study area is limited to slopes adjacent to the road network. This has been accomplished by creating a 1 km buffer around the road network using GIS spatial analysis tools.

Another spatial discontinuity exists due to the location error associated with each recorded rockslide. Coordinates given in the database indicate a position where a rockslide collided with a road, not the source zone from which it originated. Since the actual distance between these two points is relatively small (usually less than a kilometer), most of the parameters used in the WofE analysis are unaffected. The only exception to this is the slope angle parameter, which is highly affected by location error. To correct for this error, a separate source zone inventory has been created within a 25 km radius around the Village of Sandane in Sogn og Fjordane (shown in Figure 4-8). For each of the 98 rockslides in this area, digital 3D terrain imagery was studied to estimate the true source zone location. An example is shown in Figure 5-3.

![Figure 5-3: Correcting for location error using 3D terrain imagery](images from Sesam 3D)
This tool, called Sesam 3D, is available at http://kart.sesam.no/3d/, and provides 3D fly-through views of the terrain by draping air photos over a Triangulated Irregular Network (TIN). Screenshots of each relocated rockslide are provided in APPENDIX E.

5.3.2 Digital Elevation Model

A digital elevation model (DEM), is a digital representation of topography commonly used in GIS. The Norwegian Geotechnical Institute (NGI) has provided a DEM that covers all of Norway. It is a raster map with cell sizes of 25 m x 25 m, with the value of each cell representing the mean elevation for the given area, as shown in Figure 5-4.

![Digital elevation model of study area](image)

Figure 5-4: Digital elevation model of study area
A DEM is highly valuable in susceptibility mapping because it can be used to generate various topographic parameters, such as slope angle and slope aspect, which are known to influence rockslide activity. The methods of deriving these variables are described in Sections 5.5.2.2 and 5.5.2.3. The Norwegian DEM has a spatial reference defined by the Universal Transverse Mercator (UTM) coordinate system (zone 32 north), with the World Geodetic System (WGS84) as the datum. Due to a lack of metadata, it is not known how this DEM was derived; however, these types of maps are typically derived from digitized topographic maps or remotely sensed elevation data.

5.3.3 Geology Maps

A 1:2,000,000 scale digitized bedrock map of Norway has been provided by the Geological Survey of Norway (NGU). The level of detail on this map is relatively basic, but does give a sense of the rock type and its period of deposition. From this map, the “rock type” of each rockslide has been determined and applied toward WofE analysis. A bedrock map of the study area is provided in Figure 5-5 on the following page. A hardcopy of the Norwegian bedrock map can be found in Ramberg, et. al. (2008).

In addition to the bedrock map, NGU provided a lineament map, which gives the location of all known faults within the study area. A few of the major faults were mapped in the field; however, the majority of lineaments were mapped with remote sensing methods. With this map, a distance-to-fault parameter was assessed for use in the WofE mapping, as discussed in Section 5.4.2.1.
5.3.4 Political Boundaries, Infrastructure, and Land Use Maps

Additional types of GIS data provided by NGI include political boundaries like counties and fylkes (equivalent to Canadian provinces and counties), coastline, land use, and infrastructure such as roads, railroads and transmission lines. The coastline and county borders were used to establish the greater study area of Sogn og Fjordane and Hordaland, and the road map was used to outline the weights-of-evidence study area.
In many susceptibility studies, a land use map can show good correlation with landslide occurrence. For example, a heavily treed area is less likely to fail than one without vegetation. Unfortunately, the land use map of Norway is not sufficiently detailed for a rockslide analysis. Virtually all of the rockslides in the database occur on a land use called “forest”. There is no land use designated for areas of bare rock; therefore, this particular map is not valuable for WofE susceptibility mapping.

5.3.5 Daily Weather Maps

The Norwegian Meteorological Institute (met.no) maintains a database of daily precipitation and weather maps that cover the entire country with 1 km x 1 km spatial resolution. These maps, dating back to 1961, are interpolated from data collected from local weather stations around the country. From these base maps, the Norwegian Water Resources and Energy Directorate (NVE) uses algorithms to generate maps of several different weather/climate themes. The maps of interest for this study are: runoff from local rainfall+snowmelt ($QTT$), cumulative runoff ($Q$), and snow depth ($SD$). The difference between $QTT$ and $Q$ is that $QTT$ represents the rainfall and snowmelt encountered specifically in one area, whereas $Q$ is the cumulative sum of all upstream $QTT$ values. Unfortunately, full access to the weather map database was unavailable; however, members of the NVE were able to provide a limited number of weather maps. Since the majority of slides occur during extreme winter storms, data for the five most extreme storms were requested and provided. The five storms are defined as follows:
[1] February 11\textsuperscript{th} to 20\textsuperscript{th}, 2001 (10 days)
[2] January 10\textsuperscript{th} to 17\textsuperscript{th}, 2002 (8 days)
[3] January 13\textsuperscript{th} to 16\textsuperscript{th}, 2003 (4 days)
[4] March 7\textsuperscript{th} to 12\textsuperscript{th}, 2003 (6 days)
[5] February 3\textsuperscript{rd} to 8\textsuperscript{th}, 2004 (6 days)
5.4 Parameters Eliminated from Analysis

5.4.1 Weather Factors

5.4.1.1 Runoff from Local Rainfall plus Snowmelt (QTT)

Adding the daily rainfall map to the daily snowmelt map generates daily maps of QTT, measured in millimeters. This parameter is believed to be a good analog for runoff conditions in the field, with higher levels of QTT indicating higher levels of rockslide susceptibility. Indeed, the WofE analysis confirmed a correlation between QTT and rockslide occurrence, and subsequently indicated that 48-hr antecedent QTT has the best correlation with rockslides, when compared to 24-hr, 72-hr and 96-hr antecedent values. This conclusion was ascertained by studying a contrast curve generated by storm data from the January 13th to 16th, 2003, as shown in Figure 5-6.

![Figure 5-6: Contrast curve for antecedent QTT (data from Jan. 13th to 16th, 2003)]
In order to generate a contrast curve, weights are calculated for several different binary threshold levels (i.e. the weights above and below the threshold are determined to give a contrast value). For example, weights are calculated for binary threshold levels of 10 mm, 20 mm, 30 mm … 120 mm, and the contrast for each level is calculated using the formula, \( C_W = W^+ - W^- \). As a rule, the more extreme the contrast (either positive or negative), the better the association with rockslides. By studying the contrast curves in Figure 5-6, it is clear that 48-hr QTT has a better overall correlation with rockslides than any other antecedent value. Table 5-2 represents the WofE analysis for the 48-hr QTT parameter, using the combined data of all five extreme winter storms.

<table>
<thead>
<tr>
<th>48-hr QTT (mm)</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10</td>
<td>-1.249</td>
<td>-1.283</td>
</tr>
<tr>
<td>10 – 30</td>
<td>-0.388</td>
<td>-0.421</td>
</tr>
<tr>
<td>30 – 50</td>
<td>0.430</td>
<td>0.396</td>
</tr>
<tr>
<td>50 – 70</td>
<td>0.746</td>
<td>0.712</td>
</tr>
<tr>
<td>70 – 90</td>
<td>0.853</td>
<td>0.819</td>
</tr>
<tr>
<td>&gt; 90</td>
<td>0.889</td>
<td>0.856</td>
</tr>
</tbody>
</table>

Overall, 48-hr QTT is one of the better weather indicators of rockslide occurrence; however, it has been eliminated in favour of a normalized 48-hr QTT value, which has a better correlation with rockslides, and is further discussed in Section 5.5.1.1.
5.4.1.2 Daily Change in Runoff (ΔQ)

Runoff maps are similar to QTT maps, except that they represent the cumulative QTT of all upstream cells in the raster. It was speculated that ΔQ would be a good analog for predicting rockslide occurrence, and was tested using WofE analysis. Results are shown in Table 5-3.

<table>
<thead>
<tr>
<th>ΔQ (mm)</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0</td>
<td>-1.273</td>
<td>-1.300</td>
</tr>
<tr>
<td>0 – 15</td>
<td>0.056</td>
<td>0.030</td>
</tr>
<tr>
<td>15 – 30</td>
<td>0.390</td>
<td>0.364</td>
</tr>
<tr>
<td>&gt; 30</td>
<td>1.127</td>
<td>1.101</td>
</tr>
</tbody>
</table>

Indeed, the WofE analysis showed a strong correlation with ΔQ and rockslides. In fact, the contrast values indicate that ΔQ is a better predictor than QTT (though not as great as normalized QTT). Therefore, ΔQ was a good candidate to include in the WofE mapping in addition to normalized QTT; however, a contingency table and chi-square test comparing ΔQ and QTT revealed that these parameters are not conditionally independent. The x² sum was calculated to be 32, which exceeds the critical x² value of 30.6 for 15 degrees of freedom with 99% probability level. This result is not surprising considering that ΔQ is directly calculated from QTT values. Since the two parameters are not conditionally independent, only one can be chosen for WofE mapping. Consequently, normalized QTT was chosen for its better correlation with rockslides, and ΔQ was eliminated from further analysis.
5.4.1.3 Snow Depth

A snow depth parameter was tested for possible inclusion in the WofE mapping, with the belief that rockslides are more likely on slopes with little to no snow compared to slopes with a deep snowpack. Unfortunately, the factor was not consistent between storm events. For example, data from the January 2003 storm supports the suggestion that rockslides are less likely on slopes with deep snowpack; however, snow depth data from the February 2001 storm showed no correlation with rockslides whatsoever. This can probably be explained by the fact that snow cover on steep slopes is usually thin, laterally variable and intermittent, and during very cold conditions a high proportion of falling snow “flows” downslope, resulting in little to no snow cover (Gruber and Haeberli, 2007). Considering that the majority of rockslides in this region occur on steep slopes (see Section 5.5.2.3), snow cover is not expected to play a significant role in triggering.

5.4.1.4 Freeze/thaw Index

It has been suggested by others that a freeze/thaw index based on antecedent degree-days may be a useful predictor for rockslide triggering. However, this type of parameter is not easily derived from daily temperature maps. In its place, a simple binary map of “frozen” (< 0°C) or “thawed” (> 0°C) was chosen for WofE analysis. The results showed a strong correlation with rockslides (contrast of 1.094); however, this is not a real correlation. In reality, runoff-triggered rockslides will not occur during frozen conditions simply because there is no runoff. In other words, the freeze/thaw index is not conditionally independent with any of the runoff related parameters. Therefore, it is not a suitable parameter to be included in the WofE susceptibility mapping.
5.4.2 Physical Factors

5.4.2.1 Distance-to-Fault

It is not uncommon for rockslide susceptibility mapping to include a distance-to-fault parameter. The reasoning for this decision is that a rockmass close to a fault is more likely to have a higher frequency of discontinuities, and therefore a higher likelihood of rockslides. With this in mind, the lineament map supplied by NGU was used to generate a distance-to-fault map. A WofE analysis was carried out on this parameter, with results shown in Table 5-4.

<table>
<thead>
<tr>
<th>Distance-to-fault (km)</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>0.007</td>
<td>-0.001</td>
</tr>
<tr>
<td>0.5 – 1</td>
<td>-0.170</td>
<td>-0.177</td>
</tr>
<tr>
<td>1 – 2</td>
<td>0.003</td>
<td>-0.004</td>
</tr>
<tr>
<td>2 – 3</td>
<td>0.109</td>
<td>0.102</td>
</tr>
<tr>
<td>&gt; 3</td>
<td>0.381</td>
<td>0.374</td>
</tr>
</tbody>
</table>

The first observation from Table 5-4 is that the final weights and contrast values are very low, meaning that a correlation with rockslides is very weak or non-existent. In the greater scheme, including these weights in the susceptibility maps will have no discernible effect. However, the second observation is the positive weight for a distance-to-fault greater than 3 km, which is counter-intuitive and is likely explained by a matter of coincidence. For this reason, the distance-to-fault parameter was eliminated from susceptibility mapping.
5.4.2.2 Land Use

In many susceptibility studies, a land use map can show good correlations with landslide occurrence. For example, a heavily treed area is less likely to fail than one without vegetation. Unfortunately, the land use map of Norway is not sufficiently detailed for a rockslide analysis. Virtually all of the rockslides in the database occur on a landuse called “forest”. There is no landuse designated for areas of bare rock; therefore, this particular map is not valuable for WofE susceptibility mapping.

5.4.2.3 Curvature

Curvature is defined by Ohlmacher (2007) as the change in slope angle along a very small arc of a curve (i.e. it is the second derivative of the surface, and the first derivative of slope). Two types of curvature need to be considered. First, profile curvature, which is the curvature of the slope in the downslope direction, and second, plan curvature, which is the curvature of a line formed by the intersection of an imaginary horizontal plane with the ground surface. GIS calculates both types of curvature for each individual cell in the DEM, and gives negative values for surfaces that are upwardly convex and positive values for surfaces that are upwardly concave. Diagrams showing the different types of curvature are given in Figure 5-7.

Curvature is often used in susceptibility mapping projects, especially for hazards such as debris flows and earth flows. The reasoning is that a concave terrain will collect more water than convex terrain, and thus leads to higher susceptibility due to increased pore pressures. Generally speaking, most projects find that this factor plays a minor role, with lower weights that only affect susceptibility maps on a local scale. For a
hazard such as rockslides, it is expected to play an even smaller role. For this reason, curvature has not been used in this analysis. However, it is recommended to assess curvature in future studies, so as to enhance the resolution of the susceptibility map.

![Diagram of plan and profile curvature](adapted from Peschier, 1996)

**Figure 5-7: Diagrams of plan and profile curvature**

5.4.2.4 Elevation and Distance-to-coast

Technically speaking, elevation and distance-to-coast are physical terrain factors; however, they are only considered rockslide conditioning factors because they influence precipitation and temperature. If weather data were unavailable, these parameters would act as a reasonable analog for introducing weather related factors to susceptibility mapping. The problem is that these two factors are not conditionally independent with weather parameter, normalized runoff. The result of using elevation or distance-to-coast is the introduction of excessive positive and negative weights, which do not accurately represent true conditions. For this reason, elevation and distance-to-coast have not been used in the WofE susceptibility mapping.
5.5 Parameters Chosen for Analysis

5.5.1 Weather Factors

5.5.1.1 Normalized Antecedent (48-hr) Runoff (48-hr N_QTT)

Normalized runoff represents a normalization of the rainfall+snowmelt (QTT) factor described in Section 5.4.1.1. The purpose of normalizing QTT has been suggested by Sandersen et. al. (1996), who theorized that dryer areas require less runoff to cause failure than do wetter areas. In other words, a slope is more susceptible to rockslides when runoff increases significantly from normal conditions, whether the area is dry or wet, in general. To account for this phenomenon, Sandersen et. al. (1996) normalized QTT by expressing it as a percentage of the mean annual precipitation (MAP) for each location of interest. The authors of the Sandersen study found this method to be useful; however, the work presented here aims to take this concept further by normalizing QTT by the mean *monthly* precipitation (MMP). This not only takes into account the spatial variation of precipitation, but also the seasonal variation.

A 48-hr antecedent map has been chosen for analysis based on the contrast charts shown in Section 5.4.1.1, which indicated that the 48-hr antecedent is a better indicator of rockslides than any of the other antecedent values. In order to create a normalized 48-hr runoff map, the first step is to add the QTT map of “today” with the forecasted QTT map of “tomorrow”, which gives a predictive 48-hr QTT map. The second step is to divide the 48-hr QTT by the mean monthly precipitation map (expressed in percent) to give the 48-hr N_QTT map. The process is repeated each day based on the weather forecast; therefore it is a *dynamic* factor.
Similar to the QTT factor, WofE analysis was carried out on data from the five most extreme winter storms. Results of this analysis are given in Table 5-5.

Table 5-5: Weights-of-evidence for normalized antecedent runoff

<table>
<thead>
<tr>
<th>48-hr N_QTT (%)</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 10</td>
<td>-1.514</td>
<td>-1.574</td>
</tr>
<tr>
<td>10 – 20</td>
<td>-0.751</td>
<td>-0.811</td>
</tr>
<tr>
<td>20 – 30</td>
<td>0.307</td>
<td>0.247</td>
</tr>
<tr>
<td>30 – 45</td>
<td>1.069</td>
<td>1.009</td>
</tr>
<tr>
<td>45 – 60</td>
<td>1.168</td>
<td>1.108</td>
</tr>
<tr>
<td>60 – 75</td>
<td>1.341</td>
<td>1.281</td>
</tr>
<tr>
<td>&gt; 75</td>
<td>1.613</td>
<td>1.553</td>
</tr>
</tbody>
</table>

A full WofE table with all parameters is given in APPENDIX B

The first observation from this analysis is that 48-hr N_QTT has more extreme contrast values than 48-hr QTT alone, by a large margin. On the negative end, contrast values are improved 26%, and on the positive end by 81%. This strongly suggests that Sandersen’s theory is correct, i.e. dryer areas require less runoff to fail than do wetter areas. For this particular dataset, it appears that rockslide favourability becomes positive when 48-hr QTT is in the range of 15-20% of MMP, and becomes significantly favorable when the 48-hr QTT exceeds 30% of MMP.

The second observation is that contrast values are higher than the ΔQ factor. Since these two parameters are not conditionally independent, 48-hr N_QTT has been chosen for susceptibility mapping. In the future, it would be beneficial to explore other
methods of normalization, such as normalizing the QTT map by the mean 31-day precipitation, i.e. fifteen days before and after the date of interest. For example, if the date is January 25th, the mean precipitation period would be from January 10th to February 9th. This would be more accurate than dividing QTT by the MMP of January, and should improve contrast values slightly.

5.5.2 Physical Factors

5.5.2.1 Rock Type

The bedrock map shown in Figure 5-5 has been used to complete a WofE analysis on a “rock type” parameter. Weights are not assigned to each individual rock type, but rather two basic rock type groups: [1] massive rocks and [2] rocks with some degree of foliation or bedding. A complete list of each group, including the surface area and number of rockslides in each rock type, is provided in Table 5-6 on the following page.

Initially, Group 2 was separated into weak foliated rocks (phyllite, mica schist, etc.) and strong foliated rocks (gneiss) for the purposes of WofE analysis. The results indicated that weak rocks are unfavourable for rockslides (negative final weight) and strong rocks are favourable for rockslides (positive final weight). This result may seem counterintuitive considering that rockslides should be more likely in weak rockmasses; however, weak rockmasses subjected to thousands of years of erosion typically do not form very steep cliffs. In fact, of all the Group 2 “steep” cells (>25°) in the study area, only 13% occur in weak rocks, whereas 87% occur in strong rocks. In the few cases
where weak rocks are present in steep slopes, it seems likely that such a case developed because foliation dips into the rockmass, thus making rockslides less likely.

Table 5-6: Rock types in study area used in weights-of-evidence analysis

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Group 1 – Massive rocks</th>
<th>Group 2 – Rocks with foliation or bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (km²)</td>
<td># Slides</td>
</tr>
<tr>
<td>Eclogite</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Quartzite</td>
<td>109</td>
<td>7</td>
</tr>
<tr>
<td>Granite, granodiorite</td>
<td>567</td>
<td>113</td>
</tr>
<tr>
<td>Quartz diorite, tonalite, trondhjemite</td>
<td>226</td>
<td>103</td>
</tr>
<tr>
<td>Rhyolite, rhyodacite, dacite</td>
<td>93</td>
<td>34</td>
</tr>
<tr>
<td>Vulcanic rocks (non-specified)</td>
<td>133</td>
<td>68</td>
</tr>
<tr>
<td>Metabasalt</td>
<td>53</td>
<td>14</td>
</tr>
<tr>
<td>Monzonite, quartz monzonite</td>
<td>376</td>
<td>151</td>
</tr>
<tr>
<td>Mangerite syenite</td>
<td>67</td>
<td>36</td>
</tr>
<tr>
<td>Marble</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Dunite</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Anorthosite</td>
<td>232</td>
<td>56</td>
</tr>
<tr>
<td>Charnocklic to anorthosite</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Diorite, monzonite</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Gabbro, amphibolite</td>
<td>329</td>
<td>146</td>
</tr>
</tbody>
</table>
In terms of WofE mapping, these results indicate a correlation between rock strength and slope angle, which suggests that these parameters are not conditionally independent. To overcome this problem, rock types are separated into groups based on foliation, not rock strength. To further reduce the correlation between rock type and slope angle, WofE analysis has been completed only on slopes steep enough to produce rockslides (>25°). Results are provided in Table 5-7.

Table 5-7: Weights-of-evidence for rock type

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 – Massive</td>
<td>-1.166</td>
<td>-0.803</td>
</tr>
<tr>
<td>Group 2 – Foliation or bedding</td>
<td>0.440</td>
<td>0.803</td>
</tr>
</tbody>
</table>

A full WofE table with all parameters is given in APPENDIX B

5.5.2.2 Slope Aspect

As discussed in Section 4.4.5, slope aspect (i.e. the direction the slope faces: north, south, east, west) is commonly used to assess rockslide susceptibility. The reason for this is because different slope aspects receive different amounts of precipitation, depending on the weather patterns of the area, as well as differing amounts of sunlight, which contributes to freeze/thaw processes and snowmelt.

Using the Aspect function in ArcGIS, slope aspect is determined by calculating the downslope direction of the maximum rate of change from each cell to its neighbours. For example, the maximum rate of change is determined for each cell, just as it is in the Slope function, but instead of giving a slope angle as output, its gives a compass
direction, in degrees (i.e. a value of zero degrees is given for a slope directed perfectly north; a value of 90 degrees is given for slopes directed perfectly east, etc.). The resulting map is shown in Figure 5-8.

Figure 5-8: Slope aspect map of study area
WofE analysis has been carried out on all winter rockslides in the greater study area. Results are provided in Table 5-8.

### Table 5-8: Weights-of-evidence for slope aspect

<table>
<thead>
<tr>
<th>Slope Aspect</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>-0.113</td>
<td>-0.109</td>
</tr>
<tr>
<td>Northeast</td>
<td>-0.523</td>
<td>-0.520</td>
</tr>
<tr>
<td>East</td>
<td>-0.176</td>
<td>-0.173</td>
</tr>
<tr>
<td>Southeast</td>
<td>0.030</td>
<td>0.034</td>
</tr>
<tr>
<td>South</td>
<td>0.010</td>
<td>0.014</td>
</tr>
<tr>
<td>Southwest</td>
<td>0.221</td>
<td>0.224</td>
</tr>
<tr>
<td>West</td>
<td>0.170</td>
<td>0.174</td>
</tr>
<tr>
<td>Northwest</td>
<td>0.149</td>
<td>0.152</td>
</tr>
</tbody>
</table>

A full WofE table with all parameters is given in APPENDIX B

As indicated in Section 4.4.5 and Figure 4-7, northeast facing slopes receive the least amount of precipitation, hence the least amount of rockslides and lowest negative final weight. Slopes facing in the opposite direction, southwest, receive the most precipitation, hence the most rockslides and the highest positive final weight. In comparison to the other parameters used in the WofE mapping, these weights are relatively small, meaning that slope aspect has minimal significance on the final susceptibility maps. In addition, there is some concern that slope aspect is not conditionally independent from the normalized runoff parameter. Conditional independence was tested using a contingency table, and it was found that the null
hypothesis is not rejected at 97.5% probability level, but is rejected at the 95% probability level. Considering the uncertainty of the data, this level of confidence is acceptable, but it does indicate a minor violation of conditional independence. Regardless of this violation, the use of slope aspect as a parameter is still believed to improve the robustness of the final susceptibility maps, as demonstrated by the success rate curves discussed in Section 5.7.

5.5.2.3 Slope Angle

One of the surest rockslide conditioning factors is slope angle (i.e. the steepness of a slope). In GIS, a slope angle raster map is generated by calculating, for each cell, the maximum rate of change in value from that cell to its neighbours (ESRI, 2009). In other words, the maximum change in elevation over the distance between the cell and its eight neighbours identifies the steepest downhill descent from the cell. The output is a value, in degrees, of the downhill slope angle for each cell, as shown in Figure 5-9.

As mentioned in Section 5.3.1.2, rockslides in the original NGI database have coordinates of where each slide impacted a road, not the source zone from which it originated. To correct for this error, a separate source zone inventory encompassing an area within 25 km of the Village of Sandane in Sogn og Fjordane has been created. For each of the 98 rockslides in this area, digital 3D terrain imagery was studied to estimate the true source zone location. The results of this study indicated that only 54 of the 98 rockslides occurred on natural slopes, with the other slides originating from man-made rock cuts. WofE analysis was carried out on the new source zone locations, using the 54 rockslides that occurred on natural slopes. Results are given in Table 5-9.
Figure 5-9: Slope angle map of the greater study area and the Sandane sub-study

Table 5-9: Weights-of-evidence for slope angle

<table>
<thead>
<tr>
<th>Slope Angle (°)</th>
<th>Final Weight</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 25</td>
<td>-4.357</td>
<td>-4.618</td>
</tr>
<tr>
<td>25 – 30</td>
<td>-0.745</td>
<td>-1.005</td>
</tr>
<tr>
<td>30 – 40</td>
<td>1.079</td>
<td>0.819</td>
</tr>
<tr>
<td>40 – 50</td>
<td>1.807</td>
<td>1.546</td>
</tr>
<tr>
<td>50 – 60</td>
<td>2.967</td>
<td>2.706</td>
</tr>
<tr>
<td>60 – 70</td>
<td>3.146</td>
<td>2.885</td>
</tr>
<tr>
<td>70 – 90</td>
<td>3.700</td>
<td>3.439</td>
</tr>
</tbody>
</table>

A full WofE table with all parameters is given in APPENDIX B
It should be noted that there were no recorded rockslides with a slope angle in the 0-25° and 70-90° categories. This poses a problem because the positive weight will have an infinite value (logₑ(0)=∞). To overcome this problem, weights were given to these categories as if there was one rockslide recorded in each. This conservatively estimates the true weight of these two categories. In the case of the 70-90° category, near-vertical cliffs only account for 0.1% of the land area, so the sub-study area may be too small to capture a rockslide on such a cliff. A contributing factor is that a 25 m DEM is too coarse to detect many near-vertical cliffs. This is a flaw that must be accepted with the data available. In order to improve the analysis, a DEM with a finer resolution (ex. 5 m) should be studied.

The results shown in Table 5-9 indicate that slope angle is the most influential contributing factor as compared to any of the other parameters mentioned in this paper. The negative final weight of -4.357 for the 0-25° category is low enough to overcome all other positively weighted factors used in this analysis. For example, if a shallow slope has a southwest aspect (weight = +0.221), a foliated rockmass (weight = +0.440), and a normalized 48-hr QTT greater than 75% (weight = +1.613), the overall weight will still be greatly negative (-2.083). This result is reassuring, as no combination of factors, not matter how extreme, should be great enough to trigger a rockslide on a shallow slope.
5.6 Results - Daily Rockslide Susceptibility Maps

The daily rockslide susceptibility maps for this project are a combination of static terrain parameters (slope angle, slope aspect, rock type) and a dynamic weather parameter (normalized 48-hr runoff) that changes each day with the weather forecast. The first step to create these maps is to combine the static terrain parameters to create a base susceptibility map that remains constant day-to-day. The subsequent step will be to add the daily, normalized 48-hr runoff parameter.

5.6.1 The Base Susceptibility Map – Combining the Static Terrain Parameters

The three terrain parameters chosen for mapping are: rock type, slope aspect and slope angle. In order to combine these factors, the original maps must first be reclassified into WofE maps, as determined from the analyses described in the previous section. Reclassification is a function in ArcGIS that automatically converts every cell based on a given criteria. For example, when reclassifying the slope angle map, ArcGIS will reclassify every cell that has a slope angle between 0° and 25° to -4.357, and so on for each slope angle class. Figure 5-10 on the following page shows the individual reclassified maps of rock type, slope aspect and slope angle.

Once the individual maps have been reclassified, the base susceptibility map is generated by simply adding the reclassified rock type, slope aspect and slope angle maps together. The base susceptibility map is shown in Figure 5-11.
Figure 5-10: Reclassified weights-of-evidence maps (rock type, slope aspect, slope angle)
Figure 5-11: Base susceptibility map (combination of all three terrain parameters)
5.6.2 Addition of Dynamic, Normalized 48-hr Runoff

Daily susceptibility maps have been prepared by combining the base susceptibility map (Figure 5-11) with the daily, reclassified, normalized 48-hr runoff map. As an example, the map for January 14th, 2003 is shown in Figure 5-12. This particular map represents the most extreme day, with 35 rockslides, in the study period (2000-2005). To demonstrate how the susceptibility map changes day-to-day, a time-series of maps for the January 2003 storm are given in Figure 5-13 on the following two pages.

Figure 5-12: Final susceptibility map for January 14th, 2003
Figure 5-13a: Final daily susceptibility maps – January 2003 storm
continued on next page
Figure 5-13b: Final daily susceptibility maps – January 2003 storm
continued from previous page

- Weight:
  - Very low: -8 to -0.75
  - Low: -0.75 to 0
  - Moderate: 0 to 1.5
  - High: 1.5 to 2.5
  - Very high: 2.5 to 6

- Rockslide locations

Jan. 14th, Jan. 15th, Jan. 16th
5.6.3 Final Rockslide Susceptibility Classes

The final rockslide susceptibility classes shown in Figure 5-12 and Figure 5-13 are based on the success rate curves (Figure 5-14) described in the Section 5.7. The slope angle curve shows that all rockslides are captured by 28% of the highest weighted cells in the reclassified slope angle map. This corresponds to a weight of -0.75, so all cells in the final susceptibility map with a weight lower value than -0.75 are classified as VERY LOW susceptible areas. Similarly, the LOW category captures all of the slides using the base susceptibility map (three terrain parameters combined), corresponding to a weight of zero. The remaining categories are based on the speculative overall success rate, with the MODERATE category capturing 100% of slides, HIGH capturing 80%, and VERY HIGH capturing 50%. To summarize, the final rockslide susceptibility classes are as follows:
5.7 Model Verification

5.7.1 Success Rate Curves and Effect Analysis

The capability of a WofE map to predict rockslides can be verified with the help of success rate curves and effect analysis (Dahal et. al., 2008). The success rate curve indicates the percentage of the total rockslides that occur in HIGH susceptibility areas, and effect analysis helps to validate and to check the predictive power of selected factors in WofE analysis.

The success rate curves produced for this project are shown in Figure 5-14 on the following page. Curves were prepared for each of the individual susceptibility parameters: rock type, slope aspect, slope angle and normalized 48-hr runoff, in order to visualize the effectiveness of each parameter to predict rockslides on its own. In the case of normalized runoff, the success curve actually changes day-to-day, so for visualization purposes the success curve for this parameter has been averaged over the five winter storms in the database (verification on a day-to-day basis is provided in the Section 5.7.2). Curves were also prepared for the base susceptibility map, which includes the combination of all three static terrain parameters, and the final susceptibility maps, which include the normalized 48-hr runoff combined with the base map.

It should be noted that the success curve for slope angle was prepared using the Sandane sub-study database, and the other individual parameters were prepared from the greater database. The base and final susceptibility map curves were also prepared using the Sandane data since these maps include the slope angle parameter. Unfortunately, only eleven rockslides occurred in the Sandane area during the five winter storms; therefore, the success curve for the final susceptibility map has a low resolution.
and remains somewhat in question. As an alternative, a speculative success rate for the final map has been included in Figure 5-14 to demonstrate its potential effectiveness.

Figure 5-14: Success rate curves for model verification

The success curves shown in Figure 5-14 are prepared by first collecting a dataset of the “weight” values in the reclassified raster map of interest, and then sorting the dataset in descending order. The dataset is categorized into 100 classes of 1% cumulative intervals and then cross-referenced with the “weight” of each rockslide location to determine the percentage of observed rockslides captured by each 1% interval. Prediction rates were determined from effect analysis, which is performed by calculating
the area under each success curve. A total area equal to 1 indicates perfect prediction accuracy and an area equal to 0.5 indicates random prediction accuracy. The prediction rate of each curve is shown in Table 5-10.

Table 5-10: Prediction rates of susceptibility maps

<table>
<thead>
<tr>
<th>Success Curve</th>
<th>Area under curve</th>
<th>Prediction rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type</td>
<td>5542</td>
<td>55.4</td>
</tr>
<tr>
<td>Slope aspect</td>
<td>5542</td>
<td>55.4</td>
</tr>
<tr>
<td>Slope angle</td>
<td>9163</td>
<td>91.6</td>
</tr>
<tr>
<td>Base map (3 terrain factors combined)</td>
<td>9412</td>
<td>94.1</td>
</tr>
<tr>
<td>Normalized 48-hr runoff</td>
<td>7496</td>
<td>75.0</td>
</tr>
<tr>
<td>Speculative final map (all 4 factors)</td>
<td>9601</td>
<td>96.0</td>
</tr>
</tbody>
</table>

Using the slope angle curve in Figure 5-14 and Table 5-10 as an example, 10% of the highest weighted cells in the reclassified slope angle map capture 65% of all observed rockslides, and 27% of the highest weighted cells capture 100% of all observed slides. This corresponds to a “prediction rate” of 91.6%. For a single parameter, this prediction rate is considered very high, and suggests that slope angle could be used on its own as a susceptibility map. In comparison, the slope aspect and rock type maps have minimal success, and would not be suitable on their own. However, by combining all three terrain parameters, the prediction rate of the base susceptibility map increases to 94.1%. Adding the normalized 48-hr runoff to the base map increases the predictive power even more to 96.0%, where 2% of the highest weighted cells capture 50% of all observed slides, and 16% of the highest weighted cells capture 100% of all observed slides.
5.7.2 Day-to-day Verification

Success rate curves in Figure 5-14 that include normalized 48-hr runoff have been averaged over the five extreme winter storms in the database. Ideally, the best verification would be a success curve for each individual day; however, a proper success curve requires a substantial rockslide database, and there are simply too few rockslides on any particular day to produce a meaningful success curve. Alternatively, a daily verification curve showing number of rockslides vs. high-weighted cells has been assessed for verification purposes, as shown in Figure 5-15 and Figure 5-16. In these figures, the vertical bars represent the daily rockslide count and the dashed line represents the percentage of the final susceptibility map under ‘caution’, which is defined as having a susceptibility rating of MODERATE or higher. It is important to note that the baseline for the caution curve is about 15%, which represents zero runoff conditions.

![Daily verification curve for January, 2003 storm](image)

Figure 5-15: Daily verification curve for January, 2003 storm
Figure 5-16: Daily verification curves for other extreme winter storms
From these graphs, it is clear that only 3 of the 5 storm caution curves start at 15%, meaning the other two, February 2001 and February 2004, do not capture the initial ‘lead-up’ of the storm. It is expected that these events are only a day (maybe two days) late in recognizing the increase in runoff.

Initially, it was expected to find a direct linear correlation between rockslides and high susceptibility days; however, all five curves indicate that the peak day in rockslides occurs a day or two after the peak day in runoff. Since this result is consistent and provides warning early, it is sufficient to verify the method, but it is important to take note of, when developing the protocol of a warning system.

In order to visualize a trend between daily rockslide count and percentage of final map under a VERY HIGH susceptibility rating, an x-y scatter plot of the two factors was produced, as shown in Figure 5-17.
As expected, there is general linear trend, with rockslide count increasing with increasing susceptibility. However, there a few instances of high susceptibility days having only a few rockslides. Examination of the data shows that most of these cases are due to the one day lag effect evidenced in Figure 5-15 and Figure 5-16. That is, susceptibility levels have risen, but most rockslides will occur the following day. In addition, there appears to be an upper limit to the number of rockslides that can be expected given the level of susceptibility, as shown by the dashed line in Figure 5-17. This type of relationship may be helpful in giving a range of expected rockslides. For instance, if 5% of the map has a VERY HIGH rating, then 2 to 12 rockslides are likely to occur, however a maximum of 18 rockslides is possible.
5.8 Conclusions

5.8.1 Discussion

A dynamic susceptibility mapping system for rockslides has been proposed for the counties of Sogn og Fjordane and Hordaland in southwestern Norway. This mapping system uses a Bayesian, weights-of-evidence approach to statistically assess the likelihood of failure based on a historical rockslide inventory. The system is dynamic in nature because it incorporates a weather parameter that changes day-to-day (normalized 48-hr runoff). Consequently, a new susceptibility map is produced every day based on the weather forecast, which allows authorities to judge if rockslides are likely on any particular day.

Terrain parameters used in the modeling include: slope angle, slope aspect and rock type. As expected, slope angle was found to have the highest correlation with rockslides, and is the primary conditioning factor for rockslide failure in the study area. On the other hand, it was found that slope aspect and rock type are not significant predictors on their own; however, they managed to improve overall success of the base susceptibility map, as shown in the success rate curves in Figure 5-14.

Several weather parameters were analyzed for possible inclusion in the susceptibility mapping system, including antecedent runoff, QTT, daily change in cumulative runoff, ΔQ, and normalized antecedent runoff, N_QTT. The basis for normalization is the theory that a dry slope requires less runoff to fail than a wetter slope. Indeed, the weights-of-evidence analysis confirmed that normalized runoff has a significantly stronger correlation with rockslides than un-normalized runoff. In this case, normalization was accomplished by expressing runoff as a percentage of the mean
monthly precipitation, which successfully takes into account the spatial and seasonal changes in precipitation throughout the study area. Additionally, it was found that ΔQ had a strong correlation with rockslide occurrence; however, contingency tables showed that this parameter is not conditionally independent with normalized 48-hr runoff. Since weights-of-evidence requires conditional independence among parameters, ΔQ was excluded from mapping in favour of normalized 48-hr runoff.

Success rate curves confirmed that on average, normalized 48-hr runoff is 75% successful in predicting rockslides. In addition, the prediction rate increases to 96% when this factor is added to the base susceptibility map of static terrain factors. Overall, this is considered a very high success rate. In addition, the model was verified on a daily basis by assessing the daily verification curves shown in Figure 5-15 and Figure 5-16. These curves showed that the model is generally a day early in predicting the response to rockslide occurrence. This result was not intended; however, it is beneficial to authorities when it comes to preparing for these events.
5.8.2 Recommendations

5.8.2.1 Protocols for a Hazard Warning System

If this type of mapping is implemented as a hazard warning system, there are a few key points that should be considered. For all susceptibility maps, the most important decision is to establish meaningful susceptibility classes. As discussed in Section 5.6.3, the classes chosen for this project are:

![Susceptibility Classes Diagram]

The chosen susceptibility classes and colour-scheme have great influence in day-to-day decision making. If the map is excessively red, the user may interpret more severe conditions than is the case in reality. The opposite may also be true if the map is excessively green when rockslides are actually likely. For this project, susceptibility classes have been chosen based on the prediction rates discussed in Section 5.7, and should only be changed if the success rate curves in Figure 5-14 are carefully considered.

It is recommended to create a daily forecast map of “tomorrow” by using a 48-hr runoff map consisting of “today’s” runoff added to the forecast of “tomorrow’s” runoff. This will indicate the likelihood of slides during the next 24-hrs, so that appropriate
preparation measures can be carried out. The decision of when to start taking appropriate measures is up to authorities; however, the data shows that caution should be heeded when more than 20% of the map is either MODERATE or higher, and extreme caution should be heeded when this value exceeds 25%. Additionally, if the map is 10% or more in VERY HIGH, extreme caution would be prudent.

The daily verification curves discussed in Section 5.7.2 showed that rockslide response is typically a day later than the initial jump in susceptibility. This is considered a benefit because it gives authorities additional time to prepare for an extreme day of events; however, it should not be used as an excuse to ignore conditions for an extra day. The same verification curves showed that a downturn in susceptibility is followed closely by a downturn in rockslide occurrence, so a forecasted “extreme” day should be followed by at least two days of a warning. If “extreme” days are consecutive, the warning should stay in place for a full 24-hrs after conditions have returned to stable levels.

5.8.2.2 Future Work

The accuracy and robustness of the WofE modeling can be improved by additional data. In terms of future studies, the issue of utmost importance is the lack of data used to assess the 48-hr runoff parameter. Only the five most extreme winter storms were used (a total of 34 days). It is believed that this will effectively predict extreme conditions; however, further analysis of the 48-hr parameter is recommended. In the future, it would be beneficial to build the database on a daily basis, so as to automatically reassess the 48-hr parameter each day. This will improve accuracy continually until a general
equilibrium is found. In addition, it would be beneficial to consider other weather-related parameters to include in the model, as long as they are conditionally independent from the 48-hr runoff parameter.

For the base susceptibility map, the slope angle parameter was assessed using only 54 rockslides within the Sandane sub-study area, and the correlation was assumed to exist across the entire study area. This was necessary to correct for location error; however, it is not ideal for a robust mapping system. Fortunately, slope angle showed a strong correlation with rockslide occurrence, so the results found here are not expected to be far from true. Nevertheless, to improve the model one or two more sub-study areas spread across the two counties would be beneficial to check that slope angle is consistent across the greater study area. In addition, the base susceptibility map can be enhanced by considering additional terrain factors such as slope curvature, both in profile and in section.
5.9 References


Natural Hazards, 3. UNESCO, Paris, France.
Chapter 6
Theoretical Simulations of a Thaw-Induced Rockslope Failure Using the Finite-Element Modeling Software, Phase$^2$

6.1 Introduction

The analysis in Chapter 4 revealed that a high frequency of rockslides occur during thawing periods (i.e. within four days of maximum and minimum daily temperatures rising above 0°C). Matsuoka and Sakai (1999) reported similar results in the Japanese Alps. The most probable explanation of this trend is that thawing of ice-filled fractures leads to a rapid loss of shear strength (Braathen et. al., 2004).

The purpose of this chapter is to help visualize the effect of progressive thawing in a generic frozen slope. The tool chosen for this work is the finite-element modeling software, Phase$^2$, which has been used to determine the slope’s factor of safety under several hypothetical slope conditions, including diurnal and permafrost thawing. In addition, hypothetical thermal isotherms have been used as boundary conditions to account for the thermal gradient within a rock mass. In order to simulate thawing, the models have been separated into a time-series of events, which are intended to replicate the movement of thermal isotherms in the rock mass.
6.2 Assumptions

It is important to note that the Phase² model assumes a fully formed shear surface with strength properties that only vary with temperature. In reality, the nature of shear surfaces is highly variable and continually changing. For example, the spacing of a joint can change due to the expansion of ice and other mechanical forces such as root action. In addition, the Mohr-Coulomb strength parameters of a joint can change over time due to chemical weathering. These additional factors are assumed to not effect the generic Phase² model, and therefore the slope should be considered to only exist at one specific moment in time.

For this model, strength properties of ice-filled joints at temperatures of -5°C, -2°C, and -0.5°C have been used as suggested by Davies et. al. (2000). These results apply to a specific joint, with a unique asperity pattern, which is filled with "clean" ice. In nature, asperities are highly variable, and ice is likely to contain debris such as sand, clay, or organic particles. Therefore, this model only represents an idealized case.
6.3 Background Study: The Effect of Thawing on Ice-filled Discontinuities

In high mountain regions, the presence of ice in discontinuities can contribute to maintaining the stability of rock slopes (Davies et al., 2000). This assertion is supported by the fact that most rockslides occur when temperatures are above 0°C. However, Davies et al., (2000) and Günzel (2008) both determined that this hypothesis is not always correct. In fact, under certain circumstances, an ice-filled joint can have a lower shear strength than when it is thawed. Of particular importance is the notion that as ice temperature rises close to -0.5°C, the shear strength of an ice-filled joint drops below the strength of the same thawed joint. Therefore, a slope which is otherwise safe during a thawed state, may encounter a window of thawing when it is in danger of failing. A discussion of each these studies is presented below.

6.3.1 Description of Direct Shear Testing

6.3.1.1 Constant Strain Tests

Both Davies et. al., (2000) and Günzel (2008) carried out constant-strain, direct shear tests on an ice/rock boundary at various temperatures. The samples consisted of an ice block placed on top of a concrete block (the concrete was designed to have similar properties to granite). Normal stresses were applied by hanging weights vertically from the sample, and shear stresses were applied by exerting a force on half of the sample while keeping the other half stationary. Horizontal and vertical displacements were measured using linear variable displacement transducers (LVDTs), and stresses were measured using load cells. Davies tested ice temperatures of -5°C, -2°C and -0.5°C,
while Günzel tested temperatures of -4°C and -2°C. In addition, both researchers tested a thawed rock/rock boundary for purposes of comparison.

6.3.1.2 Constant Stress Tests

In reality, failures of rock slopes are not controlled by constant strain, but rather by constant stress (Günzel, 2008). To account for this, Günzel also carried out constant-stress, direct shear tests on the ice/rock samples. For these tests, a constant normal force and a constant shear force were applied to the sample, and the ice block was warmed from -5°C, at a rate of 0.3°C per hour, until failure occurred. Each sample was equipped with a temperature sensor located near the center of the ice/concrete boundary, and the temperature at failure was then recorded for evaluation.

6.3.1.3 Joint Roughness Profile

Both researchers carried out their tests on a sample consisting of two blocks that were interlocked on a horizontal saw-toothed surface. A regular pattern was used to allow for consistent, repeatable test results. It is important to note that the two researchers used different roughness surfaces (refer to Figure 6-1 on the following page). The Günzel sample shown in Figure 6-1 has are no flat surfaces, and the height of asperities is almost two times greater than the Davies sample. As a result, the Günzel sample has an overall rougher surface, and one would expect this sample to have greater shear strength than the Davies sample, everything else being equal.
6.3.2 Results of Direct Shear Testing

6.3.2.1 Günzel’s Constant Strain Tests

A peak shear stress vs. normal stress curve for the Günzel tests is shown in Figure 6-2.

Figure 6-2: Peak shear test results for concrete-ice samples from Günzel (2008)
The results indicate that at low normal stress, the joint exhibits a linear Mohr-Coulomb strength criterion. Approximations of cohesion and friction angle are given in Table 6-1. However, at higher normal stress, approximately greater than 300 kPA, the strength exhibits a parabolic relationship, with shear stress decreasing with increasing normal stress. Günzel (2008) states that these results are due to two separate failure mechanisms: [1] frictional sliding upon separation of the ice/concrete surface, and [2] shear deformation of the ice itself.

Depending on the angle of the joint surface, a normal stress of 300 kPa would equate to a depth of 12 m of greater, which is deeper than a typical seasonal frost depth of 5 ± 2 m reported by Matsuoka and Sakai (1999). Therefore, in most real-world slopes, only the linear portion of Günzel’s shear strength curve will apply to ice-filled discontinuities. The only exception would be deep-seated failures in a permafrost slope.

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Cohesion (kPa)</th>
<th>Angle of Friction (φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>510</td>
<td>37</td>
</tr>
<tr>
<td>-2</td>
<td>360</td>
<td>33</td>
</tr>
<tr>
<td>Thawed</td>
<td>0</td>
<td>62</td>
</tr>
</tbody>
</table>

6.3.2.2 Davies’ Constant Strain Tests

Davies’ direct shear tests indicated a linear relationship between peak shear stress and normal stress. Even at higher normal stress, the peak shear stress did not drop as it did in Günzel’s testing. This suggests that the failure mechanism for the Davies test was
limited to frictional sliding upon separation of the ice/rock surface. It would seem that the second failure mechanism, shear deformation of the ice itself, is dependent on the degree of roughness on the joint surface, and is unlikely to occur on a smooth surface.

The Mohr-Coulomb strength parameters for the Davies tests are provided in Table 6-2. These values are taken from Davies et. al. (2001), which is an updated version of the Davies et. al. (2000) research.

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Cohesion (kPa)</th>
<th>Angle of Friction (φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>700</td>
<td>25</td>
</tr>
<tr>
<td>-2</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>-0.5</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Thawed</td>
<td>0</td>
<td>43</td>
</tr>
</tbody>
</table>

6.3.2.3 Günzel's Constant Stress Tests

Several combinations of normal stress and shear stress were used for the constant stress tests. The temperature at failure for each test was recorded, and then plotted as a contour map vs. the applied shear and normal stresses, as shown in Figure 6-3 on the following page.
Figure 6-3: Temperatures at failure from Günzel (2008) constant stress tests.
The dotted line represents the linear relationship between shear stress and normal stress obtained for the concrete samples.

The results show that at low normal stress and low temperatures, an ice filled joint has a higher shear strength than when it is thawed. However, at sufficiently high normal stress, an ice-filled joint can become weaker than a thawed joint as it warms close to 0°C. For example, with a normal stress of 200 kPa (approximately 8 m deep), a joint with an ice temperature warmer than -1.5°C has a lower shear strength than if it were thawed.
6.3.3 Discussion of Results

6.3.3.1 Joint Roughness

When comparing the two studies, it is apparent that joint roughness has a significant effect on shear strength. Both studies tested an ice/rock sample at -2°C, as well as a thawed rock/rock sample. In both cases, Günzel’s rougher surface exhibited greater shear strength. These discrepancies are illustrated in Figure 6-4.

![Figure 6-4: Mohr-Coulomb strength envelopes for frozen (-2°C) and thawed samples from Davies et al. (2000) and Günzel (2008)](image)

6.3.3.2 Normal Stress

Using a constant strain test, Günzel (2008) showed that at normal stresses greater than 300 kPa, the peak shear vs. normal stress curve becomes parabolic, with the peak shear stress decreasing with increasing normal stress. However, the opposite was true...
during Günzel’s constant stress tests, where the shear strength of a specific temperature increased with increasing normal stress. Since real-world conditions are under constant stress rather than constant strain, the latter result is likely more realistic. Regardless, both of Günzel’s test types indicated that at higher normal stress, the shear strength would be less for an ice-filled joint than for a thawed joint. Davies et. al. (2000) provided similar results, showing that the angle of friction for an ice-filled joint, regardless of the temperature, is lower than a thawed joint. Therefore, at sufficiently high normal stresses, the peak shear strength of an ice-filled joint will be less than a thawed joint.

If the depth of seasonal frost is considered (5 ± 2 m), then normal stresses will be sufficiently low for a joint to have higher shear strength when it is frozen. The exception to this is when temperatures approach 0°C. Davies et. al. (2000) suggests that this value is close to -0.5°C, where cohesive strength is very close to zero. It is at this point where the shear strength is less than for a thawed state. The results from Günzel’s constant stress tests provide further evidence to this effect.

6.3.3.3 Summary of Results

The results from the direct shear tests indicate that for most slopes, a joint filled with ice will have a greater shear strength than if it were thawed. However, there are specific instances when the opposite is true, and these may play an important role in the detachment of rock during a thaw. The two studies have shown that as ice warms, the shear strength decreases steadily, and can even drop below the shear strength of the thawed joint.
From the analyses discussed in Chapter 4, it appears that most failures occur within four days of the air temperature rising above 0°C. Since rock temperatures lag behind the air temperature (Gruber and Haeberli, 2007), it seems plausible that a high frequency of slides may be initiated when an ice-filled joint approaches -0.5°C, rather than when it is fully thawed. In addition, a thawing environment often includes rain infiltration and/or meltwater, which decreases a joint’s shear strength and contributes to ultimate failure.
6.4 Description of Model

The model used for this analysis has been based on a study by Davies et. al. (2001). In that study, the authors compared results from a scaled centrifuge model to analytical factor of safety calculations. A similar approach has been employed in the work presented here. The same geometry and strength parameters from the Davies study have been used to obtain analytical results, which are then used to validate the model created in Phase\(^2\).

Thermal gradients have been applied to the model in order to study the effect of shear strength varying with ice temperature. This approach has been applied to a single joint, as well as a jointed rockmass (joint network). In addition, the effects of water pressure have been studied in combination with thawing discontinuities.

6.4.1 Phase\(^2\) and the Shear Strength Reduction (SSR) Method

Phase\(^2\) is a 2-dimensional elasto-plastic finite-element program for calculating stresses and displacements around underground openings, and can be used to solve a wide range of mining, geotechnical and civil engineering problems, including finite-element slope stability (RocScience, 2009). This program has the unique ability to apply different strength parameters along intervals of a single joint. In this case, intervals have been defined by the temperature isotherms referred to in Section 6.4.5.

In addition, the Shear Strength Reduction (SSR) option in Phase\(^2\) has been utilized in each model in order to assess how slope stability changes with varying ice temperature. The SSR method functions by reducing strength parameters by a Strength Reduction Factor (SRF) and computing the finite-element stress analysis (RocScience,
Several SRF values are computed until the analysis results no longer converge, indicating instability of the slope modeled. The SRF value at which the results no longer converge is called the critical SRF, or in other words, the slope's “factor of safety”.

### 6.4.2 Geometry

#### 6.4.2.1 Single Joint Model

The single joint model is a simplified slope, with a slope angle and slope height of 70° and 37.86 m, respectively. The inclination of the joint is 40°. A schematic drawing of the model is provided in Figure 6-5.

![Figure 6-5: Geometry of single joint Phase2 model](image)
6.4.2.2 Joint Network Model

The joint network model has the same slope geometry as the single joint model, but has two joint networks instead of a single joint. The geometries of the two joint networks are outlined in Table 6-3. It should be noted that the joint networks do not extend into the base of the rock mass. This decision was made to reduce computing time.

<table>
<thead>
<tr>
<th>Joint Network</th>
<th>Inclination</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40°</td>
<td>0.5 m</td>
</tr>
<tr>
<td>2</td>
<td>82°</td>
<td>2.0 m</td>
</tr>
</tbody>
</table>

6.4.3 Field Stress and Finite-element Mesh

In Phase 2, the field stress was set to “gravity”, using the actual ground surface. The finite-element mesh was created using a uniform distribution of 500, 3-noded triangles, as seen in Figure 6-5. In general, this would be considered a coarse mesh, but it proved to give reliable results. More dense meshes were attempted, but this increased computing time without significantly changing the results.
6.4.4 Strength Parameters

6.4.4.1 Rock Mass

Strength parameters were chosen to model gneiss, the predominant rock type in western Norway. Using RocLab software as a guide, the Hoek-Brown classification parameters for generic gneiss are as follows:

- Intact compressive strength, $\sigma_{ci} = 175 \text{ MPa}$
- Geological Strength Index, GSI = 40
- Intact material constant, $m_i = 28$
- Disturbance Factor, D = 1
- Intact elastic modulus, $E_i = 91,875 \text{ MPa}$

Based on this information, RocLab provides Mohr-Coulomb strength parameters for the rockmass. Using “slopes” as the “failure envelope range”, and a slope height of 43.8 m, RocLab gives the following Mohr-Coulomb parameters:

- Cohesion, $c = 0.394 \text{ MPa}$
- Friction angle, $\Phi = 49.02^\circ$
- Tensile strength, $\sigma_t = 0.0206 \text{ MPa}$
- Rockmass elastic modulus, $E_{rm} = 3,668 \text{ MPa}$
The Mohr-Coulomb parameters listed above were used as the strength parameters for the rockmass in Phase$^2$. A perfectly plastic model, with no dilation, was chosen for analysis. A copy of Phase$^2$’s “Define Material Properties” dialog box, complete with the parameters chosen for this study, is provided in Figure 6-6.

![Figure 6-6: Rockmass material properties used in Phase$^2$](image_url)
6.4.4.2 Joint Properties

The joints used in the Phase$$^2$$ model were assigned the Mohr-Coulomb slip criterion, and Phase$$^2$$'s Shear Strength Reduction (SSR) option was turned ON to assess the critical strength reduction factor (SRF, which is equivalent to a factor of safety). The Mohr-Coulomb strength parameters given by Davies (2001) have been chosen for analysis in the Phase$$^2$$ model. These parameters were chosen over the Günzel (2008) parameters because a test temperature close to zero degrees Celsius (-0.5°C) was available. In addition, the results of Davies’ study correspond to a smoother joint surface, and therefore a higher risk slope. The Davies strength parameters used in the Phase$$^2$$ model are given in Table 6-2.

Joint stiffness, both normal and shear, was set to 0.001 MPa/m. The reasoning for choosing stiffness close to zero was to reproduce a critical SRF close to an analytical factor of safety (FoS) solution (discussed further in Section 6.5). In general terms, it was found that joints with a high stiffness did not fail as expected in the Phase$$^2$$ model. Therefore, both stiffness parameters were set close to zero in order to provide no additional resistance to sliding. In this way, only the Mohr-Coulomb slip criterion needed to be exceeded for failure to occur. The stiffness could not be set directly to zero, because it would cause Phase$$^2$$ to fail during computation; however, stiffness values of 0.001 MPa/m were sufficiently low to produce accurate results that correspond to an analytical solution.
6.4.5 Thermal Regime

The premise of the Phase\textsuperscript{2} model is to assess ice-filled joints that have temperature-dependent shear strength properties. Therefore, a thermal regime, in the form of temperature isotherms, must be applied to the Phase\textsuperscript{2} model.

6.4.5.1 Permafrost Model

There have been a few studies related to thermal regimes in alpine environments (Anderson, 1998; Gruber and Haeberli, 2007; Noetzli et. al., 2007; Matsuoka and Sakai, 1999). Unfortunately, none of these studies give a clear indication of what a typical thermal gradient in a permafrost slope should be. Most of the studies only consider a shallow depth (i.e. less than 50 cm), which is insufficient for a large-scale slope. Also, the studies did not address how a thermal regime would change during an extended thaw. Therefore, a hypothetical thermal regime has been applied to the Phase\textsuperscript{2} model.

Three separate models with different thermal regimes were created in order to assess the effect of thawing. The models differed by progressively moving the colder temperature isotherms deeper into the rockmass. An example of one of the thermal regimes is given in Figure 6-7 on the following page. The temperature isotherms used in this model are \(-5^\circ\text{C}, -2^\circ\text{C}, -0.5^\circ\text{C}\).
6.4.5.2 Non-permafrost model

Discontinuous permafrost exists at the peaks of Norway’s central mountains; however, these zones do not extend into the road network of the study area. Therefore, a non-permafrost model is required to represent more realistic conditions in southwestern Norway. Matsuoka et. al. (1997) suggests that diurnal freezing rarely penetrates deeper than 50 cm and that only the seasonal cycle can reach 1 m or deeper.

For the Phase² non-permafrost model, two thermal regimes have been selected for analysis. These two regimes, provided by Matsuoka et. al. (1997), represent subsurface isotherms during the months of December and February (1994/1995), at the Padella site in Eastern Switzerland. There is no permafrost in this region; however, it is at a higher elevation (2690 m) than much of the Norwegian study area. Consequently, this region experiences colder temperatures and deeper frost depths than Norway.
Nonetheless, the model should demonstrate the effects of shallow frost on slope stability. The depths of the isotherms for the non-permafrost models are provided in Table 6-4.

The December and February models represent maximum freezing and thawing conditions, respectively. The February thawing model only included temperatures slightly below $-1.0^\circ\text{C}$, so this isotherm was added to the model and strength parameters were interpolated from Davies et. al. (2000) direct shear tests. The cohesion of a $-1.0^\circ\text{C}$ joint is 67 kPa and the friction angle is 11.7°.

<table>
<thead>
<tr>
<th>Isotherm (°C)</th>
<th>Depth (m)</th>
<th>December</th>
<th>February</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>0.15</td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>-2</td>
<td>0.52</td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>-1.0</td>
<td>n/a</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.89</td>
<td>0.89</td>
<td></td>
</tr>
</tbody>
</table>
6.5 Validation of Model

Before applying different strength parameters along the joints, the model was first validated by comparing critical SRF values obtained from Phase² with those from an analytical solution. Using the geometry given in Figure 6-5, four different Phase² models, each assuming the rockmass to be at a uniform temperature (-5°C, -2°C, -0.5°C and >0°C), were assessed for critical SRF. For comparison, the analytical solution for factor of safety is given by Hoek and Bray (1981), as follows:

\[
\text{FoS} = \frac{c \cdot L + (W \cdot \cos \beta - u \cdot L) \cdot \tan \phi}{W \cdot \sin \beta}
\]

where, 
- \(c\) = cohesion
- \(L\) = length of joint
- \(W\) = weight of block
- \(\beta\) = dip angle that the joint makes with the horizontal
- \(U\) = water pressure
- \(\phi\) = friction angle

Results of the validation procedure are given in Table 6-5.

<table>
<thead>
<tr>
<th>Model Temperature (°C)</th>
<th>C (kPa)</th>
<th>(\phi) (°)</th>
<th>FoS / Critical SRF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Analytical</td>
</tr>
<tr>
<td>-5</td>
<td>700</td>
<td>25</td>
<td>4.88</td>
</tr>
<tr>
<td>-2</td>
<td>200</td>
<td>15</td>
<td>1.55</td>
</tr>
<tr>
<td>-0.5</td>
<td>0</td>
<td>10</td>
<td>0.21</td>
</tr>
<tr>
<td>&gt;0</td>
<td>0</td>
<td>43</td>
<td>1.11</td>
</tr>
</tbody>
</table>
The Phase$^2$ models provided identical results to the analytical solution, suggesting that subsequent models with more complicated strength parameters will be accurate. It should be noted that during this process, it was discovered that joint stiffness should be set very close to zero (i.e. 0.001). As discussed earlier in Section 6.4.4.2, it was found that joints with a high stiffness did not fail as expected. In fact, the models with high stiffness often had a significantly lower SRF value than the analytical solution. Through trial and error, it was found that stiffness values of 0.001 MN/m were sufficiently low to equilibrate the Phase$^2$ and analytical solutions.
6.6 Results

6.6.1 Permafrost Models

6.6.1.1 Single Joint Model

To assess the effects of thawing, a single joint was assessed under five conditions: fully frozen, three stages of thawing, and fully thawed. Two geometries were prepared, one with a tension crack, and one without. In addition, the effects of water pressure were included in the assessment. Table 6-6 shows the critical SRF for each model tested. It should be noted that each scenario represents its own Phase² model.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Water Pressure?</th>
<th>Critical SRF (i.e. factor of safety)</th>
<th>Generic Model</th>
<th>Tension Crack Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully frozen at -5°C</td>
<td>No</td>
<td>4.88</td>
<td>3.99</td>
<td></td>
</tr>
<tr>
<td>Stage 1 thaw</td>
<td>No</td>
<td>2.17</td>
<td>2.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>2.17</td>
<td>2.13</td>
<td></td>
</tr>
<tr>
<td>Stage 2 thaw</td>
<td>No</td>
<td>1.04</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>1.02</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Stage 3 thaw</td>
<td>No</td>
<td>0.84</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.76</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Fully thawed</td>
<td>No</td>
<td>1.11</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>1.11*</td>
<td>0.97**</td>
<td></td>
</tr>
</tbody>
</table>

* The thawed generic model assumed fully drained conditions.

** The thawed tension crack model assumed peak water pressure at the base of the tension crack (100% full), and fully drained failure plane conditions.
The results given in Table 6-6 demonstrate how slope stability reaches a minimum during the thawing process. In the case of this particular slope, the critical SRF is above 1.0 (i.e. stable) when it is fully frozen and when it is fully thawed. However, by the third stage of thawing, both models have a critical SRF below 1.0 (i.e. unstable). Figure 6-8 illustrates how the critical SRF drops below 1.0 during the thaw of the tension crack model. An example of one of the Phase² permafrost models is shown in Figure 6-9 on the following page. Figures of other models are provided in APPENDIX C.

![Figure 6-8: Progression of critical SRF during permafrost thaw](image-url)
Upon further review, it seemed that the -0.5°C zone within the rockmass was larger than can be realistically expected, so a more detailed thermal gradient was tested for comparison. Isotherms of -1.0°C and -1.5°C were added to the model, and Mohr-Coulomb strength parameters were interpolated from the Davies et al. (2001) results given in Table 6-2. The new, interpolated strength parameters are given in Table 6-7 on the following page. An example of the improved thermal gradient is shown in Figure 6-10.

![Figure 6-9: Maximum shear strain of partial thaw stage 1, permafrost thaw model](image)

**Critical SRF = 2.13 (tension crack model)**
Table 6-7: Joint shear parameters used for the improved thermal gradient model

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Cohesion (kPa)</th>
<th>Angle of Friction (φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>700</td>
<td>25</td>
</tr>
<tr>
<td>-2</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>-1.5</td>
<td>133</td>
<td>13.3</td>
</tr>
<tr>
<td>-1.0</td>
<td>67</td>
<td>11.7</td>
</tr>
<tr>
<td>-0.5</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Thawed</td>
<td>0</td>
<td>43</td>
</tr>
</tbody>
</table>

Interpolated values shown in bold italics

Figure 6-10: Slope modeled with enhanced thermal gradient

The tension crack model was tested under stage 3 thaw conditions and no water pressure, using the new interpolated isotherms shown in Figure 6-10. The resulting critical SRF was 0.65, compared to a critical SRF of 0.81 found before the additional
isotherms were included. Overall, the joint is still unstable under these improved conditions; however, it is now clear that the results given in Table 6-6 underestimate the true factor of safety.

6.6.1.2 Joint Network Model

Due to excessive computing time, only two joint network models were completed: one in a fully thawed state, and the other thawed 5 m deep into the rockmass. The fully thawed model had a critical SRF of 1.0, and the partially thawed model had a critical SRF of 0.88. Neither of these models takes water pressure into account. Figure 6-11 shows the failure of the partially thawed model. The majority of failure was initiated in the -0.5°C zone, with some failure also occurring in the -2°C and thawed zones. As expected, no failure was observed in the -5°C zone.

Figure 6-11: Failure of the partially thawed, jointed permafrost model
6.6.2 Non-permafrost Models

Initially, the models were run using the same joint shown in Figure 6-5. The critical SRF for the December (extreme freezing) and February (extreme thawing) models for this joint are 1.14 and 1.06, respectively. These values do not differ significantly from the fully thawed joint (critical SRF = 1.11). To study the effect of diurnal freeze/thaw further, three other joints were added to the model to assess the effect of block size. The figure of the model with additional joint is given in Figure 6-12. The critical SRF for each of the four blocks in the December and February models is given in Table 6-8. The results show that during peak freezing conditions, the slope is stable for every block. On the other hand, during peak thawing conditions, the medium block is unstable and the larger blocks have a critical SRF only slightly above 1.

![Figure 6-12: Non-permafrost model with different block sizes](image)
### Table 6-8: Critical SRF values for the non-permafrost models

<table>
<thead>
<tr>
<th>Size of Block</th>
<th>Critical SRF</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>December</td>
<td>February</td>
</tr>
<tr>
<td>Very large</td>
<td>1.1</td>
<td>1.06</td>
</tr>
<tr>
<td>Large</td>
<td>1.4</td>
<td>1.05</td>
</tr>
<tr>
<td>Medium</td>
<td>4.4</td>
<td>0.91</td>
</tr>
<tr>
<td>Small</td>
<td>25.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### 6.6.3 Models with Water Pressure Only (i.e. No Ice)

In previous models, water pressure had a minimal effect on slope stability. This was because water pressure was assumed to accumulate only above ice level, and thus shear strength of the ice boundary had a much greater effect. To assess the full potential effects of water pressure on this slope, models were run on the tension crack geometry with no ice and various potential water pressure distributions. RocScience (2008b) identifies four different potential pressure distributions, shown below. In most cases, peak pressure at the tension crack base is the most applicable. Whether or not pressure exists along the failure plane is generally unknown, so some sensitivity analysis should be carried out. Under extreme conditions, such as ice blocking drainage at the face, the pressure distribution may have a maximum at the toe; however, this condition is likely rare (Hoek and Bray, 1981).

Since the shear strength of the failure plane was constant, RocPlane software was used in place of Phase² to reduce computing time. The failure plane was assigned the Davies et. al. (2001) rock/rock shear strength (c = 0 kPa and φ = 43°), and the following water pressure distributions were applied to the model (images from RocPlane):
- Peak pressure at tension crack base, *without* failure plane pressure
- Peak pressure at tension crack base, *with* failure plane pressure
- Peak pressure at mid-height
- Peak pressure at toe

Results are presented in Table 6-9. In general, the results indicate that water pressure can have a significant effect if the slope is sufficiently saturated. Assuming the slope is 100% full of water, the slope is unstable (i.e. FoS is below 1) for every possible pressure distribution. Even if the slope is 50% full of water, the slope is unstable under most pressure distributions.

**Table 6-9: Factors of safety for models with water pressure only (no ice)**

<table>
<thead>
<tr>
<th>Pressure Distribution</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% Full</td>
</tr>
<tr>
<td>Peak TC base – no FP pressure</td>
<td>1.07</td>
</tr>
<tr>
<td>Peak TC base – with FP pressure</td>
<td>0.93</td>
</tr>
<tr>
<td>Peak mid-height</td>
<td>0.95</td>
</tr>
<tr>
<td>Peak toe</td>
<td>0.78</td>
</tr>
<tr>
<td>None</td>
<td>1.11</td>
</tr>
</tbody>
</table>

TC = tension crack; FP = failure plane
6.7 Conclusions and Discussion

6.7.1 Shear Strength of Ice-filled Discontinuities in the Context of Slope Stability

Research by others (Davies et. al., 2000; Davies et. al. 2001; Günzel, 2008) has suggested that the shear strength of ice-filled discontinuities is both a function of temperature and normal stress. In general, at low normal stress (i.e. most slopes), shear strength is highly dependent on ice temperature. Compared to a thawed joint, an ice-filled joint will have higher shear strength if temperatures are low (i.e. -5°C or lower). On the other hand, as ice temperature rises close to -0.5°C, an ice-filled joint will have lower shear strength than a thawed joint.

In this study, finite-element models have been used to assess the effect of this phenomenon on slope stability. In the context of non-permafrost slopes, it was found that ice does not penetrate deeper than 50 cm, and yet it can have a significant effect on slope stability. For instance, one of the non-permafrost models gave a FoS of 0.91, compared to a thawed FoS of 1.1 (a decrease of 17%). In addition, two of the other models were close to a state of instability, with FoS of 1.06 and 1.05.

In comparison, the effect of thawing has an even greater effect on permafrost slopes. During the last stage of thawing, a slope with an original FoS of 1.1, can drop to a FoS = 0.81 (a decrease of 26%). This is simply because a greater portion of the joint is subjected to the weak -0.5°C isotherm. In addition, similar results were given by the joint network models, which showed primary failure in the -0.5°C temperature zone, with limited failure also occurring in the -2°C zone. As expected, there was no failure in the high-strength -5°C zone.
It is important to note that the Phase² permafrost models are based on purely hypothetical thermal gradients. In the future, it would be beneficial to apply this type of model to a real-world slope with monitored temperature data.

6.7.2 Correlation to Observed Patterns in Norway

The studies in Chapter 4 revealed that the majority of rockslides occur during winter thaw periods. Specifically, the most dangerous conditions exist when an Atlantic low-pressure system makes landfall on previously frozen terrain. These low-pressure systems typically raise temperatures above 0°C, in addition to bringing high levels of rainfall. Also, in many circumstances, a significant snowpack will be melted concurrently, and thus the terrain is subjected to high levels of runoff.

Prior to studying the shear strength of ice-filled discontinuities, it was believed that excess water pressure was the primary cause of rockslide triggering. However, with this new evidence in hand, it now appears that weak ice in discontinuities may play an important role in instability. For southwestern Norway, it was found that most slides occur within four days of maximum and minimum temperatures rising above 0°C. Not only is this period of time associated with high water levels, but also with rising rock temperatures. Since rock temperatures rise slower than air temperature, it is conceivable that ice within discontinuities is near the weak -0.5°C thermal zone, sometime during the four-day thawing period. It is at this temperature when the shear strength of joints is less than when the joint is thawed.

From the results of the Phase² models, it is clear that thawing of ice has a major effect on all slopes, especially those with permafrost. In the case of the Norwegian
study area, no permafrost exists. However, the terrain is subjected to regular diurnal freeze/thaw processes during the winter months. It is now believed that a decrease in shear strength due to thawing ice, accompanied by high runoff levels, is a likely triggering mechanism to the winter rockslides in southwestern Norway.

6.7.3 Implications to the Degradation of Permafrost Slopes

With the ongoing prospect of global warming, the effects of permafrost degradation are becoming an increasing concern. In the European Alps, permafrost temperatures have risen 0.5°C to 0.8°C in the upper decameters during the last century (Gruber and Haeberli, 2007).

In the past, it was generally accepted that frozen slopes were stronger than thawed slopes. This fact alone was considered the cause for instability when permafrost thaws. To compound this theory, the recent studies by Davies et. al. (2000) and Günzel, (2008) have revealed that as ice warms close to 0°C, shear strength actually drops below the strength of a thawed joint. In the context of this study, the Phase² models have revealed that FoS can be reduced by as much as 26% during permafrost thaw. From these findings, it is can be concluded that degradation of permafrost is certain to cause an increase in rockslides. The magnitude of this increase, and the relative volume of these slides (i.e. small rockfalls vs. deep-seated slides) remain to be seen.
6.7.4 Recommendations for Future Work

The direct shear tests by Davies et. al. (2000) and Günzel, (2008) indicated that strength of ice-filled joints was highly dependent on ice temperature, yet the strength properties were only determined for three temperatures: -5°C, -2°C, and -0.5°C. Since the strength changes so drastically from an ice-filled joint to a thawed joint, it would be beneficial to have strength parameters for a greater range of temperatures, especially between -2°C and 0°C, when ice is at its weakest.

For this model, temperature isotherms were idealized and might vary significantly in the field. It would be valuable to develop this type of model for a real-world slope that has been instrumented with thermocouples. This would give additional insight to how ice temperature affects slope stability.
6.8 References


http://www.rocscience.com/products/Phase2.asp, [visited August 28, 2009].

Chapter 7
Conclusions and Recommendations

7.1 General

The work completed for this thesis has been aimed at providing a rockslide forecasting system that changes day-to-day based on the weather forecast, as well as providing insights into the effects of climate change on rockslide activity. In order to accomplish this, a rockslide inventory has been compared to historic weather data to establish relationships between meteorological conditions and rockslide triggering. The results of these analyses are summarized in Section 7.2 below. Based on this work, two potential forecasting systems, one based on trigger threshold exceedance and the other based on weights-of-evidence susceptibility mapping have been developed. The applicability of these systems, and the positives and negatives of each are summarized in Section 7.3. In addition, recommendations for implementing these systems are provided in Section 7.6. Additional topics summarized in this Chapter include the implications of climate change, the relevance to rockslide studies in Canada, and recommendations for future work.
7.2 Meteorological Conditions as Rockslide Triggering Factors

7.2.1 From Observed Trends

In Chapter 4, a rockslide inventory was compared with historic weather data to give valuable insight as to how rockslides are triggered in southwestern Norway. Firstly, it was observed that the majority of slides occur during the winter, especially during thawing periods. Secondly, historic weather maps were studied, and it was discovered that the most extreme rockslide days occur when intense low-pressure systems from the Atlantic bring heavy rainfall over previously frozen land. The resulting severe runoff conditions from a combination of rainfall and snowmelt causes increased water pressure within rockmasses, and consequently triggers a high frequency of rockslides. The slope aspect study also revealed that southwest facing slopes are the most prone to rockslides, due to the southwest to northeast path that the low-pressure systems typically follow.

The Sandane meteorological trigger analysis in Chapter 4 found that extreme runoff, from rainfall and snowmelt, triggers approximately 76% of the slides in the region. The other meteorological trigger, frost wedging, accounted for 15% of the slides, and the remaining 9% did not have a discernible meteorological trigger. Of the rockslides triggered by runoff, it is evident that the majority occurred within 4 days after a recent thaw. Moreover, it is important to note that a melting snowpack greatly increases the likelihood of a slide due to the rapid and sustained delivery of water. Thirty-seven of the 59 runoff-triggered slides (63%) occurred during rain-on-snow conditions, even though runoff periods were characterized by rain-on-snow only 30% of the time. A general trend observed was that rockslides could be triggered by rain-on-snow up to four days after...
melting begins. This may be due to the snowpack’s capacity to absorb rain in available void space. After a few days, the snowpack becomes fully saturated and snowmelt accelerates to a point where runoff is sufficient to trigger rockslides.

Overall, the most hazardous condition from a meteorological point-of-view is when a large snowpack is rained on heavily for a sustained period of three days or more. It was observed that a 72-hr antecedent rainfall of 60 mm was required to trigger the majority of the winter rockslides recorded in the database. Overall, these extreme runoff conditions only occurred on 3% of the days studied, yet resulted in 39% of all natural slope rockslides.

Of the rockslides triggered by frost wedging (i.e. temperature below 0°C), only one occurred during dry conditions. The remaining slides were accompanied by the supply of water. In each of these cases, the slide occurred within two days of the temperature dropping below 0°C, and runoff conditions existed prior to freezing. Of the two frost wedging failure mechanisms, volumetric expansion and ice segregation, it is believed that volumetric expansion is responsible for the majority of frost-triggered rockslides in southwestern Norway. This type of failure is facilitated by a large supply of water subjected to rapid freezing, and the majority of frost-triggered slides in the Sandane meteorological trigger analysis occurred immediately after runoff conditions and a sudden drop below 0°C.
7.2.2 From Modeled Simulation

As discussed in Chapter 6, recent research by others suggests that the shear strength of ice-filled discontinuities is a function of ice temperature and normal stress. Of particular importance is the notion that as ice temperature rises close to -0.5°C, the shear strength of an ice-filled joint drops below the strength of the same thawed joint.

Results of theoretical simulations using finite-element modeling software suggests that permafrost slopes are particularly at risk of failing due to this phenomenon. To a lesser extent, non-permafrost slopes, such as those in southwestern Norway, are also affected by ice strength reduction. Simulations showed that the factor of safety of a non-permafrost slope can reduce by as much as 17%. Therefore, slopes with an unfrozen factor of safety of 1.0 to 1.2, which are otherwise stable, may become unstable as ice within the joints warms close to -0.5°C.

The simulations also demonstrated that water pressure due to runoff has a significant impact in creating instability. In fact, for non-permafrost slopes, it appears that water pressure has the potential to reduce shear strength more than ice warming alone. In all likelihood, these two forces act together to create instability within a slope. This may help to explain why the majority of slides occur immediately after a slope begins to thaw.
7.3 Forecasting Rockslides with Daily Weather Maps

7.3.1 Threshold Exceedance Maps

The high frequency of runoff triggered slides prompted the study of a runoff related trigger threshold, which could then be used to map threshold exceedance for hazard monitoring, as discussed in Chapter 4. The principle that dryer slopes require less runoff to fail, than do wetter slopes, was used by normalizing the runoff threshold to the mean monthly precipitation at each rockslide location. This method effectively accounted for the spatial and temporal variation of precipitation, and ultimately provided a threshold that is successful in predicting extreme winter runoff conditions. The threshold is defined by the equation:

\[ R = 27 \cdot \log_e(D) - 80 \]

where,  
- \( R \) = normalized runoff as a percent of mean monthly precipitation
- \( D \) = antecedent duration (i.e. time since rockslide occurred), in hours

The threshold is valid for a 96-hr window, and is mapped by highlighting areas that exceed the threshold in red, as shown in Figure 7-1 on page 214. Areas in lesser danger are highlighted in orange if they exceed 0.75-\( R \) and yellow if they exceed 0.5-\( R \). The trigger threshold exceedance maps were effective at highlighting severe runoff conditions at a regional county scale. In its current form, the trigger map would allow authorities to predict days when a high frequency of slides is likely. In addition, the map has a practical advantage, in that it is easy to use and gives obvious indications of impending danger, thereby alerting authorities to take proper action.
The downside of threshold exceedance mapping is that it does not account for physical rockslide conditioning factors. Therefore, certain areas that are relatively flat, and thus not prone to rockslides, will nonetheless appear red in the hazard map if runoff conditions are sufficiently high. By omitting these physical factors, there is potential for the map to appear more severe than actual conditions warrant. Consequently, it is a less robust system than the weights-of-evidence approach.

7.3.2 Weights-of-evidence Maps

The dynamic weights-of-evidence approach described in Chapter 5 incorporates a weather parameter that changes day-to-day (normalized 48-hr runoff) with physical terrain factors: slope angle, slope aspect and rock type. As expected, slope angle was found to have the highest correlation with rockslides, and is the primary conditioning factor for rockslide failure in the study area. On the other hand, analyses of slope aspect and rock type showed that these factors are not significant predictors on their own; however, they managed to improve the overall success of the base susceptibility map.

Several weather parameters were analyzed for possible inclusion in the susceptibility mapping system, including antecedent runoff, QTT, daily change in cumulative runoff, ΔQ, and normalized antecedent runoff, N_QTT. The weights-of-evidence analysis confirmed that normalized 48-hr runoff has the strongest correlation with rockslides, so this parameter was chosen for mapping. The other weather parameters are not conditionally independent from each other, so cannot be included in the final mapping system. Similar to the threshold exceedance method, normalization was accomplished by expressing runoff as a percentage of the mean monthly
precipitation, which successfully takes into account the spatial and seasonal changes in precipitation throughout the study area.

Success rate curves confirmed that on average, normalized 48-hr runoff is 75% successful in predicting rockslides. Moreover, the prediction rate increases to 96% when this factor is added to the static terrain factors. Overall, this is considered a very high success rate. In addition, daily verification curves showed that the model is generally a day early in predicting the response to rockslide occurrence. This result was unintentional; however, it is beneficial to authorities when it comes to preparing for these events.

7.3.3 Comparison of the Two Methods

For comparison purposes, maps of both the threshold exceedance method and the weights-of-evidence method are provided in Figure 7-1. The upper maps are for January 10th, 2003, when there was minor runoff and little reason to predict rockslides. As one would expect, both methods display large areas of green. The lower maps are for January 13th, 2003, when an intense low-pressure system made landfall. The corresponding heavy rainfall coupled with snowmelt results in extreme runoff conditions. Accordingly, both mapping systems indicate large areas of red, meaning extreme caution should be exercised.

The difference between the methods is that threshold exceedance does not account for terrain factors, so the map displays much larger areas of red. Weights-of-evidence effectively eliminates areas of low slope angle, so only steep slopes appear red. Scientifically, this is a more accurate approach than threshold exceedance, but it is
speculated that the map itself would not invoke the same warning due to lower degree of red. Consequently, it may be beneficial to employ both systems to see which is more practical for everyday use. Alternatively, the weights-of-evidence method can be supplemented with a warning system based on the percentage of “redness” in the map.
Figure 7-1: Comparison of rockslide forecast mapping systems

Jan. 10th, 2003

No Exceedance
Low - Exceeds 0.5R
Mod - Exceeds 0.75R
High - Exceeds R

Jan. 13th, 2003

Very low: -8 to -0.75
Low: -0.750 to 0
Moderate: 0 to 1.5
High: 1.5 to 2.5
Very high: 2.5 to 6

Weights-of-evidence
7.4 Implications of Climate Change

7.4.1 Changes in Temperature

Climate change projections indicate that the temperature in southwestern Norway will increase by approximately 1.5°C during the next century. During spring, summer and autumn, this will have a minimal effect on rockslide triggering. However, an increase in winter temperature may result in fewer freeze/thaw cycles and less snowfall, which would imply less rockslide triggering. However, the amount of precipitation must also be considered. A warming trend will surely result in fewer freeze/thaw cycles at lower elevations, but if precipitation levels increase, then the amount of snowfall may actually be greater during those times when temperatures manage to fall below freezing.

At higher elevations, the quantity of freeze/thaw cycles will actually increase, resulting in more frequent rockslide activity. Since the majority of Norway’s infrastructure is at relatively low elevation, the runout of small-scale rockslides may not reach road level; however, an increase in large-scale rockslides may have a significant negative effect on infrastructure.

7.4.2 Changes in Precipitation and Runoff

Projections indicate that southwestern Norway will experience a significant increase in precipitation and runoff during the next century, particularly during autumn, winter and spring. Summer on the other hand will experience little change in precipitation. Of particular importance is winter precipitation, which is estimated to increase by approximately 8%. It should be noted that different climate projection models give a
wide range of precipitation increase, from 0% to 25%, but nearly all agree that some increase in precipitation should be expected.

In terms of runoff, the only available climate model indicated that runoff will increase by over 100% by the end of the century. Without an ensemble of model results, it is imprudent to declare this result as certain; however, it provides an indication that runoff may change drastically in the future. Considering that the majority of rockslides are triggered by runoff, this implies that rockslide incidence will increase. Of course, one must consider if the increase in precipitation and runoff will be averaged over the entire season, or if it is a result of more frequent and more severe storms. If it is the former, the increase in runoff will likely have a negligible effect on triggering. On the other hand, if it is the latter, rockslide incidence will surely increase, especially if it is accompanied by the melting of a significant snowpack.

**7.4.3 Extreme Events**

Current estimates are that northern Europe will experience an increase in extreme events. For western coastal regions, the probability of exceeding the present 95\textsuperscript{th} percentile of rainfall may increase by up to 30% by 2050. This means that storms which are considered extreme today will become more common in the future and record events will be increasingly more severe. Should this projection become reality, then future winter low-pressure systems have the potential to trigger significantly more rockslides than today. For example, the January 2003 storm, which resulted in more than 100 rockslides in a week, may become more frequent in the future. The biggest question is whether or not extreme rainfall will be coupled with snowmelt. Current research fails to
answer this question, so it is difficult to say whether there will be a relative increase in rockslide activity in the future.

7.4.4 Degradation of Permafrost

Southwestern Norway has discontinuous permafrost at its highest elevations in the Caledonian Mountain peaks. The Phase² models in Chapter 6 revealed that factor of safety of a generic frozen slope can be reduced by as much as 26% during permafrost thaw. From these findings, it is can be concluded that degradation of permafrost is certain to cause an increase in rockslides. However, the proportion of land area containing permafrost is very low in the study area and it does not overlap with infrastructure or human habitation, at least at this time. Therefore, while rockslide activity may increase in these isolated areas, it will have a negligible effect on the human population, as long as land use patterns remain the same.
7.5 Relevance to Rockslide Studies in Canada

7.5.1 General

In Canada, there have been some studies related to large, catastrophic rockslides, and how they may have been triggered by meteorological conditions. However, there have been no studies dedicated to establishing meteorological triggers to a database of smaller scale rockslides or rockfalls. In order to carry out the type of analyses described in this thesis, there must be a comprehensive database of rockslides, and also a source of meteorological data.

7.5.2 Related Canadian Studies

So far, meteorological trigger thresholds for geohazards in Canada have been limited to debris flows, such as those studied by Jakob and Weatherly (2003) for Vancouver’s North Shore Mountains and Jakob et. al. (2006) for forest operations in northeast British Columbia. Both of these studies used a database of local debris flows to establish hydrometeorological trigger thresholds. Neither of the studies used a mapping method; rather, they established a meteorological trigger threshold that applied to the entire study area as a whole, and warnings were initiated if the threshold was exceeded. Not unexpectedly, both studies found that the primary trigger for debris flows was elevated levels of runoff. Interestingly, the studies observed similar weather patterns to southwestern Norway. Specifically, they observed that the majority of debris flows were triggered after a Pacific low-pressure system made landfall, with the warm front impacting first, then the cold front.
In order to create a threshold for runoff, Jakob and Weatherly (2003) used the discharge of a local creek as an analog for runoff conditions. This method proved to be successful; however, it is limited to the local watershed. Therefore, it is only valid on a small, local scale. The advantage of the methods described in this thesis is that runoff maps in Norway can be applied to large regional scales.

7.5.3 Status of Canadian Weather and Rockslide Databases

The rockslide forecast methods described in this thesis were made possible by the existence of a database of daily “rainfall+snowmelt” (runoff) maps. The Norwegian Water Resources Directorate (NVE) uses the national Norwegian database of daily precipitation and temperature maps to map daily runoff using a simple HBV hydrology model. At the present time, Canada does not have a database of precipitation and temperature maps, so the methods described in this thesis are not yet possible here. Fortunately, Canada has numerous weather stations around the country, monitored by entities such as Environment Canada, forestry departments, media and other research groups. From this base data, it is possible to create a database of precipitation and temperature maps using GIS and spatial interpolation methods.

The creation of such a database may not be financially feasible on a national scale; however, it may be possible on a provincial or local basis. In terms of geohazards, this type of database would be most beneficial for the mountainous areas of British Columbia, Alberta and the Yukon; however, NVE has also found the database to be helpful in identifying water shortage and flooding conditions, so a weather map database would be helpful to other provinces as well.
The other issue with carrying out this type of analysis for Canadian studies is that it requires a comprehensive rockslide database. Hungr et. al. (1999) assembled a database of rockslides and rockfalls along two major transportation corridors in southwestern British Columbia; however, it contains significantly less events than Norway and it does not claim to be a comprehensive database of every event that collided with a road (or railway). The lack of data may negatively affect the accuracy of statistical work; nonetheless, this particular database may be suitable for establishing meteorological triggers. As far as other databases, it is known that Canadian rail companies and some provincial highway authorities keep databases of events that impact their infrastructure; however, the extent of these inventories needs to be studied before any further judgments can be made.
7.6 Recommendations

7.6.1 Recommendations for Norwegian Government Authorities

As mentioned earlier, it may be beneficial to try both the threshold exceedance and weights-of-evidence mapping systems simultaneously to see which is more useful. Visually, threshold exceedance will give a clearer indication of when conditions are more severe; however, it will not indicate where rockslides are likely to occur. Weights-of-evidence on the other hand will indicate when and where to expect rockslides. In any event it may be beneficial to keep both systems functional.

If the weights-of-evidence method is implemented as a hazard warning system, there are a few key points that should be considered. For all susceptibility maps, the most important decision is to establish meaningful susceptibility classes. As discussed in Chapter 5, the classes chosen for this research are:

- **Very low**: -8 to -0.75
- **Low**: -0.75 to 0
- **Moderate**: 0 to 1.5
- **High**: 1.5 to 2.5
- **Very high**: 2.5 to 6

The chosen susceptibility classes and colour-scheme have great influence in day-to-day decision making. If the map is excessively red, the user may interpret more severe conditions than are the case in reality. The opposite may also be true if the map is excessively green when rockslides are actually likely. For this project, susceptibility classes have been chosen based on the prediction rates discussed in Section 5.7, and
should only be changed if the success rate curves in Figure 5-14 are carefully considered.

It is recommended to create a daily forecast map of “tomorrow” by using a 48-hr runoff map consisting of “today’s” runoff added to the forecast of “tomorrow’s” runoff. This will indicate the likelihood of slides during the next 24-hrs, so that appropriate preparation measures can be carried out. The decision of when to start taking appropriate measures is up to authorities; however, the data shows that caution should be heeded when more than 20% of the map is either MODERATE or higher, and extreme caution should be heeded when this value exceeds 25%. Additionally, if the map is 10% or more in VERY HIGH, extreme caution would be prudent.

The daily verification curves discussed in Chapter 5 showed that rockslide response is typically a day later than the initial jump in susceptibility. This is considered a benefit because it allows additional time to prepare for an extreme day of events; however, it should not be used as a justification to ignore conditions for an extra day. The same verification curves showed that a downturn in susceptibility is followed closely by a downturn in rockslide occurrence, so a forecasted “extreme” day should be followed by at least two days of a warning. If “extreme” days are consecutive, the warning should stay in place for a full 24-hrs after conditions have returned to stable levels.
7.6.2 Recommendations for Future Work

7.6.2.1 Refining Analyses with Additional Runoff Data

The runoff data used for establishing the threshold in Chapter 4 and the weights-of-evidence analysis in Chapter 5 only included days that occurred during the five most extreme storms between 2000 and 2005. It is believed that this data is sufficient to establish the conditions associated with extreme events. Nonetheless, data from additional storms would be beneficial in refining the results given in this thesis. In addition, comprehensive runoff data for every winter day, regardless of whether it is during a storm, would help to make the forecast system more robust, especially in terms of the weights-of-evidence modeling. In the future, it would be beneficial to build the database on a daily basis. This would make it possible to automatically reassess the 48-hr runoff parameter each day. This would improve accuracy continually. In addition, it would be beneficial to consider other weather-related parameters to include in the model, as long as they are conditionally independent from the 48-hr runoff parameter.

In terms of summer rockslides, the threshold managed to identify extreme conditions, but only captured about half of the events. Therefore, a more in-depth study of how meteorological conditions trigger rockslides in the summer would be beneficial in future studies.
7.6.2.2 Susceptibility Mapping

The dynamic, susceptibility map discussed in Chapter 5 included three terrain parameters: slope angle, slope aspect and rock type. The slope angle parameter was assessed using only 54 rockslides within the Sandane sub-study area, and the correlation was assumed to exist across the entire study area. This was necessary to correct for location error; however, it is not ideal for a robust mapping system. Fortunately, slope angle showed a strong correlation with rockslide occurrence, so the results found in Chapter 4 are not expected to be far from true. Nevertheless, to improve the model, one or two more sub-study areas spread across the two counties would be beneficial to check that slope angle is consistent across the greater study area. In addition, the base susceptibility map can be enhanced by considering additional terrain factors such as slope curvature, both in profile and in section.

7.6.2.3 Climate Change Studies

Before this research began, there was not a quantitative understanding of how meteorological conditions triggered rockslides. This prevented a detailed analysis of how climate change will affect future rockslide activity. Using the results of this thesis as a background, it is recommended to introduce climate change projection scenarios into a GIS-based model. This should make it possible to scientifically assess the implications of climate change.
7.7 References


Appendix A

Normalized Runoff Threshold Plots
Figure A-1: Events from February 12\textsuperscript{th} to 14\textsuperscript{th}, 2001

Figure A-2: Events from January 14\textsuperscript{th} to 17\textsuperscript{th}, 2002
Figure A-3: Events from January 13th to 16th, 2003

Figure A-4: Events from March 8th to 11th, 2003
Figure A-5: Events from February 3\textsuperscript{rd} to 6\textsuperscript{th}, 2004
Figure A-6: Sandane weather station data with 48-hr normalized runoff – Winter 2001
Figure A-7: Sandane weather station data with 48-hr normalized runoff – Winter 2002
Figure A-8: Sandane weather station data with 48-hr normalized runoff – Winter 2003
Figure A-9: Sandane weather station data with 48-hr normalized runoff – Winter 2004
Appendix B
Weights-of-Evidence Analyses Results,
Contingency Tables,
and
Final Susceptibility Maps
Table B-1: Weights-of-evidence analysis results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Class</th>
<th>% Total Area</th>
<th>% Slides</th>
<th>W⁺</th>
<th>W⁻</th>
<th>W_{final}</th>
<th>C_w</th>
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<tbody>
<tr>
<td>Slope Angle</td>
<td>0 - 25°</td>
<td>64.9</td>
<td>0.0</td>
<td>-3.570</td>
<td>1.048</td>
<td>-4.357</td>
<td>-4.618</td>
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<tr>
<td></td>
<td>25 - 30°</td>
<td>9.5</td>
<td>3.7</td>
<td>-0.943</td>
<td>0.062</td>
<td>-0.745</td>
<td>-1.005</td>
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<td></td>
<td>30 - 40°</td>
<td>14.5</td>
<td>27.8</td>
<td>0.650</td>
<td>-0.169</td>
<td>1.079</td>
<td>0.819</td>
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<tr>
<td></td>
<td>40 - 50°</td>
<td>7.6</td>
<td>27.8</td>
<td>1.300</td>
<td>-0.247</td>
<td>1.807</td>
<td>1.546</td>
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<tr>
<td></td>
<td>50 - 60°</td>
<td>2.7</td>
<td>29.6</td>
<td>2.382</td>
<td>-0.324</td>
<td>2.967</td>
<td>2.706</td>
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<td></td>
<td>60 - 70°</td>
<td>0.7</td>
<td>11.1</td>
<td>2.774</td>
<td>-0.111</td>
<td>3.146</td>
<td>2.885</td>
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<td>70 - 90°</td>
<td>0.1</td>
<td>0.0</td>
<td>3.440</td>
<td>0.001</td>
<td>3.700</td>
<td>3.439</td>
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<td>Slope</td>
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<td>-0.097</td>
<td>0.012</td>
<td>-0.113</td>
<td>-0.109</td>
</tr>
<tr>
<td>Aspect</td>
<td>Northeast</td>
<td>11.5</td>
<td>7.2</td>
<td>-0.472</td>
<td>0.048</td>
<td>-0.523</td>
<td>-0.520</td>
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<tr>
<td></td>
<td>East</td>
<td>12.1</td>
<td>10.4</td>
<td>-0.153</td>
<td>0.019</td>
<td>-0.176</td>
<td>-0.173</td>
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<tr>
<td></td>
<td>Southeast</td>
<td>13.0</td>
<td>13.4</td>
<td>0.029</td>
<td>-0.004</td>
<td>0.030</td>
<td>0.034</td>
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<td></td>
<td>South</td>
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<td>13.1</td>
<td>0.012</td>
<td>-0.002</td>
<td>0.010</td>
<td>0.014</td>
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<td></td>
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<td>14.8</td>
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<td>-0.030</td>
<td>0.221</td>
<td>0.224</td>
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<td></td>
<td>West</td>
<td>13.1</td>
<td>15.3</td>
<td>0.149</td>
<td>-0.025</td>
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<td>0.174</td>
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<td>29.6</td>
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<td>-1.166</td>
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<td>Group 2</td>
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<td>80.0</td>
<td>0.220</td>
<td>-0.583</td>
<td>0.440</td>
<td>0.803</td>
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<tr>
<td>Normalized</td>
<td>0 – 10%</td>
<td>38.3</td>
<td>11.4</td>
<td>-1.212</td>
<td>0.362</td>
<td>-1.514</td>
<td>-1.574</td>
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<td>48-hr Runoff</td>
<td>10 – 20%</td>
<td>24.6</td>
<td>12.7</td>
<td>-0.664</td>
<td>0.147</td>
<td>-0.751</td>
<td>-0.811</td>
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<td></td>
<td>20 – 30%</td>
<td>16.2</td>
<td>19.8</td>
<td>0.203</td>
<td>-0.044</td>
<td>0.307</td>
<td>0.247</td>
</tr>
<tr>
<td></td>
<td>30 – 45%</td>
<td>11.9</td>
<td>27.0</td>
<td>0.821</td>
<td>-0.188</td>
<td>1.069</td>
<td>1.009</td>
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<td></td>
<td>45 – 60%</td>
<td>5.2</td>
<td>14.3</td>
<td>1.007</td>
<td>-0.101</td>
<td>1.168</td>
<td>1.108</td>
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<td>60 – 75%</td>
<td>2.1</td>
<td>7.2</td>
<td>1.228</td>
<td>-0.053</td>
<td>1.341</td>
<td>1.281</td>
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<tr>
<td></td>
<td>75 – 200%</td>
<td>1.7</td>
<td>7.6</td>
<td>1.491</td>
<td>-0.062</td>
<td>1.613</td>
<td>1.553</td>
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235
### Table B-2: Slope angle vs. slope aspect contingency table

<table>
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<tr>
<th>Aspect</th>
<th>0 - 25</th>
<th>25 - 30</th>
<th>30 - 40</th>
<th>40 - 50</th>
<th>50 - 60</th>
<th>60 - 70</th>
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<td></td>
<td>observed</td>
<td>expected</td>
<td>χ²</td>
<td>observed</td>
<td>expected</td>
<td>χ²</td>
<td>observed</td>
</tr>
<tr>
<td>North</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>4.45</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.11</td>
<td>3.36</td>
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<td>East</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>2.14</td>
<td>4.00</td>
</tr>
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<td>Southeast</td>
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<td>0.00</td>
<td>0.44</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.26</td>
<td>2.22</td>
<td>4.00</td>
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</table>

Degrees of freedom = 42

Critical χ² value: 99% confidence = 66.18
97.5% = 61.76
95% = 58.12
90% = 54.08
Status: Conditionally Independent

### Table B-3: Slope angle vs. rock type contingency table

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<th>Rock type</th>
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<th>25 - 30</th>
<th>30 - 40</th>
<th>40 - 50</th>
<th>50 - 60</th>
<th>60 - 70</th>
<th>70 - 90</th>
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<tr>
<td></td>
<td>observed</td>
<td>expected</td>
<td>χ²</td>
<td>observed</td>
<td>expected</td>
<td>χ²</td>
<td>observed</td>
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<td>Group 1</td>
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<td>Group 2</td>
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<td>1.00</td>
<td>1.67</td>
<td>0.82</td>
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Degrees of freedom = 6

Critical χ² value: 99% confidence = 16.81
97.5% = 14.45
95% = 12.59
90% = 10.64
Status: Conditionally Independent

236
Table B-4: Slope angle vs. normalized 48-hr runoff contingency table

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<th>Normalized Runoff</th>
<th>0 - 25</th>
<th>25 - 30</th>
<th>30 - 40</th>
<th>40 - 50</th>
<th>50 - 60</th>
<th>60 - 70</th>
<th>70 - 90</th>
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<td>expected</td>
<td>$x^2$</td>
<td>observed</td>
<td>expected</td>
<td>$x^2$</td>
<td>observed</td>
<td>expected</td>
</tr>
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<td>0 - 10</td>
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<td>2.45</td>
<td>1.00</td>
<td>0.00</td>
<td>0.11</td>
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<td>10 - 20</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>20 - 30</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.45</td>
<td>2.00</td>
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<tr>
<td>30 - 45</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.30</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td>45 - 60</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.13</td>
<td>1.00</td>
</tr>
<tr>
<td>60 - 75</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>75 - 200</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Degrees of freedom = 36

critical $x^2$ value: 99% confidence = 58.57  
97.5% = 54.4  
95% = 50.96  
90% = 47.19  
Status: Conditionally Independent

Table B-5: Slope aspect vs. rock type contingency table

<table>
<thead>
<tr>
<th>Rock type</th>
<th>North</th>
<th>Northeast</th>
<th>East</th>
<th>Southeast</th>
<th>South</th>
<th>Southwest</th>
<th>West</th>
<th>Northeastwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>expected</td>
<td>$x^2$</td>
<td>observed</td>
<td>expected</td>
<td>$x^2$</td>
<td>observed</td>
<td>expected</td>
<td>$x^2$</td>
</tr>
<tr>
<td>Group 1</td>
<td>1.00</td>
<td>0.33</td>
<td>0.06</td>
<td>0.00</td>
<td>0.50</td>
<td>2.00</td>
<td>1.00</td>
<td>1.33</td>
</tr>
<tr>
<td>Group 2</td>
<td>1.00</td>
<td>1.67</td>
<td>0.82</td>
<td>3.00</td>
<td>2.50</td>
<td>0.00</td>
<td>7.00</td>
<td>6.67</td>
</tr>
</tbody>
</table>

Degrees of freedom = 7

critical $x^2$ value: 99% confidence = 18.48  
97.5% = 16.01  
95% = 14.07  
90% = 12.02  
Status: Conditionally Independent
**Table B-6: Slope aspect vs. normalized 48-hr runoff contingency table**

<table>
<thead>
<tr>
<th>Normalized Runoff</th>
<th>North</th>
<th>Northeast</th>
<th>East</th>
<th>Southeast</th>
<th>South</th>
<th>Southwest</th>
<th>West</th>
<th>Northwest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>observed</td>
<td>expected</td>
<td>x²</td>
<td>observed</td>
<td>expected</td>
<td>x²</td>
<td>observed</td>
<td>expected</td>
</tr>
<tr>
<td>0 - 10</td>
<td>1.00</td>
<td>1.59</td>
<td>0.75</td>
<td>1.00</td>
<td>1.59</td>
<td>0.75</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>10 - 20</td>
<td>1.00</td>
<td>1.77</td>
<td>0.91</td>
<td>4.00</td>
<td>1.77</td>
<td>1.68</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>20 - 30</td>
<td>2.00</td>
<td>2.76</td>
<td>0.69</td>
<td>6.00</td>
<td>2.76</td>
<td>1.07</td>
<td>6.00</td>
<td>2.97</td>
</tr>
<tr>
<td>30 - 45</td>
<td>3.00</td>
<td>3.78</td>
<td>0.43</td>
<td>4.00</td>
<td>3.78</td>
<td>0.02</td>
<td>5.00</td>
<td>4.05</td>
</tr>
<tr>
<td>45 - 60</td>
<td>5.00</td>
<td>2.01</td>
<td>3.09</td>
<td>0.00</td>
<td>2.01</td>
<td>3.13</td>
<td>0.00</td>
<td>2.15</td>
</tr>
<tr>
<td>60 - 75</td>
<td>1.00</td>
<td>1.00</td>
<td>2.25</td>
<td>0.00</td>
<td>1.00</td>
<td>2.25</td>
<td>1.00</td>
<td>1.06</td>
</tr>
<tr>
<td>75 - 200</td>
<td>2.00</td>
<td>1.06</td>
<td>0.16</td>
<td>0.00</td>
<td>1.06</td>
<td>2.30</td>
<td>0.00</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Degrees of freedom = 42

Critical $x^2$ value: 99% confidence = 66.18
97.5% = 61.76
95% = 56.12
90% = 54.08

Status: Conditionally Independent but questionable

**Table B-7: Rock type vs. normalized 48-hr runoff contingency table**

<table>
<thead>
<tr>
<th>Normalized Runoff</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>observed</td>
<td>expected</td>
</tr>
<tr>
<td>0 - 10</td>
<td>8.00</td>
<td>6.95</td>
</tr>
<tr>
<td>10 - 20</td>
<td>7.00</td>
<td>7.72</td>
</tr>
<tr>
<td>20 - 30</td>
<td>14.00</td>
<td>12.10</td>
</tr>
<tr>
<td>30 - 45</td>
<td>12.00</td>
<td>16.47</td>
</tr>
<tr>
<td>45 - 60</td>
<td>7.00</td>
<td>8.75</td>
</tr>
<tr>
<td>60 - 75</td>
<td>6.00</td>
<td>4.38</td>
</tr>
<tr>
<td>75 - 200</td>
<td>7.00</td>
<td>4.83</td>
</tr>
</tbody>
</table>

Degrees of freedom = 6

Critical $x^2$ value: 99% confidence = 16.81
97.5% = 14.45
95% = 12.59
90% = 10.64

Status: Conditionally Independent
Figure B-1: February 2001 storm - final susceptibility map
Figure B-2: January 2002 storm – final susceptibility map

Legend
- Rockslide locations
- Weight
  - 2.5 or higher
  - -2.5 or lower
Figure B-3: March 2003 storm – final susceptibility map

Legend
- Rockslide locations

Weight
- 2.5 or higher
- -2.5 or lower
Figure B-4: February 2004 storm – final susceptibility map

Legend
- Rockslide locations
- Weight
  - 2.5 or higher
  - -2.5 or lower
Appendix C

Figures of Phase² Model Results
Figure C-1: Generic permafrost model – fully frozen at -5°C

Figure C-2: Generic permafrost model – stage 1 thaw
Figure C-3: Generic permafrost model – stage 2 thaw

Figure C-4: Generic permafrost model – stage 3 thaw
Figure C-5: Generic permafrost model – fully thawed

Figure C-6: Tension crack permafrost model – fully frozen at -5°C
Figure C-7: Tension crack permafrost model – stage 1 thaw

Figure C-8: Tension crack permafrost model – stage 2 thaw
Figure C-9: Tension crack permafrost model – stage 3 thaw

Figure C-10: Tension crack permafrost model – fully thawed
Figure C-11: Tension crack model with improved thermal gradient – stage 3 thaw

Figure C-12: Joint Network Model – fully thawed
Figure C-13: Water pressure model (50%) – peak TC base, no FP pressure

Figure C-14: Water pressure model (50%) – peak TC base, with FP pressure
Figure C-15: Water pressure model (50% full) – peak pressure at mid-height

Figure C-16: Water pressure model (50% full) – peak pressure at toe
Figure C-17: Water pressure model (100%) – peak TC base, no FP pressure

Figure C-18: Water pressure model (100%) – peak TC base, with FP pressure
Figure C-19: Water pressure model (100% full) – peak pressure at mid-height

Figure C-20: Water pressure model (100% full) – peak pressure at toe
Appendix D

Raw Rockslide Database

Please see attached CD for the contents of APPENDIX D
Appendix E
Sandane Sub-study Rockslide Database and Sesam 3D Images of Relocated Rockslides

Please see attached CD for the contents of APPENDIX E