Rockslides in a changing climate: establishing meteorological trigger thresholds in south western Norway

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ABSTRACT
Carried out under the Norwegian GeoExtreme project, the aim of this work is to establish links between rockslides and meteorological conditions. A database of rockslides is being compared to weather station records to specify runoff and frost wedging thresholds required to trigger rockslides. Furthermore, a dynamic, weather-dependent, trigger threshold map is being developed to indentify slopes that are in danger of failing due to incoming weather conditions. The effects of climate change will assessed by introducing projected climate scenarios into the dynamic trigger map.

RÉSUMÉ
Effectuée dans le cadre du projet norvégien GeoExtreme, l'objectif de ce travail est d'établir des liens entre les éboulements et les conditions météorologiques. Une base de données des éboulements est comparé aux enregistrements des stations météorologiques pour préciser les eaux de ruissellement et le gel des seuils de calage nécessaire pour déclencher les éboulements. Par ailleurs, une carte dynamique, qui dépendant de la météo, et qui montre le seuil de déclenchement, est en cours d'élaboration pour indentifier les pistes qui sont en danger d'échouer à cause des nouvelles conditions météorologiques. Les effets du changement climatique seront évalués par l'introduction desprojections des scénarios de changement climatique dans la carte dynamique de déclencher.

1 INTRODUCTION

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 indicating 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 climatic conditions of historic geohazards, GeoExtreme is establishing relationships between meteorological factors and geohazards. In addition, GeoExtreme is forecasting geohazard scenarios using state-of-the-art climate change projection models and assessing the socio-economic consequences of future geohazards (Jaedicke et. al., 2008).

1.2 Scope of Work

The work presented here, carried out under the GeoExtreme project, is focused specifically on developing precipitation and temperature change thresholds for the two primary rockslide triggers in the area, runoff and freeze/thaw processes. The purposes of establishing trigger thresholds are 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 is being 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 study the effects of weather on these historic slides, the Norwegian Meteorological Institute ('met.no') has determined a set of climate variables for each slide event, which include the weather conditions on the day and days leading up to each slide. Furthermore, weather data from Norwegian climate stations and Norway's weather map database, "*www.senorge.no*" are being used to establish specific meteorological trigger thresholds for runoff and frost wedging processes.

1.3 Methodology

1.3.1 Background and Related Studies

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

1.3.2 Application of Trigger Thresholds 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 pore-pressure due to ice-blocked drainage routes (Braathen et. al., 2004; Sandersen et. al., 1996). Non-meteorological factors must also be considered, including: seismic activity, erosion, root wedging and human activity.

The reason why 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 that a rockslide database can be separated into categories of different triggers, which are then analyzed separately.

1.3.3 Meteorological Trigger Analysis

The separation of meteorological thresholds 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 rockslides that occurred in the winter in a 2000 km^2 area around the Village of Sandane in Sogn og Fjordane, and is discussed in subsequent sections.

With the database separated into different triggers, it is then possible to establish a threshold for each group. For the purposes of this work, only thresholds related to runoff and frost wedging are considered, as these triggers are responsible for the majority of slides in the region.

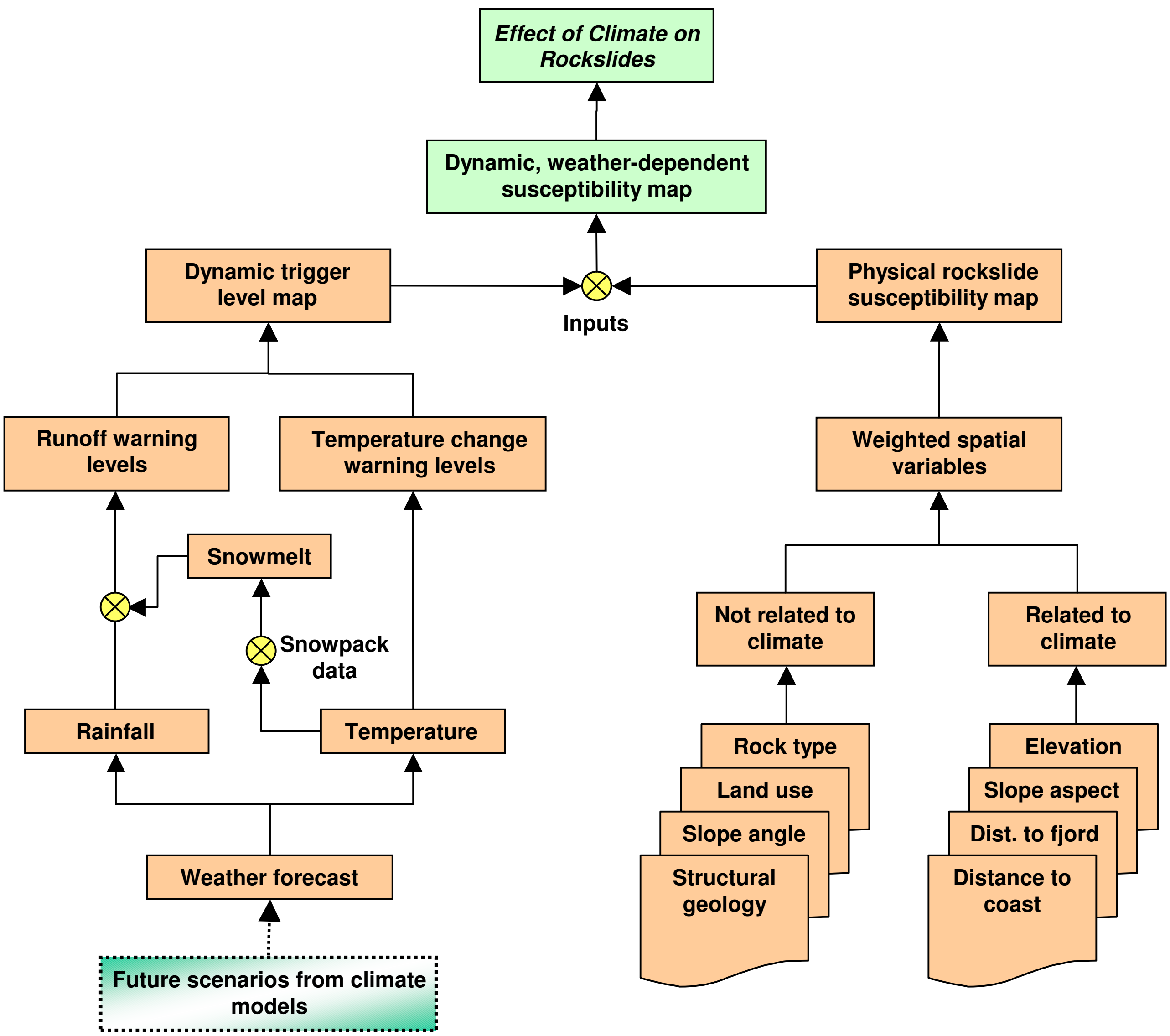

Figure 1. Methodology Flow Chart

1.3.4 Mapping

The chosen output of this analysis is a dynamic, weather-dependent susceptibility map (see flowchart, Figure 1). This map 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 will provide an effective means for studying the effects of climate change on rockslides.

The dynamic susceptibility map consists of two components: a rockslide hazard map based on physical characteristics (i.e. slope angle, rock type, etc.), and a dynamic trigger map that changes based on weather input. The idea behind this methodology is that a trigger map, which indicates hazardous areas based on the weather, can be overlain on a susceptibility map to highlight specific areas which are in danger of failing due to a meteorological trigger.

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. A map of the rockslide locations is given in Figure 2.

2.1 Limitations of Data

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 thresholds is unaffected. However, this error has a negative effect on statistically approached susceptibility mapping, as was initially planned.

The physical rockslide susceptibility map on the right-hand side of Figure 1 was planned to be completed using a Bayesian probability, weights-of-evidence approach. This method uses a historical slide inventory to assign weights to certain parameters (ex. slope angle, rock type, etc.) according to the physical characteristics of the slide source zone (Soeters and Van Westen, 1996). Since 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 must be created in order to acquire a statistically prepared susceptibility map. A procedure for this is proposed in Section 6.2.

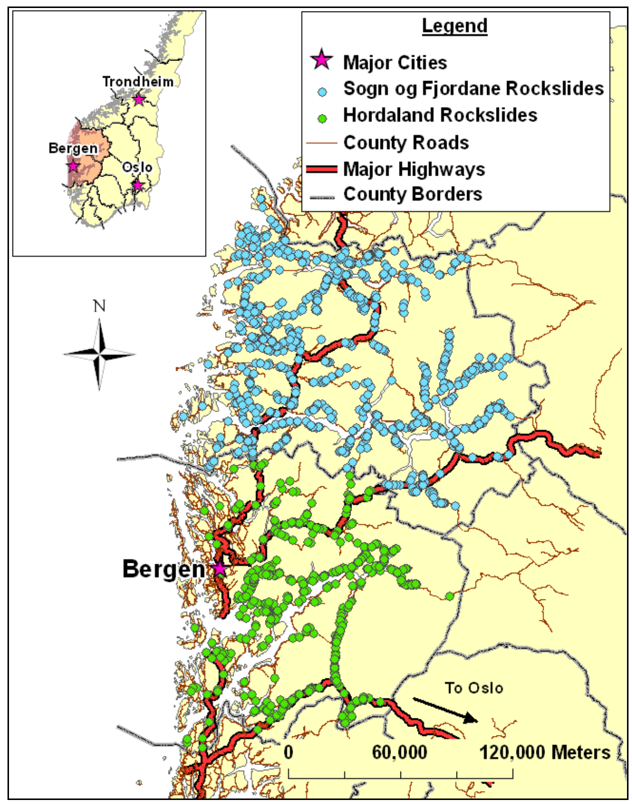

Figure 2. Map of rockslides in Sogn og Fjordane (north) and Hordaland (south) counties

2.1.2 Temporal Discontinuity

The county of Sogn og Fjordane has been recording rockslides semi-frequently since the 1970's, but there is a distinct increase in reported rockslide incidence in 1997, as recording procedures became more detailed and comprehensive. 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 these dates are considered.

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. Contained in the database is a column for volume information; though 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 a relatively small volume, meteorological trigger thresholds that are applicable to most rockslides can be established.

2.2 Climate Database

'Met.no' maintains a database of gridded climate maps that covers the entire country in 1km x 1km spatial resolution. Maps are available for each day dating back to 1961, with each day represented by several different 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). The remaining climate themes are derived from the temperature and precipitation grids by mathematical algorithms.

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

- Precipitation sum for 'n' antecedent days (n=1, 3, 5, 7, 10, 13, 30, 60 and 90),
- Average annual precipitation using the standard normal period 1961-1990,
- Extreme precipitation values for 1, 3 and 5 day(s) with return periods 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 climate variable and how it was derived is described in Vikhamar-Schuler and Isaksen (2006).

3 PREVIOUS GEOEXTREME ANALYSES

3.1 Classification Trees

The purpose of the combined geohazard-climate database was to establish links between the derived climate variables and the triggering of geohazards. Applying statistical analyses only, Kronholm et. al. (2006) describe 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 climate variables (Jaedicke et. al., 2008).

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.

3.2 Hypothesis for Negative Result

In regards to the rockslide analysis, the classification tree approach was unsuccessful because the climate 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 pore pressure in the form of runoff, or by freeze-thaw processes (Sandersen et. al., 1996). Therefore, the key factors to consider for rockslides are:

1) runoff (rainfall + snowmelt), and
2) temperature changes across 0°C during preceding days.

Unfortunately, there is no measure of runoff in the database 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 order to obtain satisfactory results, it is suggested that a set of maximum and minimum temperatures for each day during the preceding week are required.

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 3). This graph plots the frost interval of each slide against its elapsed time from January 1st (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 1st, 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 1st, frost interval rises steadily until approximately April 10th; levels off during the summer, and then begins to rise again by about October 15th. In addition, when frost interval is compared to cumulative rockslide count, it is evident that the rate of rockslide incidence decreases sharply in mid-April, about the same time that frost ceases to be a factor. This strongly suggests that frost is a triggering factor; however, a more detailed look at freeze/thaw cycles is required to establish a trigger threshold.

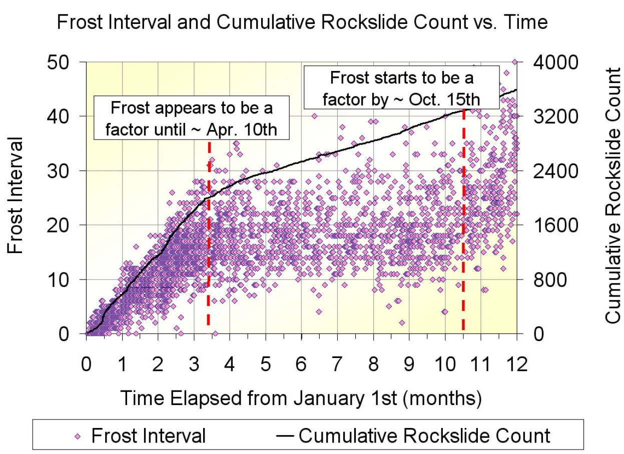

Figure 3. Graph of derived frost interval variable

4 METEOROLOGICAL TRIGGER ANALYSIS

4.1 Dynamic Weather-Dependent Trigger Map

The purpose of the weather-dependent trigger map is to highlight areas that are in danger of failing 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.

The planned trigger map will be a raster grid with 1 km^2 cells, colour-coded to display varying levels of threshold exceedance. The Norwegian Public Road Administration is currently developing such a map for debris flows, using a runoff threshold specified by Sandersen et. al. (1996). The same approach will adopted for the proposed trigger map, with established thresholds for rockslides. Research describing the establishment of these thresholds is given below.

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). The mean monthly temperature and precipitation shown here represent the average conditions for the entire study area, which were obtained by taking the statistical mean of monthly observations from 37 spatially distributed weather stations in the region.

The first observation from Figure 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. The resulting rain-on-snow produces extreme runoff that triggers a high frequency of rockslides. This observation correlates well to previous research by Sandersen et. al. (1996).

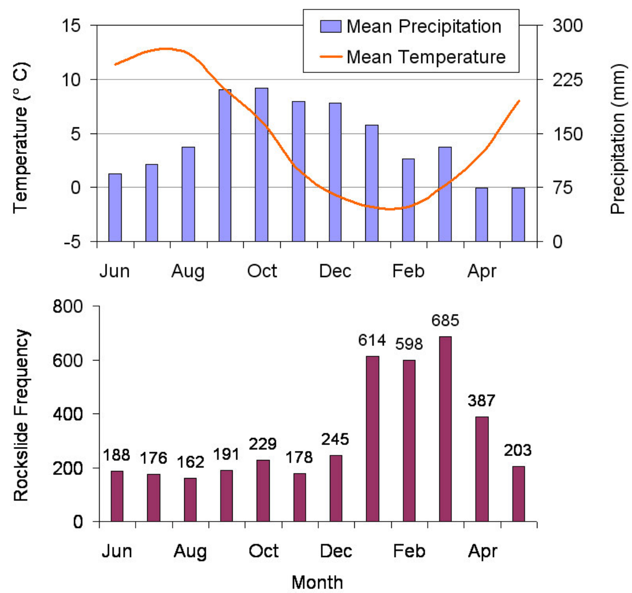

Figure 4 (top) Mean monthly precipitation and temperature (bottom) number of recorded slides by month

Furthermore, 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 snowfall, exhibit a much lower incidence of rockslides. Even the wettest months in autumn show little response to rockslide triggering. This observation suggests that runoff due to snowmelt, coupled with rainfall, is a factor that triggers more rockslides than rainfall alone.

4.3 Daily Rockslide Count

In order to further examine rockslide trends, a histogram of the daily rockslide count between 2000 and 2005 was generated (Figure 5).

Figure 5 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 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 87 times between 2000 and 2005 (5% of total days), yet they account for about 33% of all recorded rockslides.

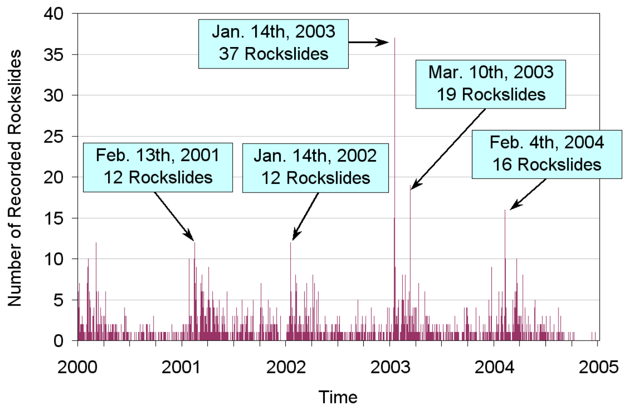

Figure 5. Number of rockslides recorded each day between 2000 to 2005 (the 5 most extreme days are highlighted)

4.4 Sandane Meteorological Analysis

A smaller study area contained within a 25 km radius around the Village of Sandane in Sogn og Fjordane, shown in Figure 6, was chosen for a detailed meteorological trigger analysis. This site was chosen because there is consistent and complete weather data from the Sandane weather station and the high frequency of slides in the region. In total, there are 98 winter rockslides used in this analysis.

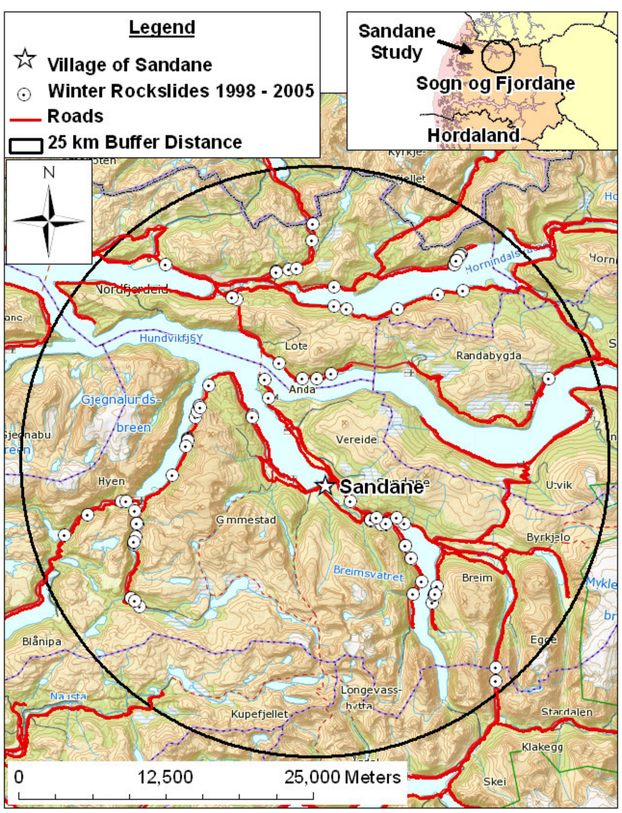

Figure 6. Sandane study area

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 climate station (ex. Figure 7). 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.

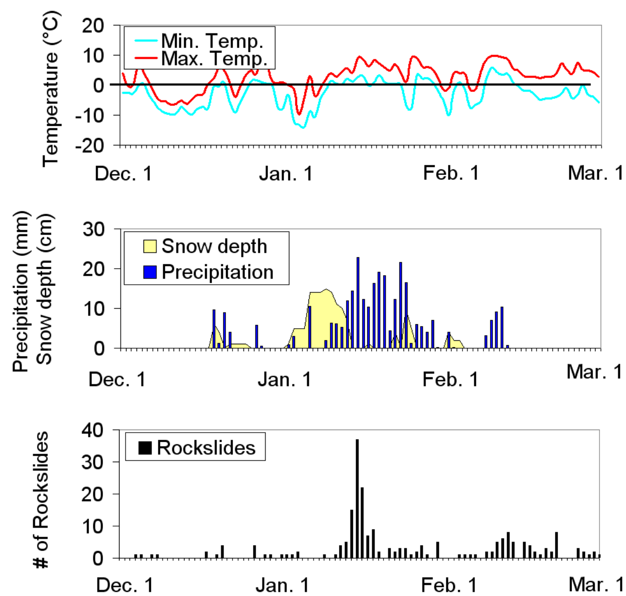

Figure 7. Example of daily weather data from Sandane weather station for winter 2002/2003 (top) maximum and minimum temperature (middle) precipitation and snow depth (bottom) daily rockslide count.

5 RESULTS AND DISCUSSION

Of the 98 rockslides studied in the Sandane climate analysis, it is estimated that 78 were triggered by runoff and 13 were triggered by frost wedging. The remaining 7 rockslides did not have a discernible meteorological trigger. Table 1 contains complete results of the Sandane meteorological trigger analysis.

5.1 Rockslides Triggered by Runoff

Taking a closer look at the slides triggered by runoff, it is evident that the majority (73%) occurred after a recent thaw (i.e. the maximum and minimum temperatures had risen above 0°C within the last 4 days). Braathen et. al. (2004) states 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 pore 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).

Table 1. Results from the Sandane Meteorological Trigger Analysis

Meteorological Conditions		**Condition Occurrence (days)**	**Number of Slides**	**Number of Slides per Trigger**		
Temperature	**Rainfall**			**Runoff**	**Freezing (Frost Wedging)**	**Unknown**
Above 0℃ *with recent thaw*[1]	Dry or light rain	84	11	57	-	-
	Light rain on snow	23	6			
	Heavy rain[2] on bare ground	13	1			
	Heavy rain on snow	10	13			
	Sustained heavy rain[3] on snow	6	26			
Above 0℃ *sustained*	Light rain on snow	18	1	21	-	-
	Heavy rain on bare ground	57	4			
	Heavy rain on snow	5	4			
	Sustained heavy rain on bare ground	20	3			
	Sustained heavy rain on snow	11	9			
Below 0℃ *freezing*	After light runoff	25	6	-	13	
	After heavy runoff	4	1			
	After sustained heavy runoff	7	4			
	Dry	45	2			
Unspecified	Dry or light rain	279	7	-	-	7
-	**Total**	**596**	**98**	**78**	**13**	**7**

[1] maximum and minimum temperatures have risen above 0℃ 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

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. Fifty-nine of the 78 runoff-triggered slides (76%) occurred during rain-on-snow conditions, even though rain-on-snow only occurred 30% of the time. A general trend observed was that rockslides can be triggered by rain-on-snow up to 4 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 the snowpack becomes fully saturated after the first few days, the runoff produced accelerates and more rockslides are triggered.

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 3 days or more. It was observed that a 3-day 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 35 of the 98 slides (36%).

5.2 Rockslides Triggered by Frost Wedging

Of the 13 rockslides triggered by frost wedging, only two occurred during dry conditions. The remaining 11 slides were accompanied by the supply of water. In each of these 11 cases, the slide occurred within two days of the temperature dropping below 0℃, 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℃, 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.

6 FUTURE WORK

6.1 Meteorological Trigger Thresholds

The next step in this research is to establish meteorological trigger thresholds. This will require a statistical analysis of each group of triggers developed from the Sandane study. An important fact to incorporate in this study is that different climatic regions have different tolerances to runoff (i.e. a slope in an area with high annual precipitation can tolerate more precipitation than a drier area of the same slope) (Sandersen, 1996). Therefore, the runoff threshold should be represented as a ratio of antecedent runoff divided by the average annual precipitation, in order to normalize the data spatially. In addition, the effect of a recent thaw is important to triggering, so a temperature change component may be added to the threshold.

Since frost wedging is dependent on available water, a frost wedging threshold will also incorporate both temperature change and water supply.

6.2 Rockslide Susceptibility Map

Presently, detailed rockslide susceptibility maps for the study area are not available. Due to the rockslide source zone location error described in Section 2.1.1, the preparation of a large-scale susceptibility maps are not feasible. For this reason, a regional rockslide susceptibility map is being prepared for the 2000 km^2 Sandane study area (Figure 6). This map is being prepared to demonstrate the usefulness of the dynamic mapping approach shown in Figure 1. In practice, a rockslide susceptibility map of the entire study area (Sogn og Fjordane and Hordaland) would exist for the methodology to function to its highest potential. However, this process is beyond the scope of the work reported here, and is left to the work of others.

The Sandane mapping will be prepared using a statistical, weight-of-evidence approach. In order to perform an accurate statistical analysis, a new rockslide inventory that corrects for location error is being created. The new inventory will consist of 98 winter rockslides that have been relocated to their respective source zones. This is accomplished by using Sesam 3D technology (*http://kart.sesam.no/3d*) to inspect air photos that have been draped on a triangular irregular network (TIN).

The bivariate approach will function by assigning weights to each class of the parameter maps given on the right side of the flow chart in Figure 1. Weights are determined with the support of GIS, which is used to calculate the rockslide density per parameter class and then comparing it to the rockslide density over the entire area (Soeters and Van Westen, 1996). The output will be a colour-coded raster grid with 25 m^2 cells.

It should be noted that the 98 rockslides used for this analysis do not constitute a full rockslide inventory of the area, and should not be considered to represent a comprehensive rockslide susceptibility map. The purpose of creating this map is to demonstrate the effectiveness of the mapping methodology laid out in Figure 1.

6.3 Climate Change Effects

An ensemble of downscaled climate scenarios has been completed by 'met.no'. These studies compare two different atmospheric-ocean general circulation models (AOGCMs) that have been dynamically downscaled with the regional HIRHAM climate model (Christensen et. al., 2007). The ensemble includes runs of three different emission scenarios defined by the Intergovernmental Panel on Climate Change (IPCC): IS92a (for years 2030-2049), A2 (years 2071-2100) and B2 (years 2071-2100).

The results of these scenarios indicate that south western Norway will experience a rise in mean annual temperature by about 2°C and an increase in precipitation by about 10-20%. The effects of these changes on day-to-day weather conditions will be studied and inferences will be made to its effects on rockslide triggering.

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