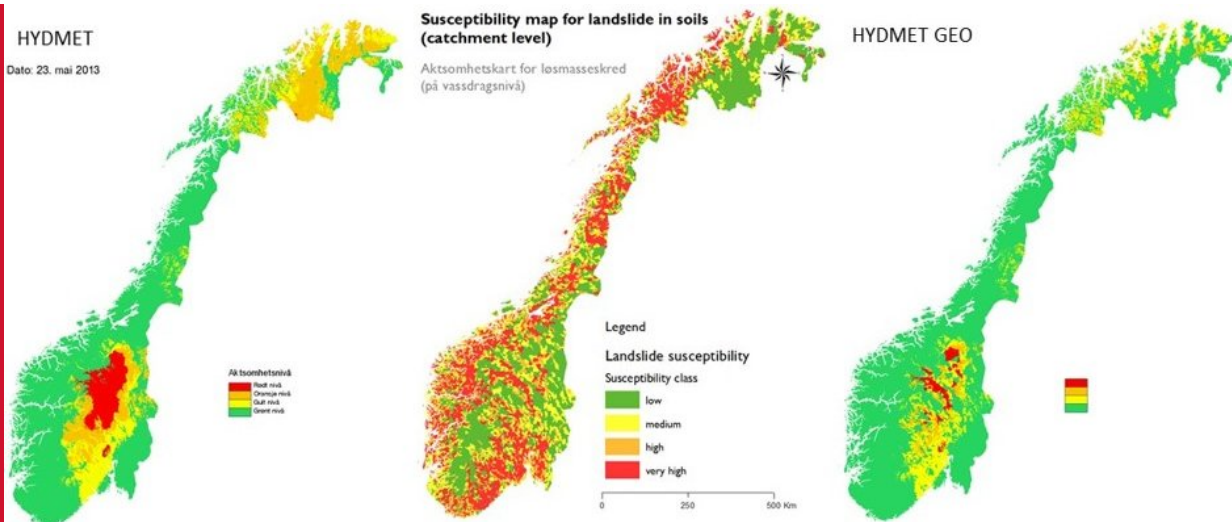


Susceptibility map at catchment level, to be used in landslide forecasting, Norway

Aktsomhetskart for løsmasseskred på nedbørfeltnivå for jordskredvarsling
Graziella Devoli (NVE), Rainer Bell (UIBK), José Cepeda (NGI)

HYDMET

Dato: 23. mai 2013



Hydro-Meteorological
(Hydmet) Index

Landslide susceptibility				
	Low (1)	Moderate (2)	High (3)	Very high (4)
low	1	1	1	2
moderate	1	2	2	2
high	1	2	3	3
very high	2	2	3	4

Rapport nr. I-2019

Susceptibility map at catchment level, to be used in landslide forecasting, Norway

Published by: Norges vassdrags- og energidirektorat
Editor: Graziella Devoli
Author(s): Graziella Devoli (NVE), Rainer Bell (UIBK), José Cepeda (NGI)

Printing: NVEs hustrykkeri
ISBN: 978-82-410-1800-8
ISSN: 1501-2832

Summary: A national “susceptibility map for landslides in soils at catchment level” was prepared, to be used in the landslide forecasting and warning service at NVE. The map was elaborated by combining five regional susceptibility assessments and maps carried out between 2013 and 2017 in five regions. This report presents the map and summarize the data and methods used to perform the regional analyses. The document also shows how the map is daily combined with the landslide thresholds, to prepare new national thresholds that take into account the landslide spatial probability.

Keywords: susceptibility map, machine learning, global additive models - GAM, landslide warning, landslide thresholds, aktsomhetskart, jordskredsvarsling

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January 2019

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Preface

It has been recognized for years, how important susceptibility maps are in the initial phase of the landslide hazard and risk assessment, since they provide a general overview, to the stakeholders and users, where landslides may form or are expected. However, these maps have always been seen as a valuable tool especially for land planning.

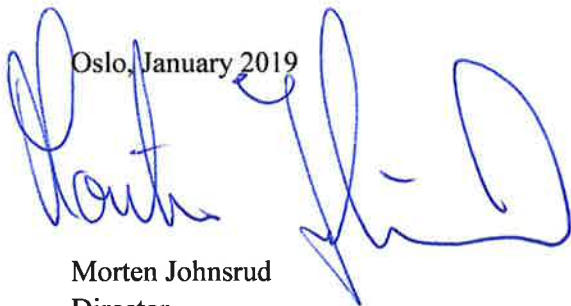
With the growing organization worldwide of early warning systems at national and regional level, many researchers recognize that susceptibility maps could also be used to improve the spatial resolution of rainfall thresholds, and provide a more dynamic hazard assessment.

This document synthesizes the work done in the last 5 years that culminated with the elaboration of a national susceptibility map for landslides in soils at catchment level, currently in use in the daily forecast of rainfall-induced landslides in Norway.

The Norwegian Water Resources and Energy Directorate (NVE) has collaborated with Rainer Bell, professor at University of Innsbruck (UIBK, Austria), and the Norwegian Geotechnical Institute (NGI, Norway) to produce the landslide susceptibility map herein presented.

We would like to thank Eli Øydvin and Delia Kejo from the Section for Hazard Mapping of NVE for the constructive discussion during the final edition of this report. Rengifo Ortega and Ivar Peereboom from the Geoinformation section at NVE helped, in different stages of the project, to make available the susceptibility map at xgeo.no, while Jess Andersen from the Hydro Informatics section at NVE worked to combine the susceptibility map with the threshold map to create the new threshold (Hydmet GEO). The contribution of J. Cepeda in the preparation of this report (excluding appendices) was funded by the innovation Centre Klima 2050 (www.klima2050.no).

Oslo, January 2019



Morten Johnsrud
Director



Hervé Colleuille
Head of section

Sammendrag

Den nasjonale “Aktsomhetskart for løsmasseskred på vassdragsnivå” (på engelsk “susceptibility map for landslides in soils at catchment level”) ble utarbeidet for å støtte Jordskredvarslingen i NVE. Varslingen startet i 2011 i en test fase, og var offisielt operativ i oktober 2013.

Aktsomhetskart ble utarbeidet med å kombinere aktsomhetsanalyser og aktsomhetskartene laget separat for fem regioner i Norge (Nord Norge, Trøndelag, Vestlandet, Østlandet og Agder) i perioden 2013 - 2017.

Denne rapport presenterer kart og oppsummere data og metoder brukt for å gjennomføre regionale analyser og kartene. Dokumentet viser også hvordan aktsomhetskartet brukes til å forbedre de eksisterende tersklene, Hydmet. Aktsomhetskartet kombineres daglig med tersklene kart og forberedes et nytt tersklene kart, Hydmet GEO som tar hensyn til jordskreds romlig sannsynlighet. Til slutt viser vi også hvordan de to eksisterende aktsomhetskart, for løsmasseskred, og for jordskred og små flømskred, brukes i ulike faser av varslingstjeneste.

Summary

A national “susceptibility map for landslides in soils at catchment level”, called in Norwegian “Aktsomhetskart for løsmasseskred på vassdragsnivå” was prepared for Norway, to be used in the landslide forecasting and warning service at NVE, that started to operate in 2011 as testing phase, and later officially operational in October 2013.

The map was elaborated by combining five regional susceptibility assessments and maps carried out between 2013 and 2017 in five regions.

This report presents the map and summarizes the data and methods used to perform the regional analyses. The document also shows how the national susceptibility map is being used to improve the existing thresholds, used in the prediction of rainfall-induced landslides. In agreement with other authors, we also recognize that a map that combines spatial and temporal landslide probabilities could assist landslide forecasters in their daily predictions, for this we show how the susceptibility map is daily combined with the landslide thresholds, to prepare new national thresholds that take into account the landslide spatial probability. Finally, we show also how the two available susceptibility maps for landslides in soils and for debris avalanches and debris flows are incorporated in the different stages of the early warning system.

1 Introduction

Landslide susceptibility is defined as “the likelihood of a landslide occurring in an area on the basis of local terrain conditions” (Brabb, 1984).

1.1 Landslide susceptibility maps and their use

A landslide susceptibility map (called “aktsomhetskart¹” in Norwegian) is a map that shows the areas where landslides may initiate (Guzzetti, 2006). In particular, following Corominas et al. (2014) “a susceptibility map subdivides the terrain into zones with differing likelihood that landslides of a certain type may occur”. The likelihood may be indicated either qualitatively (as high, moderate, low, and not susceptible) or quantitatively using indicators (e.g. as spatial probability, or as the density in number per square kilometers, or as the area affected per square kilometer).

Many different methods have been used to prepare susceptibility maps and a long list of articles have been written on this topic worldwide since the mid-1970s. Overviews of methods can be found in Soeters and Van Westen (1996), Carrara et al. (1999), Guzzetti et al. (1999), Aleotti and Chowdhury (1999), Dai et al. (2002), Chacón et al. (2006), Fell et al. (2008a and 2008b), Corominas et al. (2014), among others, and more recently in Reichenbach et al. (2018).

The choice of the most appropriate method(s) always depends on the purpose of the work, the extension of the area, the work scale, the resources available, and the data available. The methods are classified in qualitative (inventory-based and knowledge driven methods) and quantitative (data-driven methods and physically based models) methods, as shown in Figure 1.

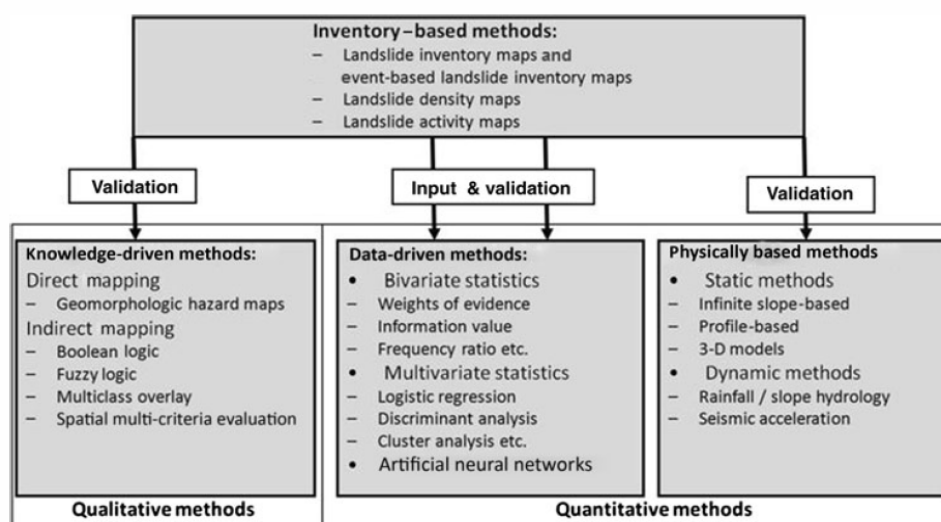


Figure 1. Overview of methods for susceptibility and hazard assessment (from Corominas et al., 2014).

¹ Aktsomhetskart viser områder hvor skred potensielt kan forekomme på grunn av lokale terrengforhold (topografiske og geologiske forhold). I et aktsomhetskart kategoriseres områder som enten stabile eller ustabile og ofte blir alle områder gitt en grad av aktsomhet (fra lav til høy). Aktsomhetskartene produseres for ulike formål og med ulike målestokk (NVE, 2011).

Different scales of work can be used for susceptibility analyses, from the local to the continental scale (i.e. Gokceoglu et al. 2005; Van Den Eeckhaut et al. 2012), but in general, national (1:250,000) and regional (1:250,000–1:25,000) scales are the most used. Landslide susceptibility assessments are usually accomplished with the aid of geographical information systems (Bonham-Carter 1994) but also other software can be used (Akgun et al. 2012).

The susceptibility maps are usually prepared in the initial phase of the landslide hazard and risk assessment, when we want to address the question “*Where a specific landslide type may occur based on the local terrain conditions?*”. Susceptibility maps, at national scale, are created to provide a general overview to the national policy makers and the public showing where the possible landslide-prone areas are located within the country (Soeters and van Westen, 1996). Maps prepared at regional scale are typically suited to the activities of planners in the early phases of regional development projects or for engineers evaluating possible constraints due to instability in the development of large engineering projects and regional development plans (Soeters and van Westen, 1996). In recent years they have become useful tools for landslide early warning systems, especially for rainfall-induced landslides² at national or regional level.

A worldwide overview of the existing local and territorial landslide early warning systems is presented in Stähli et al. (2015) and Piciullo et al. (2018). The Norwegian Landslide Forecasting and Warning Service, example of territorial system, operates at the Norwegian Water Resources and Energy Directorate (NVE), since 2011, and uses rainfall thresholds to forecast the temporal occurrence of landslides triggered by rainfall and snowmelt (Krøgli et al., 2018).

Rainfall thresholds and susceptibility maps are traditionally created independently for different needs. Landslide susceptibility maps relate landslide occurrence to the conditioning factors (e.g., morphometry, lithology, and land use), and are mainly used for spatial assessment in land management. They are static products that provide a detailed quantitative or qualitative scenario with a good spatial resolution, but they do not contain information on when landslides will be triggered (Segoni et al., 2015). On the other hand, rainfall thresholds relate landslide initiation with the main triggering factor (rainfall). They are used for temporal forecasting and for warning purposes by national and regional forecasting services to predict the temporal occurrence of landslides and have a good temporal resolution. However, they do not provide detailed indication on where a landslide might take place.

Some authors like Hong and Adler (2008), Bai et al. (2010 and 2012), Segoni et al. (2015), Jemec Auflič et al. (2016), Thiebes et al. (2017), Wei et al. (2018), Kirschbaum and Stanley (2018) and Segoni et al. (2018) recognized that combining rainfall thresholds with information on landslide susceptibility may improve the spatial resolution of rainfall thresholds, and thus give a more dynamic hazard assessment. According to Thiebes et al. (2017), even if there is no general consensus on how susceptibility maps and landslide triggering rainfall thresholds should be combined, a map combining spatial and temporal

² The term “rainfall-induced landslides” is used herein to refer to landslides in soils, mainly debris flows, debris slides, soil slides, and debris avalanches triggered by rainfall episodes, sometimes in combination with snowmelt.

landslide probabilities could assist both landslide forecasters in their daily predictions and therefore spatial planning, as well as civil protection agencies and the general public to deal with landslide hazards.

In Norway, the necessity to combine the spatial landslide probabilities and landslide thresholds was evident already in 2012. The experience acquired at NVE, during the testing phase of the landslide forecasting service (2011-2012), put in evidence that the threshold map has a tendency to overestimate the danger level in the so-called non-susceptible areas, like the Finnmark plateau in Finnmark county, in the north of Norway, and other areas in the south of Norway, where it is known that the areas are predominantly flat and/or with a reduced amount of sediments. In addition, during a project carried out in 2011-2012 by NVE and Norwegian Geotechnical Institute (NGI) to improve landslide thresholds in Norway, Cepeda et al. (2012) suggested that the “landslide dataset used in the thresholds analysis will benefit from additional features for their characterization (at least qualitatively) like landslide susceptibility, magnitude (volume or area) and intensity (depth and velocity)... These features would allow for the establishment of a more objective threshold levels that could correspond to boundaries between different levels of susceptibility, magnitude, or intensity”. During this period, a preliminary regionalization of Norway was also done using a simple heuristic approach (Devoli & Dahl, 2014) with the purpose of identifying which regions may be more prone to rainfall-induced landslides. However, the resolution of this map was too coarse to be used to improve the threshold and it was clear that a more quantitative-based susceptibility assessment would be necessary. Therefore, a map derived from statistical analyses on a regional scale, better if at catchment level, would be a better product.

1.2 Objectives of this report

The main objective of this report is to present the **national susceptibility map for landslides in soils³ at catchment level, *Aksomhetskart for løsmasseskred⁴ på vassdragsnivå*** in Norwegian. The map was obtained by combining five regional susceptibility assessments and maps carried out between 2013 and 2017 in five regions in Norway. The map is a result of a collaboration between NVE, Rainer Bell (previously working at the University of Vienna, Austria, during these projects) and NGI. This report summarizes also the data and methods used to perform the regional analyses and presents the original technical notes as appendices (Bell et al., 2014; Bell & Cepeda 2014, Bell & Cepeda 2015 and Bell & Cepeda, 2017).

The report shows how the national susceptibility map for landslides in soils at catchment level is being used to improve the prediction of rainfall-induced landslides. We describe also how the map is daily combined with the landslide thresholds, to prepare new national thresholds that take into account the landslide spatial probability. Finally, the report indicates how the national susceptibility map for landslides in soil at catchment level can coexist with other susceptibility maps, like “the national susceptibility map for debris avalanches and small debris flows”, “*Aksomhetskart for jordskred og små flomskred*” in Norwegian, prepared by Fisher et al. (2014).

³ Landslide in soils: General term that refers to all landslide types in which the material involved is described as engineering soils.

⁴ Løsmasseskred: Fellesbetegnelsen for alle skred i løsmasser.

2 The susceptibility map for landslides in soils

The **national susceptibility map for landslides in soils at catchment level**, *Aksomhetskart for løsmasseskred på vassdragsnivå*, is presented in Figure 2. The map shows which 1st order catchments areas are more susceptible to landslides in soils. With the term landslides in soils we included the following landslide types: debris slides, debris avalanches, debris flows and clay slides (quick clay slides are excluded). The map shows the degree of modelled spatial probability at catchment level, expressed in susceptibility classes. The susceptibility is divided into 4 classes, low, medium, high, and very high, which can be represented using a code value from 1 to 4. The map shows also clearly which areas in the country are less prone to landslides due to topographic and geological conditions.

The map was prepared by combining five susceptibility maps made separately for five regions in Norway, during the period 2013-2017. The project, data and methods used in the susceptibility assessments are briefly described in the following chapters and more details can be found in the Appendices A-D.

2.1 About the project

In 2011, the Norwegian Water Resources and Energy Directorate (NVE) started the organization of an operational Norwegian Landslide Forecasting and Warning Service (known as “Jordskredvarslingen”) (Krøgli et al., 2018), developed as a joint initiative across public agencies between the Norwegian Meteorological Institute (MET), the Norwegian Public Road Administration (NPRA) and the Norwegian Rail Administration (Bane NOR) with the purpose to issue warning for rainfall-induced landslides.

As part of the organization of this service, NVE ran two internal research projects between 2013 and 2017, “Beslutningsverktøy for varsling av løsmasseskredfare (project # 302H24/81024, 200903463-14)” and “Pålitelig varsling av regional jord- og flomskredfare (project # 80126, 201602064)” with the main purpose of producing reliable and high quality tools to be used in the landslide early warning system. One of the goals was to improve the landslide thresholds map (called also Hydmet map), by including the landslide spatial probability. It was thus decided to prepare a susceptibility map for landslides in soils at national scale, using the 1st order catchments, as terrain unit. The first susceptibility model was tested in the region of Western Norway in Cepeda et al. (2012). Following this first promising result, the susceptibility analyses were performed separately for five regions:

- Northern Norway = Nord Norge
- Central Norway = Trøndelag
- Western Norway = Vestlandet
- Eastern Norway = Østlandet
- Southern Norway = Agder

Susceptibility map for landslides in soils at catchment level

Aktsomhetskart for løsmasseskred
på vassdragsnivå

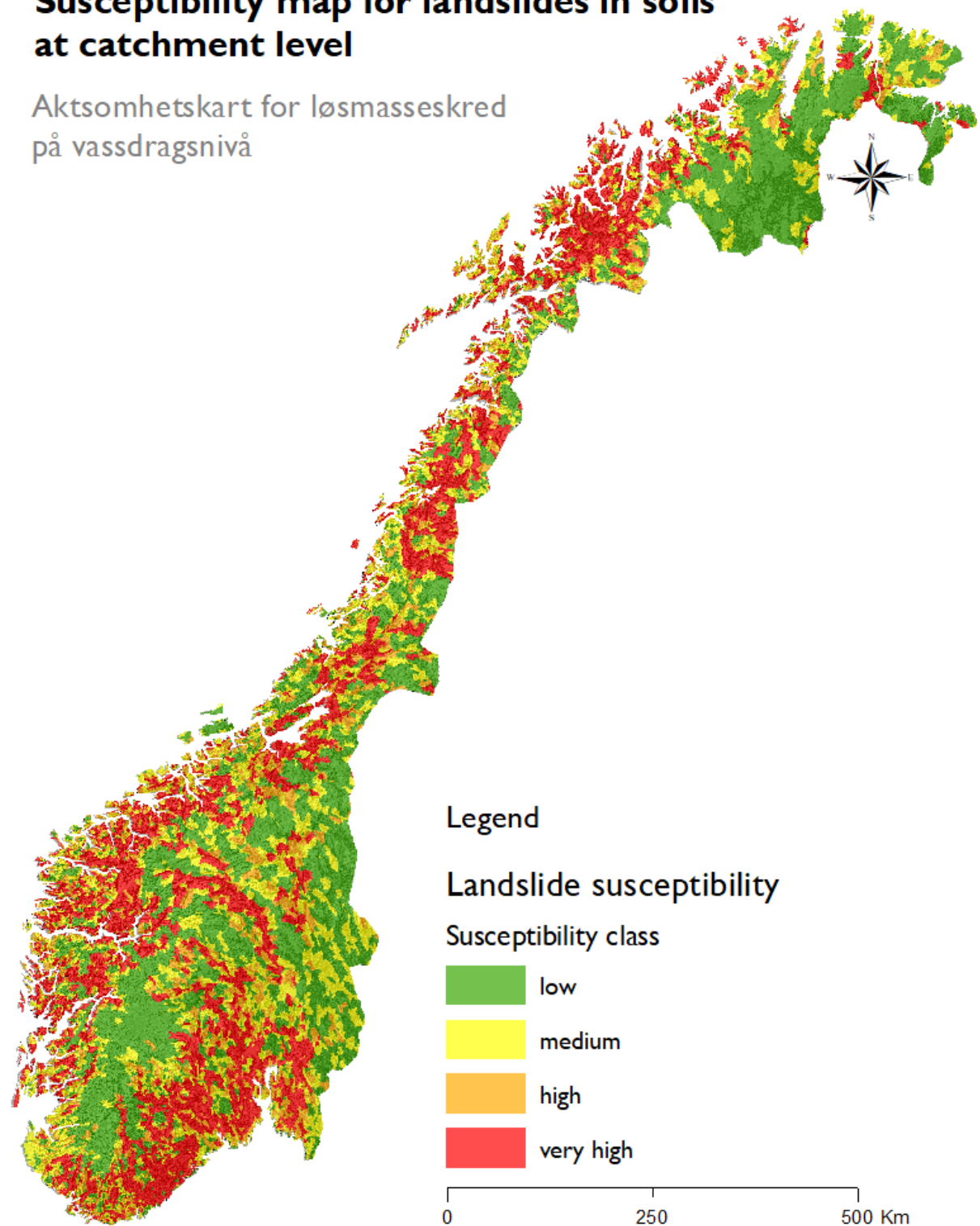


Figure 2. Susceptibility map for landslides in soils for the whole Norway. The hillshade is used in the background.

Five susceptibility assessments were carried out and five susceptibility maps for landslides in soils at catchment level were prepared for these regions. The first analysis started in 2013, modelling the susceptibility in the regions Northern and Eastern Norway (Bell et al., 2014, Appendix A). In 2014, the region Western Norway was modelled (Bell & Cepeda 2014, Appendix B), followed by the region Trøndelag in 2015 (Bell & Cepeda 2015, Appendix C), and finally Agder in 2017 (Bell & Cepeda, 2017, Appendix D). Five separated shape and raster files with the modelled spatial probability for each 1st order catchment (REGINE units) were prepared for these 5 regions. The national susceptibility map for landslides in soils at catchment level, herein presented, was prepared in December 2017, and is available in form of vector and raster map. The map can be visualized at xgeo.no under “support maps” and at nve.no.

2.2 Data

Because the ultimate goal was to improve the landslide early warning for the whole of Norway, only data sets available for the entire country were used for the susceptibility assessments. In particular, the following data were collected and analyzed: catchment units, historical landslide events, the Quaternary map, land cover, average annual rainfall, various water runoff variables, and various derivatives from the 15m x 15m digital elevation model (DEM) like e.g. slope and aspect.

2.2.1 1st order catchments (REGINE units)

The terrain units chosen to perform the analysis were the first order catchments (called herein the REGINE units). These were extracted from the REGINE database (national catchment database (<https://www.nve.no/karttjenester/kartdata/vassdragsdata/nedborfelt-regine/>; http://gis3.nve.no/metadata/produktark/produktark_regine.pdf)). From this database, the REGINE units can be extracted in form of vector polygons. The data stored in each REGINE unit used in susceptibility modelling are:

- REGINE unit area (km²),
- REGINE unit runoff 1961-1990 (million m³ per year),
- total upstream area (km²),
- total upstream runoff 1961-1990 (million km³ per year),
- average runoff 1961-1990 (liter/second km²)
- average runoff 1930-1960 (liter/second km²)

2.2.2 Landslide events

One of the most important data for landslide susceptibility modelling is the landslide inventory. Historical landslide events were obtained from the integrated national database for all types of rapid mass movements (www.skredregistrering.no; www.skrednett.no). The national database contains more than 60,000 events⁵ from the last five hundred years covering the whole country. The events are represented as point locations. The most frequent typologies are rock fall, rock slides and snow avalanches followed by debris slides. The majority of the entries result from events recorded by road authorities and railway authorities, but in recent years rainfall-induced landslides are also systematically recorded by landslide forecasters. The inventory has many limitations that should be taken into account in such analyses. Usually the landslide point is placed where the landslide hit the road or railway (Jaedicke et al. 2009) and this introduces large

⁵ Version from June 2018

inaccuracies when landslide susceptibility is modeled. In general, susceptibility modeling should be carried out using the locations of landslide initiation, especially when using pixel-based approaches. Other uncertainties result from errors in classifying the events as specific landslide types, from the lack of registration in some regions and from missing information on the slope itself, e.g. whether it occurred on an artificially cut slope or a natural slope. In spite of this, the inventory is the only countrywide available dataset. For this analysis, only landslides in soils (in Norwegian called “løsmasseskred”) were used. In particular, the events registered in the database with the following codes were extracted:

140: Landslides in soils, unspecified (*løsmasseskred uspesifisert*);

142: Debris flow/Debris flood (*flomskred*);

143: Clay slides (*leirskred*)

144: Debris avalanches/Debris- soil slide (*jordskred*).

The events registered as 141: quick clay landslides (*kvikkleireskred*) were excluded from this analysis because it is known that most of them are triggered by anthropic factors (for example, manmade fills placed at unfavorable locations on slopes (e.g., at the top of a slope)).

A synthesis of the number of events used in the regional analysis is presented in Table 1. Some events were excluded from the final dataset because they were not inside any REGINE units. This occurred in REGINE units bordering water bodies, fjords or the sea. The table shows both the initial and final number of landslide events used in the analysis. For each region the latest version of the national database was used according to the year when the susceptibility map was produced.

Table 1. Number of landslide events used in the regional datasets

Regions	Nord Norge	Trøndelag	Vestlandet	Østlandet	Agder
Final dataset	759	981; 1021 ⁶	2371	1419	273
Landslide points outside REGINE units		42			1
Initial dataset	759	1023	2371	1419	274
Date of downloading	Jan. 2013	28 th Oct. 2015	12th Nov. 2014	Jan. 2013	8 th Nov. 2017

2.2.3 Quaternary map

The Quaternary map at a scale of 1:250.000 was downloaded from www.ngu.no. The map shows the spatial distribution of the different type and subtypes of quaternary sediments separated based on their origin, and it also shows bare rock areas without sediments. The quality is rather heterogeneous with high level of detail in only a few areas.

2.2.4 Land cover data and hydrometeorological data

Land cover was obtained from the CORINE 2006 dataset, which was compiled by the Norwegian Forest and Landscape Institute (Aune-Lundberg and Strand 2010). Details are limited to a minimum mapping unit of 25 ha (0.25 km²).

⁶ Two datasets were used for this region (see chapter 3 and Bell and Cepeda, 2015, appendix C).

Spatially distributed average annual rainfall data (1961-1990) with a resolution of 1 km x 1 km were obtained from MET and www.senorge.no.

2.2.5 DEM derivatives

A digital elevation model (DEM) with a resolution of 15m x 15m was available for all of Norway, derived from 1:50:000 topographical maps. From this DEM, various derivatives were obtained like slope angle, slope aspect, etc. This resolution was initially used because it was the best available for whole Norway when the project started. At that time, only a 25m DEM could be provided for the entire country to NVE by Kartverk (the Norwegian Mapping Authority). At later stages of the project, a 10m DEM resolution became available at NVE, provided by Kartverk, but it was decided to continue using the 15m DEM resolution in order to be consistent with the three regions that had been already evaluated. Furthermore, the 15m resolution was considered acceptable for the regional scale of the warning system.

2.3 Method

The modelling of landslide susceptibility was carried out using the statistical approach of Generalized Additive Models (GAM) (Hastie 1992). A combined backward and forward stepwise variable selection in R, based on Akaike's Information Criterion (AIC) (Akaike 1974), was applied to fit the susceptibility models. Using the AIC, the best fit of variables for a model was automatically selected. For each variable, GAM decided whether a variable should be omitted, used linearly, or with a smooth function. Based on the AIC values GAM selected the model with the best combination of variables. In addition, a model run was carried out allowing only linear use of variables.

The landslide susceptibility was modelled at REGINE unit (catchment) level because this scale is sufficient for the regional nature of the landslide early warning. The main advantage is that the whole process area of the landslides is automatically considered and not only initiations areas modelled. The aforementioned poor spatial location of the landslide points of the landslide inventory does not matter anymore since it is assumed that all landslides are located in the same REGINE unit of the initiation areas. However, in some regions it was observed that some landslide points were located outside the units, in the nearest bodies of water, like lake, sea or fjords (Figure 3). In the case of Agder, the only event outside the REGINE units was deleted from the datasets (Bell & Cepeda, 2017, Appendix D). In the case of Trøndelag, the 42 events located marginally outside of the REGINE units were moved to the nearest REGINE unit and two datasets were prepared and used in the analysis (Bell & Cepeda, 2015, Appendix C). One dataset (dfssl15) with 981 events, not including the shifted landslides, and one dataset (dfssl15c) with 1021 events, including the shifted landslides (Table 1).

The modelling was carried out using a 1:1 relationship between REGINE units with landslides and REGINE units without landslides. In Table 2, we present a synthesis of the number of REGINE units with landslides used for the different regions. Figures 4 and 5 show examples of the spatial regional distribution of REGINE units with recorded landslides for three regions.

Additional models were calculated for validation purposes. Therefore, 50 % of the REGINE units with landslides were used in the train sample and the other 50 % in the independent test sample.

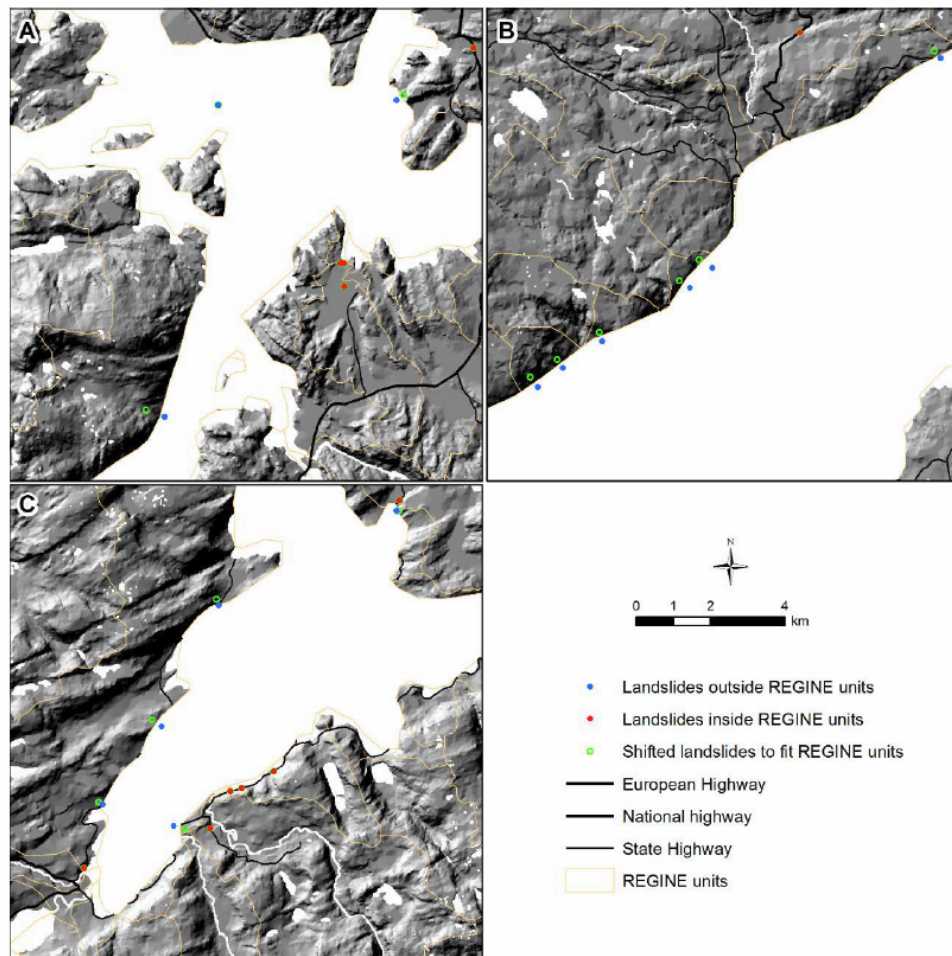


Figure 3. Example of landslide events outside the REGINE units (from Bell & Cepeda 2015, Appendix C)

Table 2. Summary of REGINE units with landslide events used in the analysis

Nord Norge	Trøndelag	Vestlandet	Østlandet	Agder
284	301; 318	801	536	152

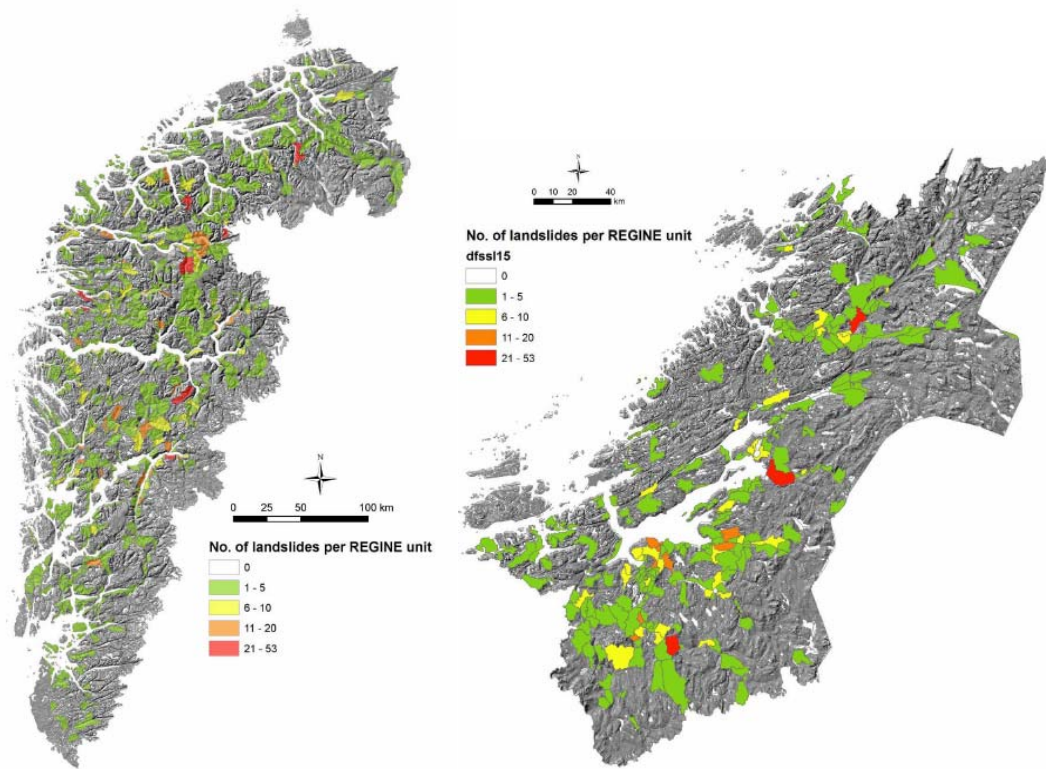


Figure 4. Distribution of landslide events per REGINE unit in Vestlandet (left, from Bell & Cepeda 2014, Appendix B) and Trøndelag (right, from Bell & Cepeda 2015, Appendix C)

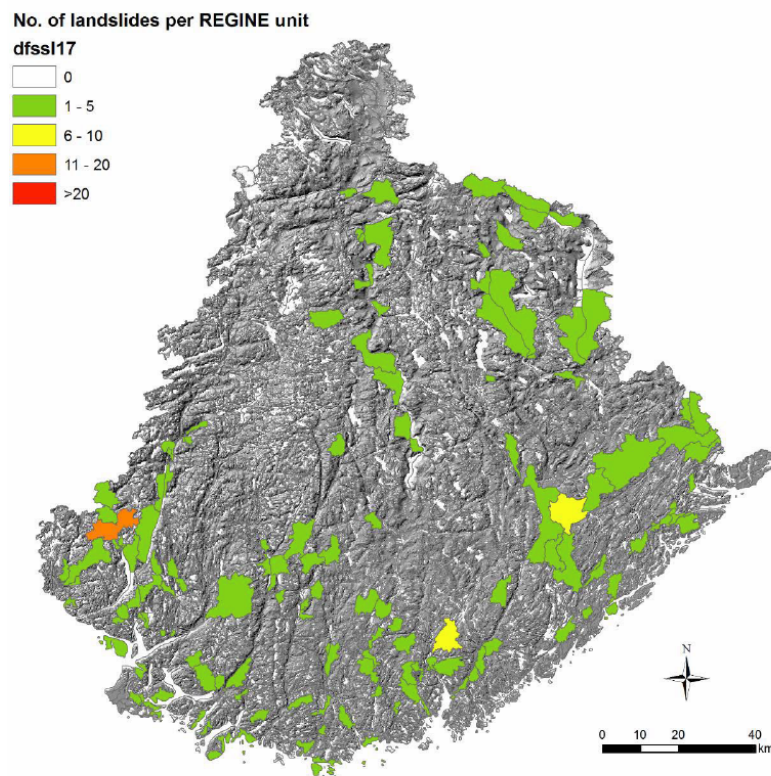


Figure 5. Distribution of landslide events per REGINE unit in Agder (from Bell & Cepeda 2017, Appendix D)

In the case of Trøndelag and Agder, it was decided to improve the validation step further by performing k-fold cross validations using randomly selected subsamples. The k-fold ($k = 4$) cross validations were applied which means that the data is subsampled in 4 subsets. Subsequently, the model is fitted to $k-1$ subsamples (training sample) and validated by the remaining subsample (testing sample). This was repeated four times until each subsample was used as testing sample. The whole process was repeated 10 times ($r = 10$) with new subsamples randomly selected during each repetition. Thus, in total 40 models are fitted and validated, calculating the median and interquartile range of the validation criterion.

For each dataset of Trøndelag and Agder the validation procedure was carried out using three different samples:

- a) All REGINE units available,
- b) A relationship of 1:1 between REGINE units with landslides and REGINE units without landslides, and
- c) A relationship of 1:5 between REGINE units with landslides and REGINE units without landslides.

The validation procedure was carried out using two different statistical methods (GAM and logistic regression).

Subsequently, all calculations were repeated for $k = 2$. Thus, in total 240 models using GAM and 240 models using logistic regression were calculated within this k-fold cross validation approach. k-fold cross validation was applied using the *sperrorest* package in R (Brenning 2012).

Table 3 summarizes the final models selected in the five regions. Before the Vestlandet susceptibility assessment in 2014, we recognized that we missed to model very few REGINE units for Østlandet in proximity of borders between these two regions. Thus, we only modelled these few missing REGINE units of Østlandet together with the Vestlandet units. Subsequently, we added the resulting REGINE units to the already existing Østlandet shape file produced in 2013.

An example of the different spatial probabilities obtained for the different models is presented in Figure 6.

Table 3. Summary of the final models used to calculate the susceptibility

Regions	Nord Norge	Trøndelag	Vestlandet	Østlandet	Agder
Number	4	16	4	4	6
Methods	GAM; logreg	GAM; logreg	GAM; logreg	GAM; logreg	GAM; logreg
Models names	nnsusc130610 pred1; pred05a; pred1dlg	dfssl15_1_gam1 dfssl15_1_gam1wlc dfssl15_1_logreg1 dfssl15_1_logreg1wlc dfssl15c_1_gam1 dfssl15c_1_gam1wlc dfssl15c_1_logreg1 dfssl15c_1_logreg1wlc dfssl15_05_gam1 dfssl15_05_gam1wlc dfssl15_05_logreg1 dfssl15_05_logreg1wlc dfssl15c_05_gam1 dfssl15c_05_gam1wlc dfssl15c_05_logreg1 dfssl15c_05_logreg1wlc	pred1a; pred1b; pred05a; pred1dlg	ostsusc140305 pred1; pred05a; pred1dlg ostsusc2015	dfssl17_1_gam_1 dfssl17_1_gam_2 dfssl17_1_logreg_1 dfssl17_05_gam_1 dfssl17_05_gam_2; dfssl17_05_logreg_1;
Finally selected model	nnsusc130610	dfssl15_1_gam1 OR dfssl15c_1_gam1	pred1a	ostsusc140305 ostsusc2015	dfssl17_1_gam_1

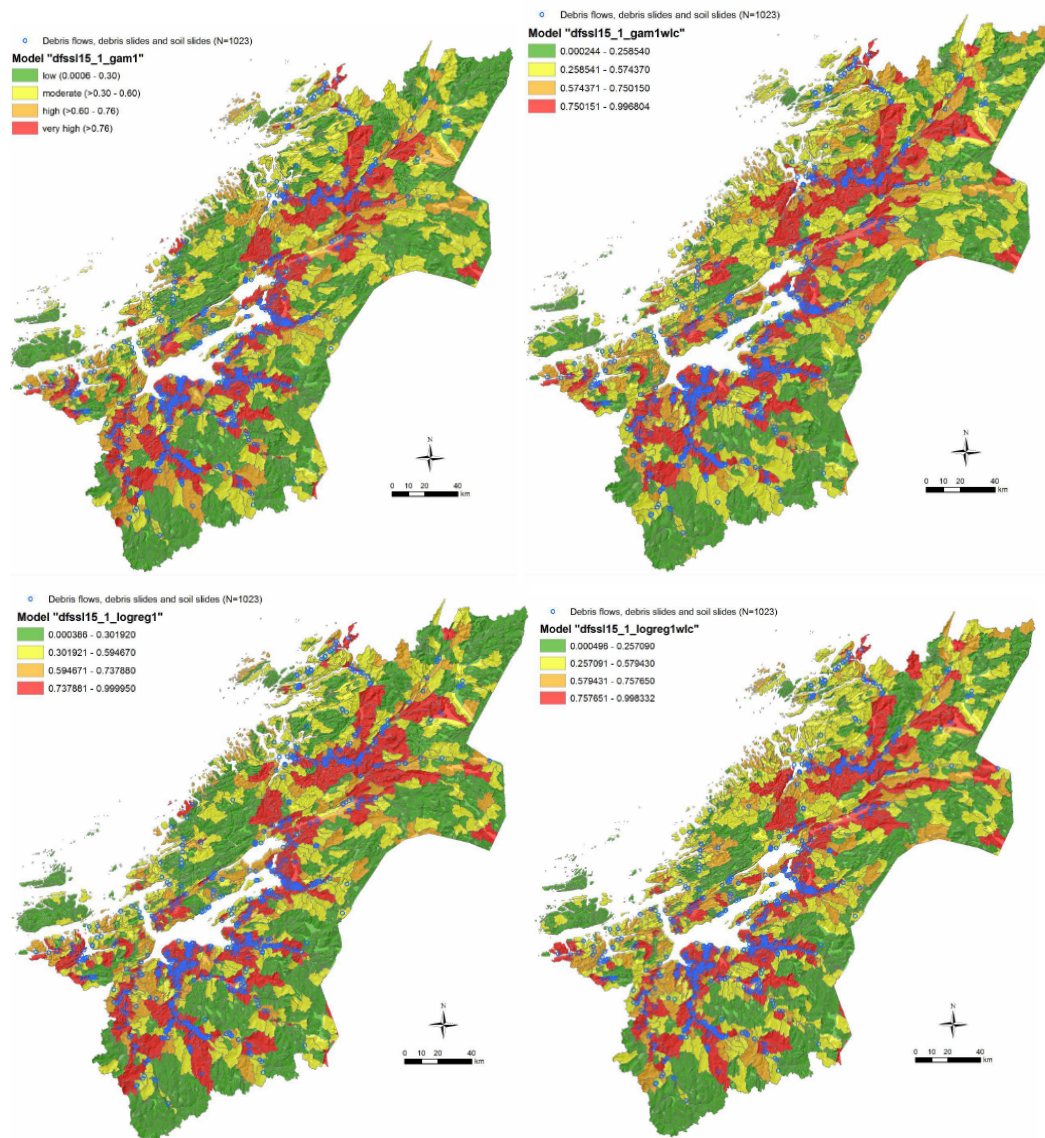


Figure 6. Susceptibility maps for Trøndelag, showing the model “dfssl15_1”. The word “gam” indicated that the GAM method was used to model the susceptibility, while “logreg” stands for logistic regression (from Bell & Cepeda 2015, Appendix C).

The explanatory variables were the geological units from the quaternary map, land cover, average annual rainfall, various water runoff variables, and various variables calculated from the 15m x 15m digital elevation model (DEM) like e.g. slope and aspect. For the categorical data, the proportion of each class in the catchment and for continuous data, either mean, median, standard deviation, or range for the catchment were calculated and used in the modelling.

Examples of variables used for the different assessment is shown in Figure 7, while the complete lists of selected variables for each regions can be found in the Appendices.

Selected variable	pred1a	pred1b	pred1dlg	pred05a
REGINE unit area	s	s	n	s
Total upstream area	s	-	-	s
Total upstream runoff 1961-1990	-	s	n	-
Average runoff 1961-1990	n	-	-	-
Mean slope	s	s	n	s
Elevation range	n	n	n	n
Mean of elevation	s	s	n	n
Moraine material, non-continuous/thin	n	n	n	s
Weathered material, unspecified	s	s	n	n
Bare rock	-	-	n	n
Hetrogenous agricultural areas, mainly farmland and natural vegetation	-	-	n	n
Moors and heath land	n	n	n	-
Open space with little or no vegetation	s	s	n	n
Forests	s	s	-	-

Figure 7. Example of variable used in the different models for Vestlandet. “s” = applied with a smoother function, “n” = without smother function, “-“ = not selected (from Bell & Cepeda 2014, Appendix B)

The performance of the resulting models and maps was evaluated using the area under the ROC curve AUROC (Figure 8) as criterion (values of 0.7 to 1 show good to very good discrimination between REGINE units with landslides and REGINE units without landslides) (Hosmer & Lemeshow, 2000).

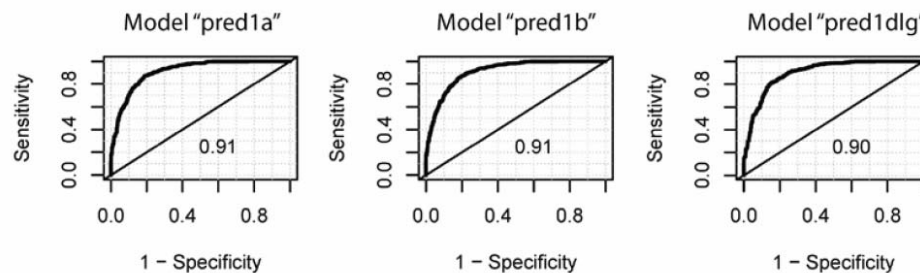


Figure 8. Example of ROC curves and AUROC values for some of the models used in Vestlandet (from Bell & Cepeda 2014, Appendix B)

Finally, landslide susceptibility was classified into four classes (low, moderate, high, very high), similar to the four classes used by the thresholds map at NVE. Classification thresholds were set based on the proportion of landslides in each class. In the first analyses of Nord Norge and Østlandet, three classification schemes were proposed: A) natural breaks; B) 40 %, 40 %, 15 %, 5% and C) 70 %, 15 %, 12 %, 3%, but in later analyses it was decided that only scheme C) would be used for all regions, and thus the national map. An example of the proposed classification schemes is presented in Figure 9.

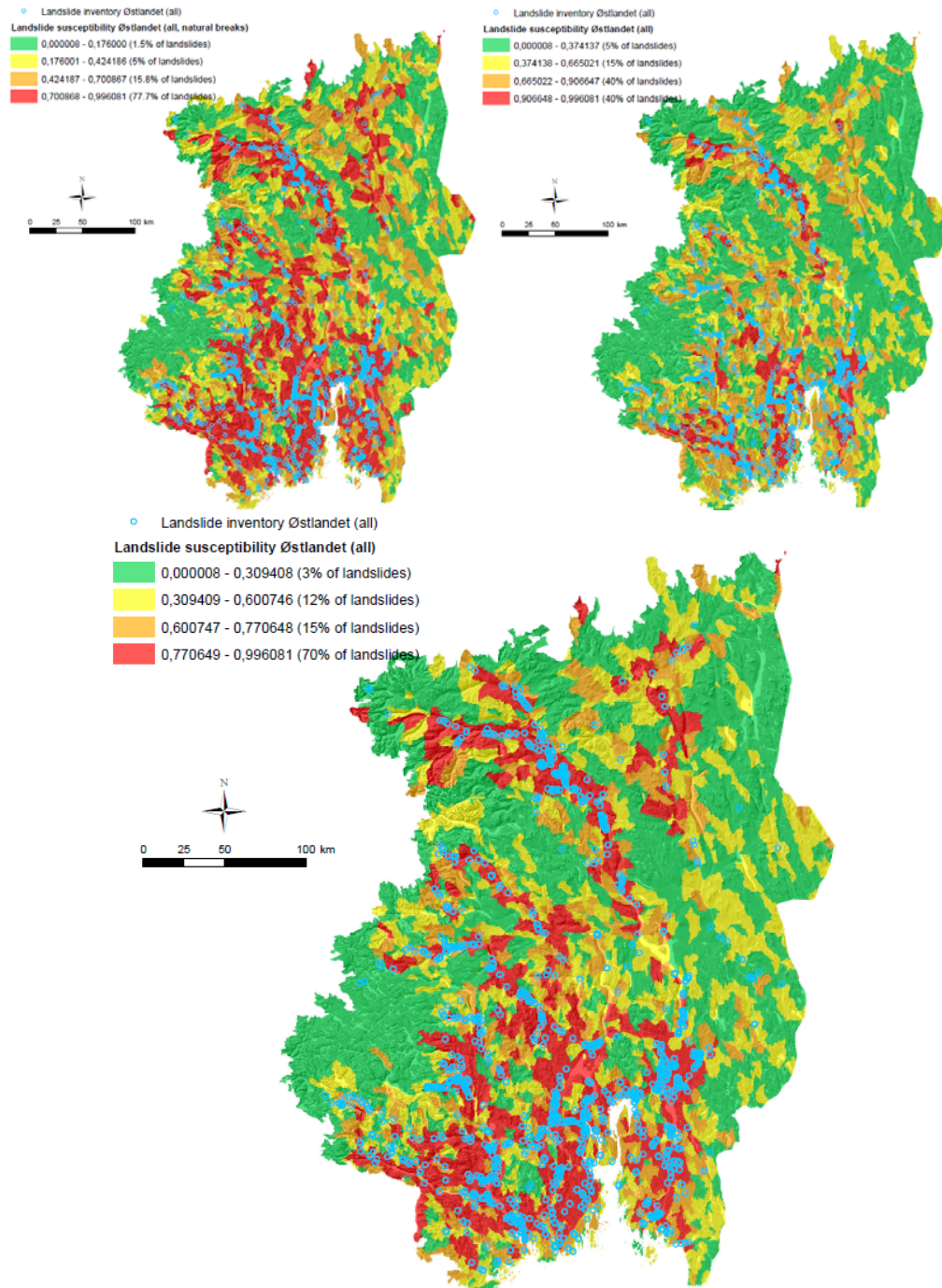


Figure 9. Example of the three landslide susceptibility classification schemes proposed for Østlandet. Upper left, natural breaks; upper right, scheme B (40 %, 40 %, 15 %, 5%) and center down, scheme C (70 %, 15 %, 12 %, 3%).

The final map (Figure 2) was prepared by combining the regional maps based on the susceptibility class. Since the reclassification of probability values into susceptibility classes is different for each region (i.e., a probability value that corresponds to a certain class in one region, might correspond to a different class in another region), all probability values were stored in separate fields of the attribute table according to the region.

3 The use of the map in the daily landslide forecasting

The map was prepared with the purpose to improve the landslide early warning at NVE and to be combined with the landslide thresholds map.

The Norwegian Landslide Forecasting and Warning Service operating at NVE uses rainfall thresholds to forecast the temporal occurrence of landslides triggered by rainfall and snowmelt (Krøgli et al., 2018). The service uses thresholds based on the combination of the relative water supply⁷ and the degree of soil water saturation⁸ (Krøgli et al., 2018). The thresholds (called Hydmet, i.e. “hydro-meteorological index”) are visualized in the form of raster map (called Hydmet map) (with 1km x 1km resolution) and are available at <http://www.xgeo.no>.

The threshold map (or Hydmet map) predicts where and when the landslide thresholds will be exceeded. Specifically, the map shows in which areas the combination of relative water supply and the degree of soil saturation will be exceeded for the coming days, indicating where landslides might occur (Figure 10).

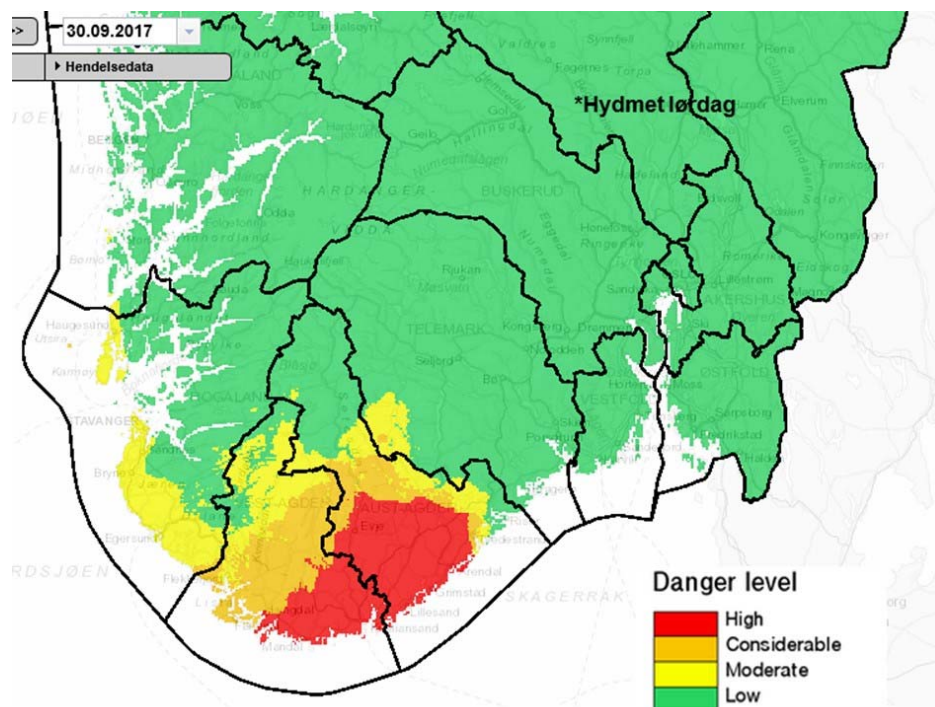


Figure 10. Example of the Hydmet map for the 30th of September 2017. Many landslides occurred on that date triggered by intense rainfall (from NVE internal archive and xgeo.no).

⁷ The relative water supply is calculated from simulated rain or snowmelt from the snowpack (in which rain may percolate), as a percentage of an annual average value for a 30-year period.

⁸ The degree of soil water saturation (%) describes the relationship between simulated total water content in the soil (groundwater and soil water) normalized by the maximum soil water content simulated for a 30-year period, which is assumed equal to a fully saturated soil. The 30-year reference period for both variables is 1981–2010.

Because of its nature, the map exclusively shows hydro-meteorological conditions and does not take into account whether an area is prone to landslides or not (i.e. it does not account for the presence of steep slopes or the availability of loose quaternary deposits).

To resolve this limitation, we have combined the **national susceptibility map for landslides in soils at catchment level, *Aksomhetskart for løsmasseskred på vassdragsnivå***, herein presented, with the thresholds map (Hydmet map), using a pixel-based approach. Therefore, the landslide susceptibility map was converted into a 1km x 1km grid. Subsequently, the raster of the Hydmet map and the susceptibility map are combined via a query using combination matrices.

Matrix approaches have been used for landslide susceptibility hazard and risk studies in various applications. A matrix approach has also been used recently to combine rainfall thresholds and susceptibility levels by other authors like Segoni et al. (2015), Thiebes et al. (2017), Wei et al. (2018), and Segoni et al. (2018). However, the selection of the best matrix is challenging, since the selected matrix has a huge impact on the final map.

For Norway, we have proposed 5 combination of matrices as presented in Figure 11.

Matrix M1				
Hydro-Meteorological (Hydmet) Index	Landslide susceptibility			
	Low (1)	Moderate (2)	High (3)	Very high (4)
	low	1	1	1
	moderate	1	2	3
	high	1	2	4
	very high	1	3	4

Matrix M2				
Hydro-Meteorological (Hydmet) Index	Landslide susceptibility			
	Low (1)	Moderate (2)	High (3)	Very high (4)
	low	1	1	2
	moderate	1	2	3
	high	1	3	4
	very high	2	3	4

Matrix M3				
Hydro-Meteorological (Hydmet) Index	Landslide susceptibility			
	Low (1)	Moderate (2)	High (3)	Very high (4)
	low	1	1	1
	moderate	1	2	3
	high	1	3	4
	very high	2	3	4

Matrix M4				
Hydro-Meteorological (Hydmet) Index	Landslide susceptibility			
	Low (1)	Moderate (2)	High (3)	Very high (4)
	low	1	1	1
	moderate	1	2	2
	high	1	2	3
	very high	1	2	4

Matrix M5				
Hydro-Meteorological (Hydmet) Index	Landslide susceptibility			
	Low (1)	Moderate (2)	High (3)	Very high (4)
	low	1	1	2
	moderate	1	2	2
	high	1	2	3
	very high	2	2	4

Figure 11. Proposed matrices for combining landslide susceptibility and thresholds maps in Norway.

The first combination of susceptibility map and threshold map was tested using two matrices, M1 and M2 (Figure 11), in Bell et al. (2014), Appendix A, for the Nord-Norge region (Figure 12). In this region we knew that the thresholds map had the tendency to overestimate the danger level, especially in the Finnmark plateau, a predominant flat area (Figure 12A), and considered as non-susceptible area for the topographic and geological characteristics. And we could not remove this overestimation from the Hydmet map without combine this map with a susceptibility map (Figure 12B).

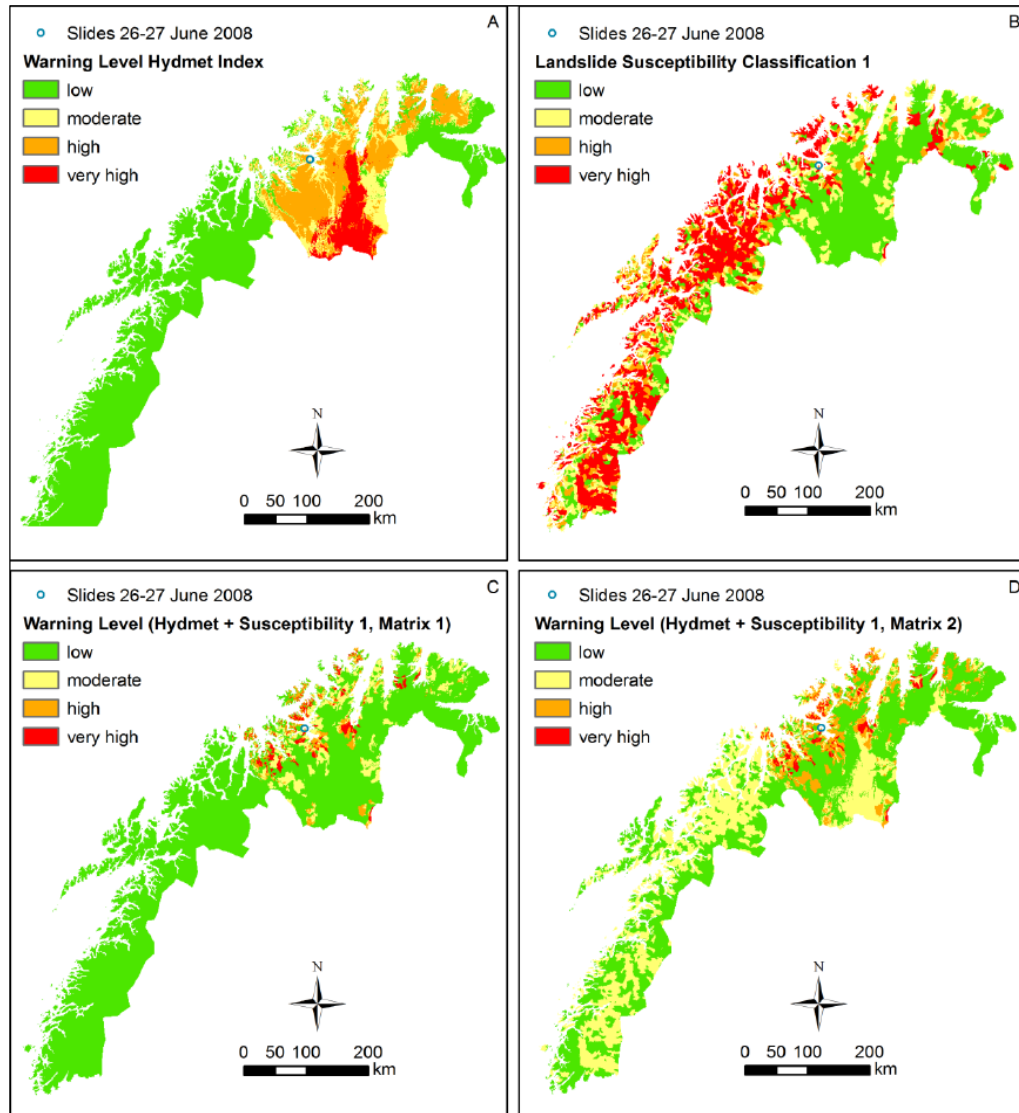


Figure 12. Example of combination of landslide threshold map (Hydmet map, upper left) and landslide susceptibility map (upper right) to obtain the new thresholds map (Hydmet GEO, lower right and lower left). (from Bell et al., 2014, Appendix A).

The resulting combination map (Figure 12C) succeed in “removing” the non-susceptible areas and provided a more realistic landslide susceptibility zonation. This combined map was the new threshold map (called Hydmet GEO) which was later implemented in the warning system, daily published at xgeo.no and used in the daily assessment.

Matrices M1 and M2 were derived using experience from applications in landslide risk assessments, combining landslide hazard and damage potential maps. In a reassessment of matrices M1 and M2 it seemed that these were too conservative for the application in landslide early warning systems. Thus, new matrices were developed. Matrix M2 was not used in the landslide warning because it was overly conservative showing far too many areas at higher warning levels. Matrix M1 was used during 2015 but showed too often very high level of landslide warning compared to the distribution of actual occurrences. Therefore we tried others combinations using matrices M3, M4 and M5.

Figures 13 and 14 show, for two selected dates, how the different Hydmet GEO maps can be obtained by combining the original Hydmet map (upper right) and the national susceptibility map for landslides in soils at catchment level (lower right) by using the 5 proposed matrices.

The Hydmet GEO derived from the combination using the M1 and M4 are the one that have been implemented in the operational service. The one derived from M1 was used during the year 2013-2015, while the one derived from M4 is the one in use at present. A new evaluation is under progress.

The examples herein presented are for two dates when many landslide events occurred and warnings were issued. The first example is from the 23rd of May 2013, when orange and red level was issued for the South-Eastern area in Norway. This case is presented in Devoli et al. (2018). The second case is from the 12nd of March 2012 when a yellow warning was issued for the Trøndelag and Møre og Romsdal area. This case is described in Væringstad and Devoli (2012). Both cases occurred when the forecasting service was still in a testing phase and not officially operational. Note that all threshold maps (original and new) presented in both figures show the observed landslide thresholds and not the forecasted thresholds for that specific date.

3.1 Use of different work-scale susceptibility assessments in landslide forecasting

Besides the map herein presented, there is a more detailed susceptibility map that is used in the daily landslide forecasting. The map, called “the national susceptibility map for debris avalanches and small debris flows”, “Aktsomhetskart for jordskred og små flomskred” in Norwegian, is described in Fischer et al. (2012 and 2014), and was specifically prepared for debris avalanches and small debris flows at regional scale (1:50 000). This map displays the modelled potential source areas, tracks, and runout areas. The source areas were determined based on an index approach, which includes topographic parameters, obtained from a 10 m digital terrain model (e.g. slope angle and planar curvature) and hydrological settings (i.e. drainage area). For the runout modelling, the Flow-R model, which is based on combined probabilistic and energetic algorithms for the assessment of the spreading of the flow and maximum runout distances, was used (Fischer et al., 2012, 2014). The map is available at the following link (<https://gis3.nve.no/link/?link=jordflomskredaktsomhet>).

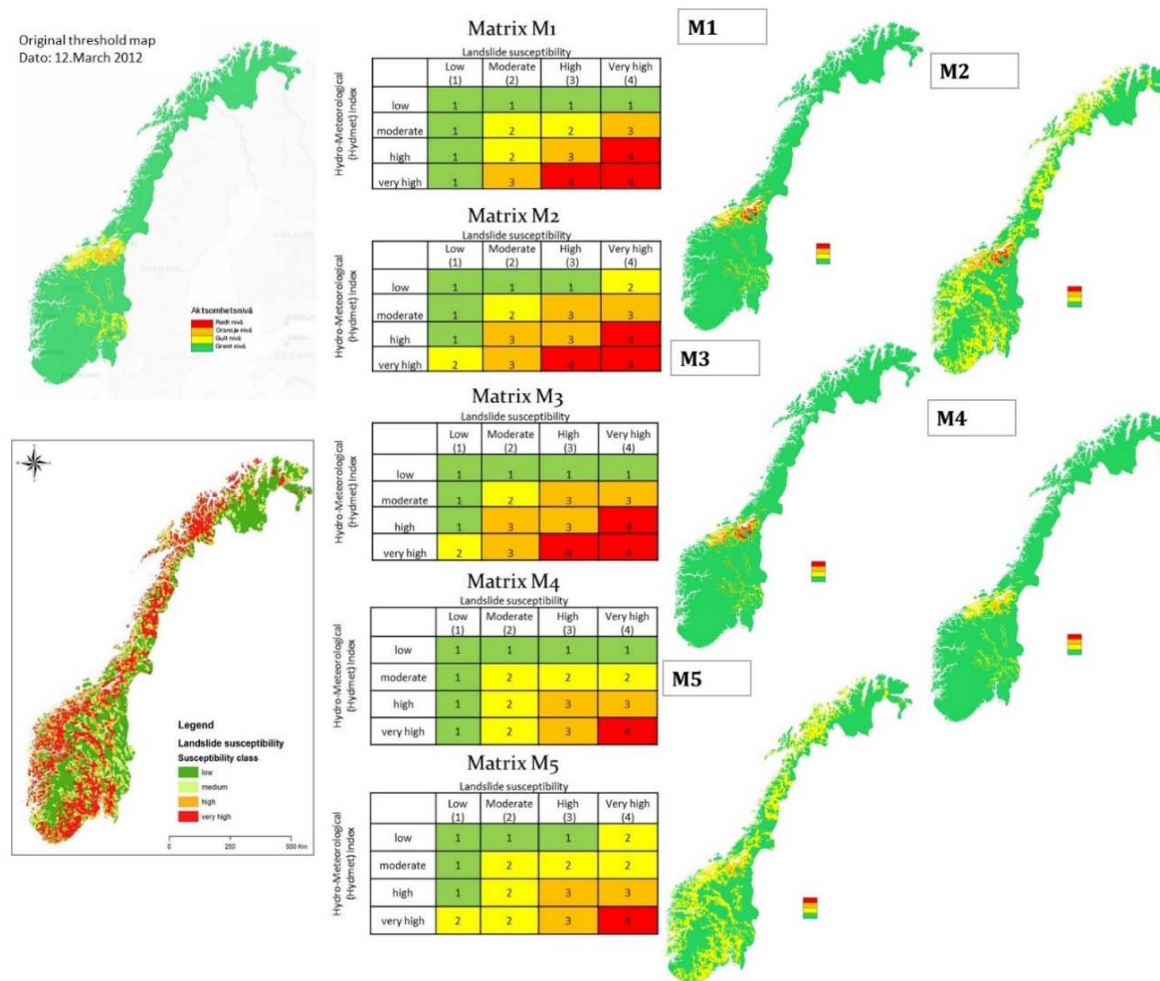


Figure 14. Examples of new threshold maps (called Hydmet GEO) on the right side by using the 5 different combination matrices, for the 12nd of March 2012 in the Central area of Norway. The original landslide threshold map is presented in the upper left, while the landslide susceptibility map is in the lower left side of the figure.

The national susceptibility map for landslides in soils at catchment level, and the national susceptibility map for debris avalanches and small debris flows have been prepared for different purposes and for different types of landslides and using different methods and work scale, therefore the resolution is different. A comparison between the two susceptibility maps is presented in Figure 15.

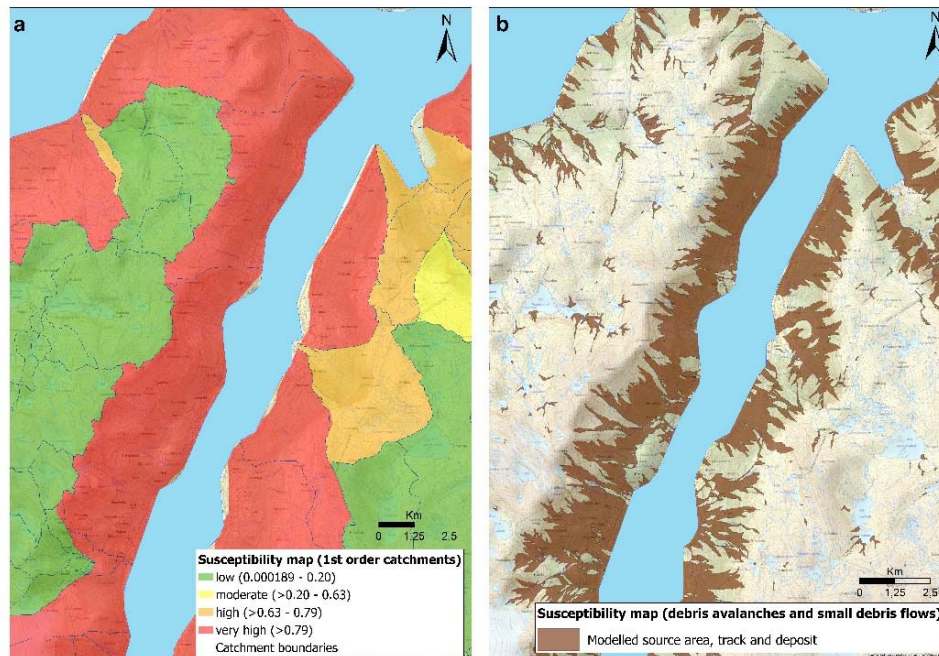


Figure 15. Susceptibility map at Sør fjorden, Western Norway: (a) at first-order catchments for landslides in soil from Bell et al. (2014); (b) at 1:50000 scale, for debris avalanches and small debris flows from Fischer et al. (2014) (from Krøgli et al 2018).

Both maps are used in landslide early warning, but at different stages. The flow chart in Figure 16 explains how at the present time the two susceptibility maps are used in the daily landslide forecasting. We use the case of the 30th of September 2017 when an orange and yellow level were sent in Southern Norway because of large amount of rainfall was expected in the area. The landslide susceptibility maps at catchment level (Figure 15a) is itself sufficient for the aim of improving landslide early warning and especially to define warning levels and warning area more precisely, while the second map (Figure 15b) is used in the landslide early warning after the warning is issued to show where landslides are expected to occur. In absence of more detailed hazard maps, this map together with information on critical sites can be used to assist local emergency authorities to decide in which landslides prone area they should take more actions within the warning zone.

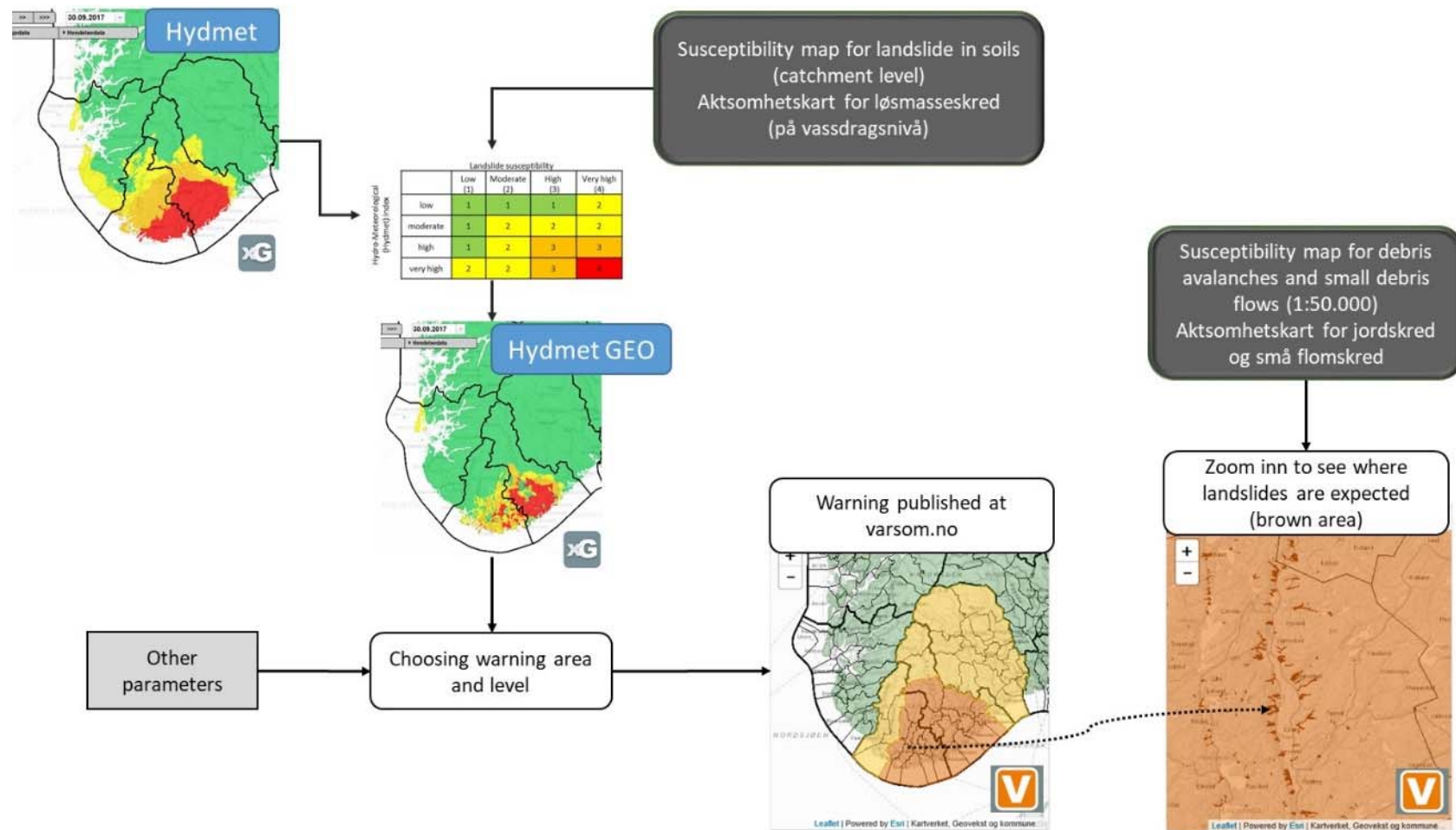


Figure 16. Flow chart that summarize the use in the daily landslide forecasting of the two susceptibility maps available for Norway for landslide in soils, showing the example of the 30th of September 2017 in Southern Norway. The map at catchment level is used before the warning is issued, while the map at 1:50000 scale, is used after the warning is sent out.

4 Conclusions

The **national susceptibility map for landslides in soils at catchment level, *Aksomhetskart for løsmasseskred på vassdragsnivå*** was prepared in last five years as part of a collaborative effort between NVE, Rainer Bell and NGI and to improve the landslide early warning system at NVE. The map shows the susceptibility level of 1st order catchments to landslides in soils. Regional susceptibility assessments were performed using global additive models (GAM) in 5 regions in Norway between 2013 and 2017 and afterwards combined to obtain a national map. The approach of modelling in REGINE units works very well, especially given the uncertainty of the spatial location of the landslide initiation areas. When modelling at REGINE unit level, it does not matter that most of the landslide points are located where consequences were registered (which is the case in most situations). It is sufficient that the registered landslide point and the actual initiation area are located within the same REGINE unit. Future efforts should focus on improving the landslide inventory. It might be worth trying to focus on selected areas of low and moderate susceptibility and check the completeness of the landslide inventory using remote sensing data (e.g., airborne laser scanning data, satellite images and aerial photographs). When a significantly improved landslide inventory is available, new landslide susceptibility modelling should improve the predictive performance of the maps when used as part of a warning system.

The map presented herein was prepared to support the NVE's landslide forecasting and warning service. The map is currently used at NVE to improve the landslide threshold map (called Hydmet) published every day at xgeo.no and varsom.no and used for the daily landslide hazard assessment.

The **national susceptibility map for landslides in soil at catchment level, *Aksomhetskart for løsmasseskred på vassdragsnivå*** was combined with landslide thresholds using a matrix approach. The so called Hydmet GEO used in the daily evaluation is done using matrix M4, and can be visualized at xgeo.no. As already observed in Thiebes et al., 2017, the matrix approach is very useful for the combination of spatial and temporal landslide probabilities. However, it must be noted that this matrix approach is extremely sensitive to the classification of the input data.

As future works, it is recommended to test the other susceptibility classification schemes (see Figure 9) and evaluate the performance of the map, but also test matrix combinations in different regions and for other selected dates, also when a low number of landslides has occurred and validate which combination could be the best.

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Appendices

Appendix A

Bell, R., Cepeda, J. og Devoli, G. (2014). Landslide susceptibility modeling at catchment level for improvement of the landslide early warning system in Norway. Proceedings of World Landslide Forum 3, 2-6th June 2014, Beijing.



Landslide susceptibility modeling at catchment level for improvement of the landslide early warning system in Norway

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Abstract In recent years many severe landslide events have occurred in Norway. These events are mainly shallow debris, soil slides and debris flows, which have caused significant damage. To prevent such damage an early warning system (EWS) for shallow slides and debris flows is being developed by the Norwegian Water Resources and Energy Directorate (NVE) based on hydro-meteorological thresholds. The experience in a testing phase shows that the EWS overestimates the warning level especially in some areas which are not prone to landslides. Thus, the combination of the aforementioned index with information on landslide susceptibility may allow improving the performance of the EWS.

In this study, two regions Northern and South-Eastern Norway are investigated. It was decided that modeling landslide susceptibility at the level of first order catchments would be appropriate. The landslide inventories for Northern and South-Eastern Norway contain 759 and 1419 landslides which occurred in 284 and 536 catchments, respectively. Landslide susceptibility modeling is carried out using Generalized Additive Models (GAM). Explaining variables are the Quaternary map, land cover, average yearly rainfall, various water runoff variables, and various derivatives from the 15m x 15m digital elevation model (DEM) like e.g. slope and aspect. Results of susceptibility modeling are good proofed by AUROC values for Northern Norway of 0.87 for the train sample and 0.84 for the test sample and for Eastern Norway of 0.88 and 0.86, respectively. In addition, the hydro-geomorphological plausibility proofed to be good. Combining the

susceptibility map with the warning levels to establish new warning levels shows a clear improvement. Furthermore, modeling landslide susceptibility at catchment level suits the aim of improving the early warning system much better than e.g. a pixel-based approach.

Keywords Landslide susceptibility, generalized additive model (GAM), debris flow, debris slide, landslide early warning system, Norway

Introduction

Many severe rainfall- and snowmelt-induced landslide events have occurred in Norway in recent years (e.g. 2000, 2005, 2008, 2011 and most recently in May 2013). These events are mainly shallow debris slides, soil slides and debris flows, which have caused significant damage to roads, railway lines and buildings. As a preventive measure, an early warning system (EWS) for shallow slides and debris flows is under development by the Norwegian Water Resources and Energy Directorate (NVE) based on hydro-meteorological thresholds (Colleuille et al, 2010). The EWS, operational from October 2013, sends out daily warnings to road and railway authorities, municipalities and emergency authorities in general, published at www.varsom.no. The experience during the testing phase (2011-2013) shows that in some areas that are not prone to soil slides and debris flows, the hydro-meteorological index (*hydmet* index, 1km x 1km resolution) used in the warning indicates high landslide warning levels, which

in practice leads to issuing false alarms. Thus, the combination of the *hydmet* index with information on landslide susceptibility may allow improving the performance of the EWS.

Landslide susceptibility gives information on the spatial probability of landslides given a set of geoenvironmental factors (Varnes 1984, Guzzetti et al. 1999). Thus, landslide susceptibility maps give an indication where landslides may occur but not the timing. Most commonly statistical approaches like logistic regression (e.g. van den Eeckhaut et al. 2006), weights of evidence (e.g. Meyer et al. submitted), artificial neural networks (e.g. Pradhahn and Lee 2010) or support vector machines (e.g. Brenning 2005) are applied. Recently, the nonlinear generalized additive model (GAM, Hastie and Tibshirani 1990) has been used to model landslide susceptibility (e.g. Brenning 2008, Goetz et al. 2011, Petschko et al. 2013a). It is an extension of the generalized linear models like logistic regression and has the capability of modeling nonlinear relationships between response and explanatory variables.

For the quality assessment of the resulting models and maps various measures are available like misclassification rates, the area under the ROC (receiver operating characteristic) curve (AUROC) or prediction- and success rate curves (Chung and Fabbri 2003; Brenning 2005; Begueria 2006). Validation should be always carried out using independent training and test samples. In addition the final landslide susceptibility maps should be checked for the geomorphic plausibility (Bell 2007, Petschko et al. 2013b, Steger et al. submitted).

Several regional landslide early warning systems were or have been implemented (e.g. Baum and Godt 2010, D'Orsi et al. 2004) but most of them are depending only on hydrological thresholds combined with field measurements. Only few studies are available which integrate landslide susceptibility, commonly applying deterministic models (e.g. Apip et al. 2010, Liao et al. 2010, Montrasio et al. 2011) and only single studies using statistical approaches (e.g. Hou et al. 2013, Liao et al. 2010). A review on landslide early warning systems can be found in Mayer et al. 2010 and Thiebes 2012.

Within this study, landslide susceptibility is modeled using the statistical approach of a GAM. Attempts to elaborate susceptibility maps for debris slides and debris flows are in progress in Norway at the Norwegian Geological Survey (NGU) at national scale (Fischer et al., 2012) and at regional level (Meyer et al. submitted), however they are prepared for areal planning purposes with medium scale accuracy. Since the aim is the integration of landslide susceptibility into the landslide early warning system and due to

limitations especially of the landslide inventory (see further below), it was decided that modeling landslide susceptibility at the level of first order catchments would be appropriate. The final combination of the susceptibility map and the hydro-meteorological index was carried out using a pixel-based approach with a resolution of 1km x 1km to improve the landslide warning levels for Norway.

Study area

In this study, two regions Northern and South-Eastern Norway, covering more than 200.000 km² are investigated (Fig. 1).

Northern Norway (Nordland and Troms counties) is dominated by pointed mountains and numerous fjords, valleys and large islands. Debris flows and debris slides events are frequent and triggered by intense rainfall and/or combination of snow melting (recent events occurred in January 2002, May 2010, July 2012 and May 2013). The interior and eastern part of the Northern region (Finnmark county) is dominated by the large plateau of Finnmark characterized by elevations below 400 m (a.s.l). The eastern area is less prone to landsliding. Here debris flows are not common and the few debris slides events occurred on artificial slopes along the road, not always strictly associated to rainfall events.

South-Eastern Norway is mostly a hilly area with very large lowlands surrounding the Oslo fjord and dominated by valleys. The longest valleys are Østerdal and Gudbrandsdal. This region contains extensive areas of forest and rich arable land areas and the longest river in the country, Glomma and the biggest lake Mjøsa. Debris flows and debris slides are very frequent especially along the valleys where loose quaternary deposits are abundant. Recent events occurred here in July 2007, May 2008, June 2011 and May 2013, under intense rainfall or snow melting episodes. In the lowlands of the southern part of this region, dominated by clay deposits of marine origins, shallow slides on artificial slopes along road and railway are more common. In November 2000 many events occurred here due to a combination of prolonged rainfall and high groundwater conditions.

The landslide inventories for Northern and South-Eastern Norway contain 759 and 1419 rapid mass movements which occurred in 284 and 536 catchments, respectively.

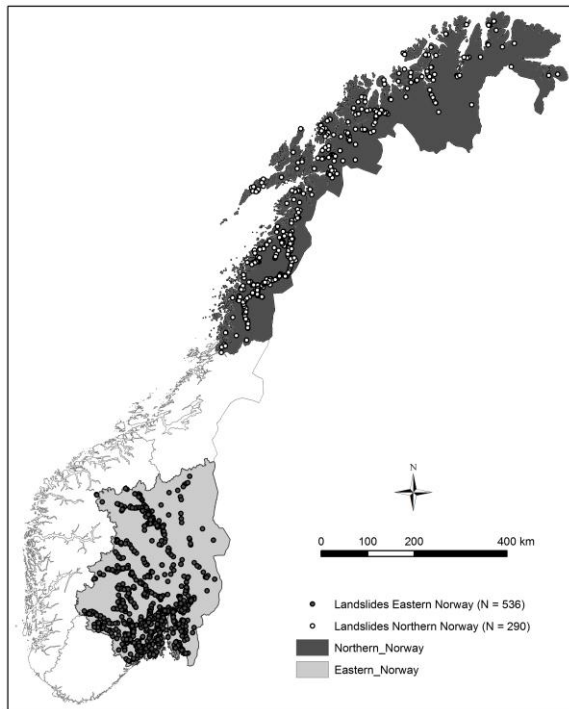


Fig. 1: Location of and landslide distribution in the study areas Northern and South-Eastern Norway (Source of landslide inventory: www.skrednett.no; Source of regions: NVE, Devoli, in preparation)

Data

Since the ultimate goal is to improve landslide early warning for whole Norway and not only for the two regions investigated in this study, only data sets available for the whole country were used. The most essential data for landslide susceptibility modeling is the landslide inventory. Further data used are the national catchment database, Quaternary map, land cover data, rainfall data, and various derivatives from a digital elevation model (DEM). All data will be briefly described in the following.

The integrated national database for all types of rapid mass movements (www.skrednett.no) contains more than 33,000 events (just point location) from the last five hundred years covering the whole country. Most frequent events are rock slides and snow avalanches followed by debris slides. The majority of the entries result from events recorded by road authorities and rail authorities (more than 26,000). Thus, usually the landslide point is placed where the landslide hit the road or railway (Jaedicke et al. 2009), which introduces huge inaccuracies when landslide susceptibility is modeled, since in general susceptibility modeling should be carried out with the initiation points of the

landslides, especially when using pixel-based approaches. Further uncertainties result from errors in classifying the events as specific landslide types, from the lack of registration in some regions and from missing information on the slope itself, if it occurred on an artificially cut slope or a natural slope. However, it is the only available country-wide landslide inventory, so this had to be used. Soil and debris slides as well as debris flows were extracted for the two regions investigated.

The national catchment database (REGINE) was used to extract the information on first order catchments (vector polygon data). Information stored with each catchment and used in susceptibility modeling is catchment area (km^2), catchment runoff 1961-1990 (million m^3 per year), total upstream area (km^2), total upstream runoff 1961-1990 (million km^3 per year) and average runoff 1961-1990 (litre/second km^2) (NVE n.d.).

The Quaternary map at a scale of 1:250,000 (www.ngu.no) gives information of various types and subtypes of sediments, but also shows bedrock areas where no sediments are available. The quality is rather heterogeneous with more details in only some areas.

Land cover data was obtained from CORINE land cover 2006 data, which was compiled by the Norwegian Forest and Landscape Institute (Aune-Lundberg and Strand 2010). Details are limited to a minimum mapping unit of 25 ha.

Spatially distributed average yearly rainfall data (1961-1990) with a resolution of $1\text{ km} \times 1\text{ km}$ was available (Source: MET and www.senorge.no).

A digital elevation model (DEM) with a resolution of $10\text{ m} \times 10\text{ m}$ is available for whole Norway (Statens Kartverk).

Methods

Landslide susceptibility modelling

Landslide susceptibility modeling was carried out using the statistical approach of generalized additive Models (GAM) (Hastie 1992). A combined backward and forward stepwise variable selection in R based on Akaike's Information Criterion (AIC, Akaike 1974) was applied to fit the susceptibility models. Using the AIC, the best fit of variables for a model is automatically selected by evaluating the significance of the variables and penalizing for model complexity. The GAM chooses for each variable if the variable is omitted, used linearly or with a smooth function. Based on the AIC values the GAM selects the model with the best combination of variables.

Landslide susceptibility was modeled at catchment level since for improving the current early warning this is absolutely sufficient. The main advantage is, that the whole process area of the landslides is automatically

considered and not only initiations areas modeled. Second, the poor spatial location of the landslide points of the landslide inventory (see above) does not matter anymore since it is assumed that all landslides are still located in the same catchment where they were initiated.

Modeling was carried out using a 1:1 relationship between catchments with landslides and catchments without landslides. 50 % of the catchments with landslides were used in the train sample and the other 50% in the independent test sample.

Explaining variables are the Quaternary map, land cover, average yearly rainfall, various water runoff variables (see above), and various derivatives from the 15m x 15m digital elevation model (DEM) like e.g. slope and aspect. For the categorical data the proportion of each class in the catchment and for continuous data either mean, median, standard deviation or range for the catchment were calculated and used in modeling.

Validation of the resulting models and maps were carried out using the AUROC criterion (values of 0.7 to 1 show good to very good discrimination between catchments with landslides and catchments without landslides) and the hydro-geomorphological plausibility.

Finally, landslide susceptibility was classified into four classes (low, moderate, high, very high), similar to the four classes of the hydro-meteorological index. Classification thresholds were set based on the proportion of landslides in each class. Two classification schemes were tested: 1) 70%, 15 %, 12 % and 3% of the landslides in the susceptibility classes very high, high, moderate and low, respectively; 2) 40%, 40%, 15% and 5% of the landslides in the susceptibility classes very high, high, moderate and low, respectively.

Hydro-meteorological index

The hydro-meteorological thresholds for all Norway, currently in use in the EWS, are based on a combination of water supply (rain and snowmelt) and soil saturation and were determined by Colleuille et al. (2010). The thresholds were applied to establish the hydro-meteorological index in a WebGIS environment (NVE, www.xgeo.no). For the last 2 years NVE is conducting a revision and updating of these thresholds in collaboration with the Norwegian Geotechnical Institute (NGI) using statistical analysis of various hydro-meteorological data for registered and dated landslide events (Cepeda et al. 2012, NGI 2013a, NGI 2013b, Boje et al., submitted). In a first phase data from the entire country have been analyzed, but later two separate analyses were performed for Northern Norway and South-Eastern Norway respectively.

The dynamic results of the hydro-meteorological index can be accessed via the web-interface www.xgeo.no.

The index from 1st January 2000 until today can be visualized and analyzed, also in combination with the registered landslides. Four colors are used to distinguish the critical values for the index based on four warning levels (see Table 1 and Table 2). In Fig. 2A the warning level using the hydro-meteorological index of 27 June 2008 is displayed. The high and very high warning levels in the northern part of Northern Norway are clearly visible.

Combination of hydro-meteorological index and landslide susceptibility

To combine the landslide susceptibility map with the hydro-meteorological index a pixel-based approach was chosen. Therefore, the landslide susceptibility map at catchment level was converted into a 1km x 1km grid. Subsequently, both data sets were combined via a query using the combination matrixes M₁ (Table 1) and M₂ (Table 2).

Table 1: Matrix M₁ for combining the different classes of the hydro-meteorological index and of the landslide susceptibility map to new warning level classes low (1), moderate (2), high (3) and very high (4).

Hydro-Meteorological (Hydmet) Index	landslide susceptibility			
	low	moderate	high	very high
	low	1	1	1
	moderate	1	2	3
	high	1	2	4
	very high	1	3	4

Table 2: Matrix M₂ for combining the different classes of the hydro-meteorological index and of the landslide susceptibility map to new warning level classes low (1), moderate (2), high (3) and very high (4).

Hydro-Meteorological (Hydmet) Index	landslide susceptibility			
	low	moderate	high	very high
	low	1	1	2
	moderate	1	2	3
	high	1	3	4
	very high	2	3	4

Results

Landslide susceptibility modelling

Preliminary results show already good results proofed by AUROC values for Northern Norway of 0.87 for train sample and 0.84 for the test sample and for South-

Eastern Norway of 0.88 and 0.86, respectively. In addition, the hydro-geomorphological plausibility proofed to be good meaning that catchments with high proportions of flat areas which are less prone to landsliding are mainly located in the low susceptibility class whereas catchments with a high proportion of landslide prone lithologies and steeper slopes are in the higher susceptibility classes.

Selected variables for Northern Norway are: catchment area (*smoothed*), catchment mean slope, elevation range of catchment (*smoothed*), forest, open space with little or no vegetation, moraines, river and stream deposits.

Selected variables for South-Eastern Norway are: catchment area (*smoothed*), std. deviation of catchment slope, elevation range of catchment, total upstream runoff 1961-1990, average total rainfall per year, forest, open space with little or no vegetation, heterogeneous agricultural areas (mainly farmland and natural vegetation), marine and fjord deposits (*smoothed*), river and stream deposits, weathered material, peat and marshlands.

Large differences in the resulting landslide susceptibility maps are introduced by the two different classification schemes. Since classification scheme 1 seems to be more reasonable, the resulting map was selected and is presented in Fig. 2B.

Combination of hydro-meteorological index and landslide susceptibility

The result of the combination of the hydro-meteorological index and the landslide susceptibility map for 27 June 2008 is shown in Fig. 2C using matrix M1 and in Fig. 2D using matrix M2.

Discussion and Conclusion

The good results of the landslide susceptibility modeling indicate that the chosen approach of modeling in first order catchments is well suited given especially the poor accuracy of the spatial location of

the landslide points. The GAM might have only a small benefit compared to e.g. logistic regression since only a few variables were selected in a nonlinear (smoothed) way. However, this would have to be checked in future studies. The landslide classification scheme 1 worked better than scheme 2. Using the proportion of landslides per class as classification thresholds is well suited when susceptibility maps are to be implemented since this enables a better understanding of the classification thresholds by the authorities than just numbers derived by natural breaks or any other method.

Using the example of the 27 June 2008 the benefits of combining landslide susceptibility and the previously solely used hydro-meteorological index for setting the landslide early warning levels could be clearly presented. Especially the north of Northern Norway (Finnmark county) is rather less prone to landsliding. Thus, without using landslide susceptibility the warning levels were often far too high for wide areas. This example also shows that Matrix M1 works in this case much better than Matrix M2. Analyzing two other examples in Nordland and Troms county, the difference between M1 and M2 is not that large. Anyway, further examples also for South-Eastern Norway have to be analyzed before taking the final decisions on which Matrix to use.

The landslide susceptibility maps at catchment level so far seem to be fully sufficient for the aim of improving landslide early warning. They might be even better suited for this purpose than pixel-based approaches as e.g. applied by Meyer et al. (submitted) or Fischer et al. (2012) for Norway. However, for implementation in spatial planning the catchment level susceptibility maps would be too coarse, so that the mentioned pixel-based approaches are better. Thus, the setup of the modeling strategy heavily depends on the aim of the study.

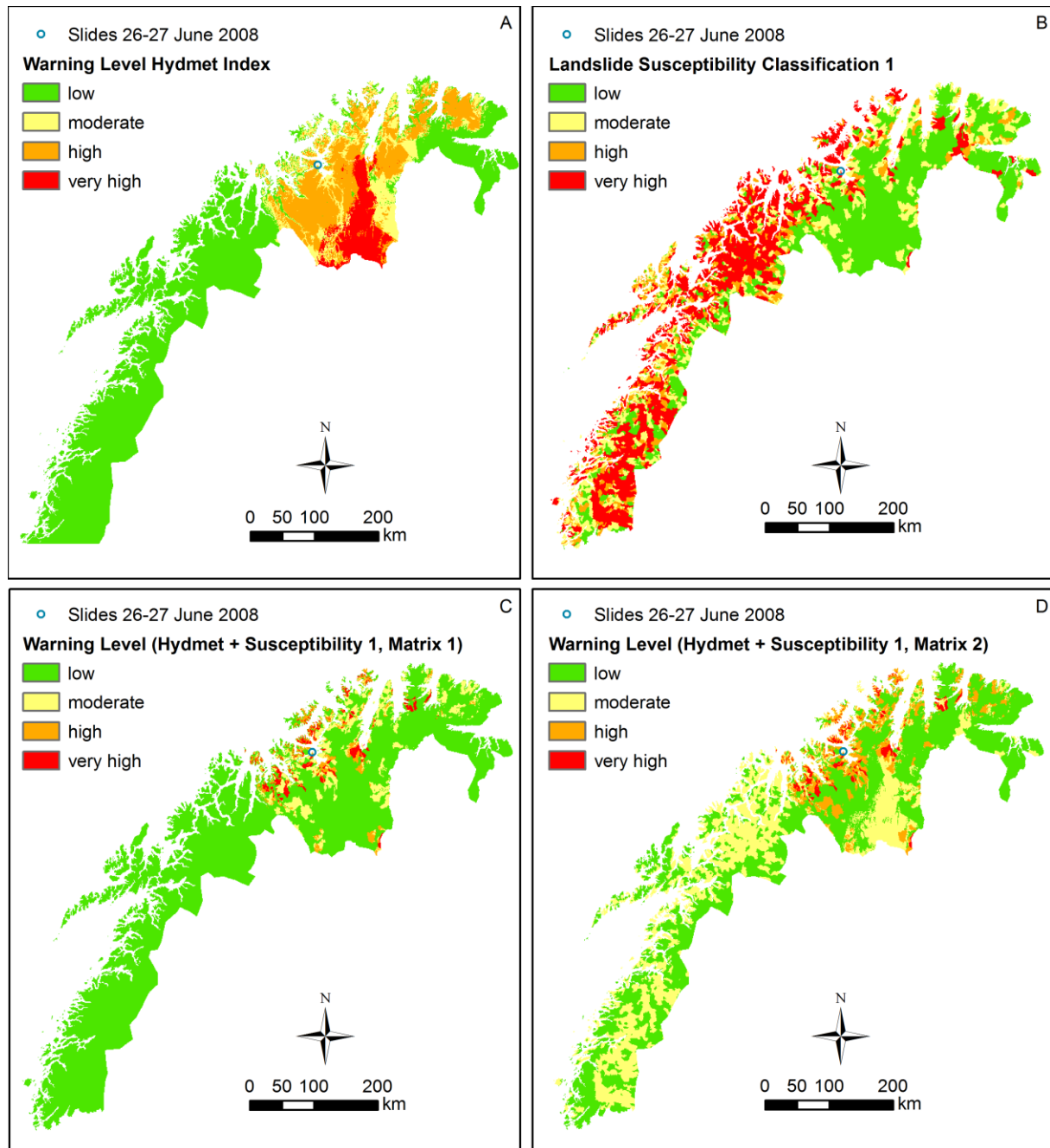


Fig. 2 Resulting maps showing A) the warning levels only using the hydrometeorological index, B) the landslide susceptibility map using the classification scheme 1, C) the “new” warning levels using the hydro-meteorological index and the susceptibility map based on combination matrix M₁ and D) the “new” warning levels using the hydro-meteorological index and the susceptibility map based on combination matrix M₂

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Appendix B

Technical Note: Bell R., Cepeda J. (2014). Susceptibility map for debris flows, debris slides and soil slides in Western Norway. Technical note 20130802-01-TN. Norges Geotekniske Institutt, Oslo, Norway

To: Norges vassdrags- og energidirektorat (NVE)
Attn.: Graziella Devoli
Copy:
Date: 12 December 2014
Revision/Rev. date: 0
Document No.: 20130802-01-TN
Project: Improvement of warning levels for precipitation-induced landslides in Western Norway
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Susceptibility map for debris flows, debris slides and soil slides in Western Norway

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Review and reference page

1 Introduction

The aim of this project is the improvement of warning levels for precipitation-induced landslides (debris flows, debris slides and soil slides) in Western Norway (Vestlandet region). Similar to the applications in Northern and Eastern Norway (Bell et al. 2014), landslide susceptibility at REGINE unit level is modelled and will subsequently be combined with the hydmet index by NVE. This technical note presents the data used, the methodology applied, the results and its discussion.

2 Data

As for the projects for modelling landslide susceptibility for Northern and Eastern Norway, only data sets available for the whole country were used. The most essential data for landslide susceptibility modelling is the landslide inventory. Additional data are the REGINE database (national catchment database), Quaternary map, land cover data, hydrometeorological data, and various derivatives from a digital elevation model (DEM). All data is briefly described in the following paragraphs.

The integrated national database for all types of rapid mass movements (www.skrednett.no) contains 47,100 events (just point location, date retrieved: 12 November 2014) from the last five hundred years covering the whole country. The most frequent events are rockslides and snow avalanches followed by debris slides. For Western Norway 20,954 mass movements are stored in the database. The majority of the entries result from events recorded by road authorities and railway authorities. Thus, usually the points are placed where landslides have hit roads or railways (Jaedicke et al. 2009), which may introduce large inaccuracies for long runout events when modelling landslide susceptibility, since in general susceptibility modelling should be carried out at the initiation areas of landslides, especially when using pixel-based approaches. Further uncertainties result from errors in classifying the events as specific landslide types, from the lack of registration in some regions and from missing information on the slope itself, if it occurred on an artificially cut slope or on a natural slope. However, it is the only available countrywide landslide inventory, so this had to be used (Bell et al. 2014). Soil and debris slides as well as debris flows were extracted for Western Norway and will be termed landslides in this project.

The REGINE database was used to extract the information on first order catchments (REGINE units, vector polygon data). Information stored in each REGINE unit and used in susceptibility modelling is REGINE unit area (km²), REGINE unit runoff 1961-1990 (million m³ per year), total upstream area (km²), total upstream runoff 1961-1990 (million km³ per year), average runoff 1961-1990 (litre/second km²) and average runoff 1930-1960 (litre/second km²) (NVE n.d.).

The Quaternary map at a scale of 1:250,000 (www.ngu.no) gives information of various types and subtypes of sediments, but also shows bare rock outcrops. The quality is rather heterogeneous with more details in only some areas (Bell et al. 2014).

Land cover data was obtained from CORINE land cover 2006 data, which was compiled by the Norwegian Forest and Landscape Institute (Aune-Lundberg and Strand 2010). Details are limited to a minimum mapping unit of 25 ha.

Spatially distributed average yearly rainfall data (1961-1990) with a resolution of 1km x 1km was available (Source: MET and www.senorge.no).

A digital elevation model (DEM) with a resolution of 15 m x 15 m was available for whole Norway, derived from 1:50.000 topographical maps at (NGI).

3 Methods

Landslide susceptibility modelling was carried out using the statistical approach of Generalized Additive Models (GAM) (Hastie 1992), a further development of logistic regression. A combined backward and forward stepwise variable selection in R based on Akaike's Information Criterion (AIC, Akaike 1974) was applied to fit the susceptibility models. Using the AIC, the best fit of variables for a model is automatically selected by evaluating the significance of the variables and penalizing for model complexity. The GAM decides for each variable whether it should be omitted, used linearly or with a smooth function. Based on the AIC values the GAM selects the model with the best combination of variables. In addition, a model run was carried out allowing only linear use of variables which means that this is an approach of logistic regression.

Landslide susceptibility was modelled at REGINE unit (catchment) level since for improving the current early warning this is sufficient. The main advantage is that the whole process area of the landslides is automatically considered and not only initiations areas modelled. The poor spatial location of the landslide points of the landslide inventory (see above) does not matter anymore since it is assumed that all landslides are located in the same REGINE unit of the initiation areas.

Modelling was carried out using a 1:1 relationship between REGINE units with landslides and REGINE units without landslides. For the final landslide susceptibility map all 801 REGINE units with landslides and randomly sampled 801 REGINE units without landslides were used in susceptibility modelling. This ensures that all known information on landslides was considered in the development of the final map. Additional models were calculated for validation purposes. Therefore, 50 % of the REGINE units with landslides were used in the train sample and the other 50 % in the independent test sample.

Explanatory variables are the Quaternary map, land cover, average annual rainfall, various water runoff variables (see above), and various derivatives from the 15 m x 15 m digital elevation model (DEM) like e.g. slope and aspect. For the categorical data, the proportion of each class in the catchment and for continuous data (mean, median, standard deviation or range for the catchment) were calculated and used in modelling. Altogether 62 variables were available (Appendix A). Boxplots (Appendix B), spineplots (Appendix C) and correlation matrices (Appendix D) were used to pre-select variables.

Validation of the resulting models and maps were carried out using the AUROC criterion (values of 0.7 to 1 show good to very good discrimination between REGINE units with landslides and REGINE units without landslides).

Finally, landslide susceptibility was classified into four classes (low, moderate, high, very high), similar to the four classes of the hydro-meteorological index. Classification thresholds were set based on the proportion of landslides in each class. The same classification scheme as applied to Northern and Eastern Norway were used: 70 %, 15 %, 12 % and 3% of the landslides in the susceptibility classes very high, high, moderate and low, respectively.

4 Results

4.1 *Landslide inventory*

Fig. 1 shows the distribution of different types of rapid mass movements for Western Norway. Finally, in cooperation with NVE it was decided to take the mass movement types 140, 141, 142 and 143. This resulted in a landslide inventory of 2,371 debris flows, debris slides and soil slides. These 2,371 landslides occurred in 801 REGINE units (Fig. 2).

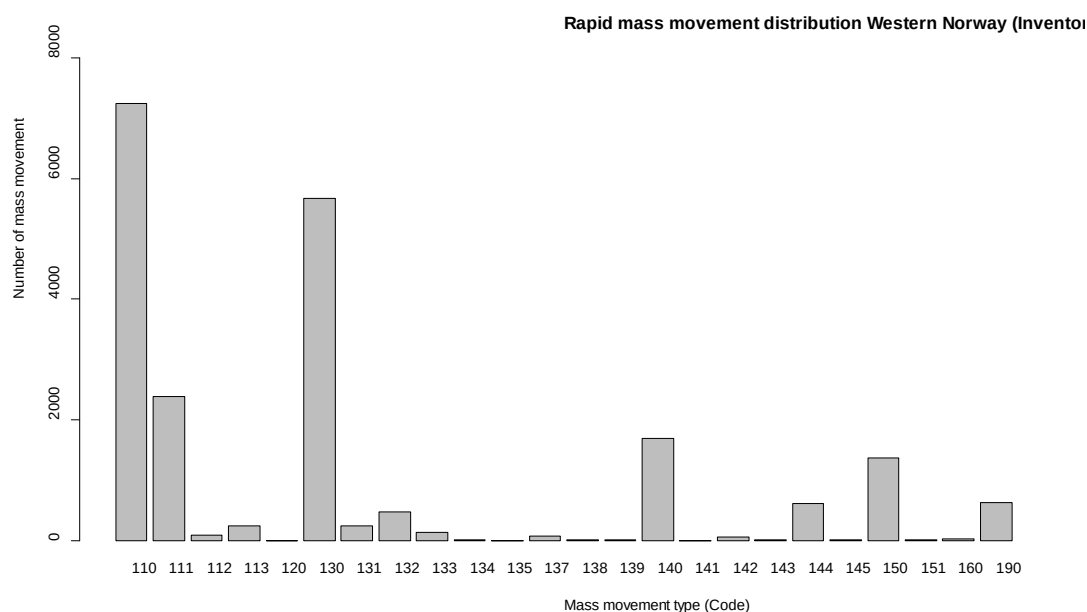


Figure 1 Distribution of different types of rapid mass movements. (110: Landslides in rock, unspecified; 111: Rock fall (< 100 m³); 112: Rock fall (100-10,000 m³); 113: Large rock avalanche (>10,000 m³); 120: Submarine landslides; 130: Snow avalanche, unspecified; 131: Wet snow avalanche; 132: Dry snow avalanche; 133: Slush flow; 134: Loose snow avalanche, not specified; 135: Wet loose snow avalanche; 136: Dry loose snow avalanche; 137: Slab avalanche, unspecified; 138: Wet slab snow avalanche; 139: Dry slab snow avalanche; 140: Landslides in soils, unspecified; 141: Quick clay slides; 142: Debris slide/Debris flow/Debris flood; 143: Clay slides; 144: Soil slide; 145: Soil slide, unspecified; 150: Ice fall; 151: ??; 160: Debris slide along road; 190: Not specified; Source: Integrated national database for all types of rapid mass movements, www.skrednett.no)

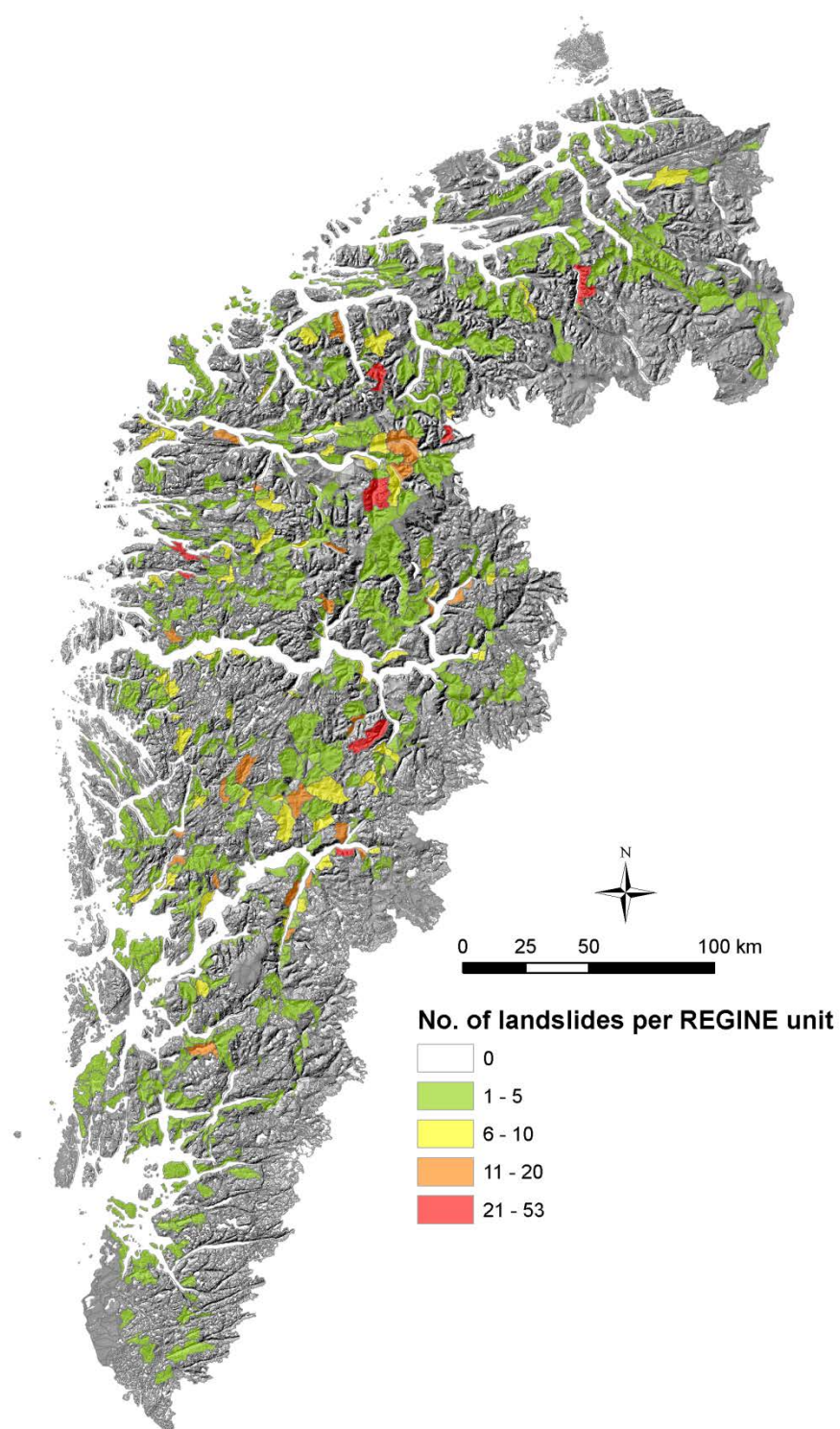


Figure 2 Distribution of debris flows, debris slides and soil slides per REGINE unit in Western Norway.

4.2 Landslide susceptibility modelling

Several hundreds of models were calculated. Finally, the following four models were selected: “pred1a”, “pred1b” and “pred05a” using GAM and “pred1dlg” using logistic regression. Whereas the models “pred1a”, “pred1b” and “pred1dlg” used all 801 REGINE units with landslides, “pred05a” used only 50% of these. The variables selected for each model are presented in Table 1.

Table 1 Variables finally used in the different models (s = applied with a smoother function, n = without smoother function, - = not selected; Note: Since model “pred1dlg” was modelled using logistic regression, no smoother function was available)

Selected variable	pred1a	pred1b	pred1dlg	pred05a
REGINE unit area	s	s	n	s
Total upstream area	s	-	-	s
Total upstream runoff 1961-1990	-	s	n	-
Average runoff 1961-1990	n	-	-	-
Mean slope	s	s	n	s
Elevation range	n	n	n	n
Mean of elevation	s	s	n	n
Moraine material, non-continuous/thin	n	n	n	s
Weathered material, unspecified	s	s	n	n
Bare rock	-	-	n	n
Hetrogenous agricultural areas, mainly farmland and natural vegetation	-	-	n	n
Moors and heath land	n	n	n	-
Open space with little or no vegetation	s	s	n	n
Forests	s	s	-	-

For the model “pred1a” the transformation plots used by the model can be found in Appendix E.

The AUROC values for the models “pred1a”, “pred1b” and “pred1dlg” were very high. As the AUROC values were higher, the GAM models “pred1a” and “pred1b” were slightly better than “pred1dlg” using logistic regression (Fig. 3) and “pred1a” was slightly better than “pred1b”, meaning that the AIC value was slightly lower (1234.936 compared to 1235.435).

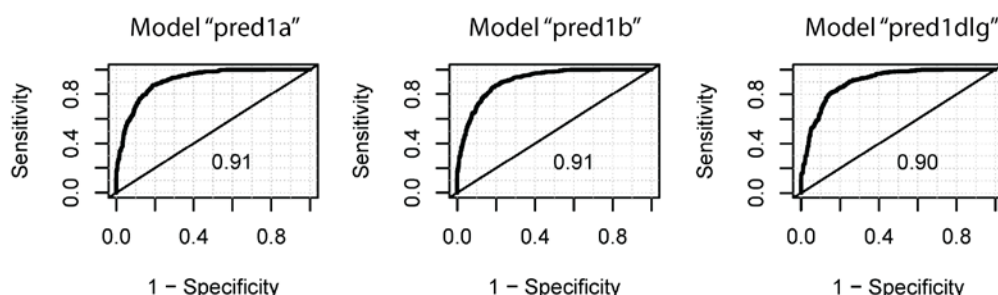


Figure 3 ROC-Curve and AUROC value for the models “pred1a”, “pred1b” and “pred1dlg”.

The random cross-validation using 50 % of the REGINE units with landslides in the train sample and the other 50 % in the independent test sample led also to very high AUROC values of 0.91 (train sample) and 0.89 (test sample) (Fig. 4).

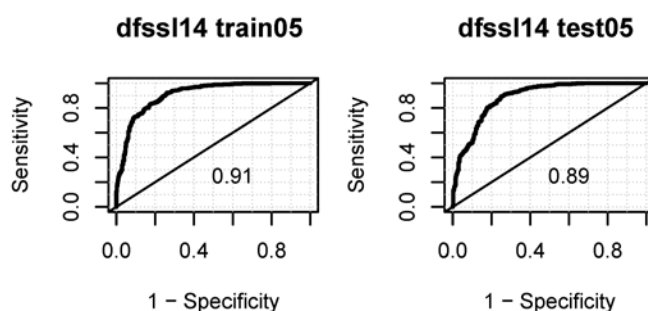


Figure 4 ROC-Curve and AUROC value for the train sample “train05” and test sample “test05” for the validation model “pred05a”. 50 % of the REGINE units with landslides were used in the train sample and the other 50 % in the independent test sample.

Based on all the four models, landslide susceptibility maps were created using class thresholds defined by 70 %, 15 %, 12 % and 3 % of the landslides in the susceptibility classes very high, high, moderate and low, respectively (Table 2, Fig. 5 – 8).

Table 2 Landslide susceptibility thresholds for the different models using class thresholds defined by 70 %, 15 %, 12 % and 3 % of the landslides in the susceptibility classes very high, high, moderate and low, respectively

Model	low	moderate	high	very high
pred1a	0.000189 – 0.20	>0.20 – 0.63	>0.63 – 0.79	>0.79
pred1b	0.000209 – 0.23	>0.23 – 0.61	>0.61 – 0.79	>0.79
pred1dlg	0.000422 – 0.24	>0.24 – 0.61	>0.61 – 0.77	>0.77
pred05a	0.000087 – 0.20	>0.20 – 0.61	>0.61 – 0.77	>0.77

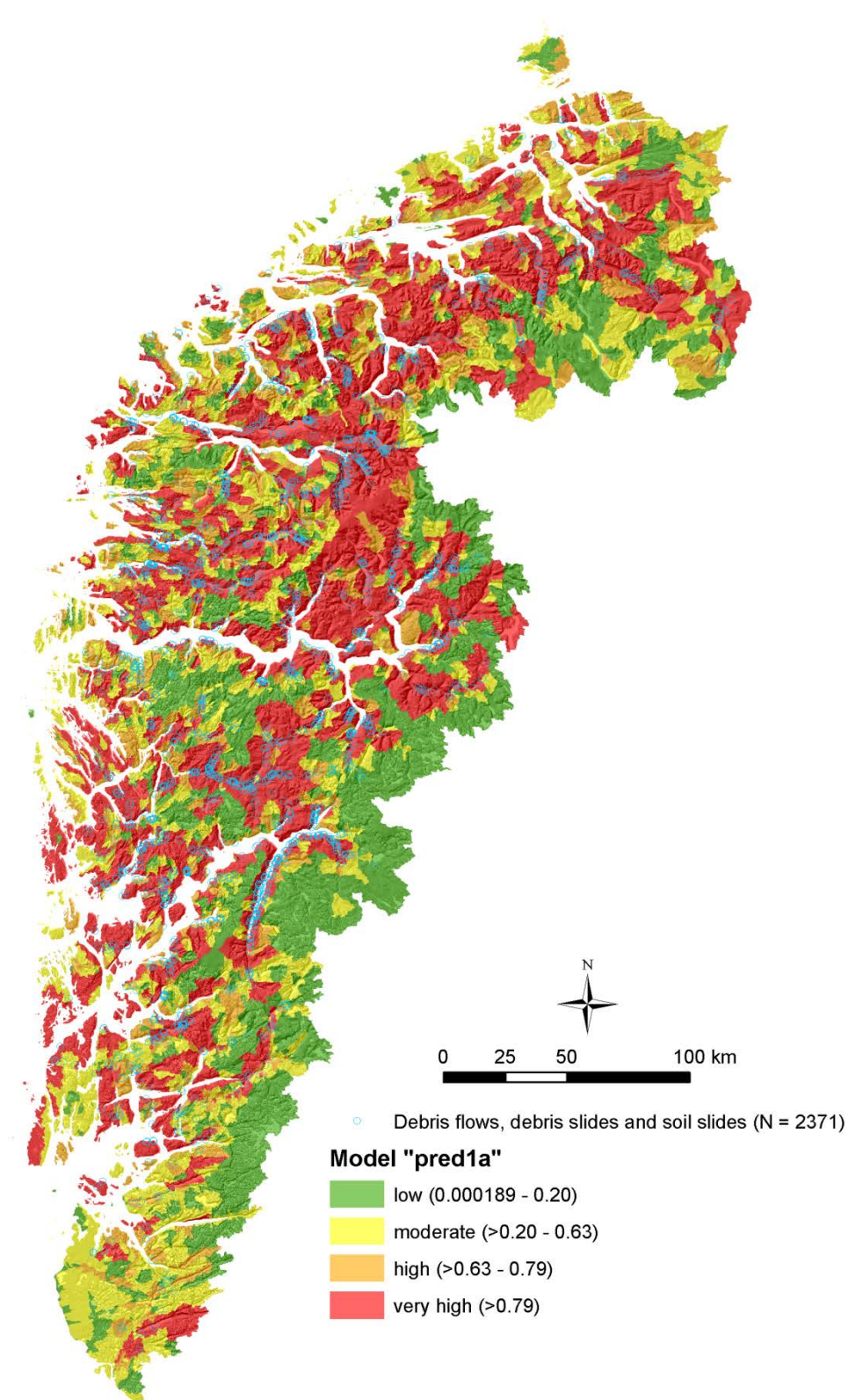


Figure 5 Landslide susceptibility in Western Norway, Model "pred1a".

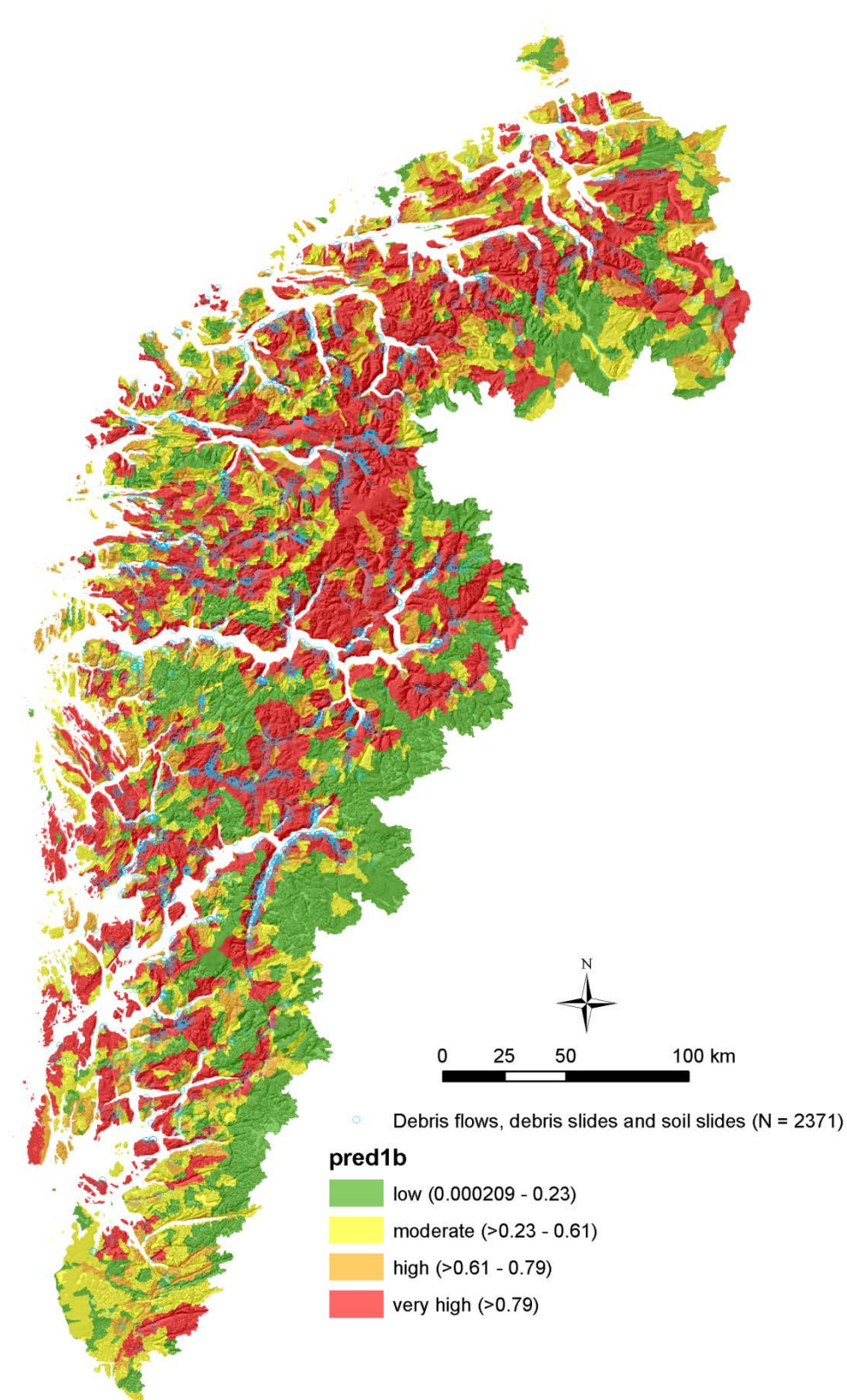


Figure 6 Landslide susceptibility in Western Norway, Model “pred1b”.

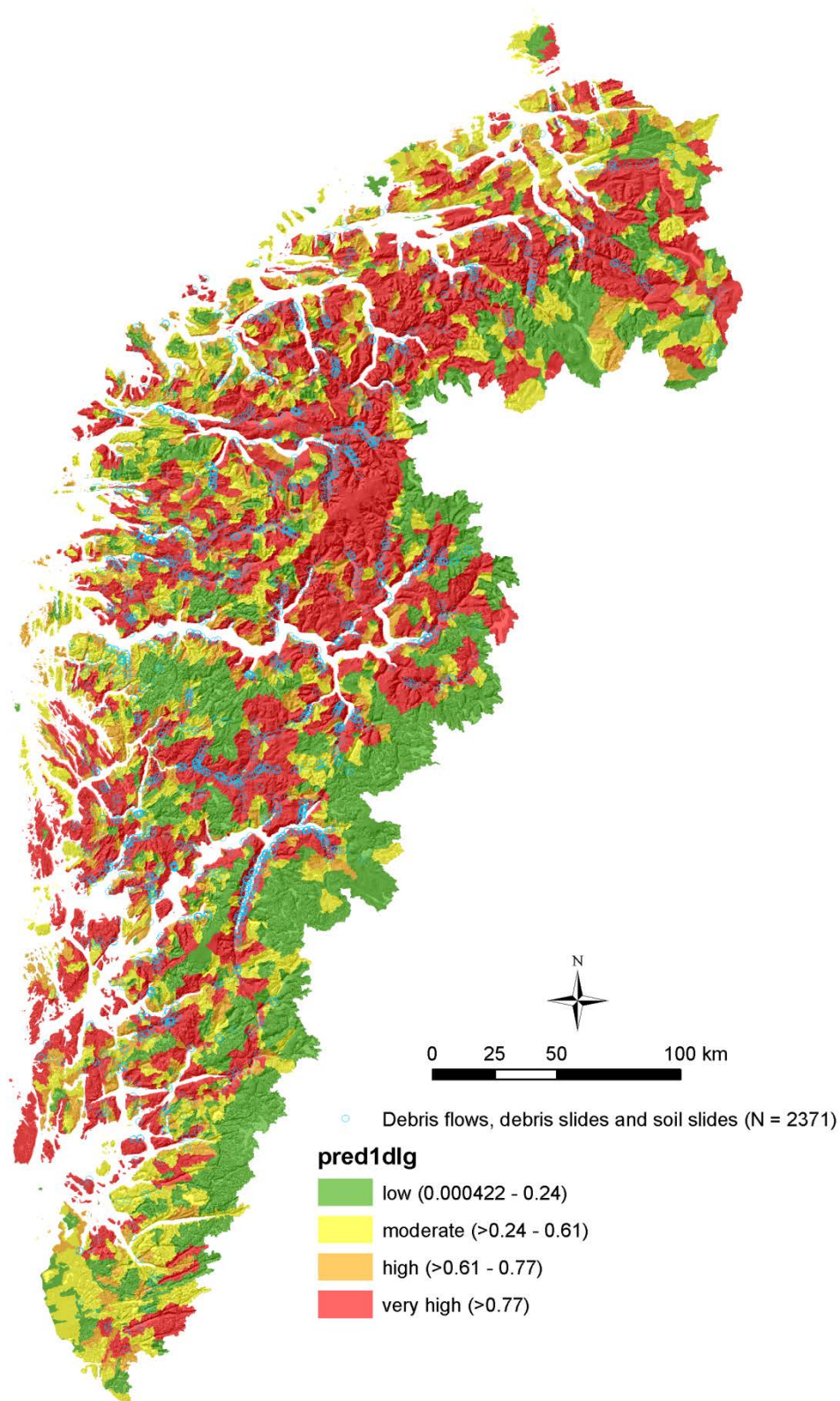


Figure 7 Landslide susceptibility in Western Norway, Model “pred1dlg”.

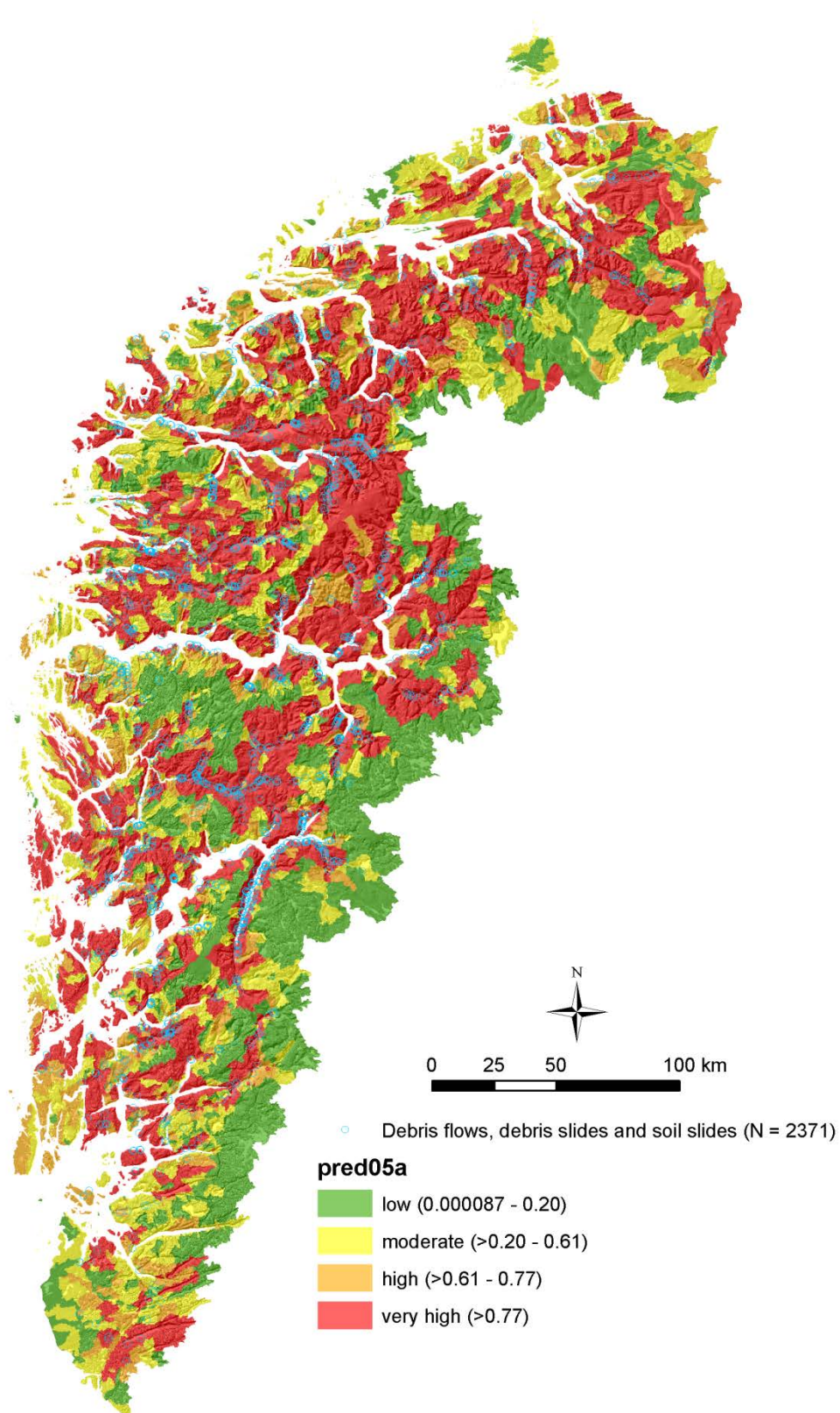


Figure 8 Landslide susceptibility in Western Norway, Model “pred05a”.

5 Discussion

All models using all 801 REGINE units with landslides in the modelling step (“pred1a”, “pred1b” and “pred1dlg”) show very high AUROC values. Even when splitting the REGINE units with landslides in a train sample and independent test sample (model “pred05a”), the resulting AUROC values remain very high. This indicates that in all models the discrimination between the REGINE units with landslides and the REGINE units without landslides is very good. There are only small differences between the models. As also found in the previous study on landslide susceptibility in Northern and Eastern Norway for improvement of warning levels for precipitation-induced landslides (Bell et al. 2014), the approach of modelling in REGINE units works very well especially given the poor accuracy of the spatial location of the landslide points. When modelling at REGINE unit level, it does not matter that most of the points are located where consequences were registered. It is sufficient that the landslide point and the initiation area are located within the same REGINE unit.

However, the landslide susceptibility map can only be as good as the input data. Based on the available data, the resulting landslide susceptibility map is of very good quality. The most important question remains if the landslide inventory is representative for all Western Norway. Fig. 9 shows that most of the 2,371 landslides are located along roads since most of the records are registered by the road and railway authorities. It should be noted that landslides in local or private roads may be unreported. It can also be seen in Fig. 9 that there are large areas of low and moderate landslide susceptibility where no roads exist. Thus, the question is, if no landslides have occurred especially in these areas or if landslides have occurred but were not registered by the road authority due to inexistent infrastructure. So, the main limitation of the final landslide susceptibility map results from the incomplete landslide inventory. If landslides have occurred but were not registered, the final landslide susceptibility map might look different if the missing landslides were eventually used to re-evaluate the model. This should be a bigger issue for areas of low and moderate susceptibility. In the other two susceptibility classes, information on high and very high susceptibility is statistically transferred from REGINE units with landslides to similar units for which so far no landslides have been recorded. However, some uncertainty also remains there.

Future efforts should focus on improving the landslide inventory. It might be worth trying to focus on selected areas of low and moderate susceptibility and check the completeness of the landslide inventory using remote sensing data (e.g. airborne laser scanning data, satellite images and aerial photographs). When a significantly improved landslide inventory is available, new landslide susceptibility modelling should improve the predictive performance of the maps.

For application in the landslide early warning system, we recommend to take the susceptibility map resulting from model “pred1a”, since this has slightly better statistical performance parameters than the others. Furthermore, this model

considers all available landslide information, and thus it is a better representation of the real situation than e.g. the model “pred05a”. The model “pred05a” was calculated to carry out a true random cross-validation. The same strategy had been previously applied to Northern and Eastern Norway.

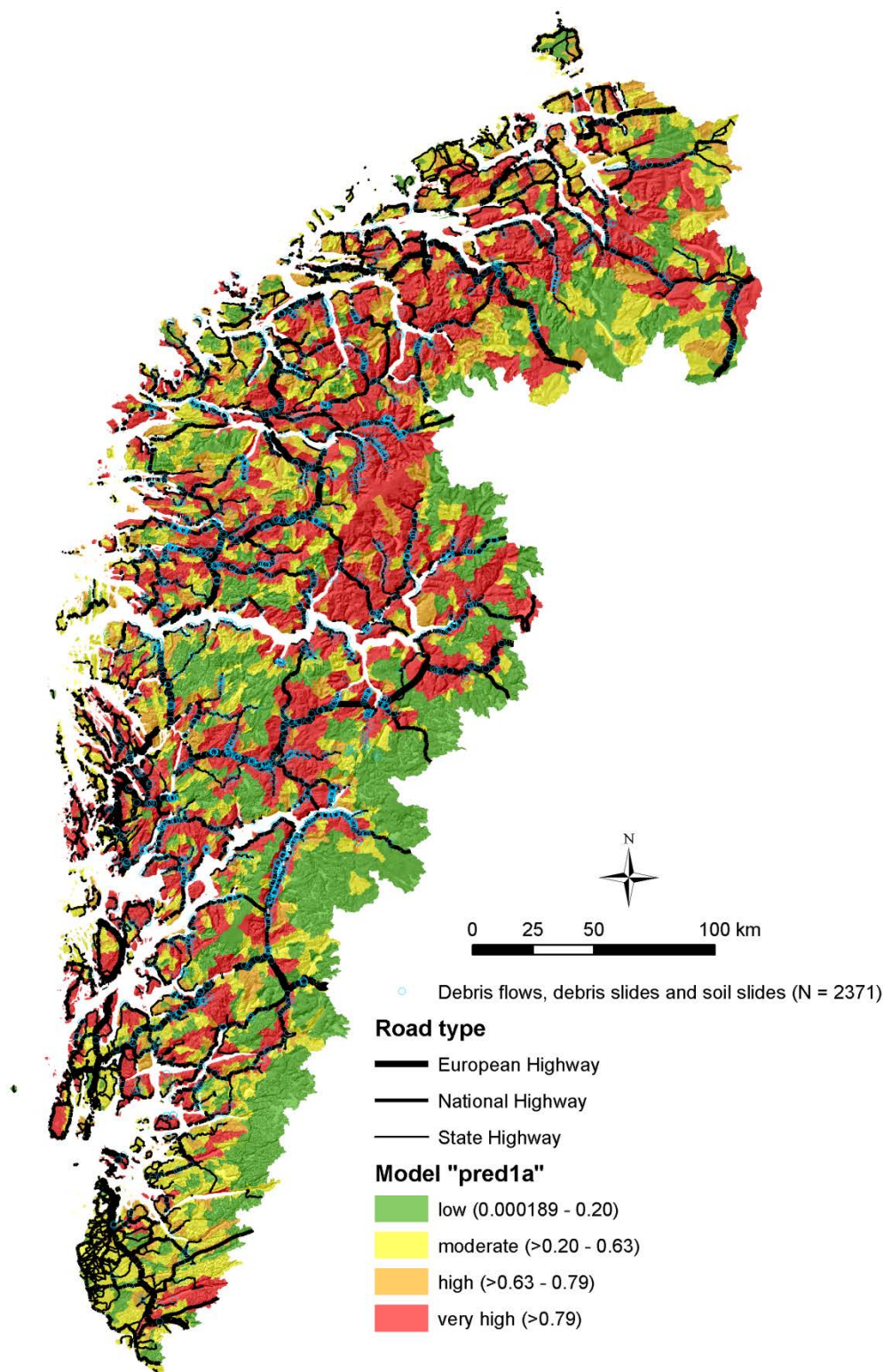


Figure 9 Landslides, landslide susceptibility and highways in Western Norway, Model "pred1a".

6 References

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http://www.nve.no/Global/Vann%20og%20vassdrag/Databaser%20og%20kart/REGINE/REGINE_Classification_Description.pdf [Last accessed: 14/10/2013].

Appendix A - List of variables

Contents

1 List of variables

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1 List of variables

No.	Code	Description
1	AREALENH	REGINE unit area (km ²)
2	TILSIGENH	REGINE unit runoff 1961-1990 (million m ³ per year)
3	AREALTOTAL	Total upstream area (km ²)
4	TILSIGTOTA	Total upstream runoff 1961-1990 (million m ³ per year)
5	AVR6190	Average runoff 1961-1990 (litre/second km ²)
6	AVR3060	Average runoff 1930-1960 (litre/second km ²)
7	SHAPE_AREA	Shape area
8	LMV0	not specified (% of REGINE unit)
9	LMV1	Soils/rocks under water, unspecified (% of REGINE unit)
10	LMV10	Moraine material, unspecified (% of REGINE unit)
11	LMV11	Moraine material, continuous, locally thick (% of REGINE unit)
12	LMV12	Moraine material, non-continuous/thin (% of REGINE unit)
13	LMV13	Clay till, boudel clay, drift clay (% of REGINE unit)
14	LMV14	Ablation moraine (% of REGINE unit)
15	LMV15	Terminal moraine (% of REGINE unit)
16	LMV16	Drumlin (% of REGINE unit)
17	LMV20	Glaciofluvial deposit (% of REGINE unit)
18	LMV21	Glaciofluvial and fluvial deposit (% of REGINE unit)
19	LMV22	Saddle-shaped glaciofluvial deposit (% of REGINE unit)
20	LMV30	Glaciolacustrine deposit (% of REGINE unit)
21	LMV31	Glaciolacustrine and glaciofluvial deposit (% of REGINE unit)
22	LMV35	Lacustrine deposit (% of REGINE unit)
23	LMV40	Marine and fjord deposits, unspecified (% of REGINE unit)
24	LMV41	Marine and fjord deposits, continuous, locally thick (% of REGINE unit)
25	LMV42	Marine and fjord deposits, continuous (% of REGINE unit)
26	LMV43	Marine and fjord deposits, non-continuous/thin (% of REGINE unit)
27	LMV50	River and stream deposits, unspecified (% of REGINE unit)
28	LMV54	Floodplain deposits, continuous (% of REGINE unit)
29	LMV55	Floodplain deposits, non-continuous/thin (% of REGINE unit)
30	LMV60	Eolian deposits (% of REGINE unit)
31	LMV70	Weathered material, unspecified (% of REGINE unit)
32	LMV71	Weathered material, continuous, locally thick (% of REGINE unit)
33	LMV72	Weathered material, non-continuous/thin (% of REGINE unit)
34	LMV73	Block field (% of REGINE unit)
35	LMV80	Landslide material, not divided by thickness (% of REGINE unit)

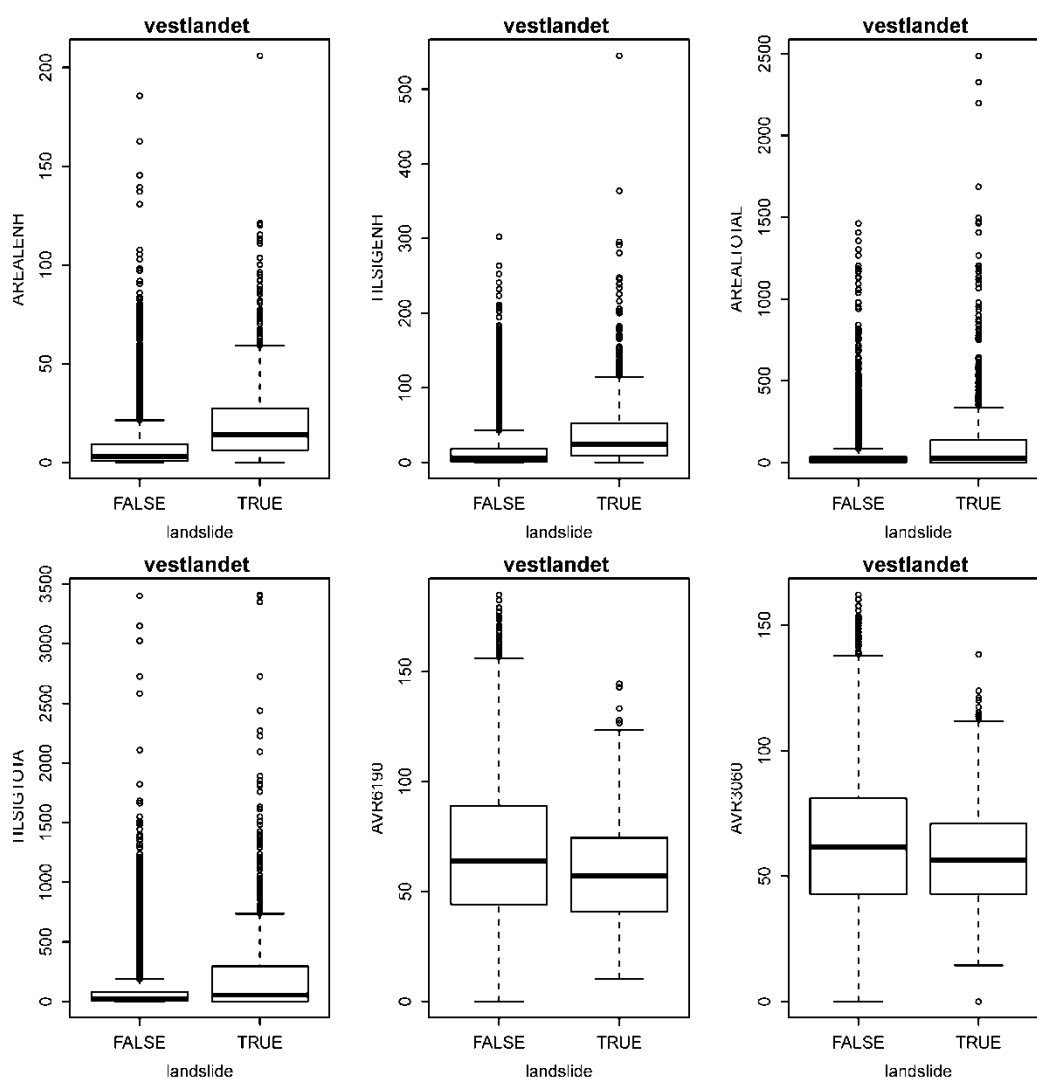
36	LMV81	Landslide material, continuous, locally thick (% of REGINE unit)
37	LMV82	Landslide material, non-continuous/thin (% of REGINE unit)
38	LMV90	Peat and marshland (organic material) (% of REGINE unit)
39	LMV100	Humus blanket/thin peat blanket overlying bedrock (% of REGINE unit)
40	LMV101	Discontinuous or thin soil cover on bedrock (% of REGINE unit)
41	LMV120	Fill (anthropogenic material), unspecified (% of REGINE unit)
42	LMV130	Bare rock (% of REGINE unit)
43	LMV140	Bare rock/rock with patchy or thin cover (% of REGINE unit)
44	DEM_RANGE	Elevation range in REGINE unit
45	DEM_MEAN	Mean elevation of REGINE unit
46	DEM_MEDIAN	Median elevation of REGINE unit
47	East_MEAN	Mean of easternness of REGINE unit
48	north_MEAN	Mean of northness of REGINE unit
49	SL_MEAN	Mean slope of REGINE unit
50	SL_STD	Standard deviation of slope of REGINE unit
51	SL_MEDIAN	Median slope of REGINE unit
52	RF_MEAN	Mean of average yearly rainfall 1961-1990 in REGINE unit
53	RF_SUMrm	Sum of average yearly rainfall 1961-1990 in REGINE unit
54	C1ap	Artificial surfaces (% of REGINE unit)
55	C211ap	Arable land, not irrigated (% of REGINE unit)
56	C231ap	Pastures (% of REGINE unit)
57	C245ap	Heterogenous agricultural areas, mainly farmland and natural vegetation (% of REGINE unit)
58	C322ap	Moors and heath land (% of REGINE unit)
59	C324ap	Transitional woodland-shrub (% of REGINE unit)
60	C339ap	Open space with little or no vegetation (% of REGINE unit)
61	C4ap	Inland marshes, peat bogs and intertidal flats (% of REGINE unit)
62	c316ap	Forests (% of REGINE unit)

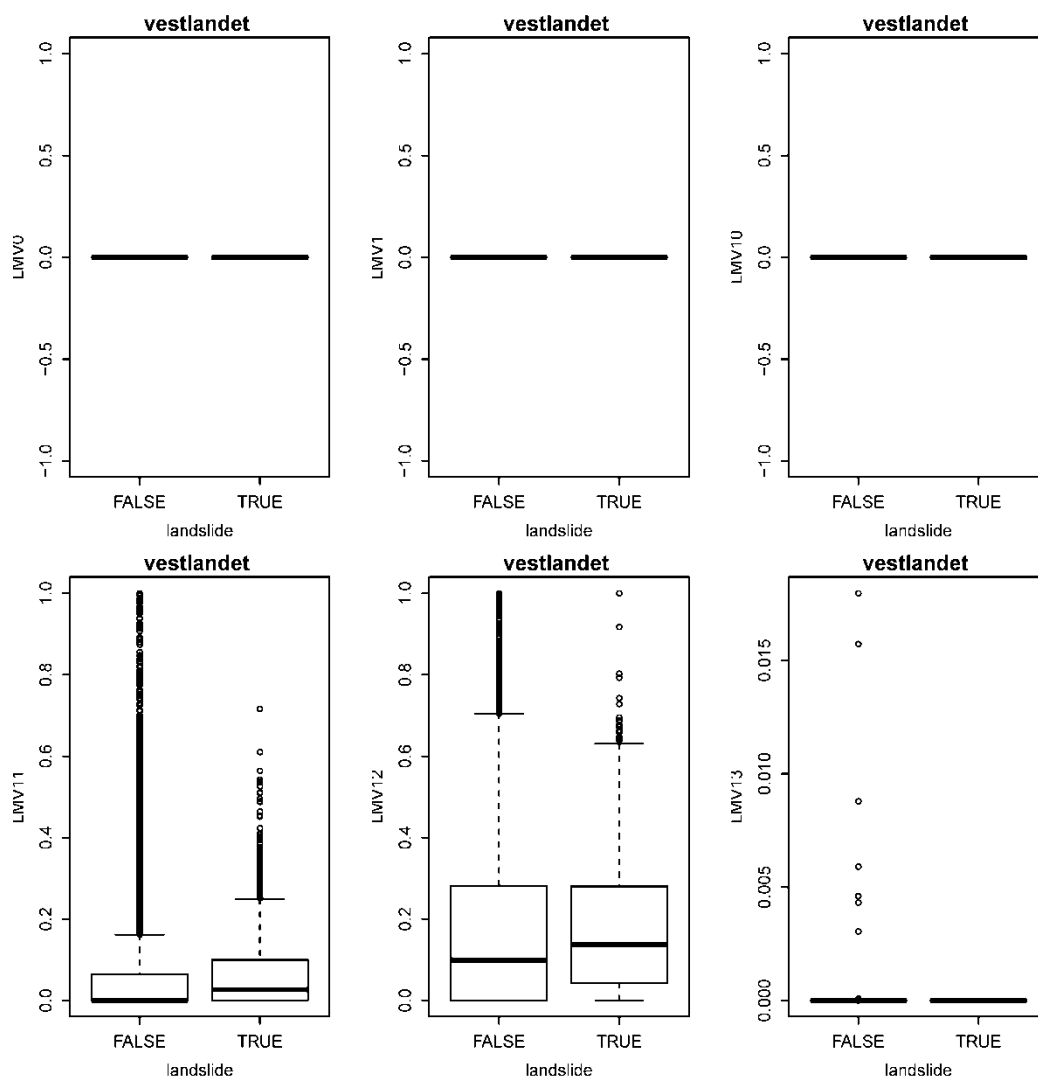
Appendix B - Boxplots of variables

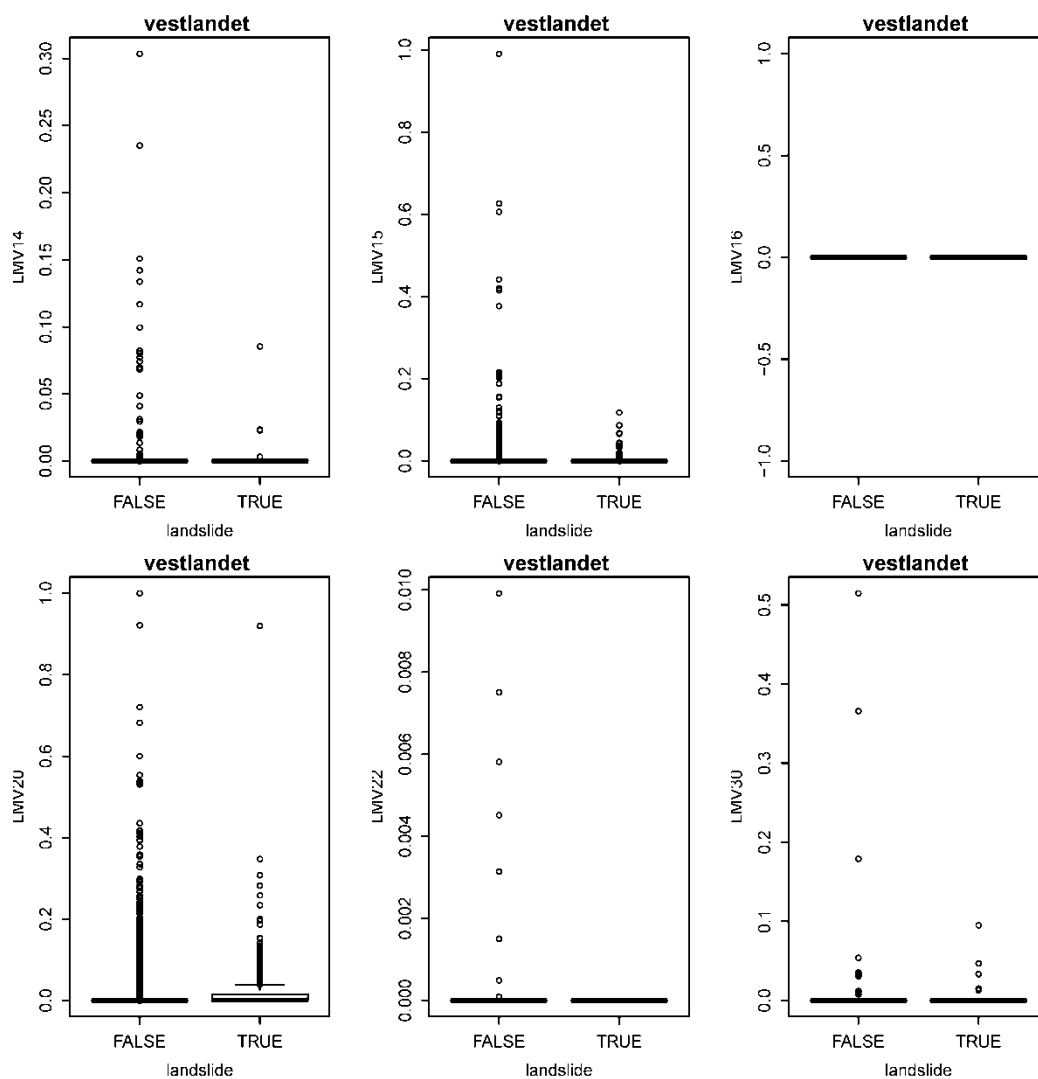
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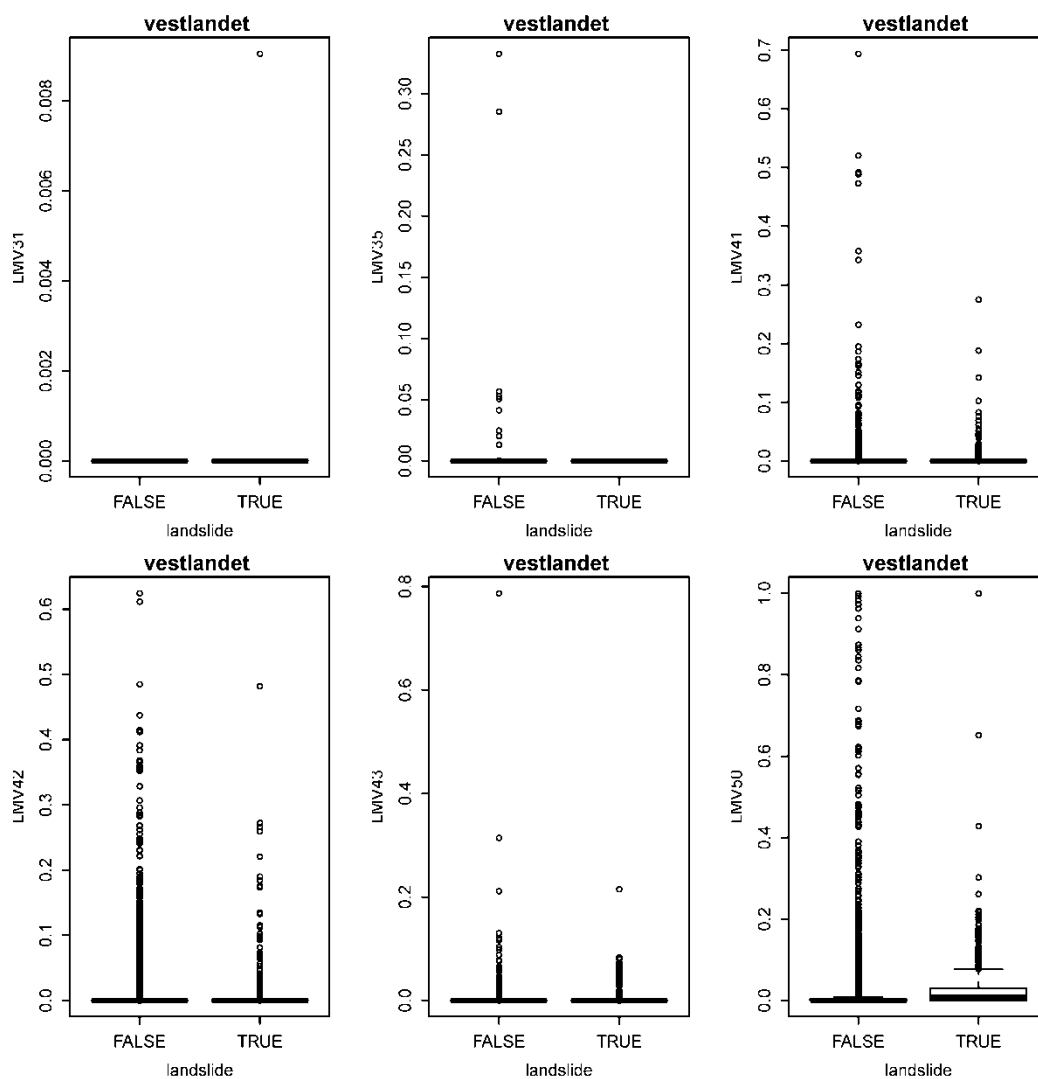
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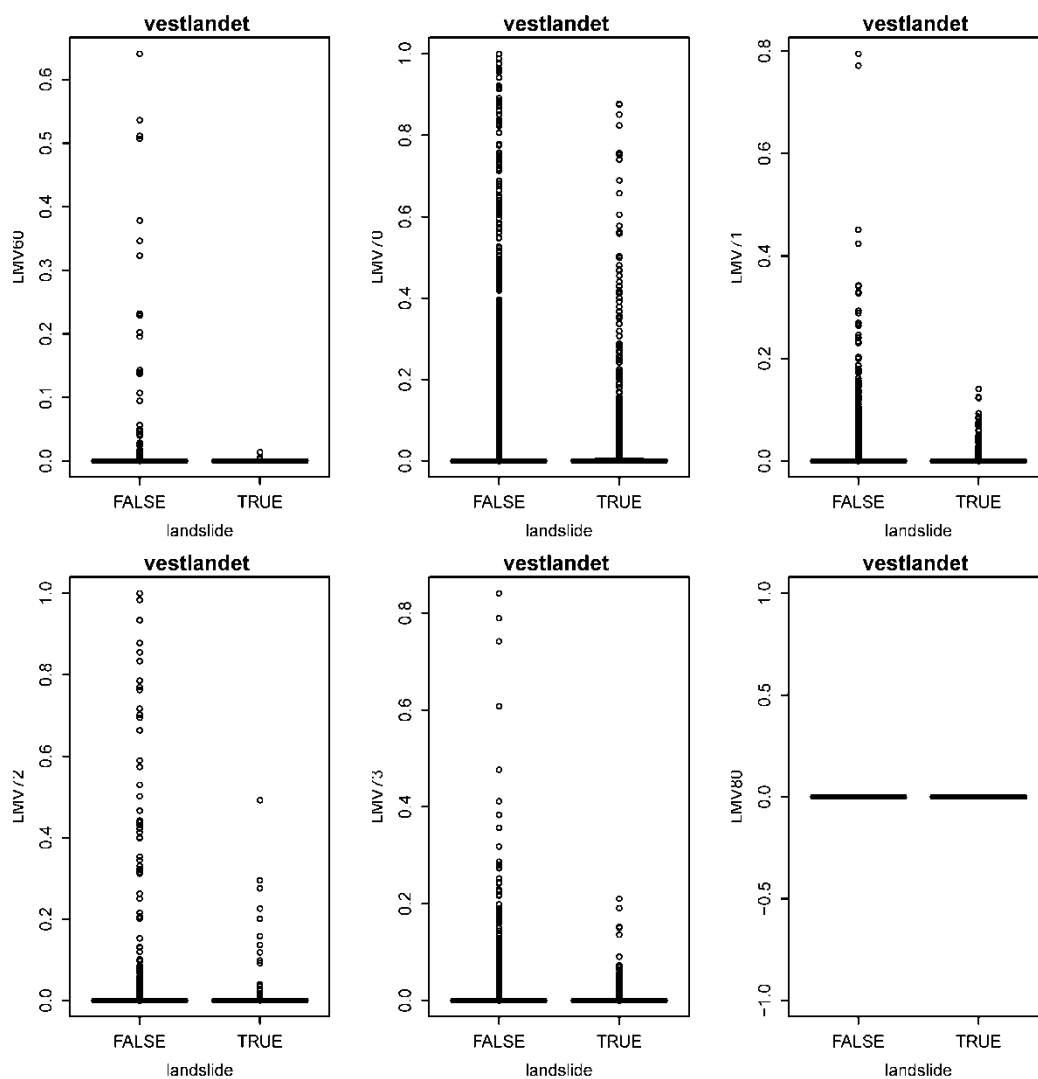
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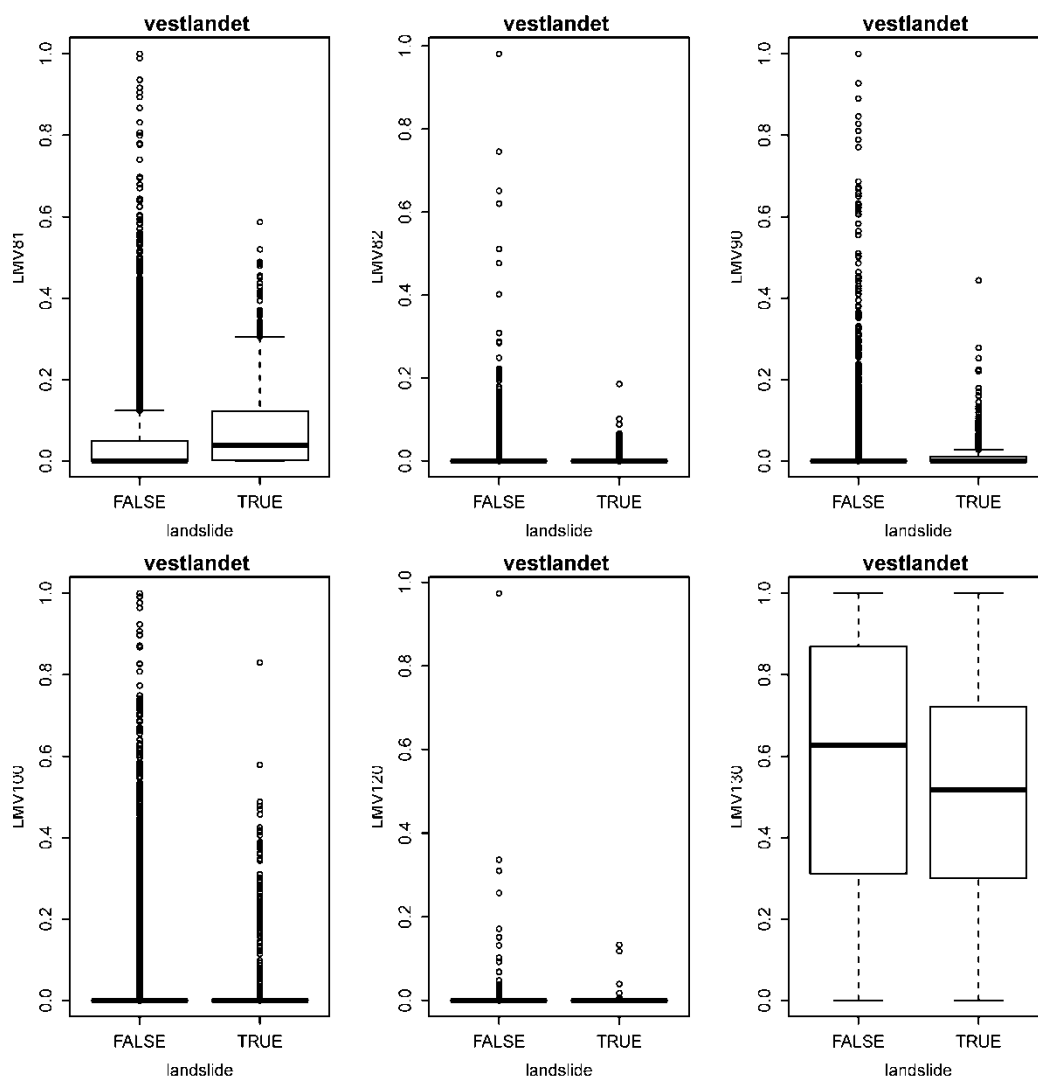


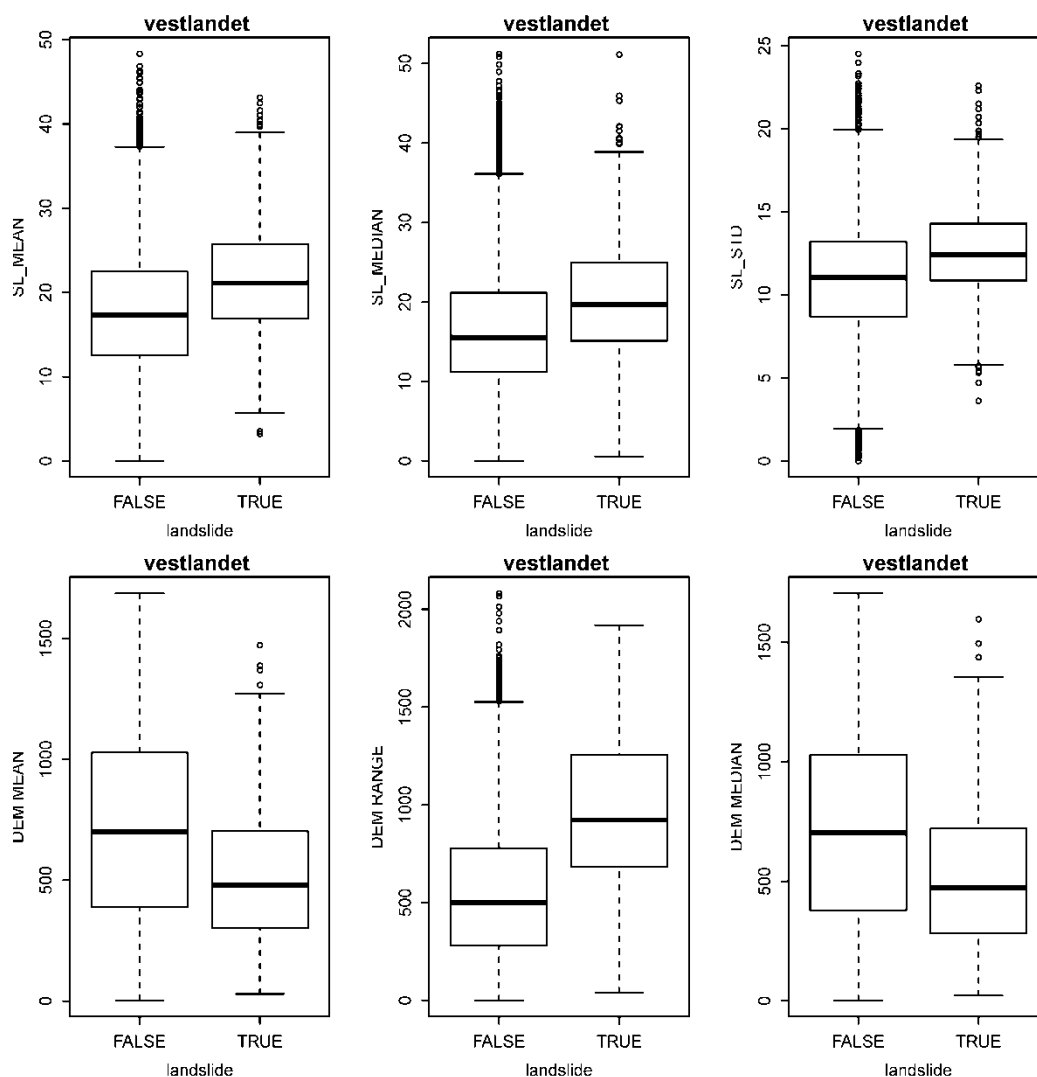


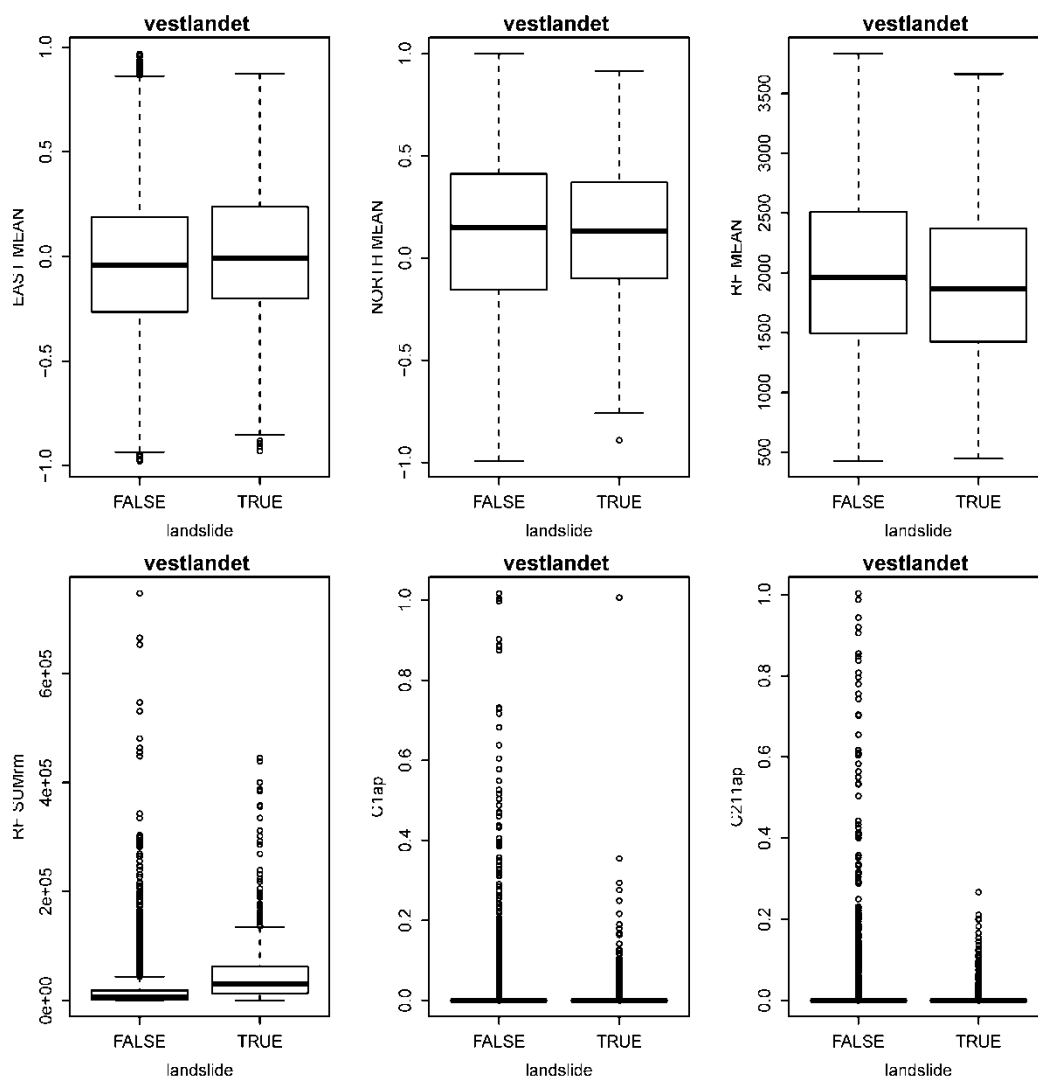


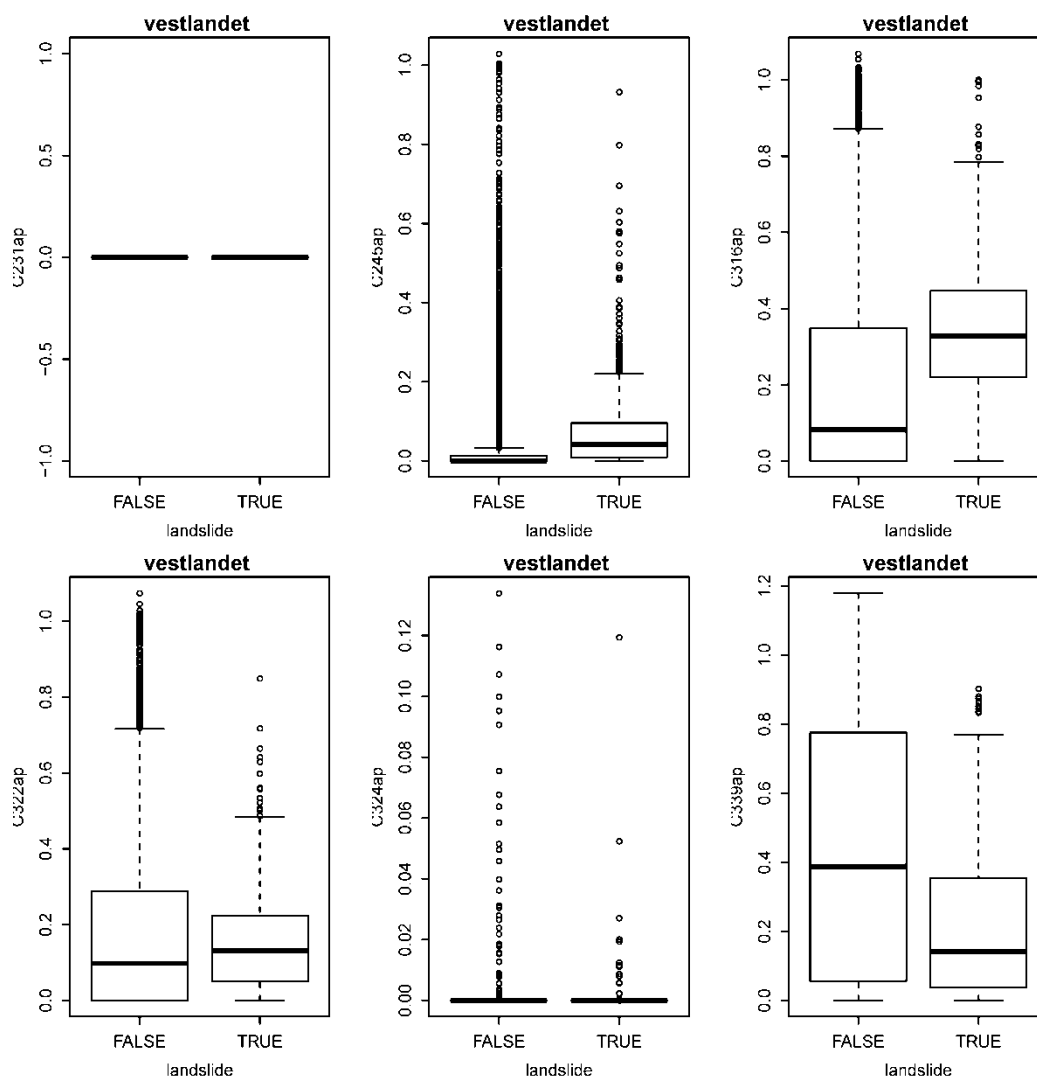


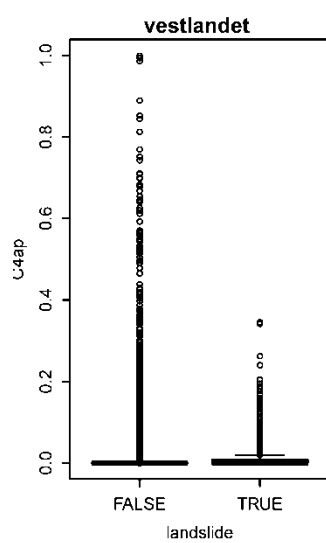
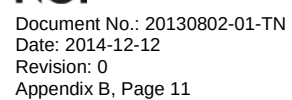












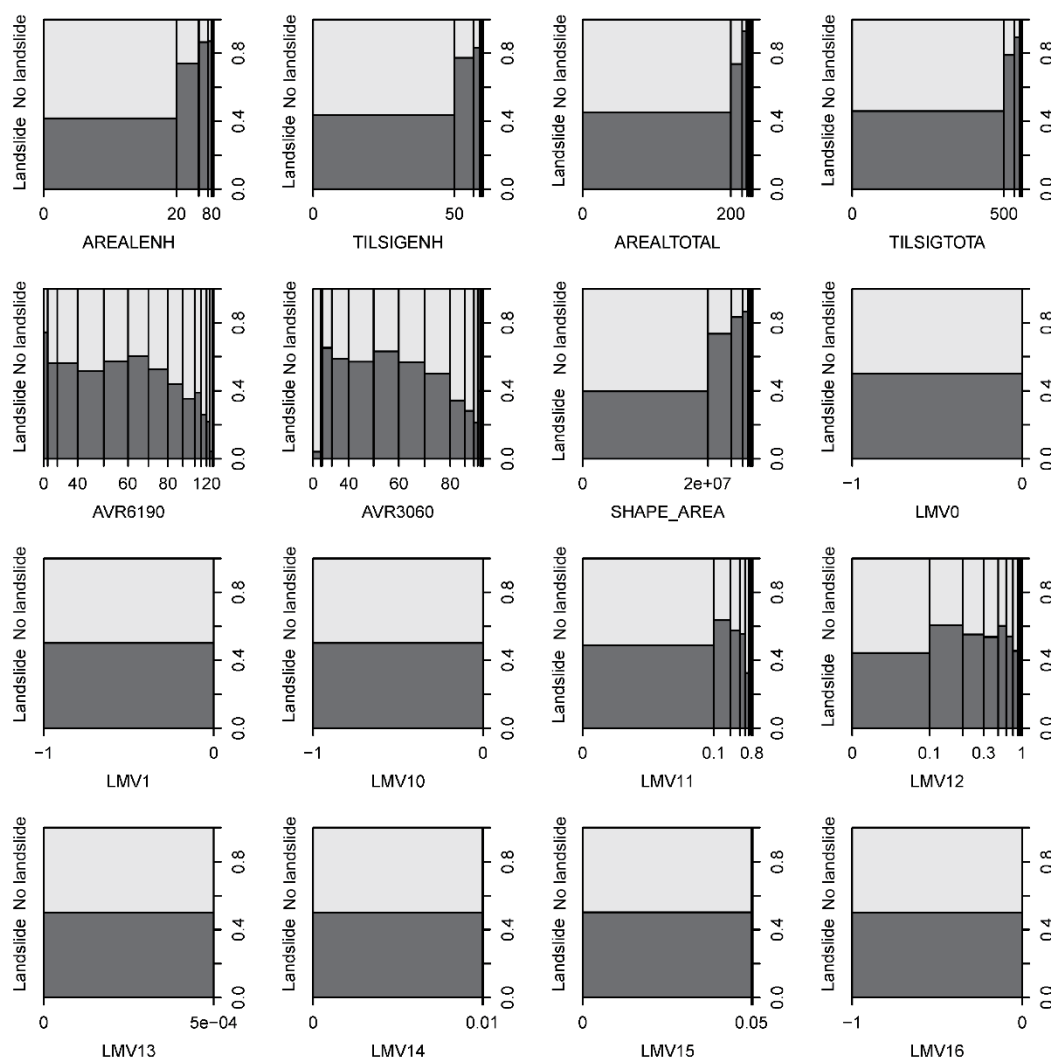
Appendix C - Spineplots of variables

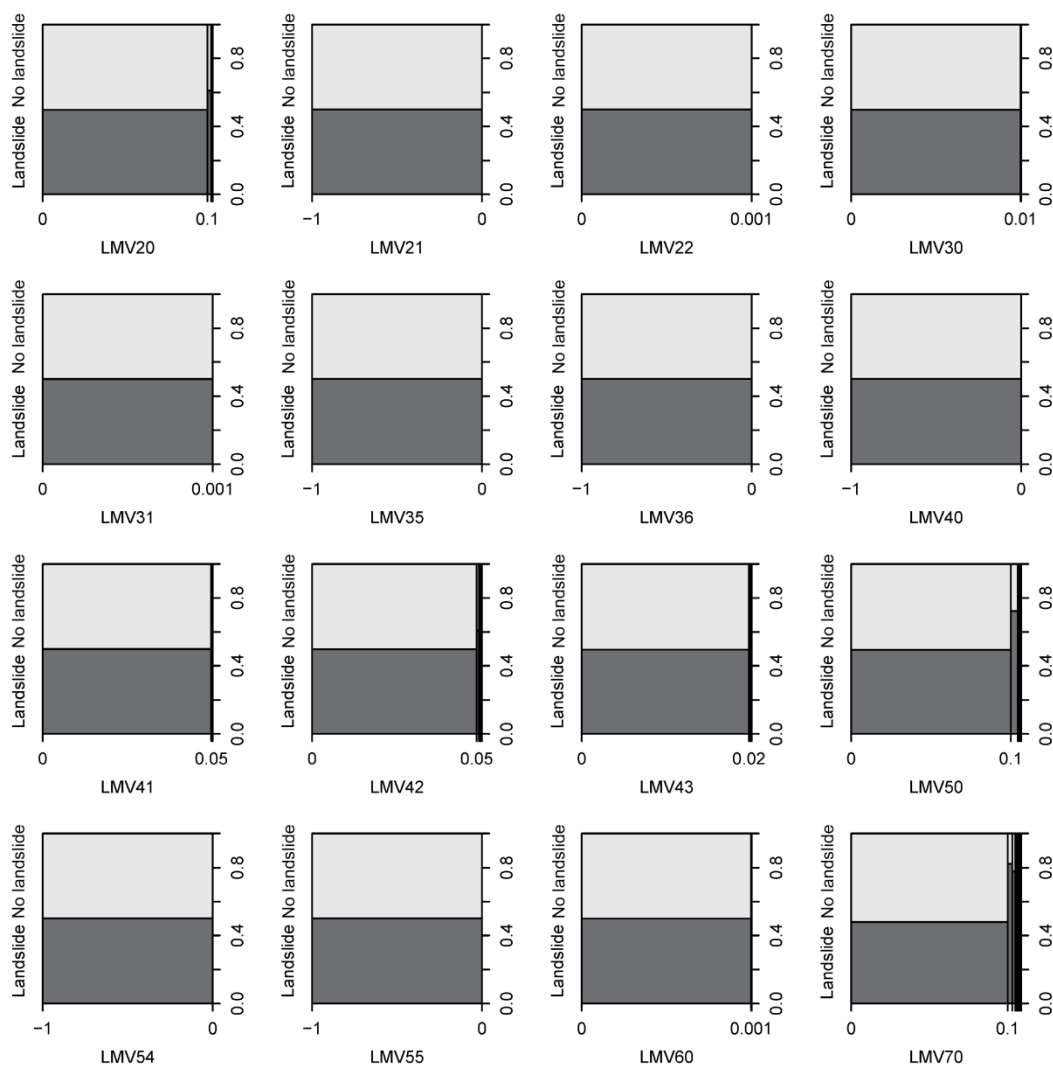
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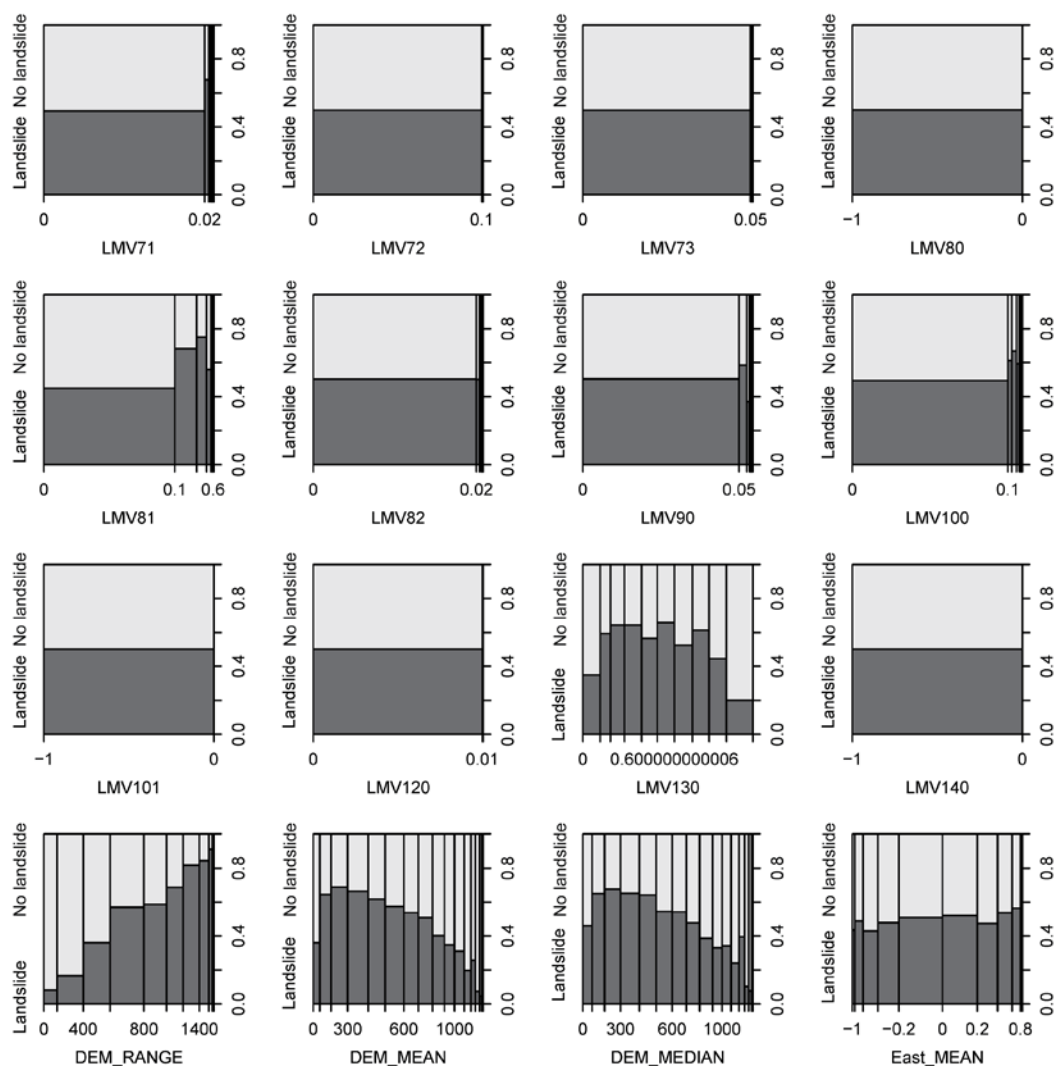
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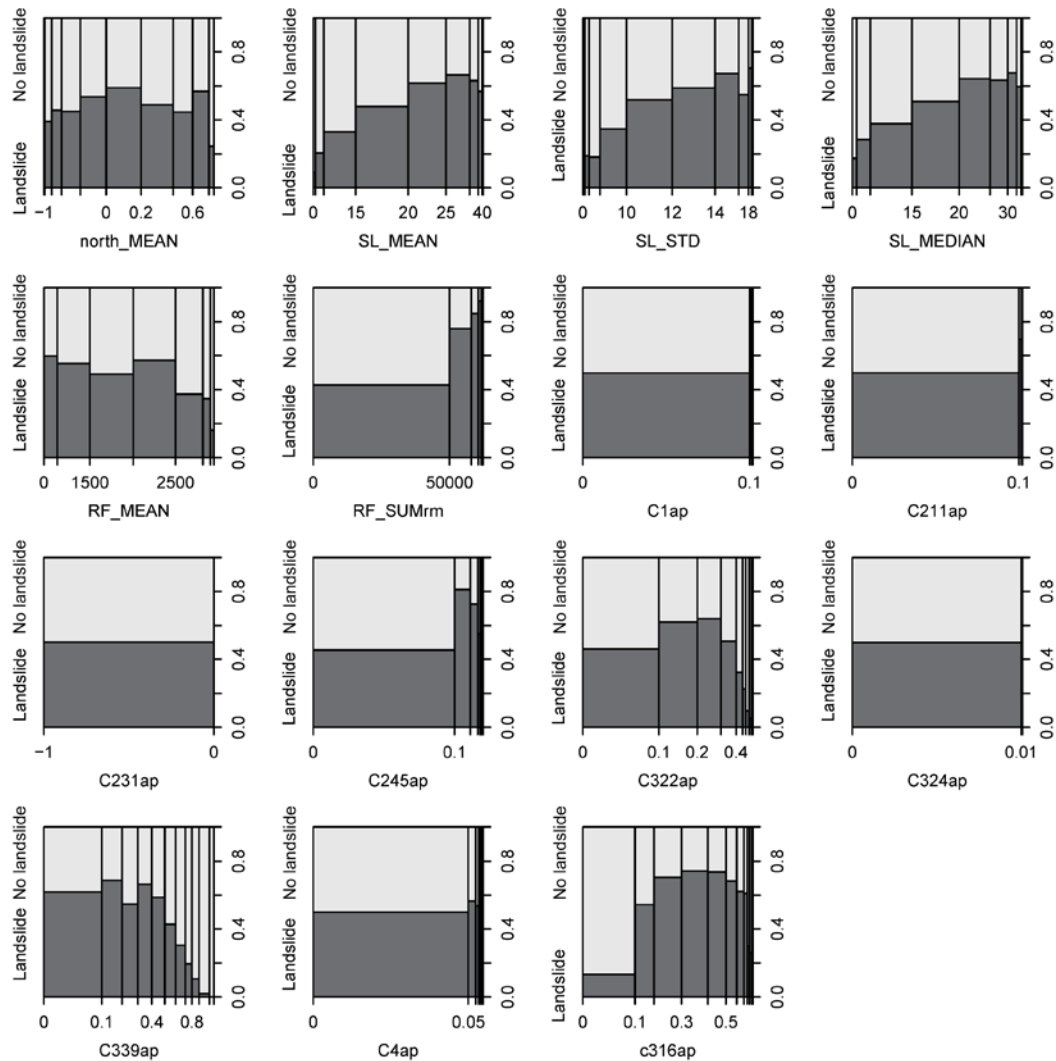
1 Spineplots of variables

The spineplots shown here are simultaneously plotting the empirical frequency of landslide occurrence conditional on a predictor variable and the empirical frequency of that variable. Bar widths in the spineplots are proportional to the empirical frequency of the given interval of predictor values.









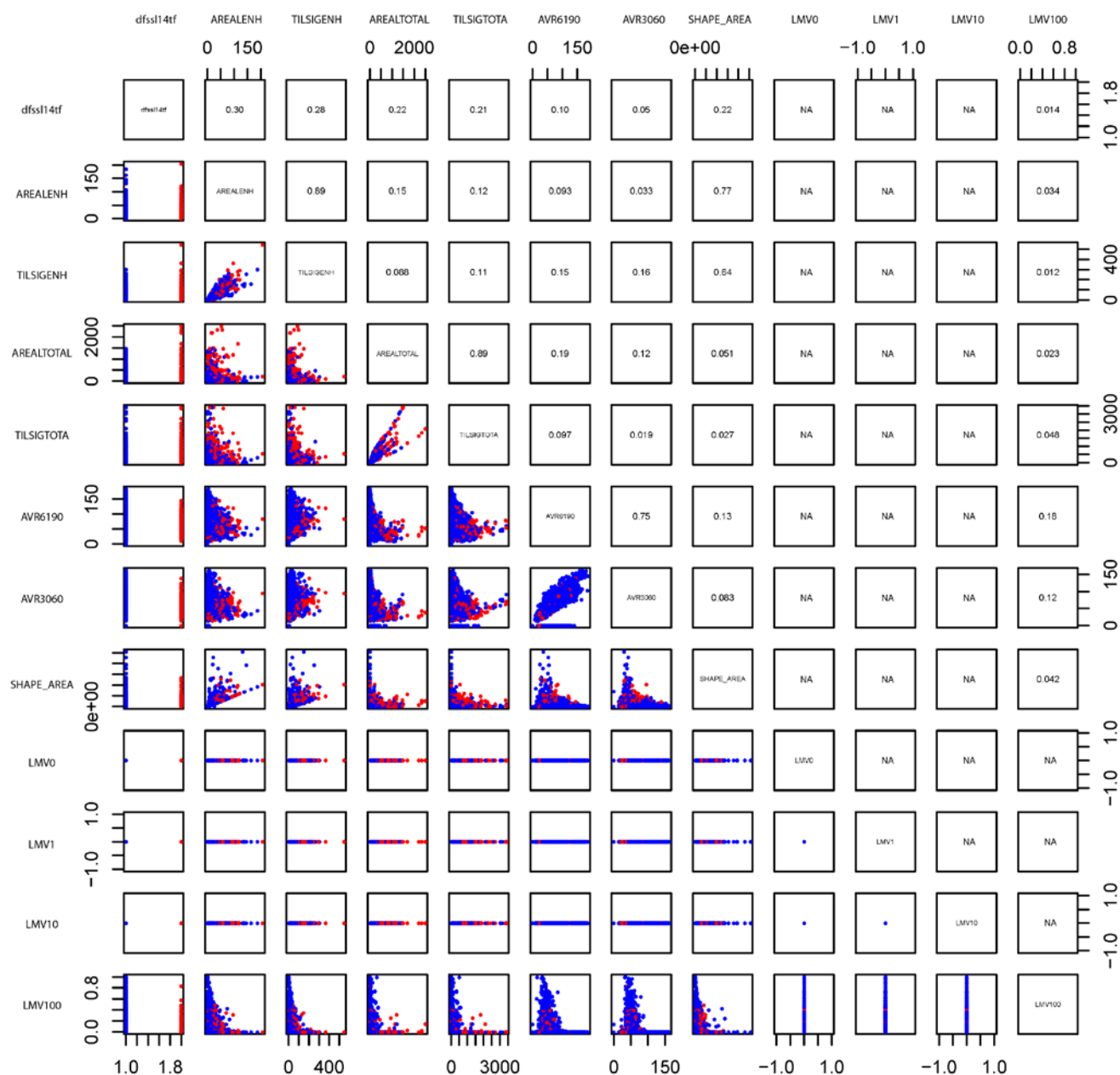
Appendix D - Correlation matrices of variables

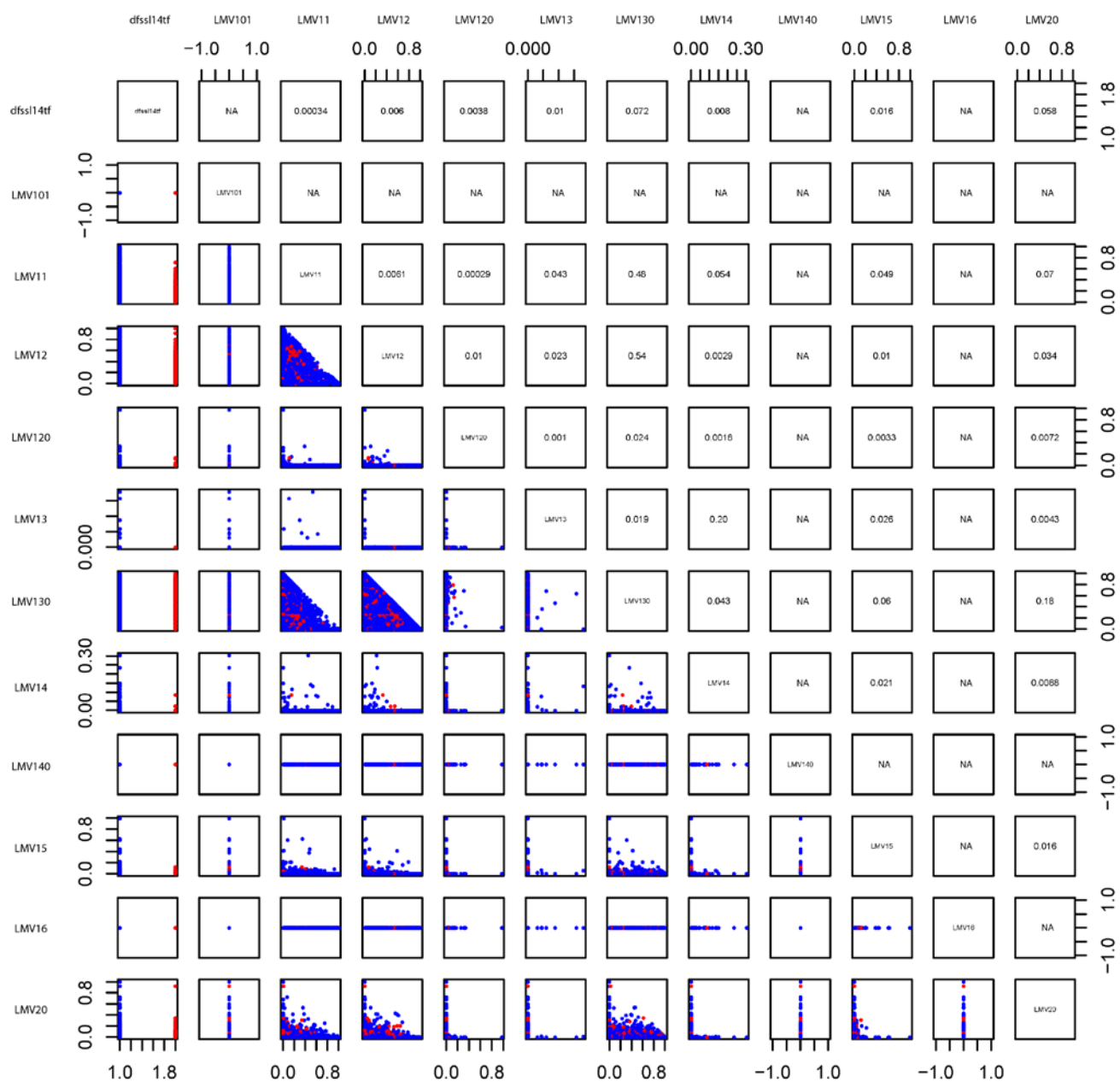
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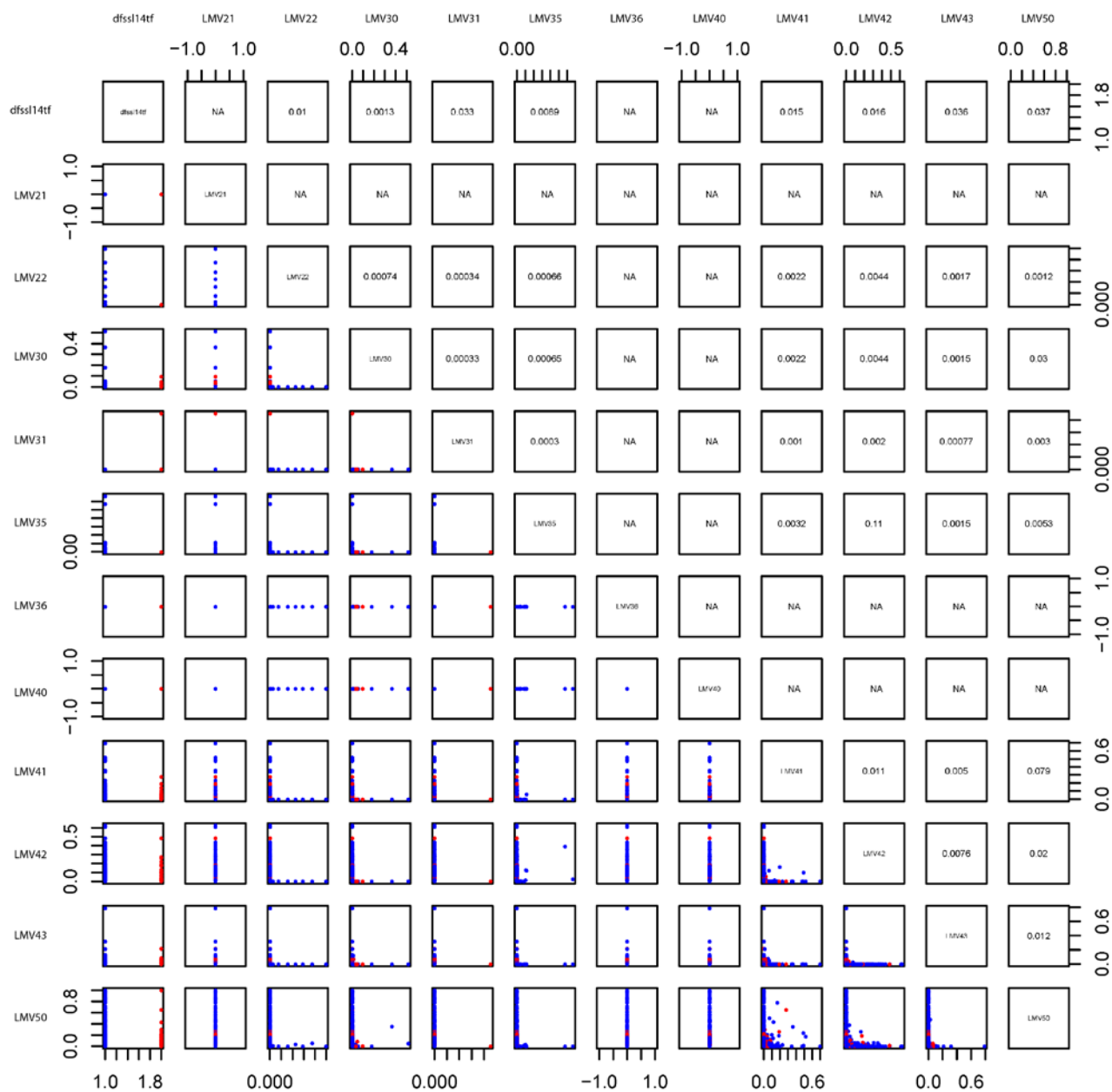
1	Correlation matrices of the variables	2
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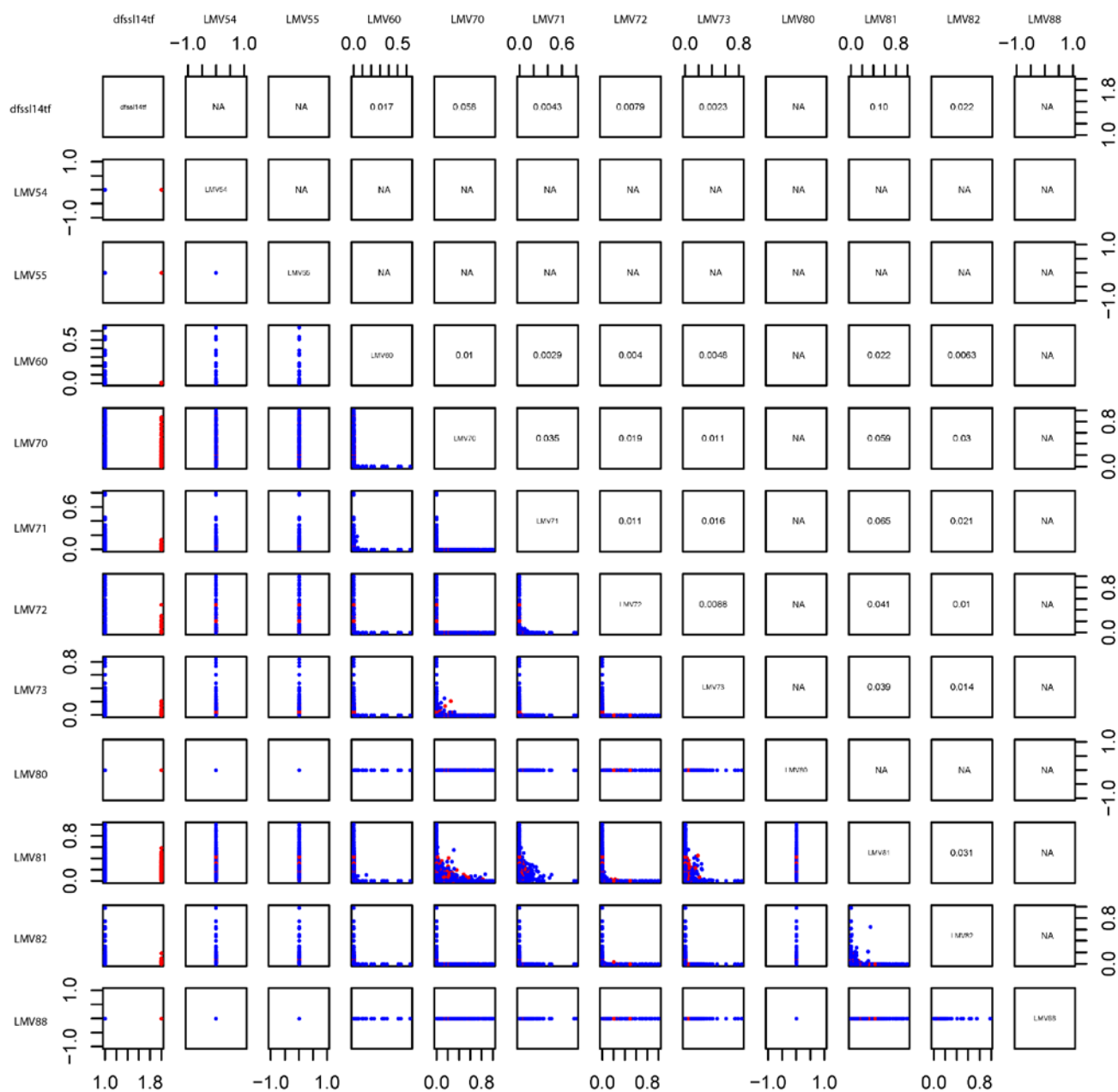
1 Correlation matrices of the variables

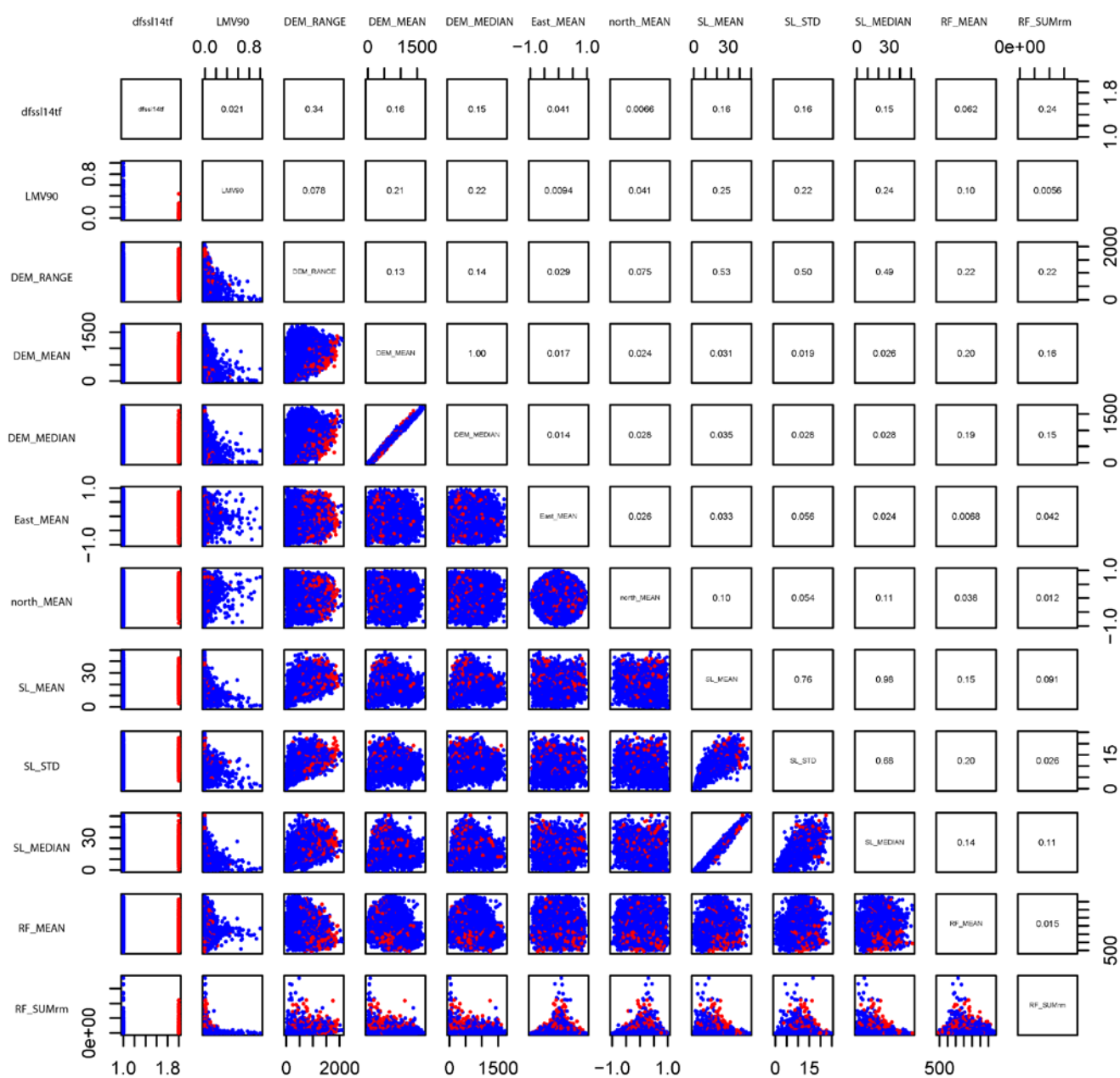
The cells in the lower left part of the matrices are showing the distribution of landslide (red) and non-landslide (blue) points for each pair of variables. The cells in the upper right part of the matrices show the correlation coefficients between each pair of variables.

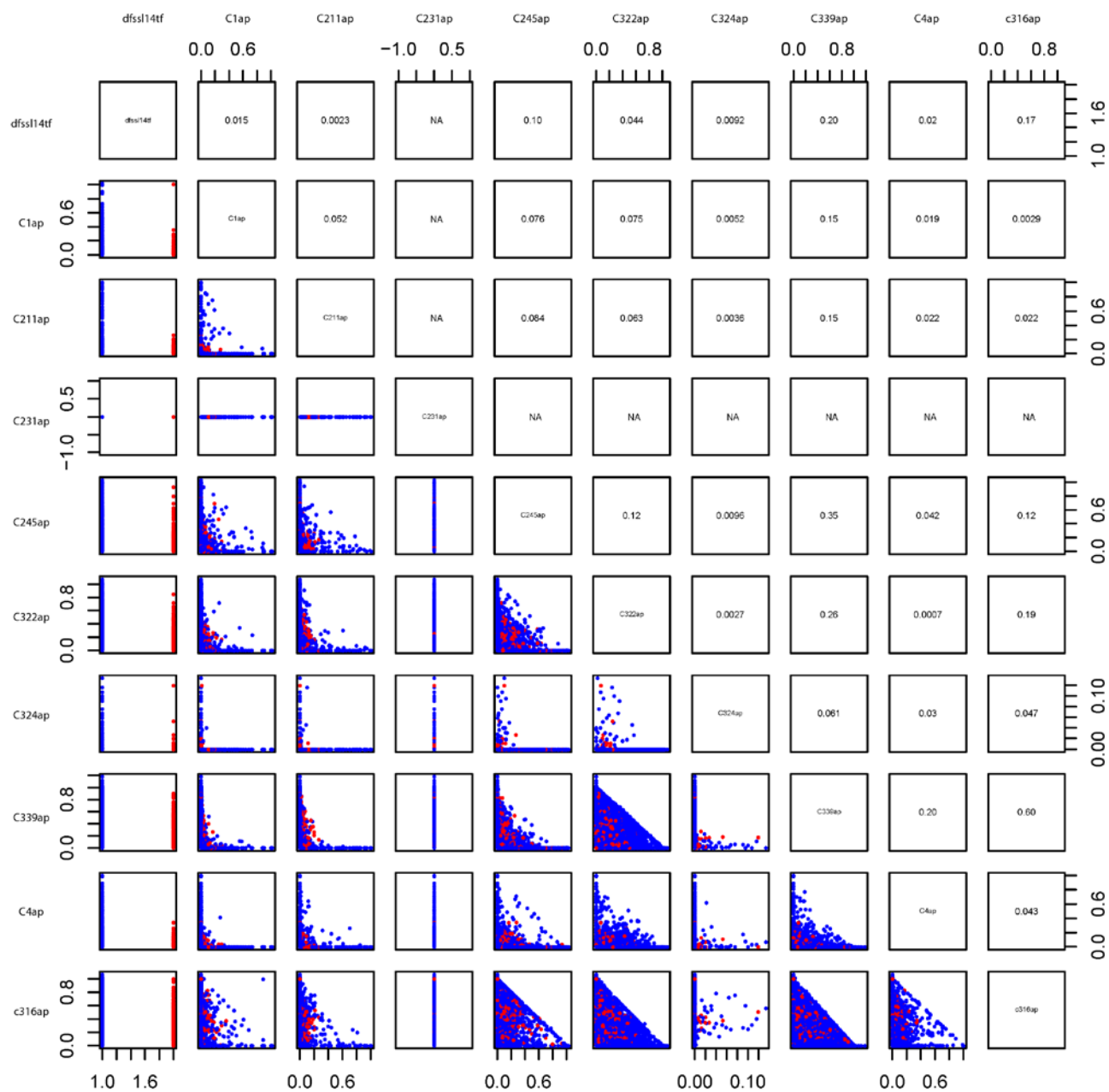












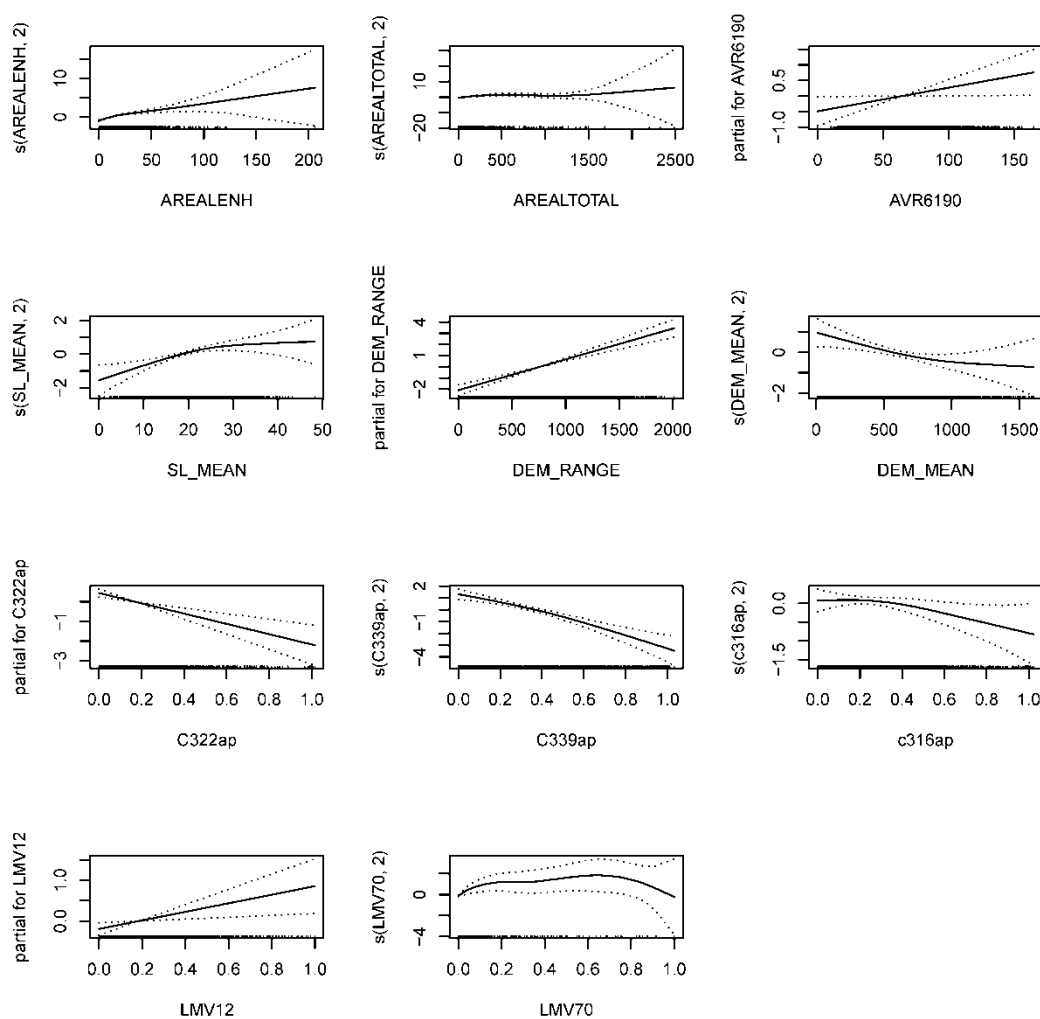
Appendix E - Transformation plots of predictor variables

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1 Transformation plots of predictor variables

Transformation of predictor variables in the Generalized Additive Model “pred1a”. A spline function for non-parametric smoothing of the variable, $s(\text{variable})$, indicates a nonlinear transformation. The dotted lines represent confidence bands.



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Dokumentinformasjon/Document information						
Dokumenttittel/Document title Susceptibility map for debris flows, debris slides and soil slides in Western Norway					Dokumentnr./Document No. 20130802-01-TN	
Dokumenttype/Type of document Technical Note		Distribusjon/Distribution Limited			Dato/Date 2014-12-12	
					Rev.nr.&dato/Rev.No&date. 0	
Oppdragsgiver/Client Norges vassdrags- og energidirektorat (NVE)						
Emneord/Keywords Landslide susceptibility, precipitation-induced landslides, debris flows, debris slides, soil slides						
Stedfesting/Geographical information						
Land /Country Norge					Havområde/Offshore area	
Fylke/County Hordaland, Rogaland, Møre og Romsdal, Sogn og Fjordane					Felt navn/Field name	
Sted/Location					Sted/Location	
Kartblad/Map					Felt, blokknr./Field, Block No.	
UTM-koordinater/UTM-coordinates						
Dokumentkontroll/Document control						
Kvalitetssikring i henhold til/Quality assurance according to NS-EN ISO9001						
Rev./ Rev.	Revisjonsgrunnlag/Reason for revision	Egen- kontroll/ Self review av/by:	Sidemanns- kontroll/ Colleague review av/by:	Uavhengig kontroll/ Independent review av/by:	Tverrfaglig kontroll/ Inter- disciplinary review av/by:	
0	Original document	R. Bell	JMC			
Dokument godkjent for utsendelse/ Document approved for release		Dato/Date 2014-12-12		Sign. Prosjektleder/Project Manager José Cepeda		

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BSI EN ISO 9001
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Appendix C

Technical Note: Bell R., and Cepeda J. (2015). Susceptibility map for debris flows, debris slides and soil slides in Trøndelag. Technical note 20150747-01-TN. Norges Geotekniske Institutt, Oslo, Norway

To: Norges vassdrags- og energidirektorat (NVE)
Attn.: Graziella Devoli
Copy to:
Date: 2015-12-18
Revision no./Rev.date: 0 /
Document no.: 20150747-01-TN
Project: Improvement of warning levels for precipitation-induced landslides in Trøndelag
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Reviewed by: José Cepeda

Susceptibility map for debris flows, debris slides and soil slides in Trøndelag

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Review and reference page

1 Introduction

The aim of this project is the improvement of warning levels for precipitation-induced landslides (debris flows, debris slides and soil slides) in Trøndelag. Similar to the applications in Northern and Eastern Norway (Bell et al. 2014) and Western Norway (Bell & Cepeda 2014), landslide susceptibility at REGINE unit level is modelled. NVE plans to combine this landslide map with NVE's hydmet index for warning services.. The study area includes also some REGINE units of Northern Norway which were not modelled in the previous study. However, in the following the study area is named Trøndelag only. This technical note presents a description of the data, the methodology for analysis, the results and a discussion.

2 Data

In consistence with past projects for modelling landslide susceptibility in Northern, Eastern and Western Norway, only data sets available for the whole country were used as input. One of the most important data for landslide susceptibility modelling is the landslide inventory. Additional data are the REGINE database (national catchment database), the Quaternary map, land cover data, hydrometeorological data, and various derivatives from a digital elevation model (DEM). All data is briefly described in the following paragraphs.

The integrated national database for all types of rapid mass movements (www.skrednett.no) contains more than 47000 events (just point location) from the last five hundred years covering the whole country. The most frequent events are rockslides and snow avalanches followed by debris slides (Bell & Cepeda 2014). Currently, 7013 debris flows, debris slides and soil slides are stored in the database (date retrieved: 28 October 2015), of which 1054 are located in the study area. The majority of the entries result from events recorded by road authorities and railway authorities. Thus, usually the points are placed where landslides have hit roads or railways (Jaedicke et al. 2009), which may introduce large inaccuracies for long runout events when modelling landslide susceptibility, since in general susceptibility modelling should be carried out at the initiation areas of landslides, especially when using pixel-based approaches. Further uncertainties result from: errors in classifying the events according to the landslide type, lack of registration in some regions and missing information on the slope (artificial cut/fill slope or natural slope). In spite of this, the inventory was used since it is the only available country-wide (Bell et al. 2014). A total of 1023 soil and debris slides as well as debris flows were extracted for Trøndelag and will be termed landslides in this technical note.

The REGINE database was used to extract the information on first order catchments (REGINE units, vector polygon data). The data stored in each REGINE unit and used in susceptibility modelling are: REGINE unit area (km²), REGINE unit runoff 1961-1990 (million m³ per year), total upstream area (km²), total upstream runoff 1961-1990

(million km³ per year), average runoff 1961-1990 (litre/second km²) and average runoff 1930-1960 (litre/second km²) (NVE n.d.).

The Quaternary map at a scale of 1:250,000 (www.ngu.no) gives information of various types and subtypes of sediments, but also shows bare rock outcrops. The quality is rather heterogeneous with higher level of detail in some areas only (Bell et al. 2014).

Land cover data was obtained from CORINE land cover 2006 data, which was compiled by the Norwegian Forest and Landscape Institute (Aune-Lundberg and Strand 2010). Details are limited to a minimum mapping unit of 25 ha (0.25 km²).

Spatially distributed average yearly rainfall data (1961-1990) with a resolution of 1km x 1km was available (Source: MET and www.senorge.no).

A digital elevation model (DEM) with a resolution of 15 m x 15 m was available for all Norway, derived from 1:50 000 topographical maps.

3 Methods

Landslide susceptibility modelling was carried out using the statistical approach of Generalized Additive Models (GAM) (Hastie 1992), a further development of logistic regression. A combined backward and forward stepwise variable selection in R (version 3.2.2, www.r-project.org) based on Akaike's Information Criterion AIC (Akaike 1974) was applied to fit the susceptibility models. Using the AIC, the best fit of variables for a model is automatically selected by evaluating the significance of the variables and penalizing for model complexity. The GAM decides for each variable whether it should be omitted, used linearly or with a smooth function. Based on the AIC values, the GAM selects the model with the best combination of variables. In addition, model runs were carried out allowing only linear use of variables which means that this is an approach of logistic regression.

Landslide susceptibility was modelled at REGINE unit (catchment) level since for improving the current early warning this is deemed sufficient. The main advantage is that the whole process area of the landslides is automatically considered and not only initiation areas. The poor spatial location of the landslide points of the landslide inventory (see above) does not matter in general since it is assumed that all landslides are located in the same REGINE unit of the initiation areas. However, 42 landslide points were located marginally outside of the REGINE units. Assuming that this is due to the spatial inaccuracies of both the landslides and the REGINE units, it was decided to move (shift) those landslides into the nearest REGINE unit. Thus, two landslide inventories were prepared, one not including the shifted landslides (dfssl15, N = 981) and one including the shifted landslides (dfssl15c, N = 1021, in two cases it was not clear to which REGINE unit the landslides belong to, so these were left out of the analyses). These two landslide inventories led to 301 and 318 REGINE units with landslides for the dfssl15 and dfssl15c sets, respectively.

Modelling was carried out using a 1:1 relationship between REGINE units with landslides and REGINE units without landslides. For the final landslide susceptibility map all 301 (318) REGINE units with landslides and randomly sampled 301 (318) REGINE units without landslides were used in susceptibility modelling. This ensures that all known information on landslides was considered in the development of the final map. Additional models were calculated for validation purposes. Therefore, 50 % of the REGINE units with landslides were used in the training sample and the other 50 % in the independent testing sample. However, using this approach only one validation estimate results, which might be rather random. As preliminary results showed that the differences between the validation estimates are relatively small, it was decided to improve the validation step further by performing k-fold cross validations using randomly selected subsamples.

We applied k-fold ($k = 4$) cross validations which means that the data is subsampled in 4 subsets. Subsequently, the model is fitted to $k-1$ subsamples (training sample) and validated by the remaining subsample (testing sample). This was repeated four times until each subsample was used as testing sample. The whole process was repeated 10 times ($r = 10$). During each repetition new subsamples were randomly selected. Thus, in total 40 models are fitted and validated calculating the median and interquartile range of the validation criterion.

For each dataset (dfssl15 and dfssl15c) this validation procedure was carried out using three different samples – a) using all REGINE units available, b) using a relationship of 1:1 between REGINE units with landslides and REGINE units without landslides and c) using a relationship of 1:5 between REGINE units with landslides and REGINE units without landslides – and two different statistical methods (GAM and logistic regression).

Subsequently, all calculations were repeated for $k = 2$. Thus, in total 240 models using GAM and 240 models using logistic regression were calculated within this k-fold cross validation approach. k-fold cross validation was applied using the *sperrorest* package in R (Brenning 2012).

Explanatory variables are the Quaternary map, land cover, average annual rainfall, various water runoff variables (see above), and various derivatives from the 15 m x 15 m digital elevation model (DEM) like e.g. slope and aspect. For the categorical data, the proportion of each class in the catchment and for continuous data either mean, median, standard deviation or range for the catchment were calculated and used in modelling. Altogether 64 variables were available (Appendix A). Boxplots (Appendix B), spineplots (Appendix C) and correlation matrices (Appendix D) were used to pre-select variables.

The performance of the resulting models and maps was evaluated using the area under the ROC curve AUROC as criterion (values of 0.7 to 1 show good to very good discrimination between REGINE units with landslides and REGINE units without landslides (Hosmer & Lemeshow 2000)).

Finally, landslide susceptibility was classified into four classes (low, moderate, high, very high), using the same four classes of the hydro-meteorological index. Classification thresholds were set based on the proportion of landslides in each class. The same classification scheme as applied to Northern, Eastern and Western Norway were used: 70 %, 15 %, 12 % and 3% of the landslides in the susceptibility classes very high, high, moderate and low, respectively. For each landslide susceptibility map the classification thresholds are based on the landslide inventory used in modelling, either dfssl15 or dfssl15c.

4 Results

4.1 Landslide inventory

Fig. 1 shows the distribution of different types of landslides for all Norway. Finally, in agreement with NVE it was decided to analyse the landslide types 140, 142, 143 and 144 only (quick clay slides (141) were excluded), as done in the previous assessments. This resulted in 1,023 debris flows, debris slides and soil slides within the study area (Fig. 2). Due to spatial inaccuracies (described in chapter 3), two landslide inventories were prepared, having 981 and 1021 events occurring in 301 and 318 REGINE units, respectively (Fig. 3 and Fig.4). The distribution of landslides in the study area for both inventories is shown in Fig. 5 and Fig. 6.

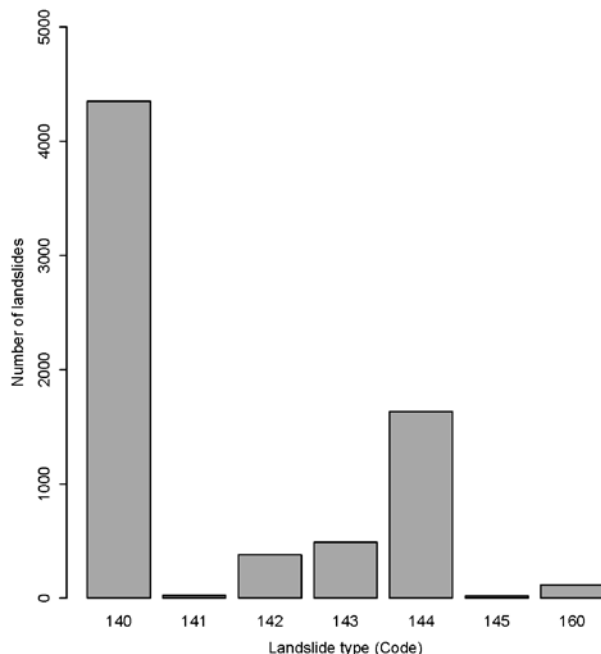


Figure 1 Distribution of different types of rapid landslides in all Norway. (140: Landslides in soils, unspecified; 141: Quick clay slides; 142: Debris slide/Debris flow/Debris flood; 143: Clay slides; 144: Soil slide; 145: Soil slide, unspecified; 160: Debris slide along road. Source: Integrated national database for all types of rapid mass movements, www.skrednett.no)

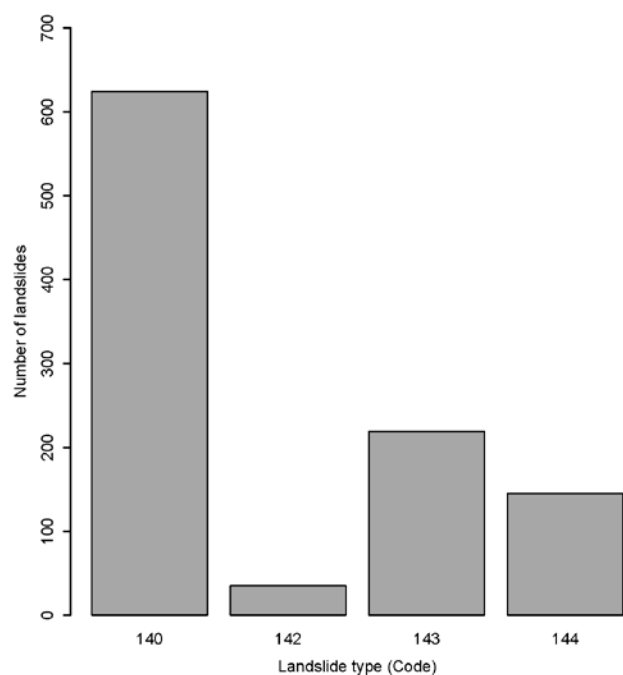


Figure 2 Distribution of different types of rapid landslides in the study area. (140: Landslides in soils, unspecified; 142: Debris slide/Debris flow/Debris flood; 143: Clay slides; 144: Soil slide. Source: Integrated national database for all types of rapid mass movements, www.skrednett.no)

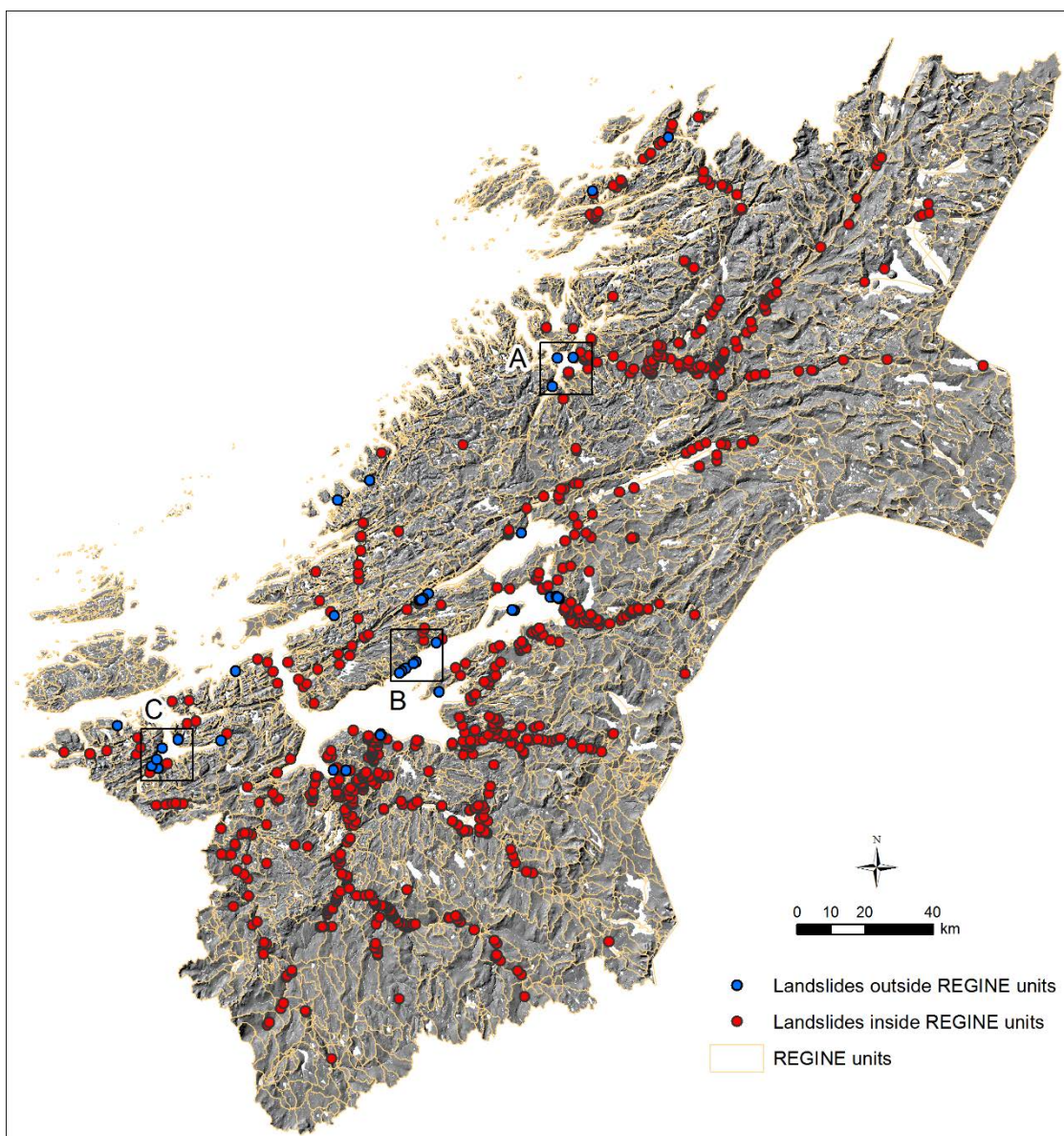


Figure 3 Location of landslides inside and outside of REGINE units. Note: Landslides are located outside of REGINE units due to spatial inaccuracies. The boxes A, B and C indicate the location of the examples shown in Figure 4.

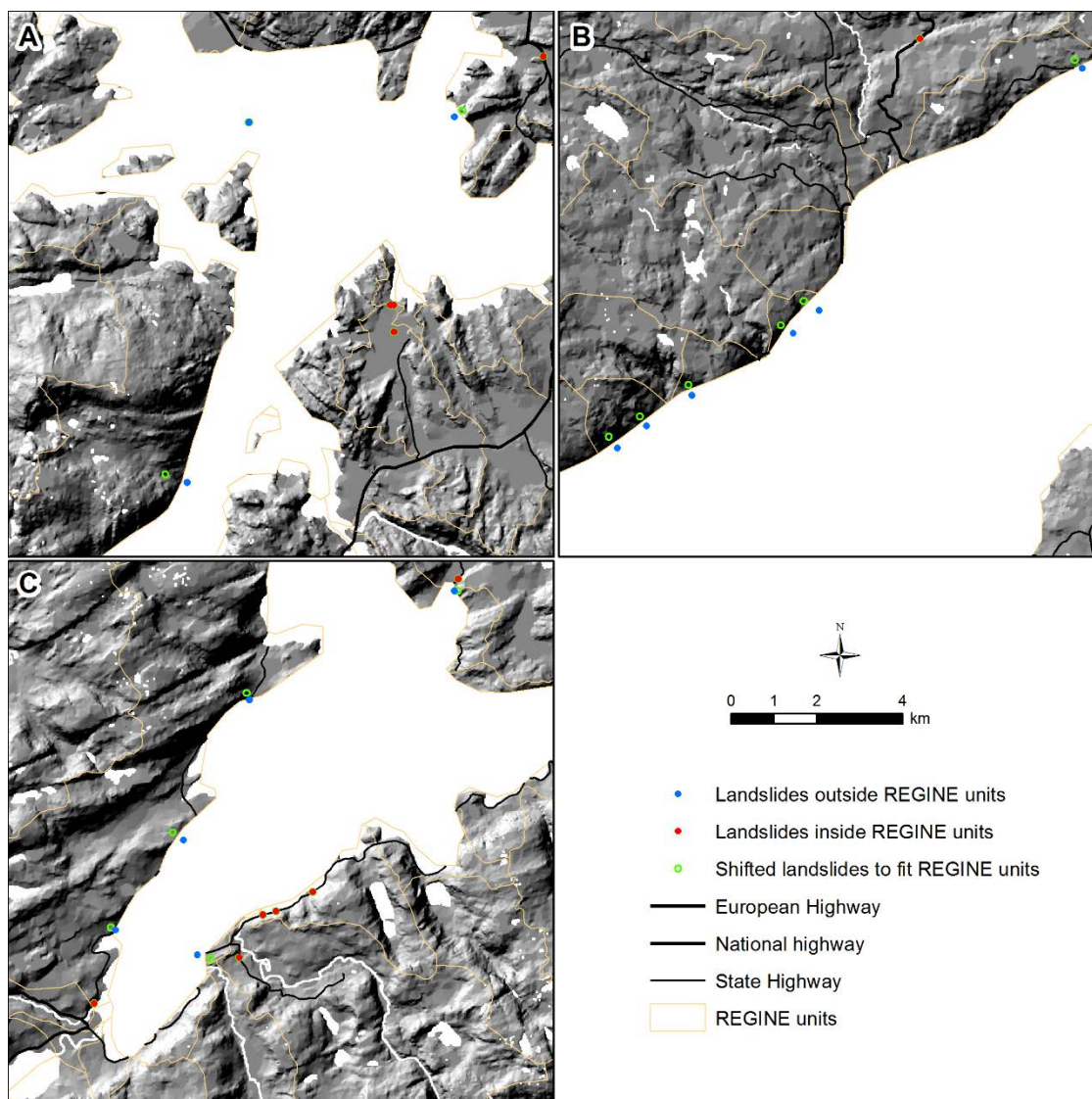


Figure 4 Location of landslides inside and outside of REGINE units as well as the location of the shifted landslides. Note: In most cases landslides were easily assigned to a single REGINE unit. Only 2 of 42 landslides were not shifted. One example is shown in A, which is located in the middle of the fjord and it was not clear to which REGINE unit it belongs to. The location of the examples A, B and C is given in Figure 3.

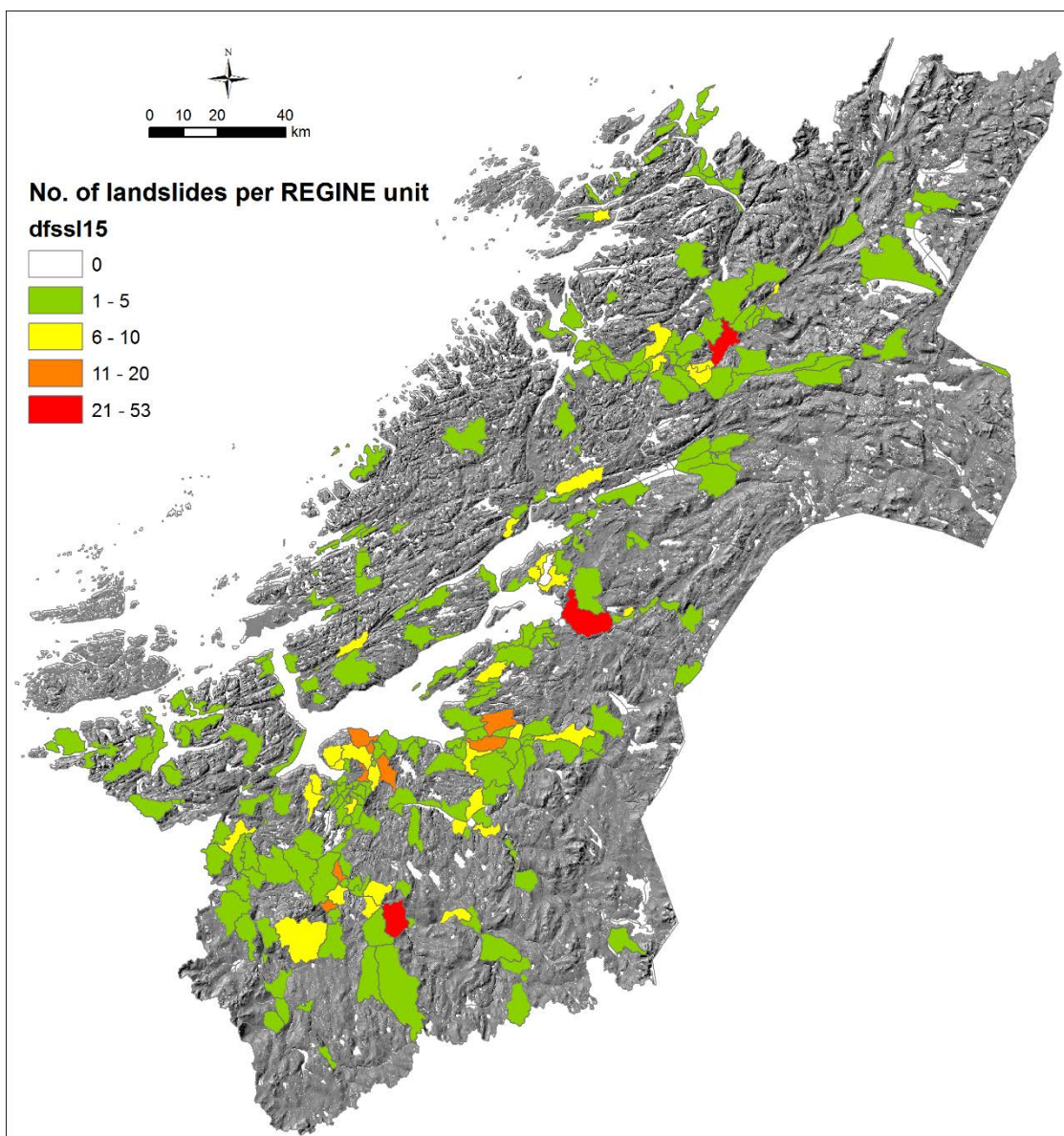


Figure 5 Distribution of debris flows, debris slides and soil slides per REGINE unit in the study area without the shifted landslides (dfssl15, N = 981)

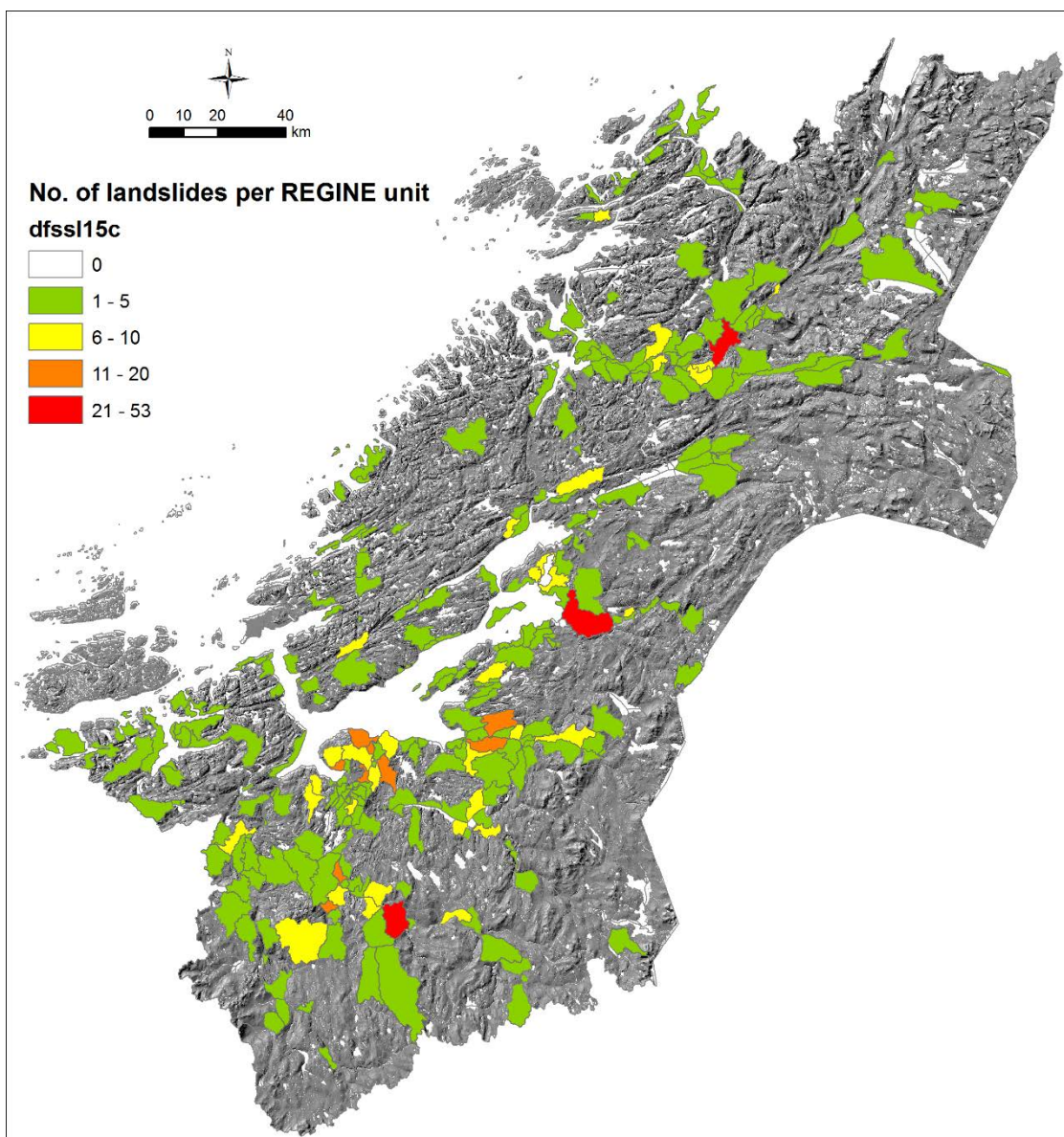


Figure 6 Distribution of debris flows, debris slides and soil slides per REGINE unit in the study area including the shifted landslides (dfssl15c, N = 1021)

4.2 Landslide susceptibility

Several hundreds of models were calculated (see chapter 3 for details). Finally, the following 16 models were selected using either 100 % of the REGINE units with landslides (Table 1) or 50 % of the REGINE units with landslides (Table 2). Half of the selected models were applied using GAM (model name contains “gam”), the other half using logistic regression (model name contains “logreg”). Since some models only selected land cover variables and no variables from the Quaternary map, also models without land cover variables were calculated (model name contains “wlc”). The models are based on the datasets without the shifted landslides (model name contains “dfssl15”) or including the shifted landslides (model name contains “dfssl15c”). See chapter 3 for details.

Table 1 Variables finally used in the different models using 100 % of the REGINE units with landslides (s = applied with a smoother function, n = without smoother function, - = not selected; Note: Since the “logreg”-models were modelled using logistic regression, no smoother function was available)

Code	Description	dfssl15_1_gam1	dfssl15c_1_gam1	dfssl15_1_gam1wlc	dfssl15c_1_gam1wlc	dfssl15_1_logreg1	dfssl15c_1_logreg1	dfssl15_1_logreg1wlc	dfssl15c_1_logreg1wlc
AREALENH	REGINE unit area (km ²)	s	s	s	s	n	n	n	n
AREALTOTAL	Total upstream area (km ²)	s	s	s	n	n	n	n	n
AVR6190	Average runoff 1961-1990 (litre/second km ²)	-	-	-	s	-	-	n	n
LMV11	Moraine material, continuous, locally thick (% of REGINE unit)	-	-	-	-	-	n	-	n
LMV12	Moraine material, non-continuous/thin (% of REGINE unit)	-	-	-	-	-	-	-	-
LMV1112	LMV11 and LMV12 combined	-	-	n	-	-	-	-	-
LMV41	Marine and fjord deposits, continuous, locally thick (% of REGINE unit)	-	n	n	n	-	n	n	n
LMV42	Marine and fjord deposits, continuous (% of REGINE unit)	-	-	-	s	-	-	n	-
LMV50	River and stream deposits, unspecified (% of REGINE unit)	-	-	-	s	-	-	-	-
LMV72	Weathered material, non-continuous/thin (% of REGINE unit)	-	n	-	n	-	n	n	n
LMV90	Peat and marshland (organic material) (% of REGINE unit)	-	-	n	-	-	-	n	-
LMV100	Humus blanket/thin peat blanket overlying bedrock (% of REGINE unit)	-	-	n	-	-	-	-	-
LMV130	Bare rock (% of REGINE unit)	-	-	n	-	-	-	n	-
DEM_RANGE	Elevation range in REGINE unit	n	s	s	s	n	n	n	n
DEM_MEAN	Mean elevation of REGINE unit	n	n	n	n	n	n	n	n
SL_MEAN	Mean slope of REGINE unit	n	s	-	s	n	n	-	n
C1ap	Artificial surfaces (% of REGINE unit)	s	-	-	-	n	-	-	-
C211ap	Arable land, not irrigated (% of REGINE unit)	n	n	-	-	n	n	-	-
C245ap	Heterogenous agricultural areas, mainly farmland and natural vegetation (% of REGINE unit)	s	-	-	-	n	-	-	-
C322ap	Moors and heath land (% of REGINE unit)	-	n	-	-	-	-	-	-
C339ap	Open space with little or no vegetation (% of REGINE unit)	n	n	-	-	n	n	-	-
C4ap	Inland marshes, peat bogs and intertidal flats (% of REGINE unit)	n	n	-	-	n	n	-	-
c316ap	Forests (% of REGINE unit)	-	n	-	-	-	n	-	-

Table 2 Variables finally used in the different validation models using only 50 % of the REGINE units with landslides (s = applied with a smoother function, n = without smoother function, - = not selected; Note: Since the “logreg”-models were modelled using logistic regression, no smoother function was available)

Code	Description	dfssl15_05_gam1	dfssl15c_05_gam1	dfssl15_05_gam1wlc	dfssl15c_05_gam1wlc	dfssl15_05_logreg1	dfssl15c_05_logreg1	dfssl15_05_logreg1wlc	dfssl15c_05_logreg1wlc
AREALENH	REGINE unit area (km²)	n	-	n	-	n	-	n	-
AREALTOTAL	Total upstream area (km²)	n	n	n	n	n	n	n	n
AVR6190	Average runoff 1961-1990 (litre/second km²)	s	-	-	-	n	-	-	-
LMV11	Moraine material, continuous, locally thick (% of REGINE unit)	-	-	-	-	-	n	-	n
LMV12	Moraine material, non-continuous/thin (% of REGINE unit)	-	-	s	-	-	-	n	-
LMV1112	LMV11 and LMV12 combined	-	-	-	-	-	-	-	-
LMV41	Marine and fjord deposits, continuous, locally thick (% of REGINE unit)	n	n	-	n	n	n	-	n
LMV42	Marine and fjord deposits, continuous (% of REGINE unit)	n	-	-	-	-	-	-	-
LMV50	River and stream deposits, unspecified (% of REGINE unit)	n	-	-	-	n	-	-	-
LMV72	Weathered material, non-continuous/thin (% of REGINE unit)	n	n	-	n	n	n	-	n
LMV90	Peat and marshland (organic material) (% of REGINE unit)	s	-	s	-	-	-	-	n
LMV100	Humus blanket/thin peat blanket overlying bedrock (% of REGINE unit)	n	-	n	-	n	-	n	-
LMV130	Bare rock (% of REGINE unit)	-	-	s	-	-	-	n	-
DEM_RANGE	Elevation range in REGINE unit	n	s	n	s	n	n	n	n
DEM_MEAN	Mean elevation of REGINE unit	s	n	s	n	-	n	n	n
SL_MEAN	Mean slope of REGINE unit	s	n	s	-	-	-	-	-
C1ap	Artificial surfaces (% of REGINE unit)	-	-	-	-	-	-	-	-
C211ap	Arable land, not irrigated (% of REGINE unit)	-	-	-	-	-	-	-	-
C245ap	Heterogenous agricultural areas, mainly farmland and natural vegetation (% of REGINE unit)	-	n	-	n	-	n	-	-
C322ap	Moors and heath land (% of REGINE unit)	n	n	-	n	n	-	-	-
C339ap	Open space with little or no vegetation (% of REGINE unit)	n	n	-	n	n	n	-	-
C4ap	Inland marshes, peat bogs and intertidal flats (% of REGINE unit)	-	n	-	n	n	n	-	-
c316ap	Forests (% of REGINE unit)	-	n	-	n	-	n	-	-

For the GAM models using 100% of the REGINE units with landslides the transformation plots used by the models can be found in Appendix E.

The AUROC values for all 16 selected models indicate very good performance (AUROC greater than 0.7). The models “dfssl15_1_gam1” and “dfssl15c_1_gam1” turned out to be the best models since the AUROC values are slightly higher and the AIC values are generally lower than most of the other “dfssl15”- or “dfssl15c”-models (Table 3). The random cross-validation using 50 % of the REGINE units with landslides in the training sample and the other 50 % in the independent testing sample led also to very high AUROC values (Table 4), which is a first indication that the models are rather stable. This is supported by the high AUROC values of the k-fold cross validations (Fig. 7).

Table 3 AUROC values for selected models. 100 % of the REGINE units with landslides were used in the training sample. Therefore no independent testing samples could be prepared. In addition the AIC values are shown.

Model	AUROC (train1)	AIC
dfssl15_1_gam1	0.89	533
dfssl15c_1_gam1	0.89	567
dfssl15_1_gam1wlc	0.88	557
dfssl15c_1_gam1wlc	0.88	580
dfssl15_1_logreg1	0.88	547
dfssl15c_1_logreg1	0.88	586
dfssl15_1_logreg1wlc	0.87	567
dfssl15c_1_logreg1wlc	0.86	606

Table 4 AUROC values for the training samples “train05” and testing samples “test05” of the selected models. 50 % of the REGINE units with landslides were used in the training sample and the other 50 % in the independent testing sample. In addition the AIC values are shown.

Model	AUROC (train05)	AUROC (test05)	AIC
dfssl15_05_gam1	0.92	0.86	250
dfssl15c_05_gam1	0.90	0.85	276
dfssl15_05_gam1wlc	0.91	0.85	257
dfssl15c_05_gam1wlc	0.90	0.85	300
dfssl15_05_logreg1	0.90	0.85	255
dfssl15c_05_logreg1	0.90	0.85	276
dfssl15_05_logreg1wlc	0.89	0.85	262
dfssl15c_05_logreg1wlc	0.87	0.84	301

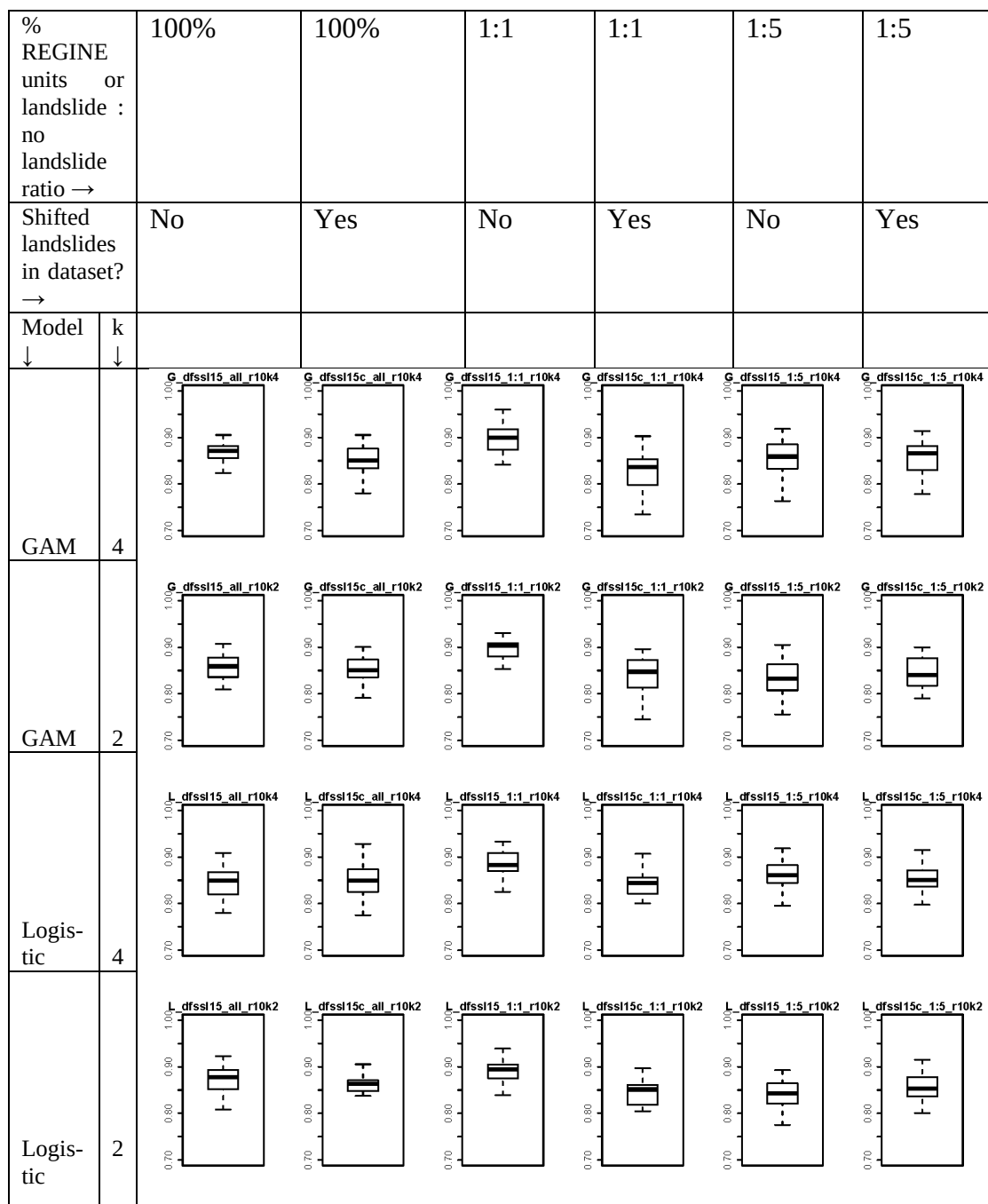


Figure 7 Results of 10-times ($r=10$) repeated k -fold ($k = 4$ or 2) cross validations using either GAM ("G") or logistic regression ("L") and the datasets dfssl15 or dfssl15c. The vertical axes of the boxplots show the range of the calculated AUROC values.

Fig. 7 further shows that the models using the landslide inventory without the shifted landslides (dfssl15) perform slightly better than the models using the landslide inventory including the shifted landslides (dfssl15c). The strongest difference can be seen when the models are compared using a 1:1 relationship between REGINE units with landslides

and those without landslides. The results are rather similar comparing GAM models and logistic regression models.

Based on all eight models using 100% of the REGINE units with landslides, landslide susceptibility maps were created using class thresholds defined by 70 %, 15 %, 12 % and 3 % of the landslides in the susceptibility classes very high, high, moderate and low, respectively (Table 5, Fig. 8-15).

Table 5 Landslide susceptibility thresholds for the different models using class thresholds defined by 70 %, 15 %, 12 % and 3 % of the landslides in the susceptibility classes very high, high, moderate and low, respectively. Class boundaries are probabilities (maximum possible range is from 0 to 1).

Model	Figure	low	moderate	high	very high
dfssl15_1_gam1	8	0.000559 – 0.30	>0.30 – 0.60	>0.60 – 0.76	>0.76
dfssl15c_1_gam1	9	0.000544 – 0.33	>0.33 – 0.58	>0.58 – 0.75	>0.75
dfssl15_1_gam1wlc	10	0.000244 – 0.26	>0.26 – 0.57	>0.57 – 0.75	>0.75
dfssl15c_1_gam1wlc	11	0.002035 – 0.30	>0.30 – 0.54	>0.54 – 0.75	>0.75
dfssl15_1_logreg1	12	0.000386 – 0.30	>0.30 – 0.59	>0.59 – 0.74	>0.74
dfssl15c_1_logreg1	13	0.000275 – 0.34	>0.34 – 0.58	>0.58 – 0.75	>0.75
dfssl15_1_logreg1wlc	14	0.000496 – 0.26	>0.26 – 0.58	>0.58 – 0.76	>0.76
dfssl15c_1_logreg1wlc	15	0.000252 – 0.27	>0.27 – 0.54	>0.54 – 0.73	>0.73

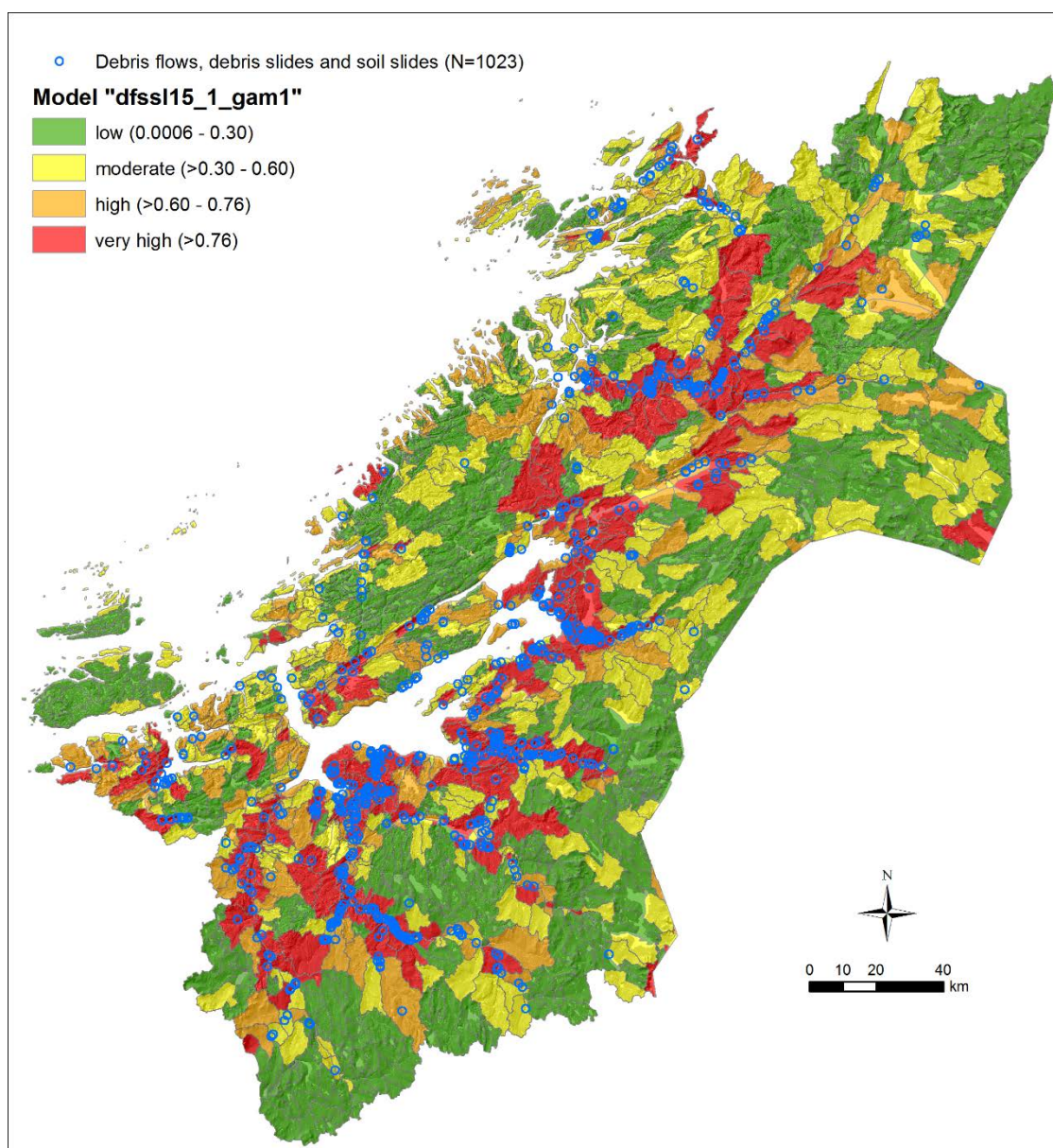


Figure 8 Landslide susceptibility in Trøndelag, Model "dfssl15_1_gam1".

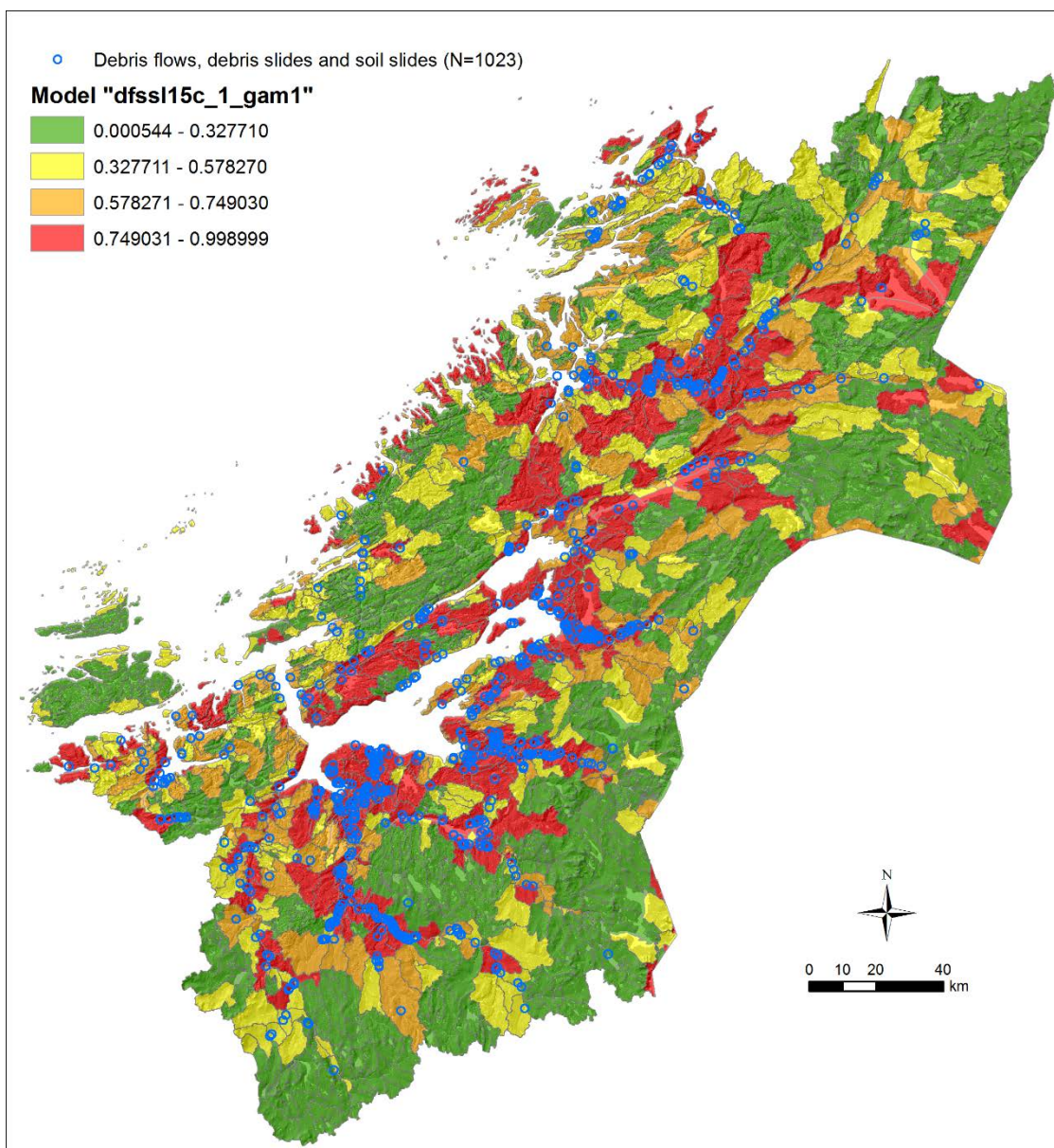


Figure 9 Landslide susceptibility in Trøndelag, Model "dfssl15c_1_gam1".

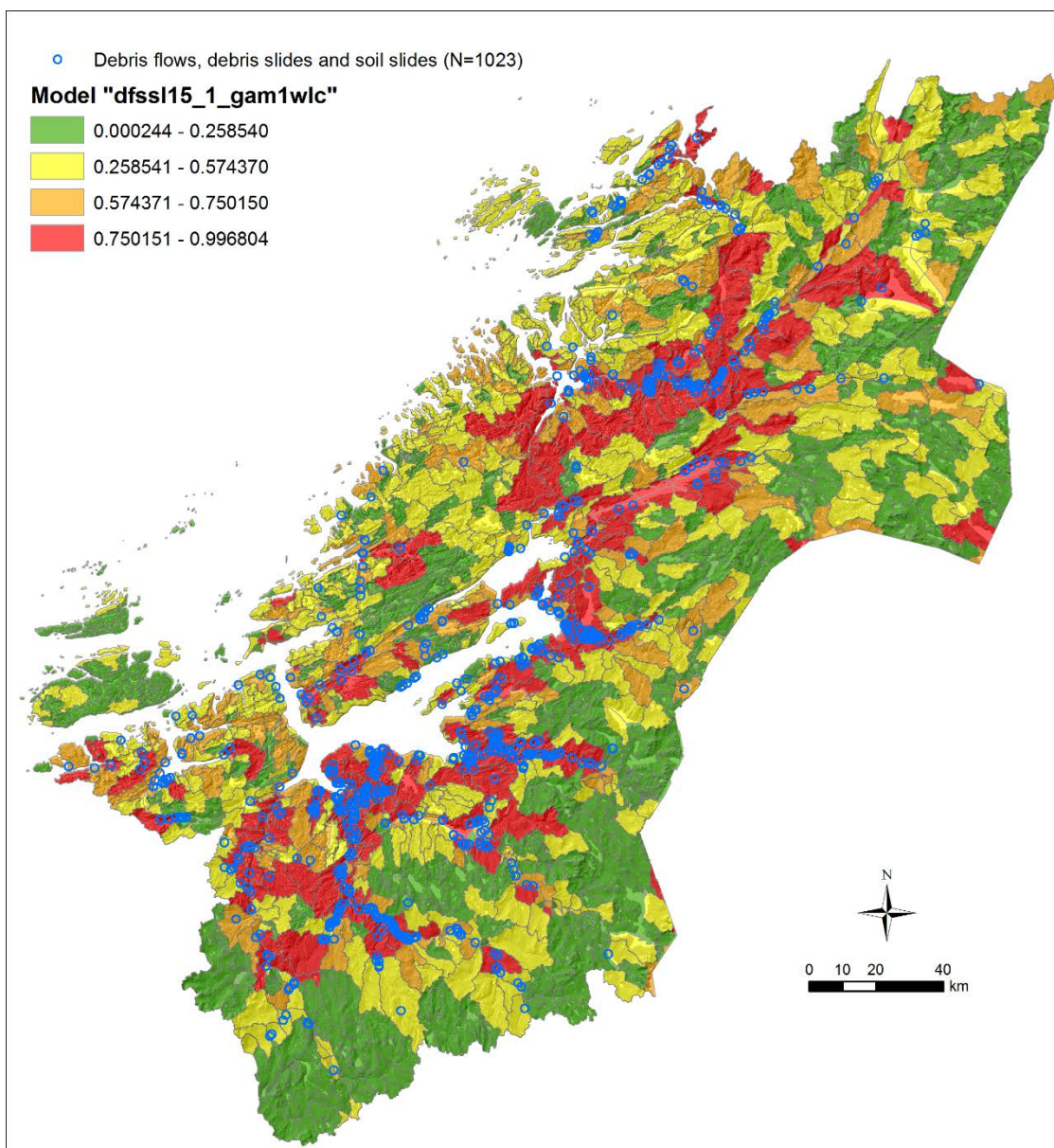


Figure 10 Landslide susceptibility in Trøndelag, Model "dfssl15_1_gam1wlc".

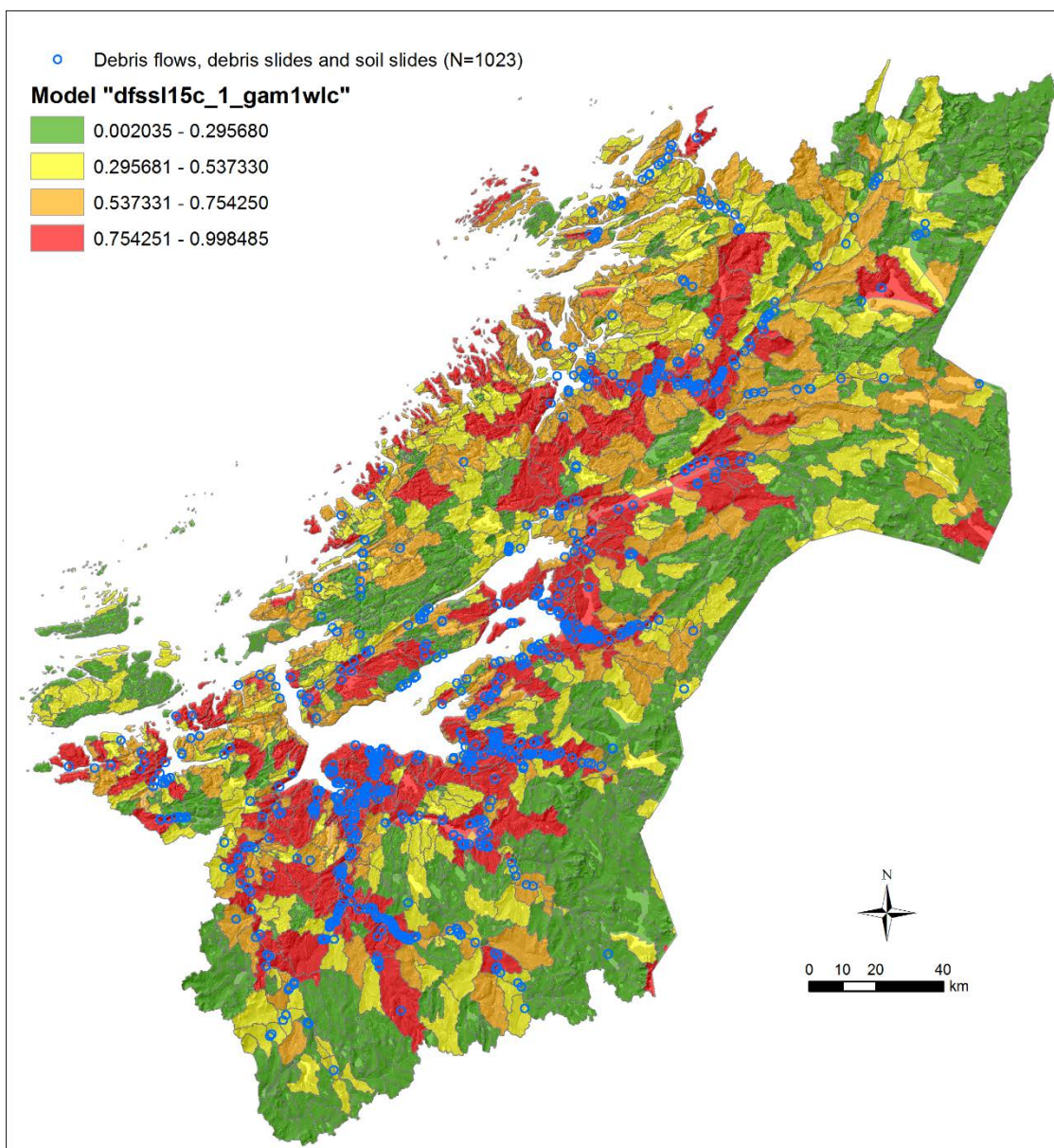


Figure 11 Landslide susceptibility in Trøndelag, Model "dfssl15c_1_gam1wlc".

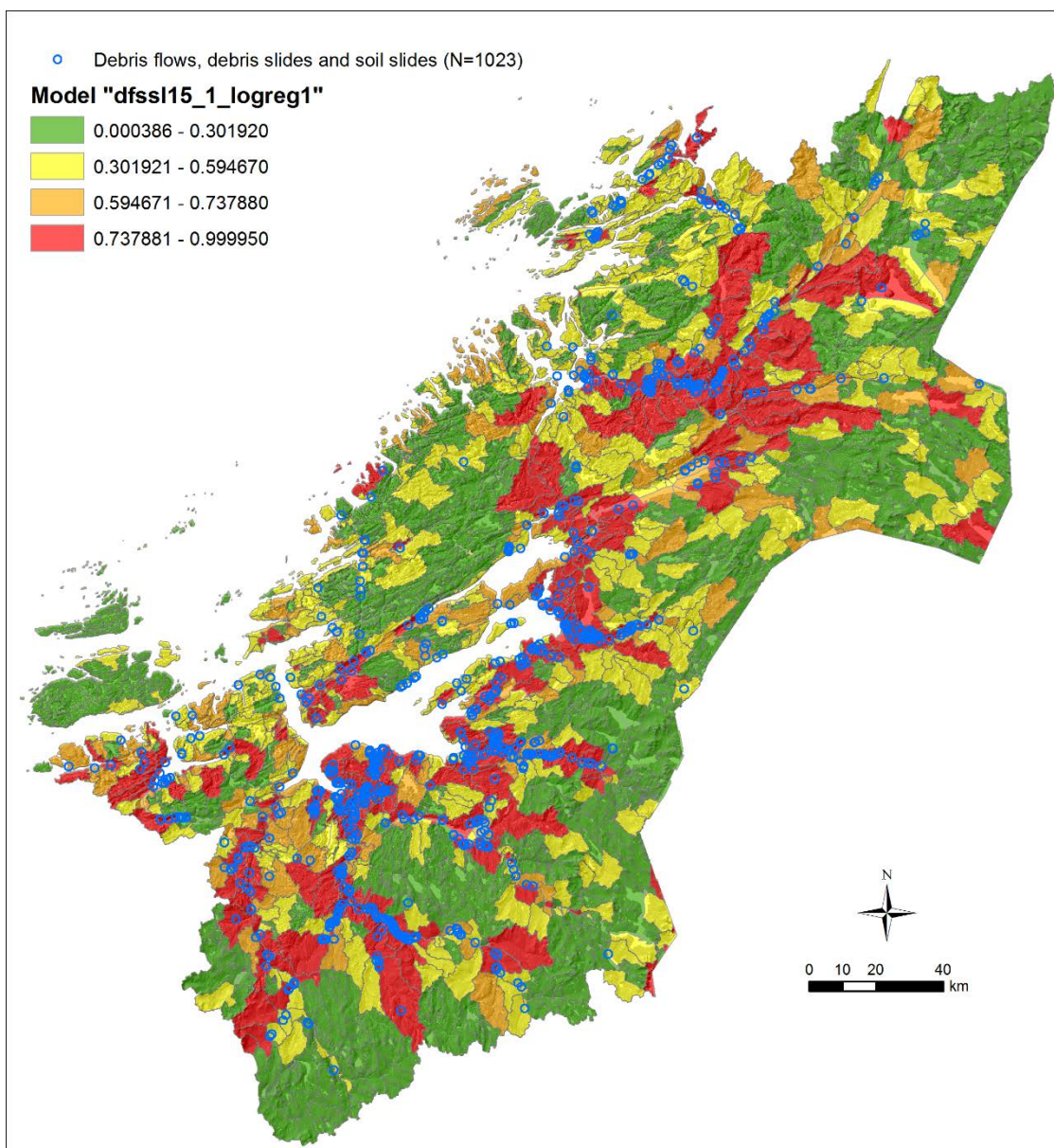


Figure 12 Landslide susceptibility in Trøndelag, Model "dfssl15_1_logreg1".

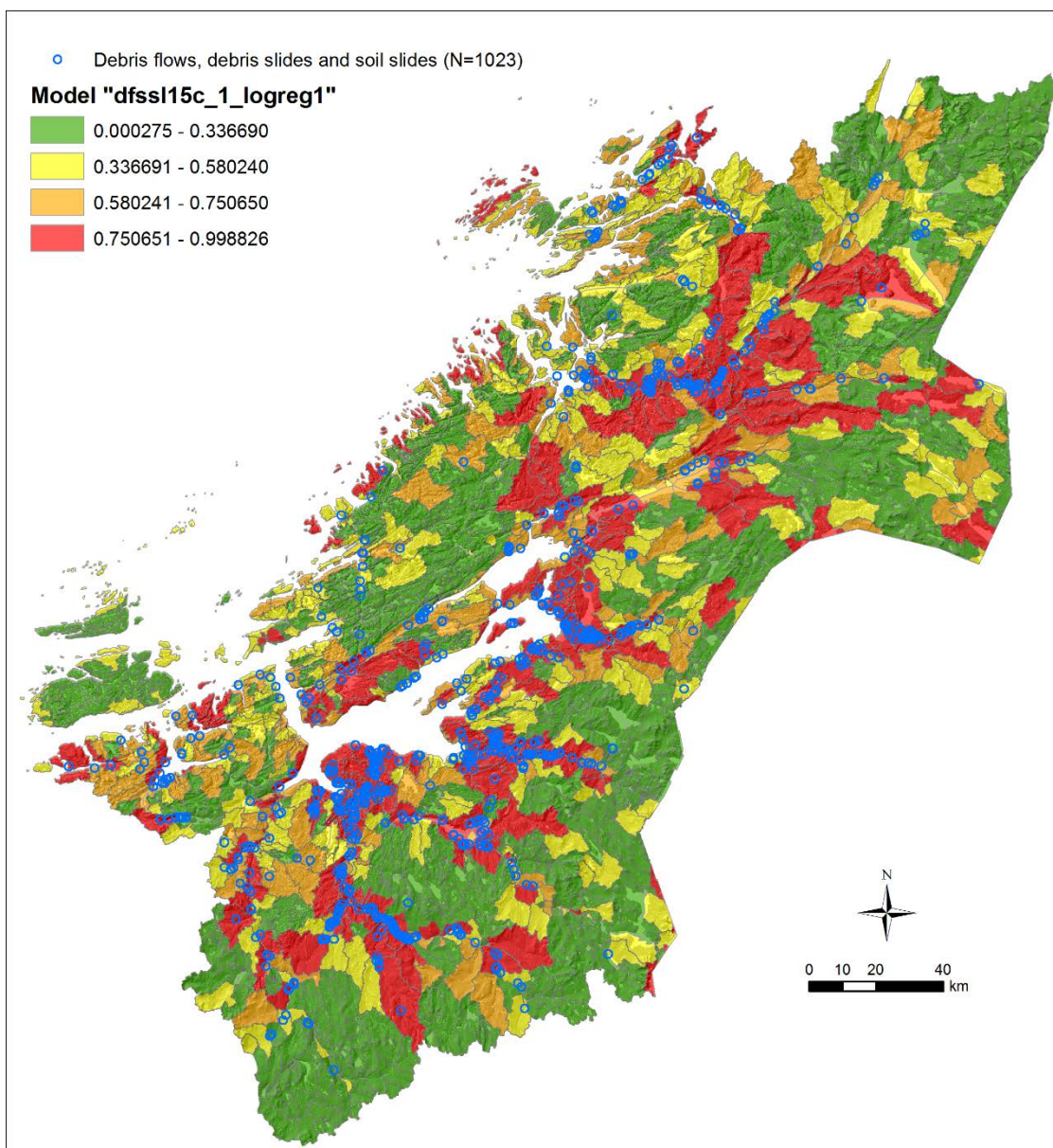


Figure 13 Landslide susceptibility in Trøndelag, Model "dfssl15c_1_logreg1".

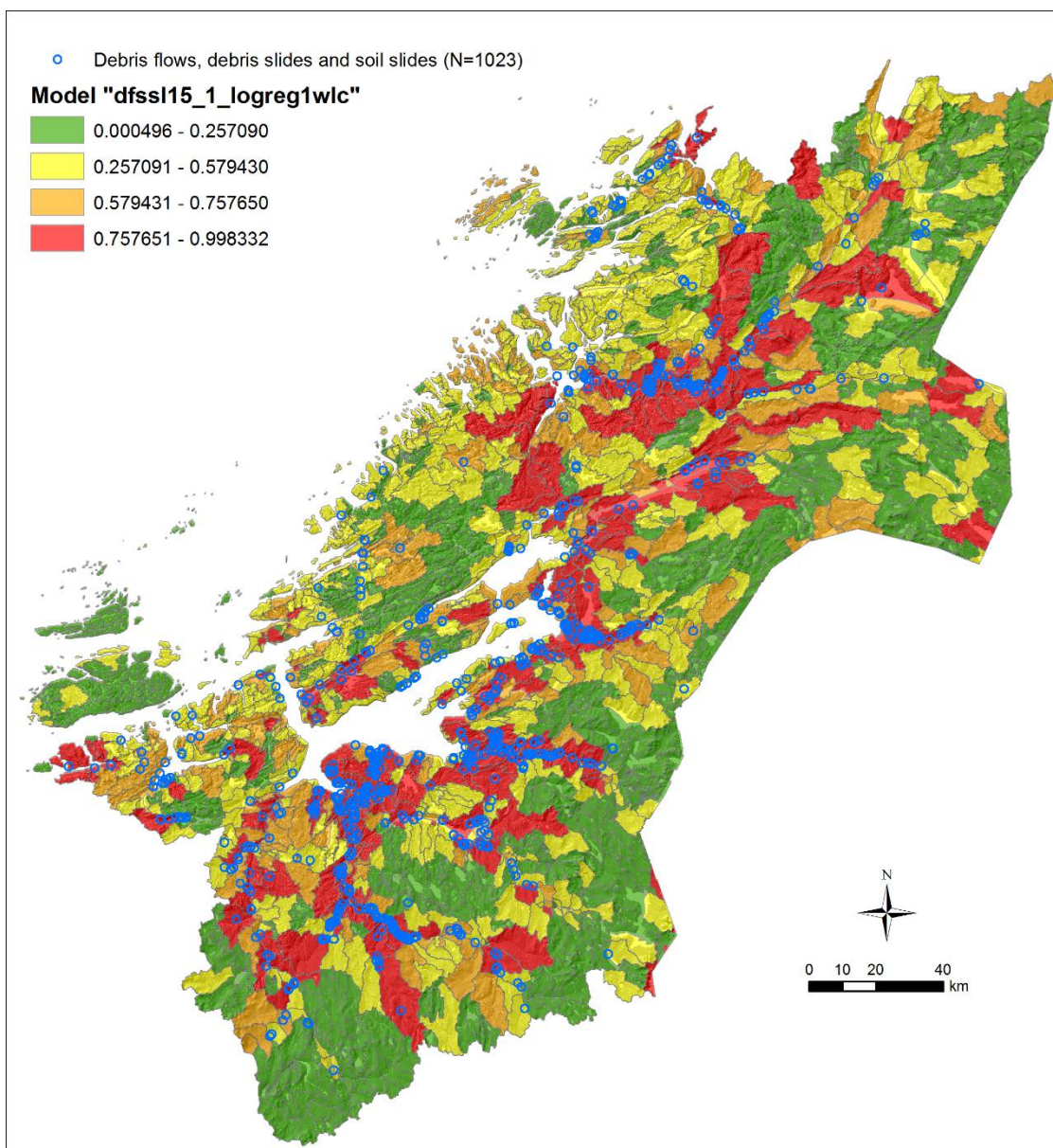


Figure 14 Landslide susceptibility in Trøndelag, Model "dfssl15_1_logreg1wlc".

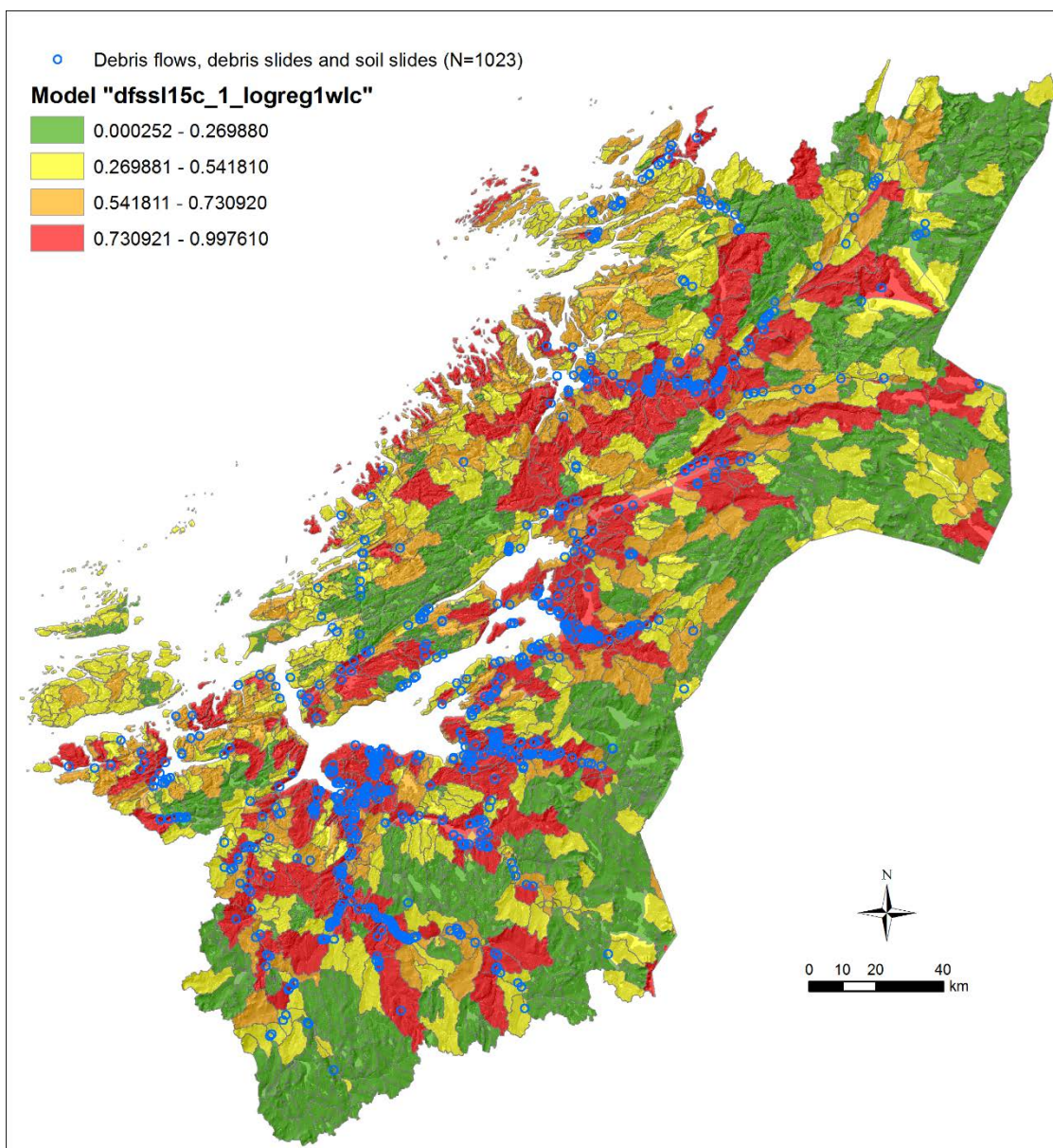


Figure 15 Landslide susceptibility in Trøndelag, Model "dfssl15c_1_logreg1wlc".

5 Discussion

All models using 100% of REGINE units with landslides in the regression show very high AUROC values. Even within the new k-fold cross validation step, the AUROC values remain high. This indicates that in all models the discrimination between the REGINE units with landslides and the REGINE units without landslides is good. There are only small differences in the AUROC values between the models. As found in the previous evaluations in Northern, Eastern and Western Norway (Bell & Cepeda 2014, Bell et al. 2014), the approach of modelling in REGINE units works very well especially given the unknown uncertainty of the spatial location of the landslide initiation areas. When modelling at REGINE unit level, it does not matter that most of the points are located where consequences were registered. It is sufficient that the landslide point and the initiation area are located within the same REGINE unit. In 42 cases the landslide point was located outside of the REGINE units. Therefore, two different landslide inventories and subsequently, two different REGINE unit datasets were created, one without the shifted landslides (dfssl15) and one including the shifted landslides (dfssl15c). There were 2 landslide points which could not be assigned to a specific REGINE unit. The shifted 40 landslide points led to an increase of 17 REGINE units with landslides. Most of the landslide points were shifted to REGINE units within which at least one landslide was already available. This had no consequences for landslide susceptibility modelling. The 17 REGINE units which changed from no-landslide units to landslide units had a consequence for susceptibility modelling.

The initial idea was to use exclusively the landslide inventory with the shifted events. However, considering the special location of these 40 landslides, it was decided to perform the analyses using both inventories (dfssl15 and dfssl15c). Thus, differences between the results can be assessed in order to decide which landslide susceptibility map is best suited for improving the warning system for Trøndelag. After investigating the results, it turned out that this approach was very valuable.

Even though the differences in the statistical performance are rather small, the resulting landslide susceptibility maps show clear differences. All models calculated without land cover led to landslide susceptibility maps with fewer REGINE units in the low susceptibility class. These models might slightly overestimate landslide susceptibility. The models which could freely select from various land cover and Quaternary variables preferred selecting land cover variables over Quaternary variables. Thus, the distribution of these land cover variables seem to better represent landslide distribution and susceptibility than the distribution of the Quaternary variables. While discussing this, it should be kept in mind that for all categorical data the proportion of each class in the catchment was calculated and used as a variable during the regression of the model. Therefore, models which could freely select various land cover variables should be preferred.

Analysing the statistical validation criteria as well as the final landslide susceptibility maps (Fig. 8-15), we recommend either to use model “dfssl15_1_gam1” (Fig. 8) or

“dfssl15c_1_gam1” (Fig. 9). Comparing these two models and maps, it turns out that both models show identical AUROC values, but the model using the inventory without the shifted landslides (dfssl15_1_gam1) has a lower AIC value. k-fold cross validation led to higher AUROC values for all models using the dfssl15 dataset. Thus, these models seem to be more stable. However, the 17 REGINE units with the shifted landslides led to changes in the resulting susceptibility map (Fig. 9), so that especially coastal REGINE units which show similar characteristics like these 17 REGINE units received a higher susceptibility class (Fig. 16). This might be correct and preferable. Fig. 16 also displays that in most places there is no difference between both maps and if there is a difference, it is of one susceptibility class in the majority of units. Larger differences are rare.

The final decision for selection of the model depends on whether these 40 landslides are typical for the region and should be represented within both the susceptibility map and subsequently the early warning system. Therefore, we recommend to carefully control these 40 landslides and check how these are related to the new 17 REGINE units with landslides. Depending on the outcome of this assessment, the map of either model “dfssl15_1_gam1” or model “dfssl15c_1_gam1” should be selected for implementation in the warning system.

This discussion nicely shows, that the final landslide susceptibility map can only be as good as the input data. Based on the available data, both resulting landslide susceptibility maps are of very good quality. Besides the final selection of maps, the most important question is whether the landslide inventory is in general representative for all Trøndelag. Fig. 17 and Fig. 18 show that most of the 1021 landslides are located along roads since most of the records are registered by the road and railway authorities. It can also be seen in both maps that there are large areas of low and moderate landslide susceptibility where no roads exist. Thus, the question is, whether landslides have actually occurred or not in these areas, the former situation likely due to the lack of registers associated with few exposed elements. So, the main limitation of the final landslide susceptibility map results from the incomplete landslide inventory. If landslides have occurred but were not registered, the final landslide susceptibility map might look different if the missing landslides were eventually used to re-evaluate the model. This should be a bigger issue for areas of low and moderate susceptibility. In the other two susceptibility classes, information on high and very high susceptibility is statistically transferred from REGINE units with landslides to similar units for which so far no landslides have been recorded. However, some uncertainty also remains there.

Future efforts should focus on improving the landslide inventory. It might be worth trying to focus on selected areas of low and moderate susceptibility and check the completeness of the landslide inventory using remote sensing data (e.g. airborne laser scanning data, satellite images and aerial photographs). When a significantly improved landslide inventory is available, new landslide susceptibility modelling should improve the predictive performance of the maps when used as part of a warning system.

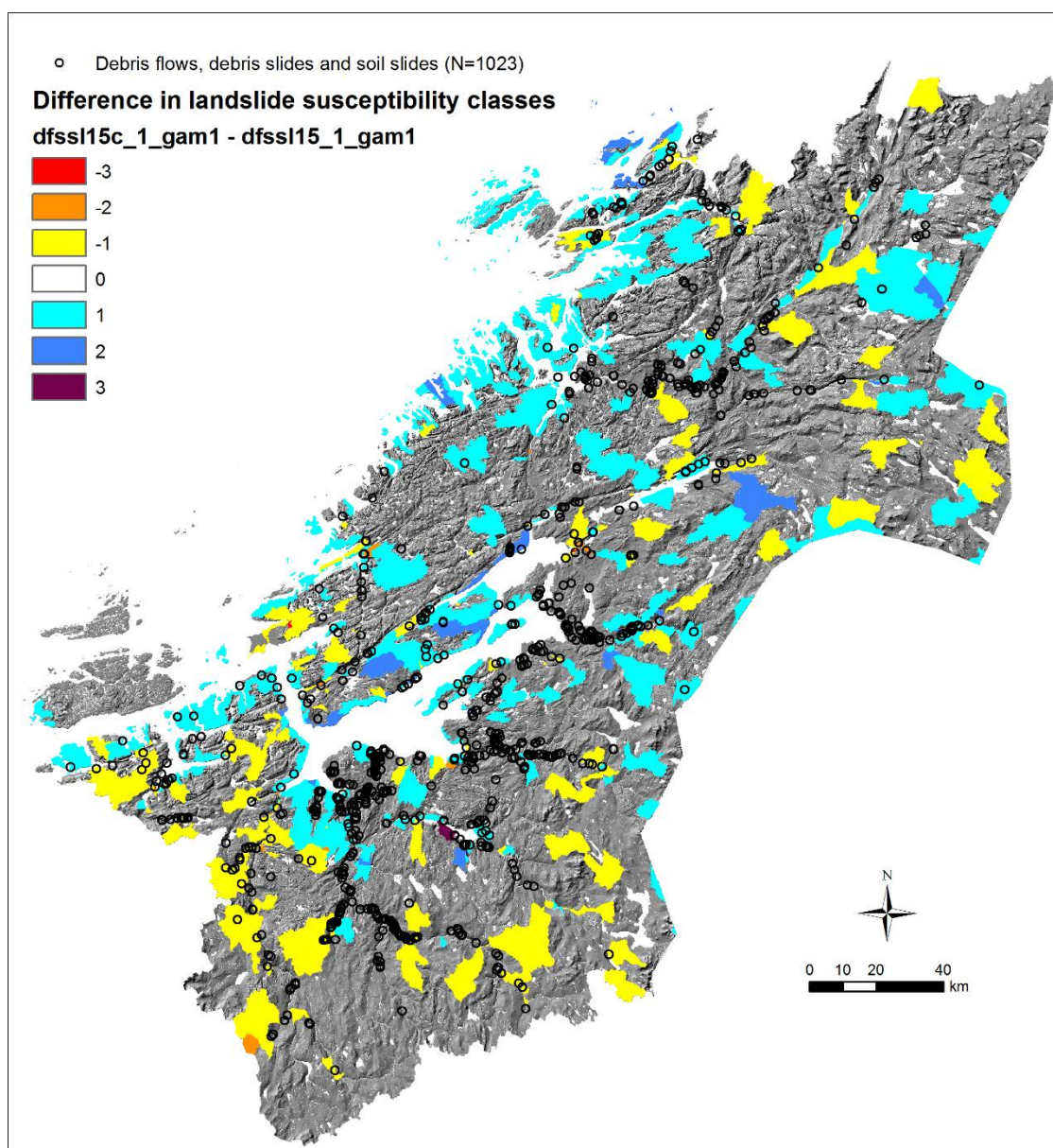


Figure 16 Difference in landslide susceptibility classes in Trøndelag between the models “dfssl15_1_gam1” and “dfssl15c_1_gam1”. Note: Positive values mean that the susceptibility class in “dfssl15c_1_gam1” is higher than in “dfssl15_1_gam1”. Negative values mean that the susceptibility class in “dfssl15c_1_gam1” is lower than in “dfssl15_1_gam1”.

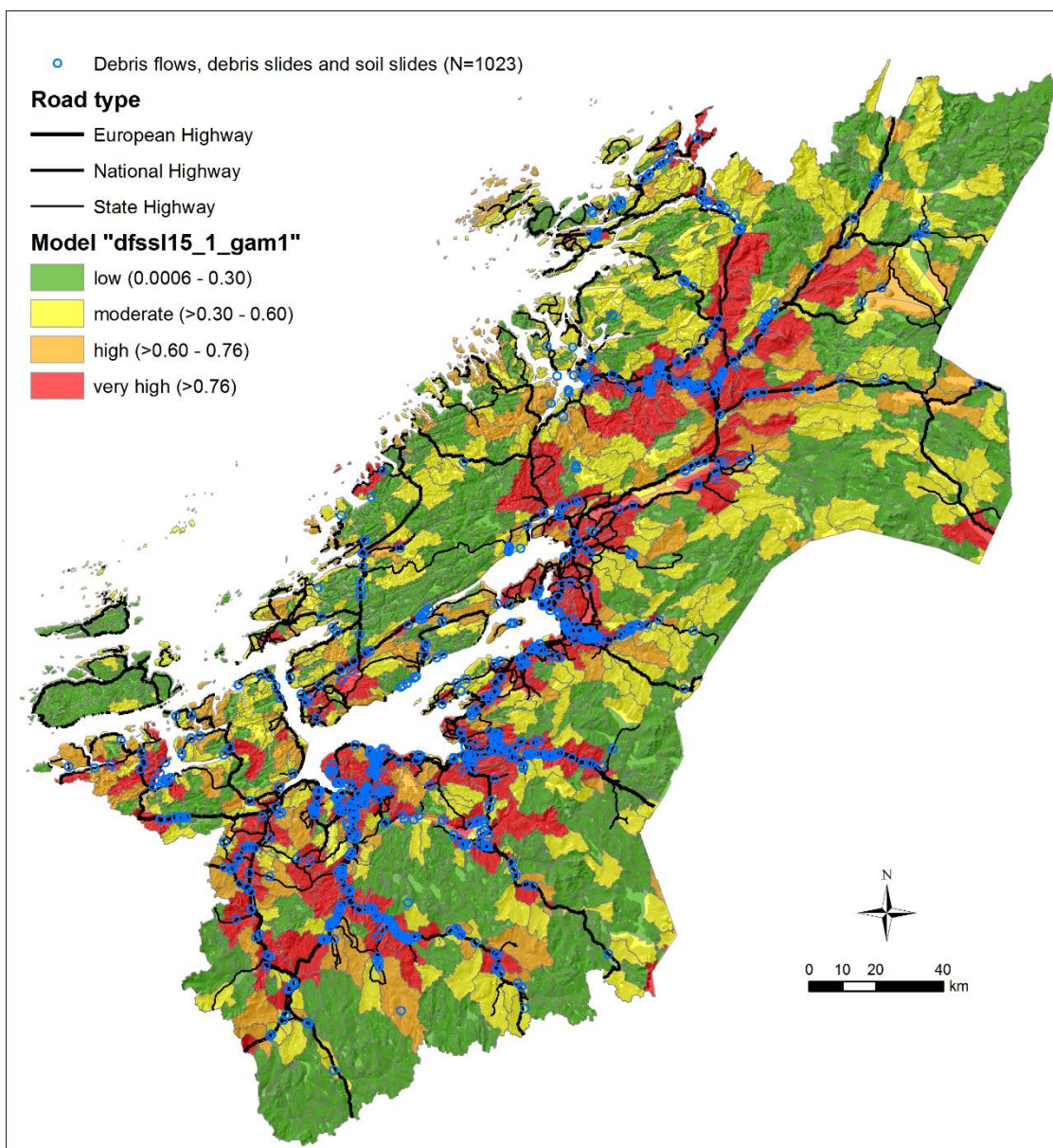


Figure 17 Landslides, landslide susceptibility and highways in Trøndelag, Model "dfssl15_1_gam1wlc".

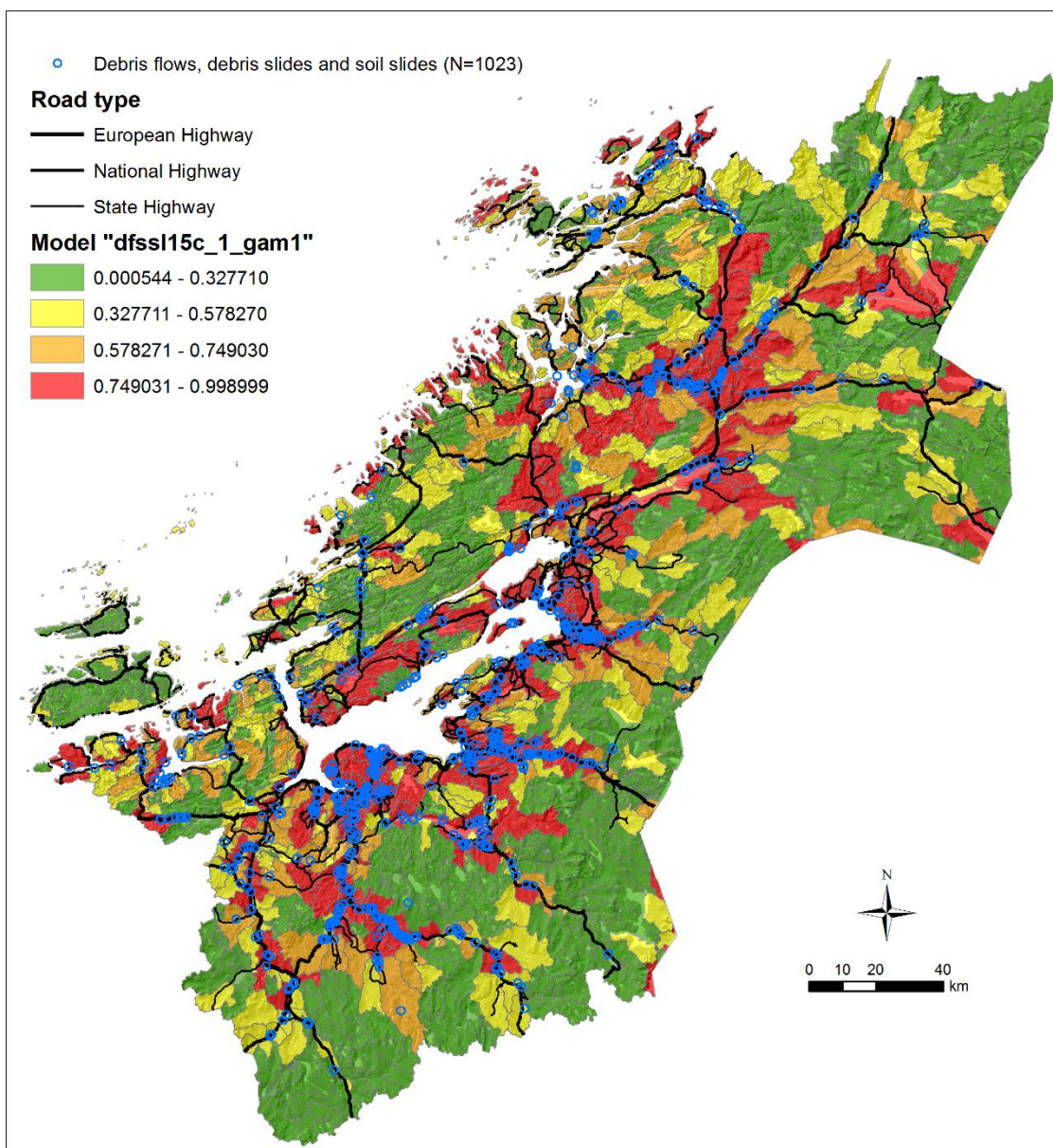


Figure 18 Landslides, landslide susceptibility and highways in Trøndelag, Model "dfssl15c_1_gam1wlc".

6 References

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Appendix A

LIST OF VARIABLES

Contents

A1	List of variables
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2

A1 List of variables

No.	Code	Description
1	AREALENH	REGINE unit area (km ²)
2	TILSIGENH	REGINE unit runoff 1961-1990 (million m ³ per year)
3	AREALTOTAL	Total upstream area (km ²)
4	TILSIGTOTA	Total upstream runoff 1961-1990 (million m ³ per year)
5	AVR6190	Average runoff 1961-1990 (litre/second km ²)
6	AVR3060	Average runoff 1930-1960 (litre/second km ²)
7	SHAPE_AREA	Shape area
8	LMV0	not specified (% of REGINE unit)
9	LMV1	Soils/rocks under water, unspecified (% of REGINE unit)
10	LMV10	Moraine material, unspecified (% of REGINE unit)
11	LMV11	Moraine material, continuous, locally thick (% of REGINE unit)
12	LMV12	Moraine material, non-continuous/thin (% of REGINE unit)
13	LMV1112	LMV11 + LMV12
14	LMV13	Clay till, boulder clay, drift clay (% of REGINE unit)
15	LMV14	Ablation moraine (% of REGINE unit)
16	LMV15	Terminal moraine (% of REGINE unit)
17	LMV16	Drumlin (% of REGINE unit)
18	LMV20	Glaciofluvial deposit (% of REGINE unit)
19	LMV21	Glaciofluvial and fluvial deposit (% of REGINE unit)
20	LMV22	Saddle-shaped glaciofluvial deposit (% of REGINE unit)
21	LMV30	Glaciolacustrine deposit (% of REGINE unit)
22	LMV31	Glaciolacustrine and glaciofluvial deposit (% of REGINE unit)
23	LMV35	Lacustrine deposit (% of REGINE unit)
24	LMV40	Marine and fjord deposits, unspecified (% of REGINE unit)
25	LMV41	Marine and fjord deposits, continuous, locally thick (% of REGINE unit)
26	LMV42	Marine and fjord deposits, continuous (% of REGINE unit)
27	LMV43	Marine and fjord deposits, non-continuous/thin (% of REGINE unit)
28	LMV4143	LMV41 + LMV43
29	LMV50	River and stream deposits, unspecified (% of REGINE unit)
30	LMV54	Floodplain deposits, continuous (% of REGINE unit)
31	LMV55	Floodplain deposits, non-continuous/thin (% of REGINE unit)
32	LMV60	Eolian deposits (% of REGINE unit)
33	LMV70	Weathered material, unspecified (% of REGINE unit)
34	LMV71	Weathered material, continuous, locally thick (% of REGINE unit)

35	LMV72	Weathered material, non-continuous/thin (% of REGINE unit)
36	LMV73	Block field (% of REGINE unit)
37	LMV80	Landslide material, not divided by thickness (% of REGINE unit)
38	LMV81	Landslide material, continuous, locally thick (% of REGINE unit)
39	LMV82	Landslide material, non-continuous/thin (% of REGINE unit)
40	LMV90	Peat and marshland (organic material) (% of REGINE unit)
41	LMV100	Humus blanket/thin peat blanket overlying bedrock (% of REGINE unit)
42	LMV101	Discontinuous or thin soil cover on bedrock (% of REGINE unit)
43	LMV120	Fill (anthropogenic material), unspecified (% of REGINE unit)
44	LMV130	Bare rock (% of REGINE unit)
45	LMV140	Bare rock/rock with patchy or thin cover (% of REGINE unit)
46	DEM_RANGE	Elevation range in REGINE unit
47	DEM_MEAN	Mean elevation of REGINE unit
48	DEM_MEDIAN	Median elevation of REGINE unit
49	East_MEAN	Mean of eastern coordinates of REGINE unit
50	north_MEAN	Mean of northern coordinates of REGINE unit
51	SL_MEAN	Mean slope of REGINE unit
52	SL_STD	Standard deviation of slope of REGINE unit
53	SL_MEDIAN	Median slope of REGINE unit
54	RF_MEAN	Mean of average yearly rainfall 1961-1990 in REGINE unit
55	RF_SUMrm	Sum of average yearly rainfall 1961-1990 in REGINE unit
56	C1ap	Artificial surfaces (% of REGINE unit)
57	C211ap	Arable land, not irrigated (% of REGINE unit)
58	C231ap	Pastures (% of REGINE unit)
59	C245ap	Heterogeneous agricultural areas, mainly farmland and natural vegetation (% of REGINE unit)
60	C322ap	Moors and heath land (% of REGINE unit)
61	C324ap	Transitional woodland-shrub (% of REGINE unit)
62	C339ap	Open space with little or no vegetation (% of REGINE unit)
63	C4ap	Inland marshes, peat bogs and intertidal flats (% of REGINE unit)
64	c316ap	Forests (% of REGINE unit)

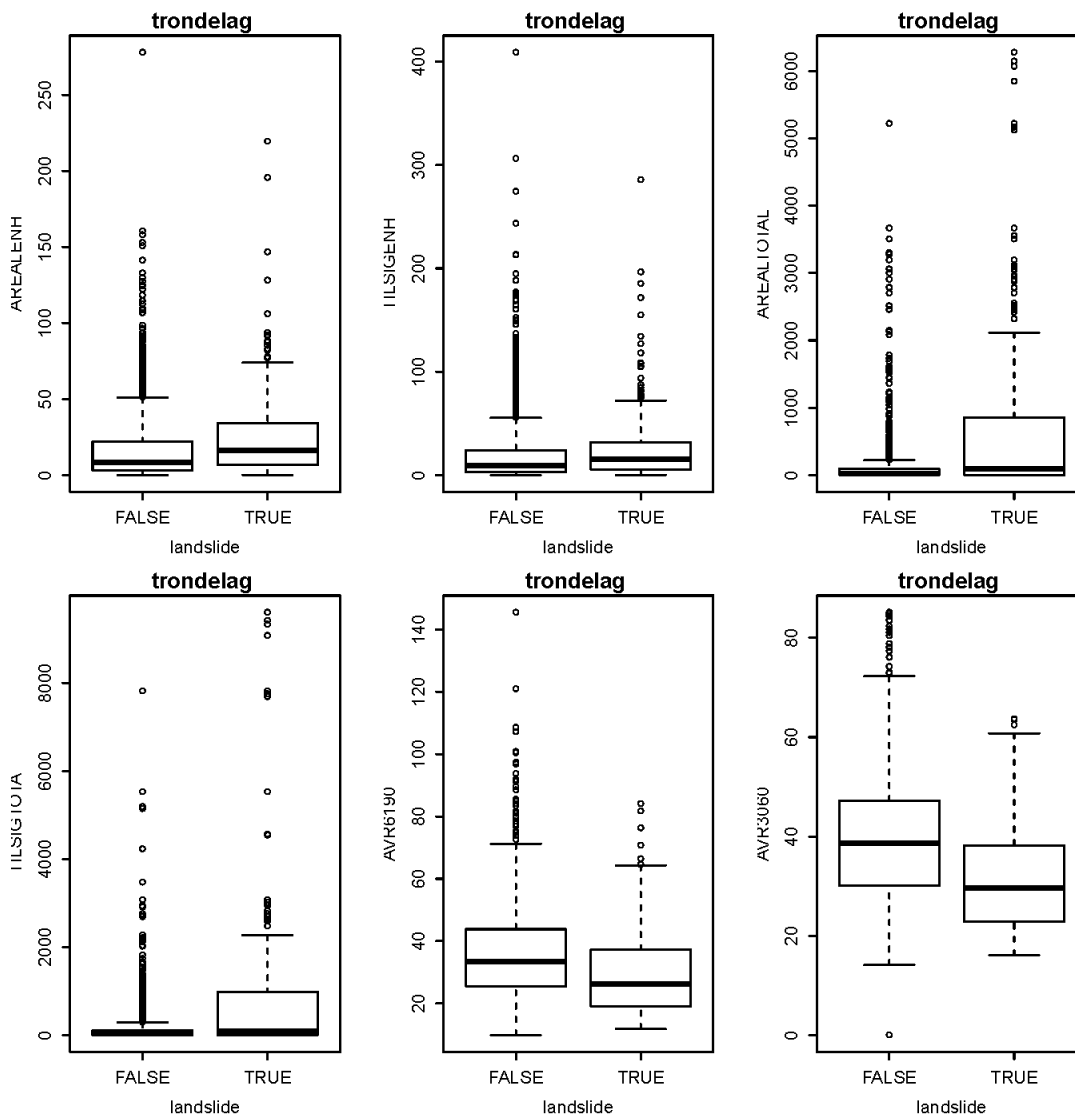
Appendix B

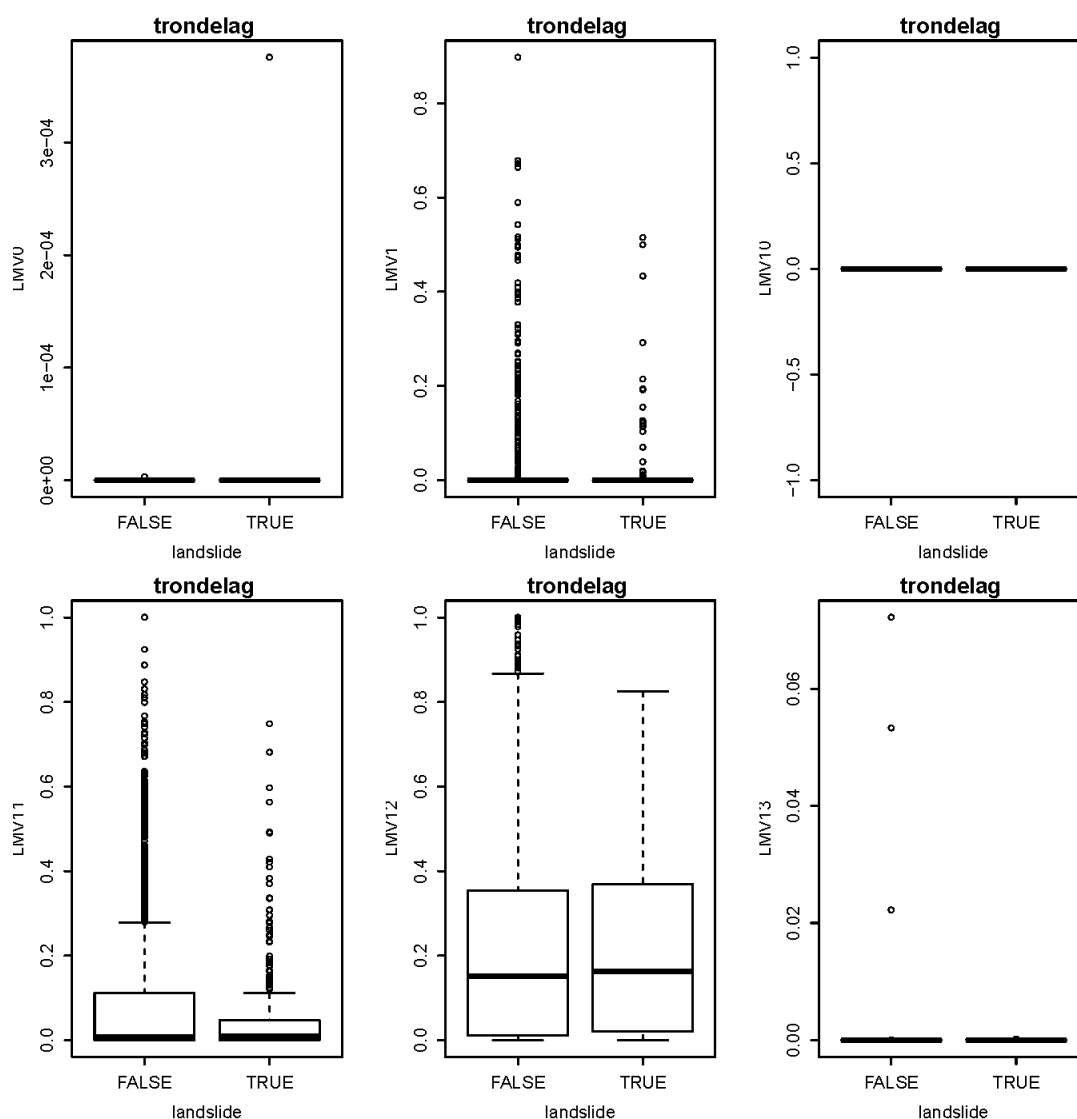
BOXPLOTS OF VARIABLES

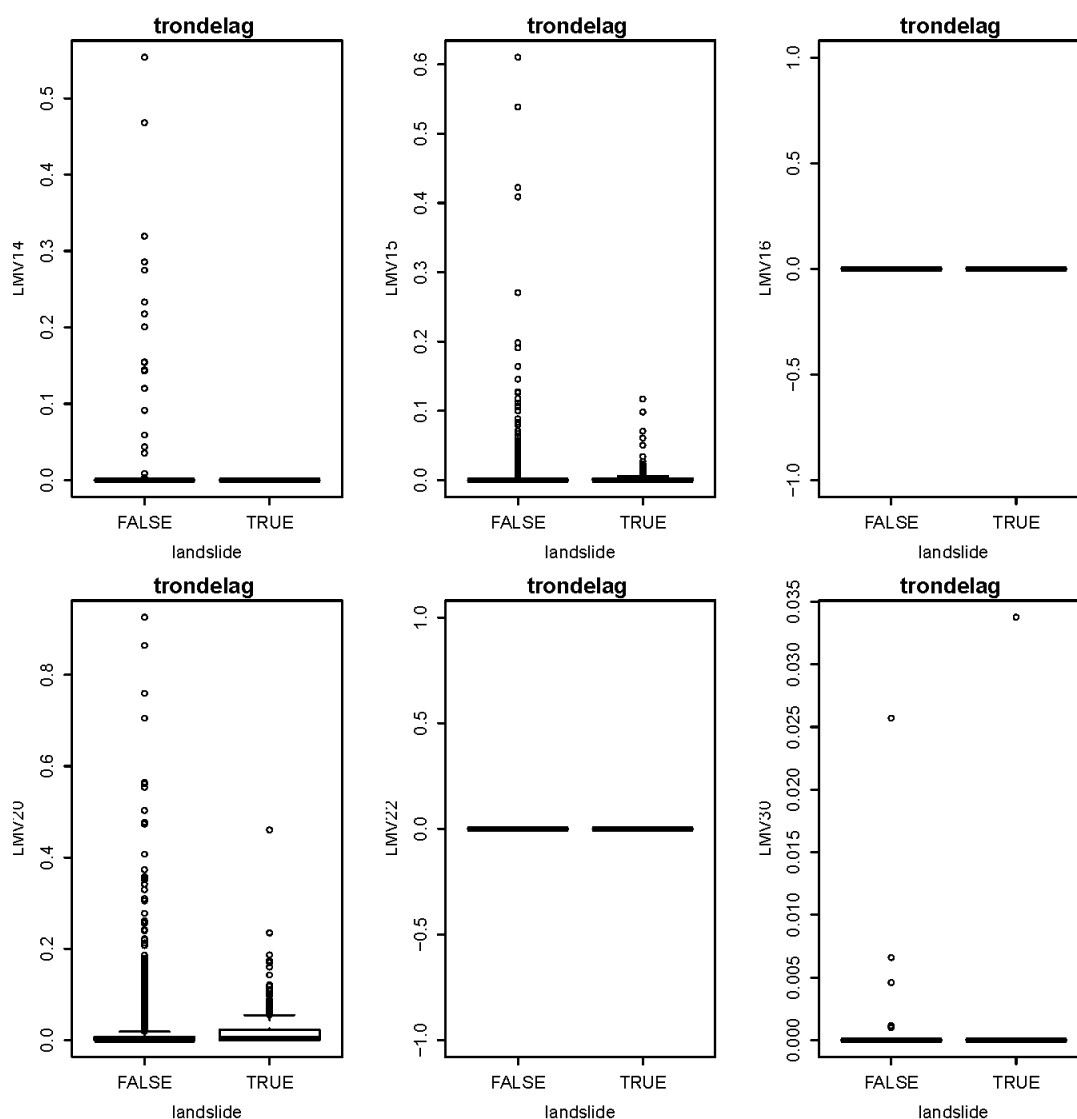
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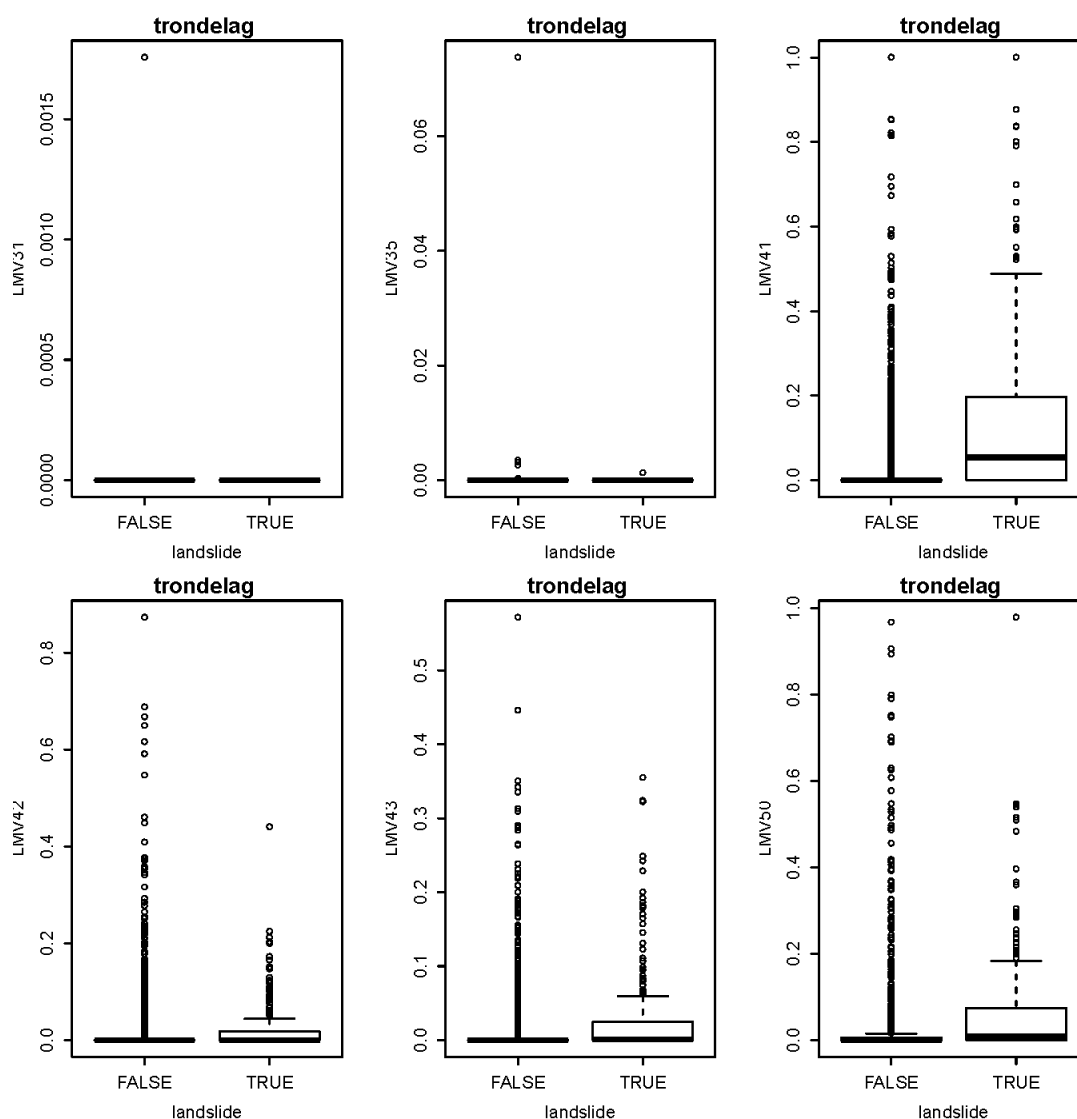
B1	Boxplots of variables in REGINE units with and without landslides	2
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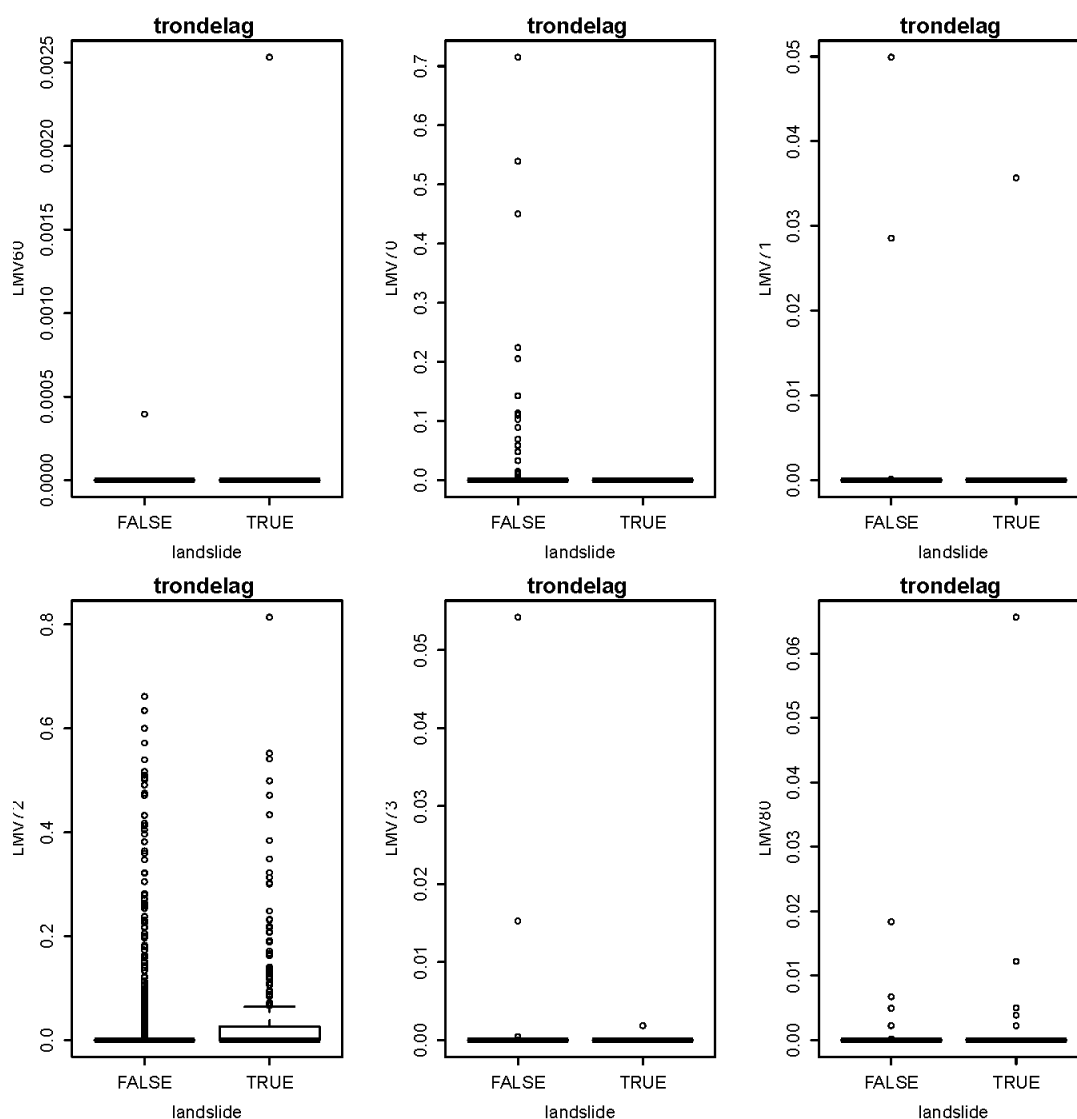
B1 Boxplots of variables in REGINE units with and without landslides

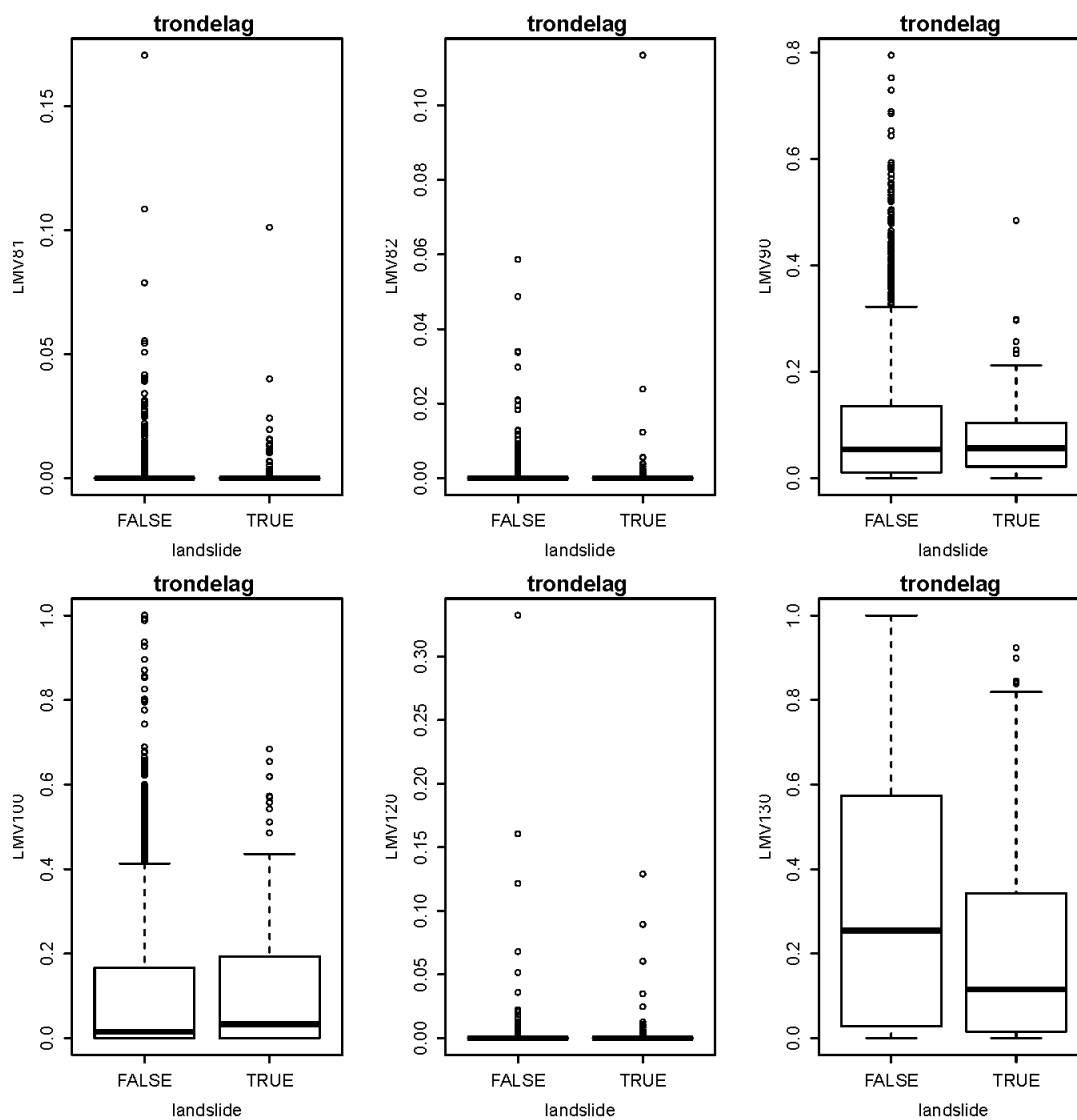


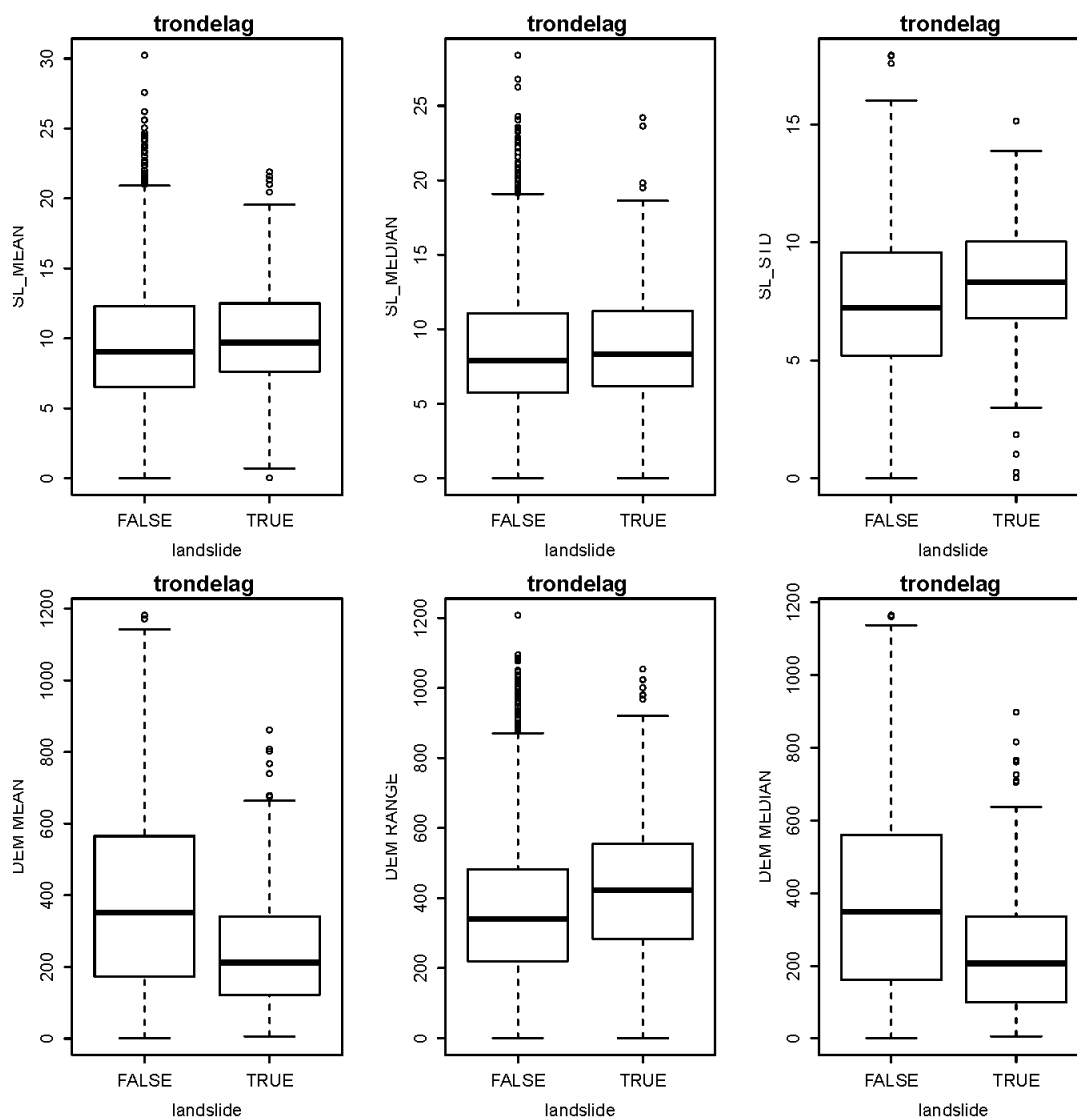


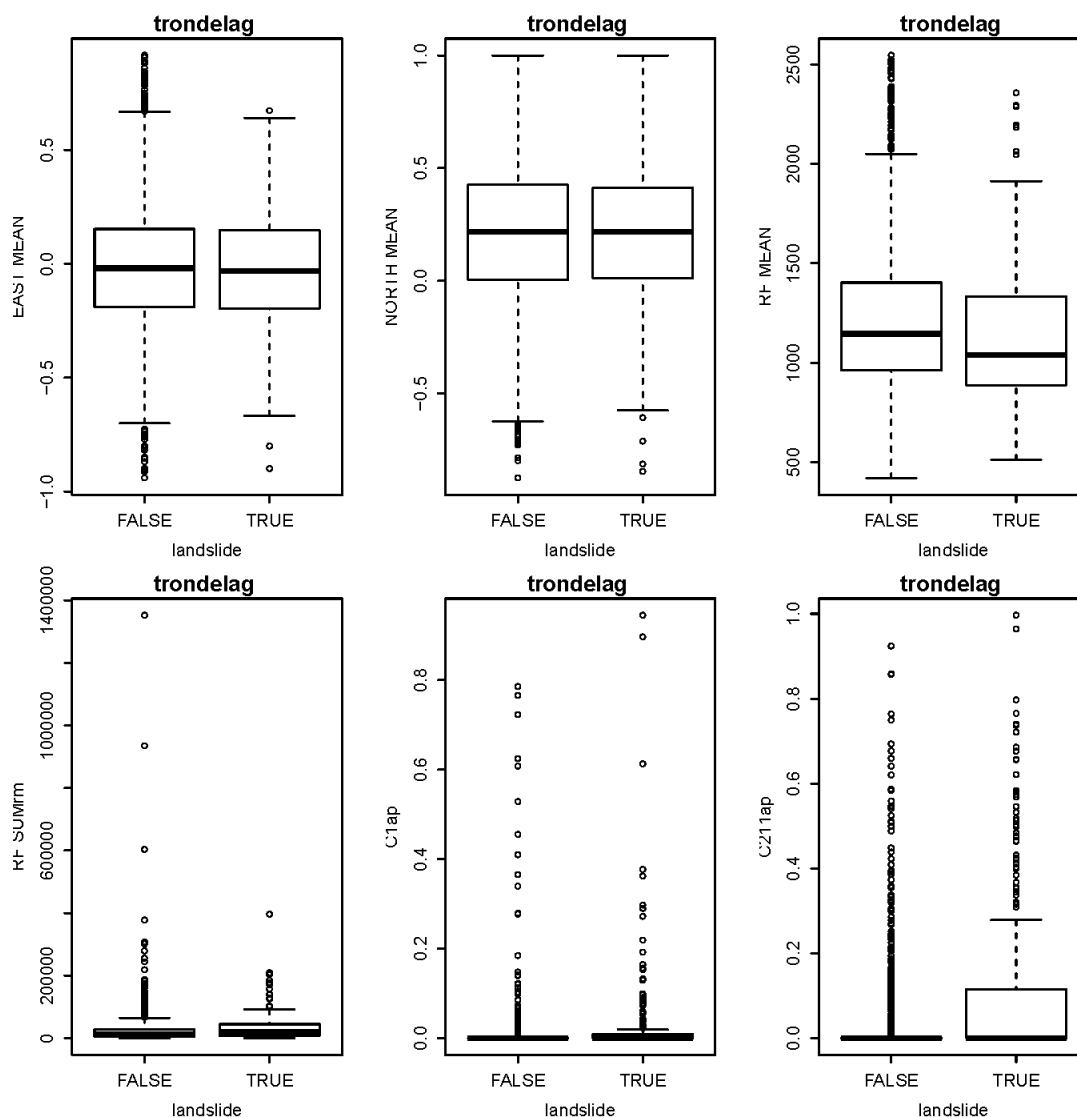


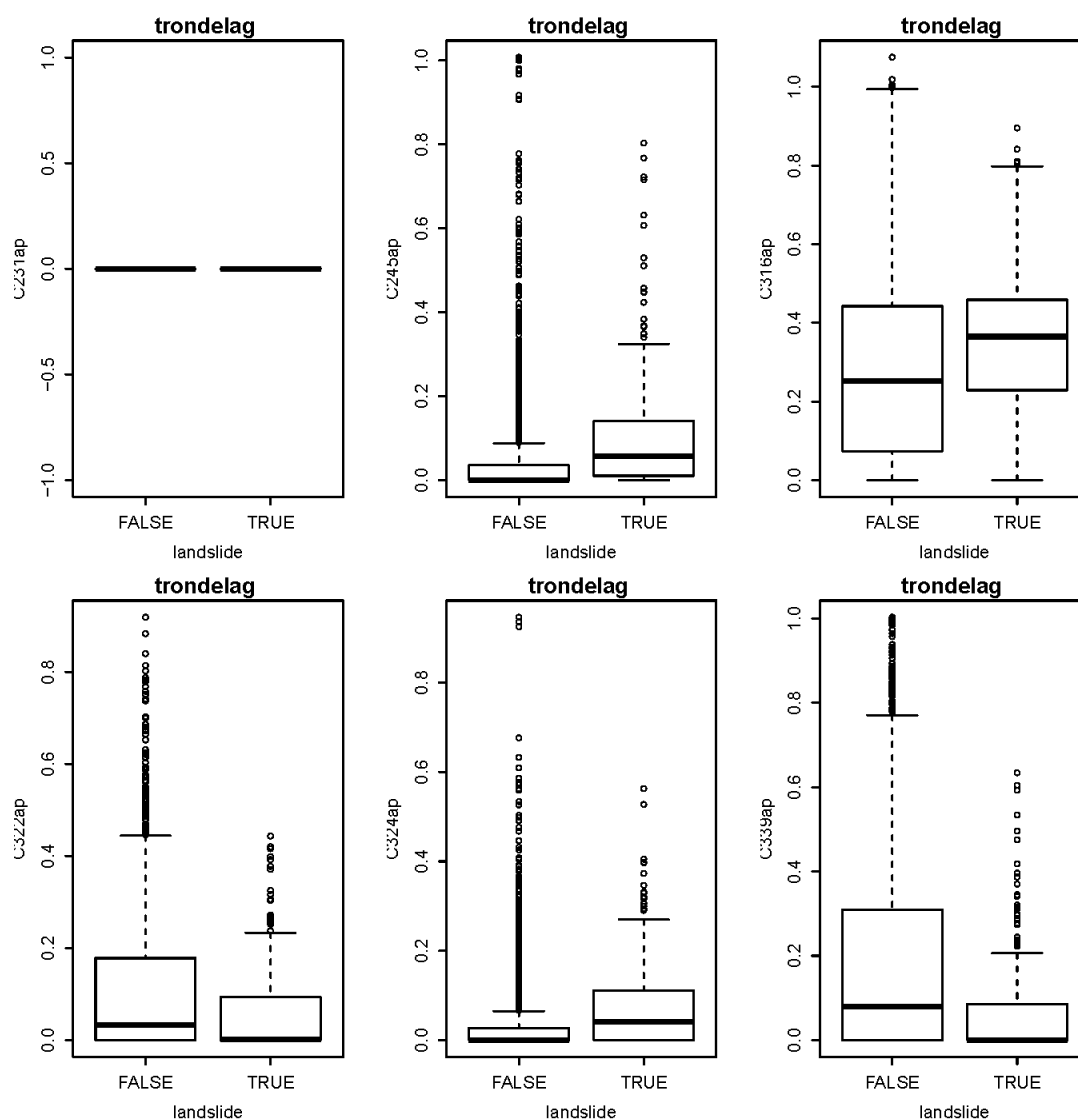


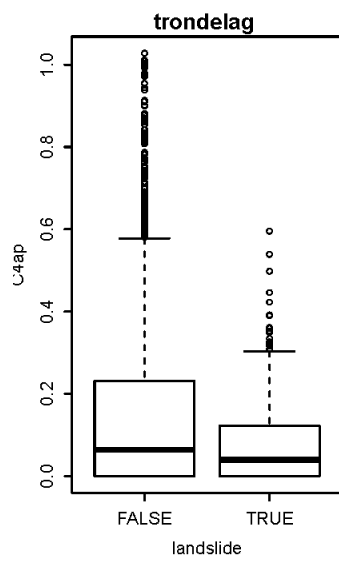












Appendix C

SPINEPLOTS OF VARIABLES

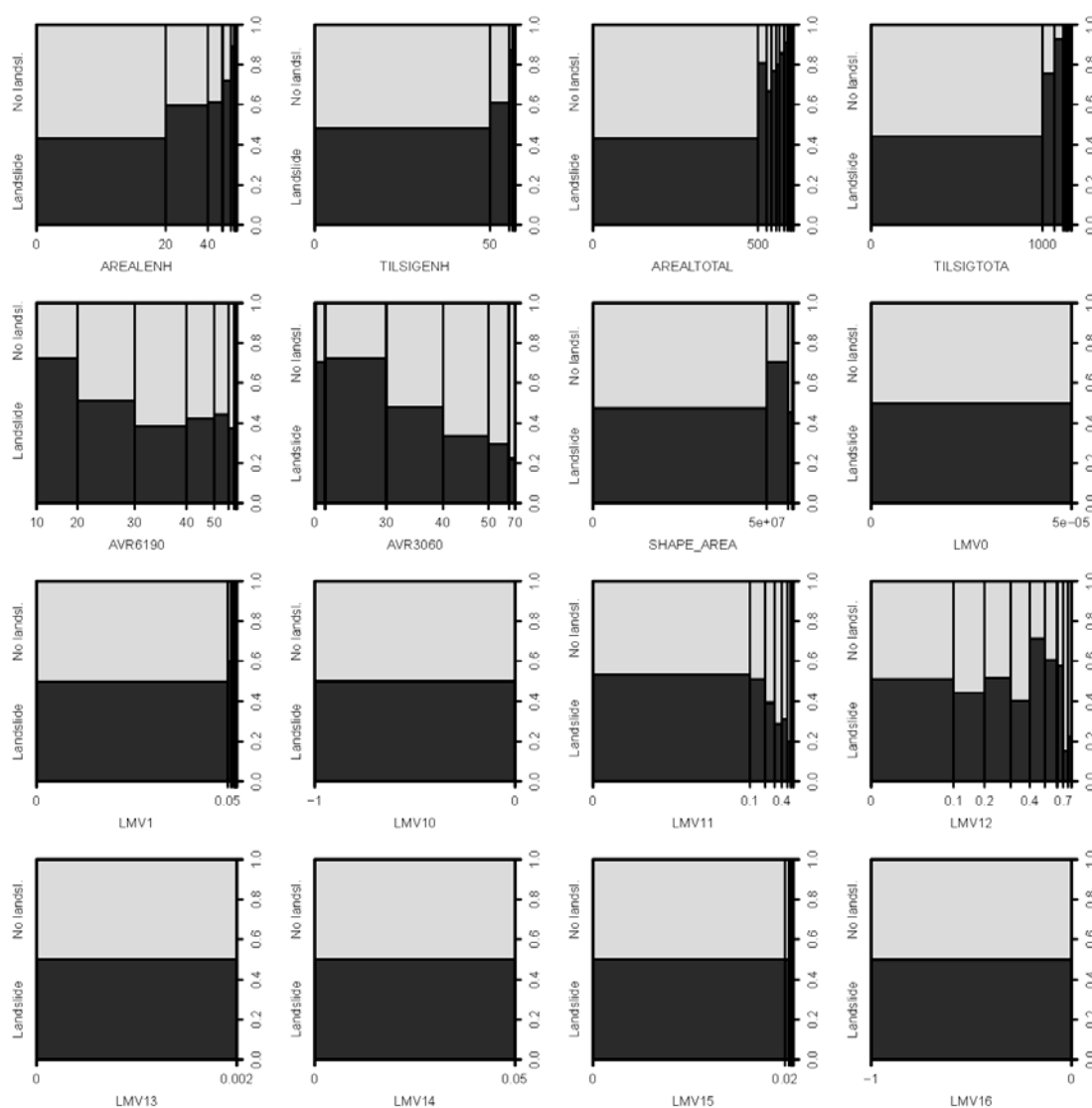
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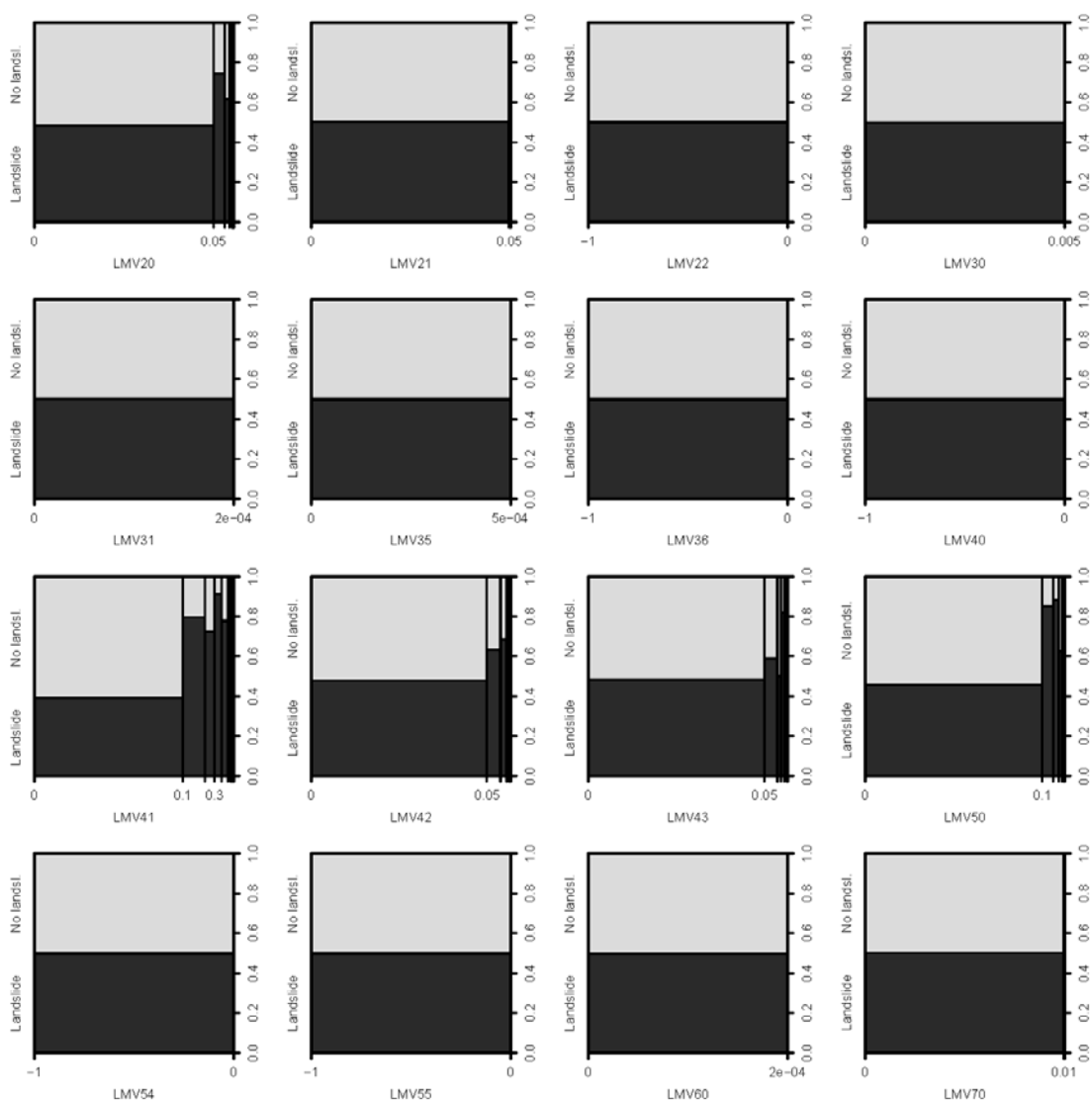
C1	Spineplots of variables
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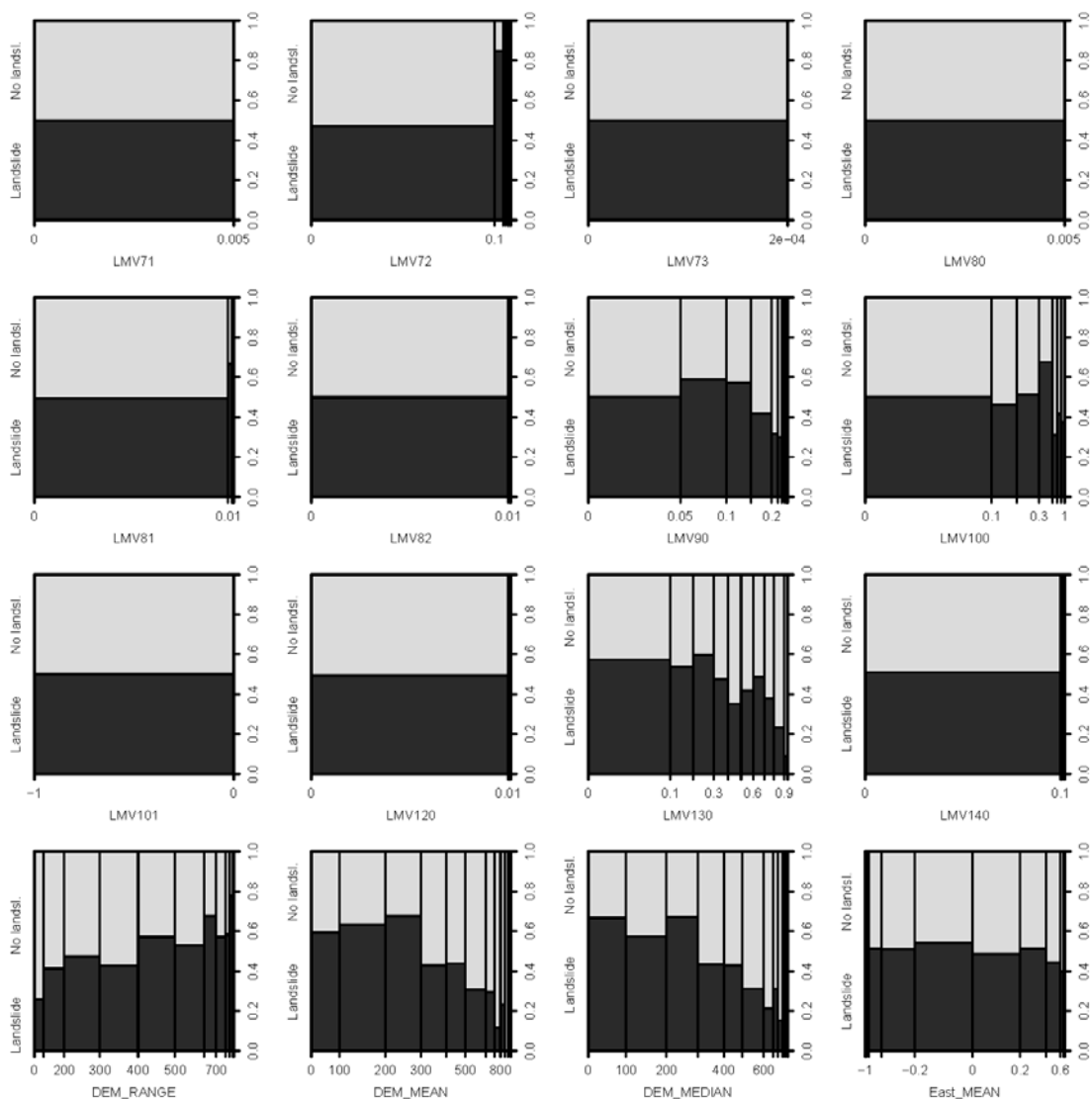
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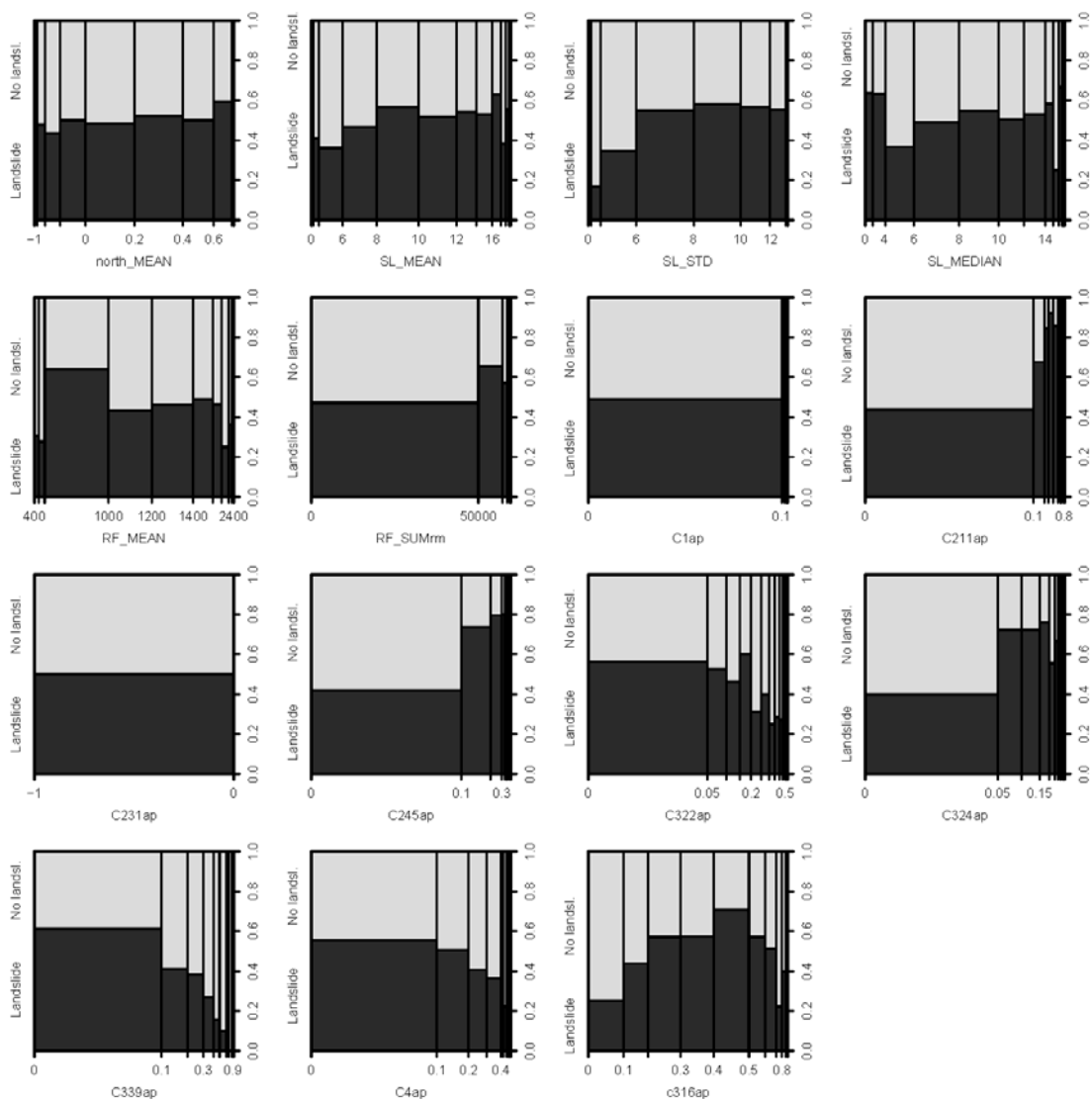
C1 Spineplots of variables

The spineplots shown here are simultaneously plotting the empirical frequency of landslide occurrence conditional on a predictor variable and the empirical frequency of that variable. Bar widths in the spineplots are proportional to the empirical frequency of the given interval of predictor values.









Appendix D

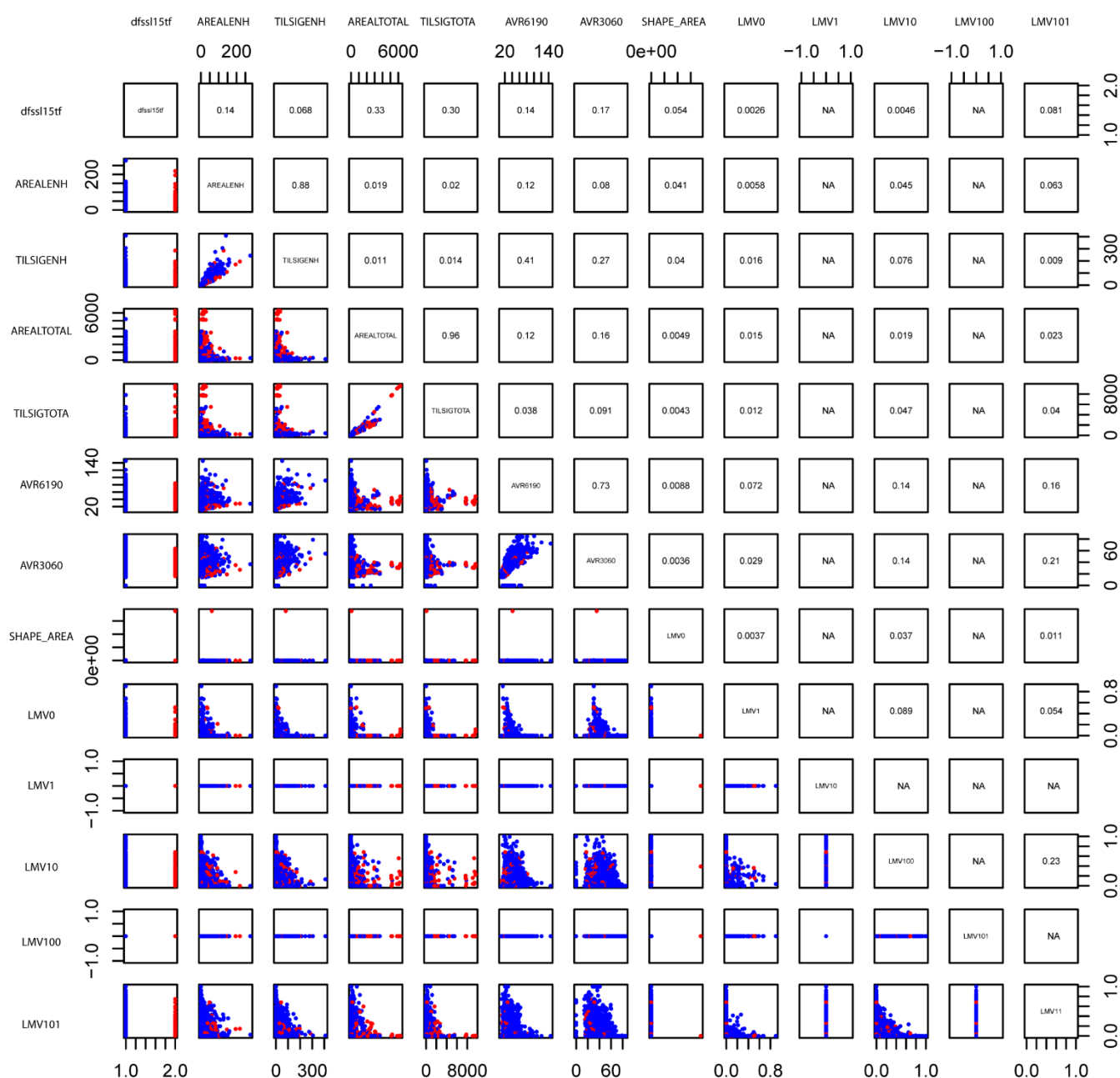
CORRELATION MATRICES OF VARIABLES

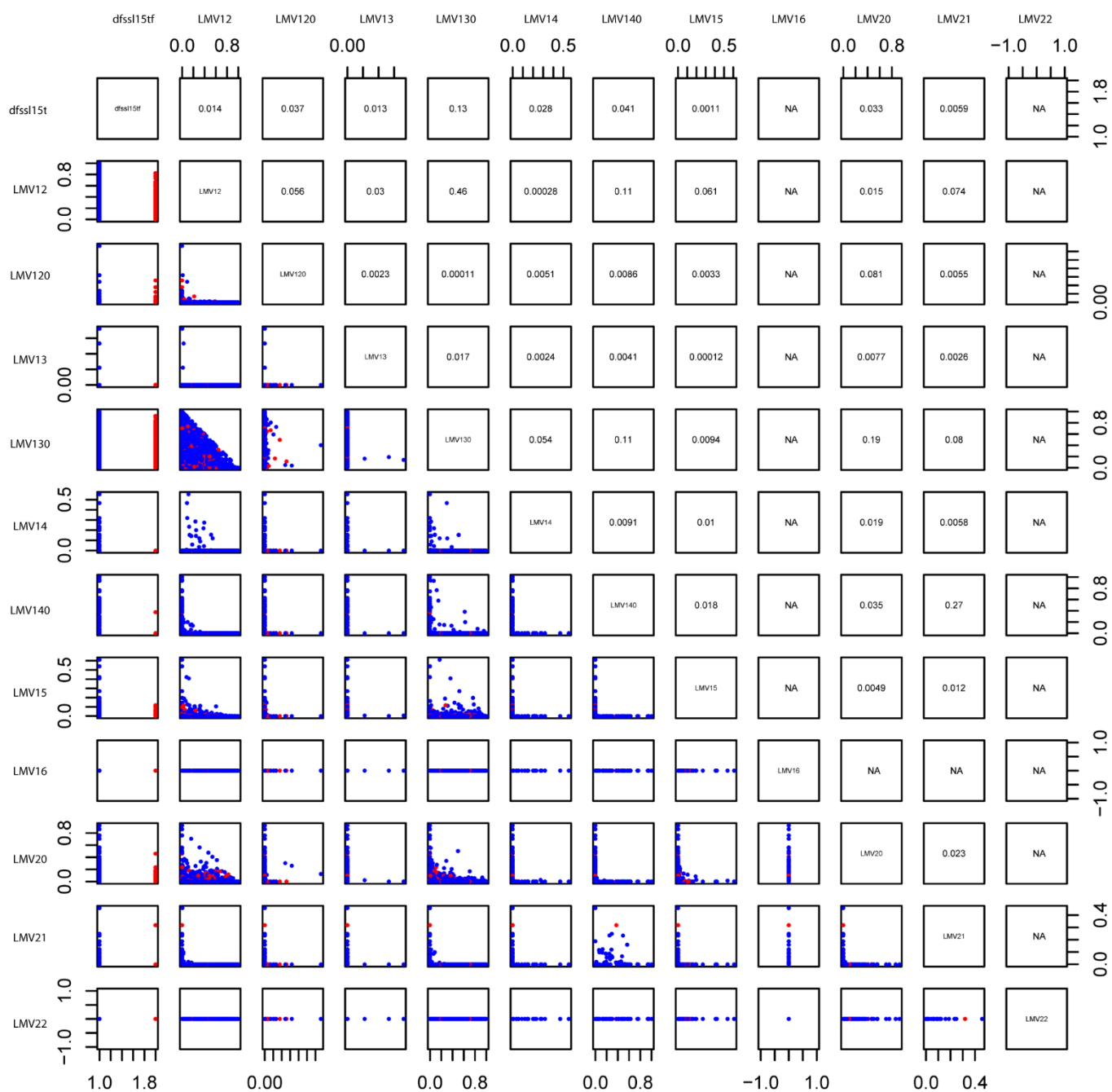
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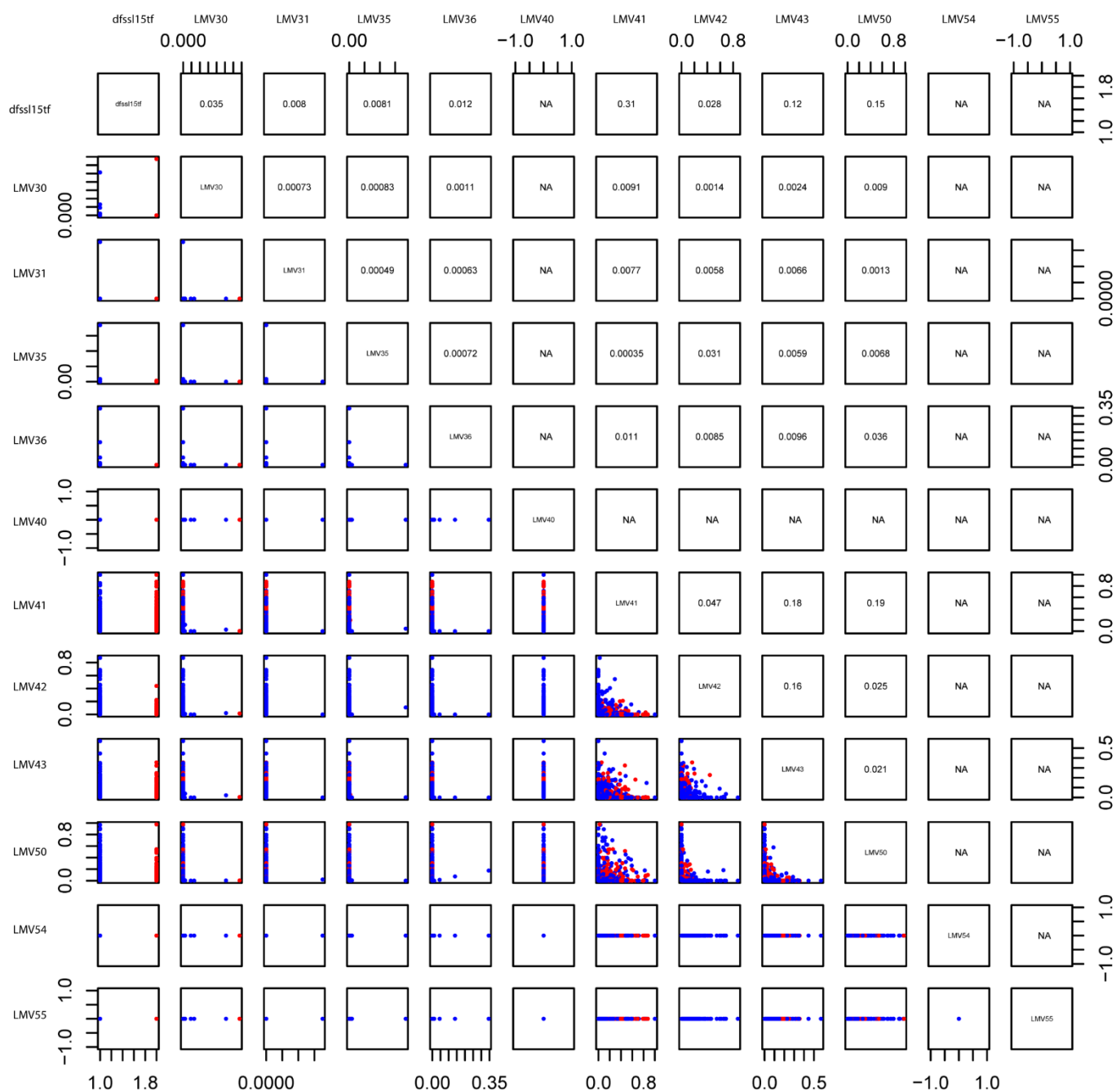
D1	Correlation matrices of variables	2
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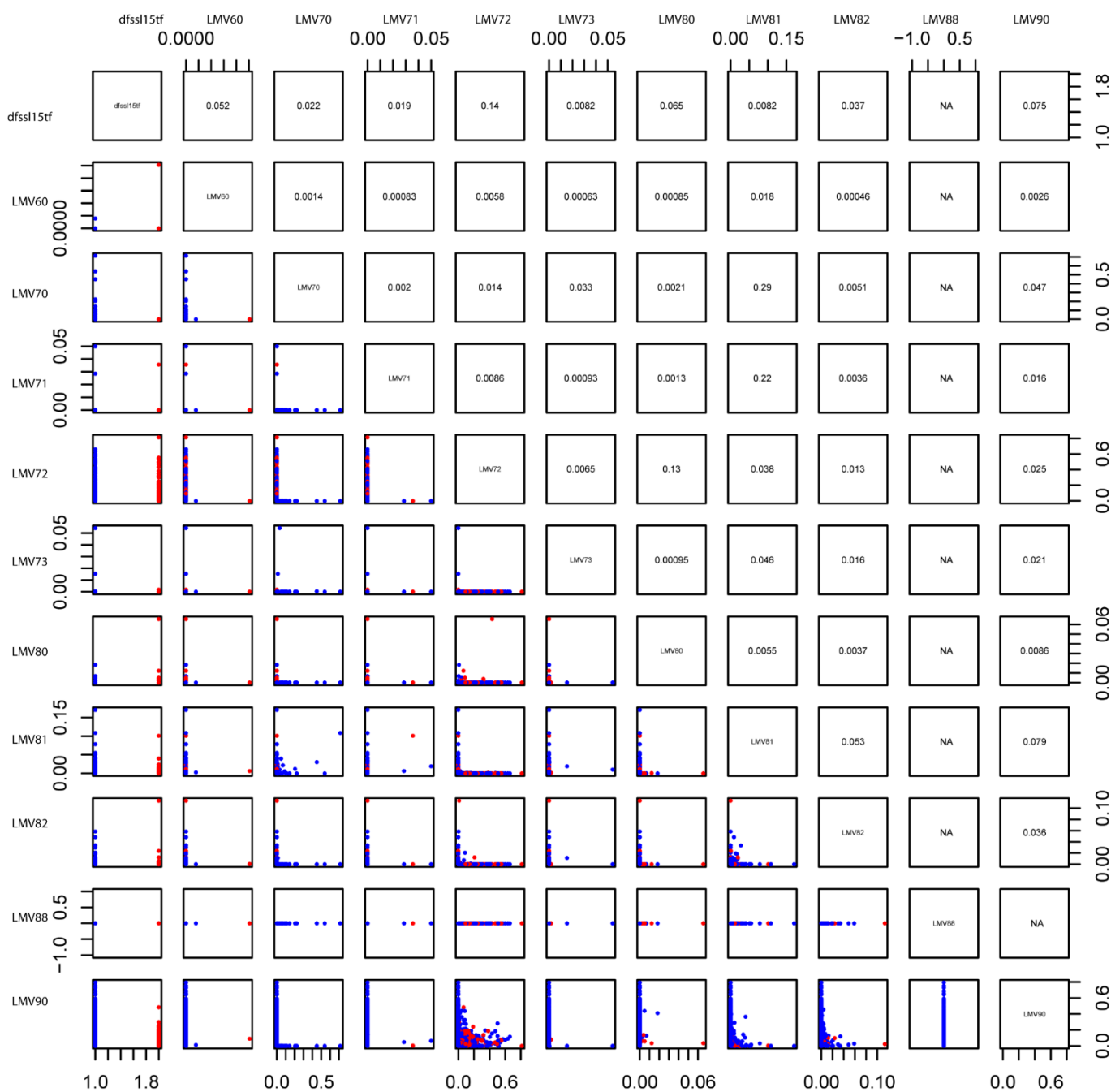
D1 Correlation matrices of variables

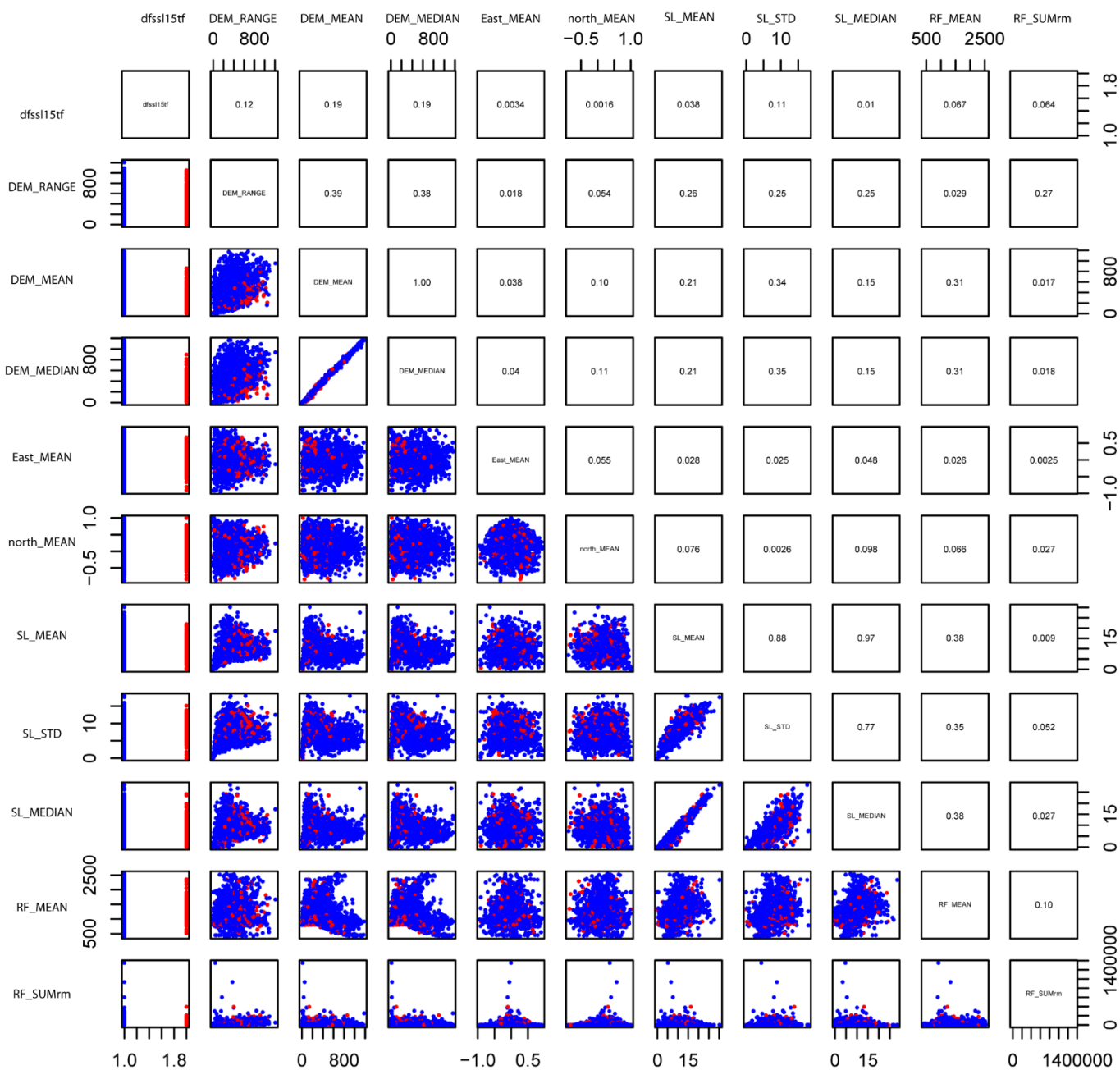
The axes labels are given in the diagonal cells in the middle from upper left to lower right. The cells in the lower left part of the matrices are showing the distribution of landslide (red) and non-landslide (blue) points for each pair of variables. The cells in the upper right part of the matrices show the correlation coefficients between each pair of variables.

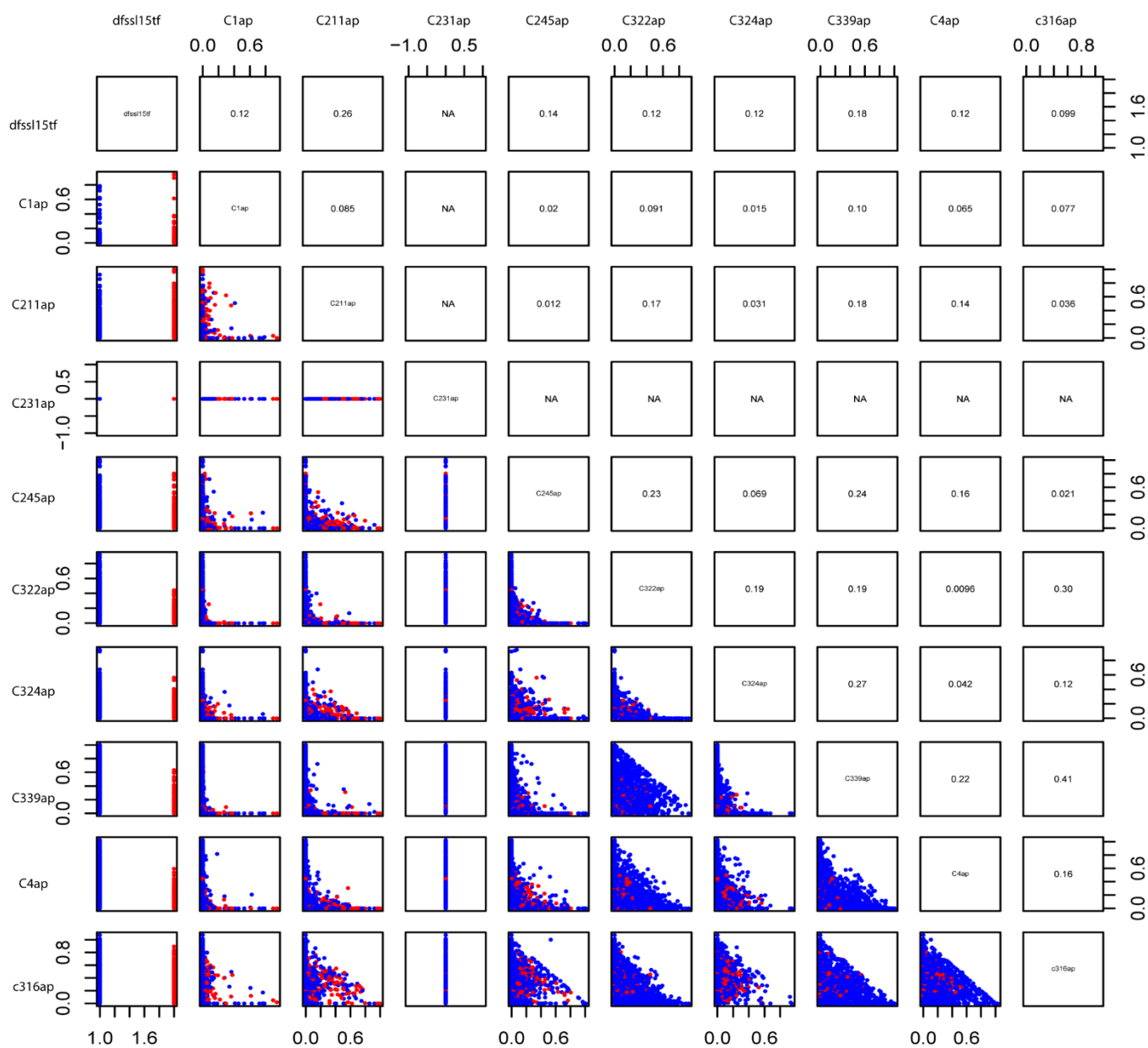












Appendix E

TRANSFORMATION PLOTS OF PREDICTOR VARIABLES

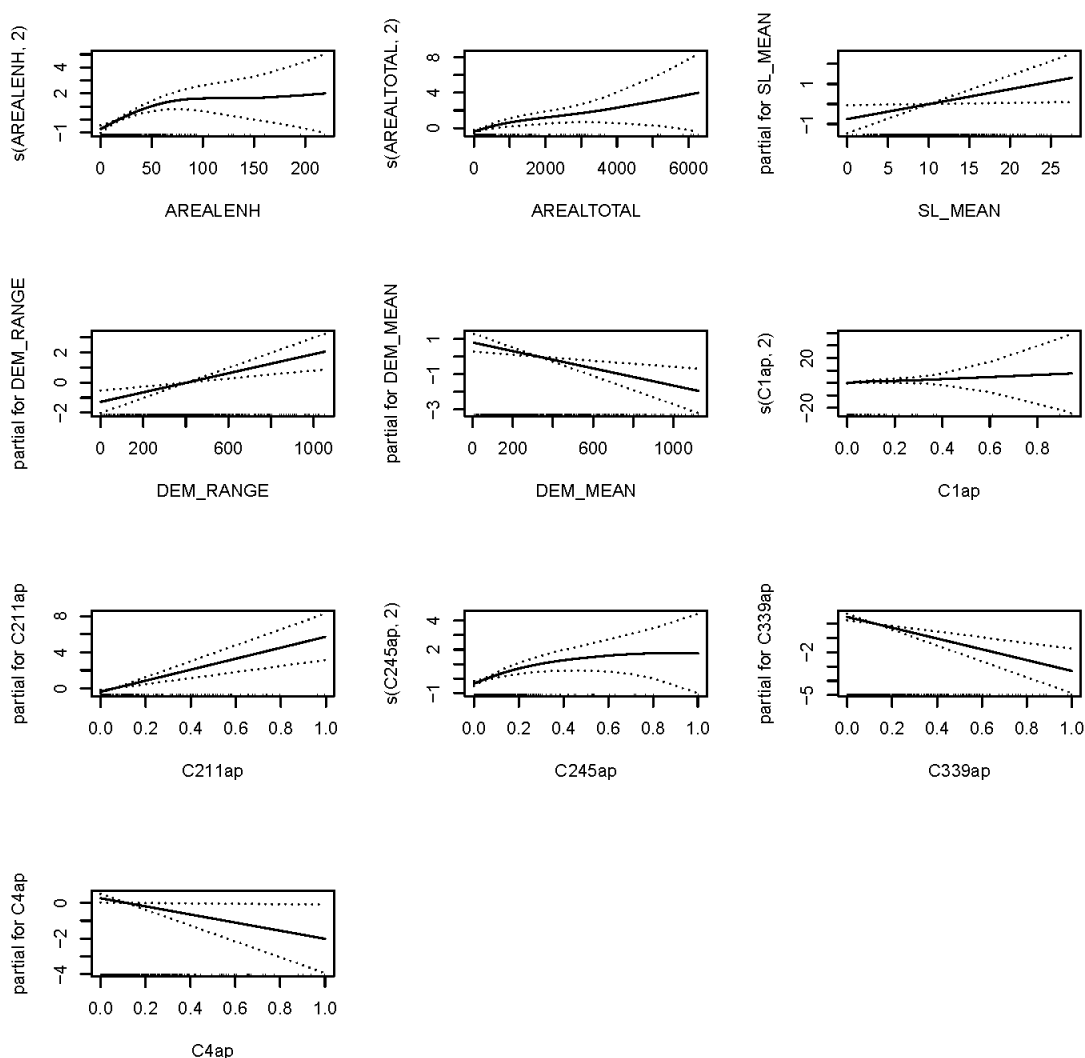
Contents

E1	Transformation plots of predictor variables	2
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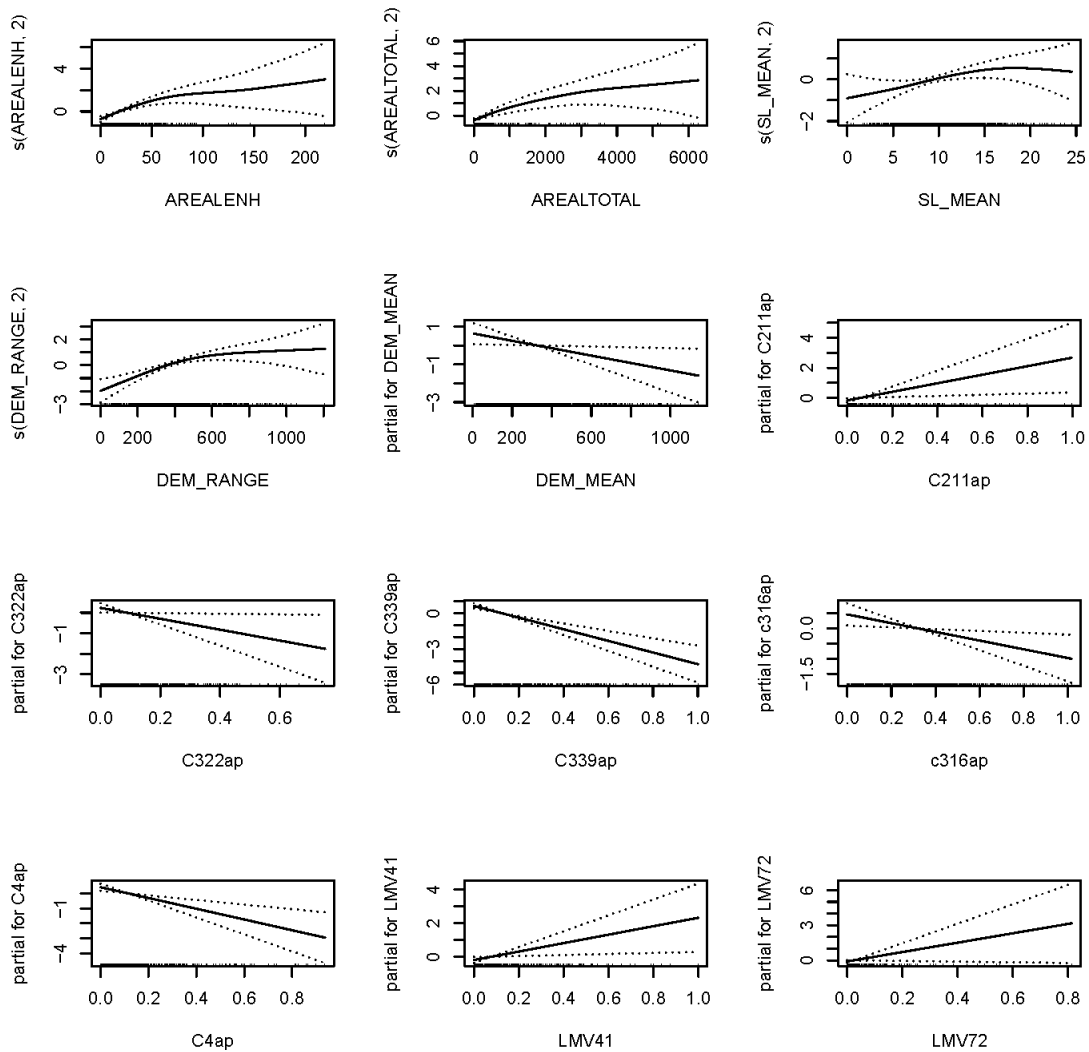
E1 Transformation plots of predictor variables

Transformation of predictor variables in the Generalized Additive Model “pred1a”. A spline function for non-parametric smoothing of the variable, $s(\text{variable})$, indicates a nonlinear transformation. The dotted lines represent confidence bands.

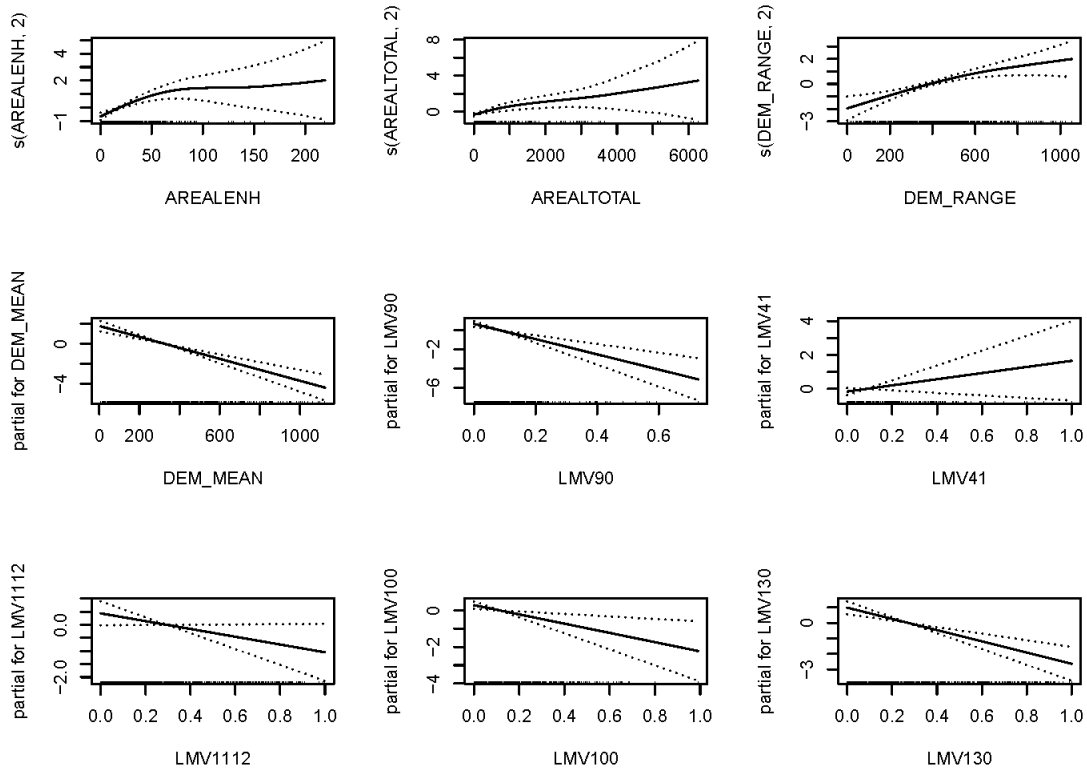
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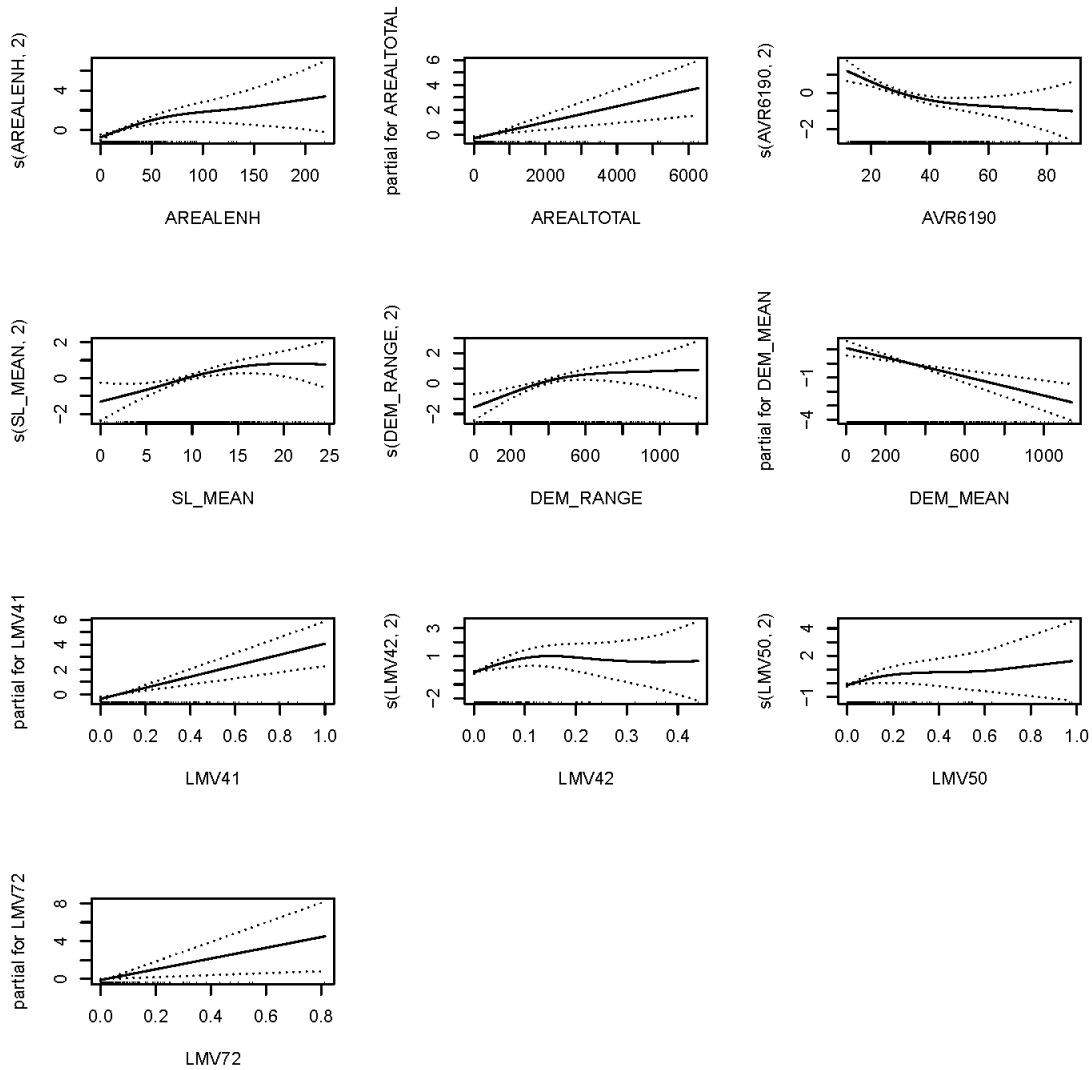
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Model “dssl15_1_gam1wlc”



Model “dssl15c_1_gam1wlc”



Dokumentinformasjon/Document information		
Dokumenttittel/Document title Susceptibility map for debris flows, debris slides and soil slides in Trøndelag		Dokumentnr./Document no. 20150747-01-TN
Dokumenttype/Type of document Teknisk notat / Technical note	Oppdragsgiver/Client NVE	Dato/Date 2015-12-18
		Rev.nr.&dato/Rev.no.&date 0 /
Distribusjon/Distribution BEGRENSET: Distribueres til oppdragsgiver og er tilgjengelig for NGIs ansatte / LIMITED: Distributed to client and available for NGI employees		
Emneord/Keywords Landslide susceptibility, precipitation-induced landslides, debris flows, debris slides, soil slides		

Stedfesting/Geographical information	
Land, fylke/Country Norge, Nord Trøndelag og Sør Trøndelag	Havområde/Offshore area
Kommune/Municipality	Feltnavn/Field name
Sted/Location	Sted/Location
Kartblad/Map	Felt, blokknr./Field, Block No.
UTM-koordinater/UTM-coordinates Zone: East: North:	Koordinater/Coordinates Projection, datum: East: North:

Dokumentkontroll/Document control					
Kvalitetssikring i henhold til/Quality assurance according to NS-EN ISO9001					
Rev/ Rev.	Revisjonsgrunnlag/Reason for revision	Egenkontroll av/ Self review by:	Sidemanns- kontroll av/ Colleague review by:	Uavhengig kontroll av/ Independent review by:	Tverrfaglig kontroll av/ Interdisciplinary review by:
0	Original document	2015-12-16 Rainer Bell	2015-12-18 José Cepeda		

Dokument godkjent for utsendelse/ Document approved for release	Dato/Date 18 December 2015	Prosjektleder/Project Manager José Cepeda
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Appendix D

Technical Note: Bell R., Cepeda J. (2017). Susceptibility map for debris flows, debris slides and soil slides in Agder. Technical note 20170858-01-TN. Norges Geotekniske Institutt, Oslo, Norway

To: Norges vassdrags- og energidirektorat (NVE)
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Date: 2017-12-21
Revision no./Rev.date: 0 /
Document no.: 20170858-01-TN
Project: Improvement of warning levels for precipitation-induced landslides in Agder
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Susceptibility map for debris flows, debris slides and soil slides in Agder

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1 Introduction

The aim of this project is the improvement of warning levels for precipitation-induced landslides (debris flows, debris slides and soil slides) in Agder. Similar to the applications in Northern and Eastern Norway (Bell et al. 2014), Western Norway (Bell & Cepeda 2014) and Trøndelag (Bell & Cepeda 2015), landslide susceptibility at REGINE unit level is modelled. NVE plans to combine this landslide map with NVE's Hydmet index for warning services. The study area includes also some REGINE units of Western and Eastern Norway which were not modelled in previous studies. However, in the following the study area is named Agder for the sake of simplicity. This technical note presents a description of the data, the methodology for analysis, the results and a discussion.

2 Data

In consistence with past projects for modelling landslide susceptibility in Northern, Eastern and Western Norway and Trøndelag, only data sets available for the whole country were used as input. One of the most important data for landslide susceptibility modelling is the landslide inventory. Additional data are the REGINE database (national catchment database), the Quaternary map, land cover data, hydrometeorological data, and various derivatives from a digital elevation model (DEM). All data is briefly described in the following paragraphs.

The integrated national database for all types of rapid mass movements (www.skrednett.no) contains more than 47000 events (just point location) from the last five hundred years covering the whole country. The most frequent events are rockslides and snow avalanches followed by debris slides (Bell & Cepeda 2014). Currently, 274 debris flows, debris slides and soil slides located in the study area are stored in the database (date retrieved: 8 November 2017). The majority of the entries result from events recorded by road authorities and railway authorities. Thus, usually the points are placed where landslides have hit roads or railways (Jaedicke et al. 2009). This characteristic of the inventory may introduce large inaccuracies for long runout events when modelling landslide susceptibility, since in general susceptibility modelling should be carried out at the initiation areas of landslides, especially when using pixel-based approaches. Further uncertainties result from: errors in classifying the events according to the landslide type, lack of registration in some regions and missing information on the slope (artificial cut/fill slope or natural slope). In spite of this, the inventory was used since it is the only available country-wide (Bell et al. 2014). In this technical note, soil and debris slides as well as debris flows will be termed landslides.

The REGINE database was used to extract the information on first order catchments (REGINE units, vector polygon data). The data stored in each REGINE unit and used in susceptibility modelling are: REGINE unit area (km²), REGINE unit runoff 1961-1990 (million m³ per year), total upstream area (km²), total upstream runoff 1961-1990

(million km³ per year), average runoff 1961-1990 (litre/second km²) and average runoff 1930-1960 (litre/second km²) (NVE n.d.).

The Quaternary map at a scale of 1:250,000 (www.ngu.no) gives information of geological units of various types and subtypes of sediments and shows rock outcrops. The quality is rather heterogeneous with higher level of detail in some areas only (Bell et al. 2014).

Land cover data was obtained from CORINE land cover 2006 data, which was compiled by the Norwegian Forest and Landscape Institute (Aune-Lundberg and Strand 2010). Details are limited to a minimum mapping unit of 25 ha (0.25 km²).

Spatially distributed average yearly rainfall data (1961-1990) with a resolution of 1km x 1km was available (Source: MET and www.senorge.no).

A digital elevation model (DEM) with a resolution of 15 m x 15 m was available for all Norway, derived from 1:50000 topographical maps.

3 Methods

Landslide susceptibility modelling was carried out using the statistical approach of Generalized Additive Models (GAM) (Hastie 1992), a further development of logistic regression. A combined backward and forward stepwise variable selection in R (version 3.4.3, www.r-project.org) based on Akaike's Information Criterion AIC (Akaike 1974) was applied to fit the susceptibility models. Using the AIC, the best fit of variables for a model is automatically selected by evaluating the significance of the variables and penalizing for model complexity. The GAM decides for each variable whether it should be omitted, used linearly or with a smooth function. Based on the AIC values, the GAM selects the model with the best combination of variables. In addition, model runs were carried out allowing only linear use of variables which means that this is an approach of logistic regression.

Landslide susceptibility was modelled at REGINE unit (catchment) level since for the regional scale of the current early warning, the resolution of this unit of analysis is deemed sufficient. The main advantage is that the whole process area of the landslides is automatically considered and not only initiation areas. The poor spatial location of the landslide points of the landslide inventory (see above) does not matter in general since it is assumed that all landslides are located in the same REGINE unit of the initiation areas. However, 1 landslide point was located marginally outside of the REGINE units. Since it was not clear to which REGINE unit the landslide point belongs to, this landslide point was deleted, so that finally modelling was carried out with 273 landslides. This corrected landslide inventory led to 152 REGINE units with landslides for the dfssl17 set.

Modelling was carried out using a 1:1 relationship between REGINE units with landslides and REGINE units without landslides. For the final landslide susceptibility map all 152 REGINE units with landslides and randomly sampled 152 REGINE units without landslides were used in susceptibility modelling. This ensures that all known information on landslides was considered in the development of the final map. Additional models were calculated for validation purposes. Therefore, 50% of the REGINE units with landslides were used in the training sample and the other 50% in the independent testing sample. However, by using this approach only one validation estimate is obtained, which might be rather random. As preliminary results showed that the differences between the validation estimates are relatively small, it was decided to improve the validation step further by performing k-fold cross validations using randomly selected subsamples.

We applied k-fold ($k = 4$) cross validations which means that the data is subsampled in 4 subsets. Subsequently, the model is fitted to $k-1$ subsamples (training sample) and validated by the remaining subsample (testing sample). This was repeated four times until each subsample was used as testing sample. The whole process was repeated 10 times ($r = 10$). During each repetition, new subsamples were randomly selected. Thus, in total 40 models are fitted and validated calculating the median and interquartile range of the validation criterion.

For the dataset dfssl17, this validation procedure was carried out using three different samples – a) using all REGINE units available, b) using a relationship of 1:1 between REGINE units with landslides and REGINE units without landslides and c) using a relationship of 1:5 between REGINE units with landslides and REGINE units without landslides – and two different statistical methods (GAM and logistic regression).

Subsequently, all calculations were repeated for $k = 2$. Thus, in total 240 models using GAM and 240 models using logistic regression were calculated within this k-fold cross validation approach. k-fold cross validation was applied using the *sperrorest* package in R (Brenning 2012).

The explanatory variables are geological units from the Quaternary map, land cover, average annual rainfall, various water runoff variables (see above), and various derivatives from the 15 m x 15 m digital elevation model (DEM) like e.g. slope and aspect. For the categorical data, the proportion of each class in the catchment and for continuous data either mean, median, standard deviation or range for the catchment were calculated and used in modelling. Altogether 65 variables were available (Appendix A). Boxplots (Appendix B), spineplots (Appendix C) and correlation matrices (Appendix D) were used to pre-select variables.

The performance of the resulting models and maps was evaluated using the area under the ROC curve AUROC as criterion. (values of 0.7 to 1 show good to very good discrimination between REGINE units with landslides and REGINE units without landslides (Hosmer & Lemeshow 2000)).

Finally, landslide susceptibility was classified into four classes (low, moderate, high, very high), using the same four classes of the hydro-meteorological index. Classification thresholds were set based on the proportion of landslides in each class. The same classification scheme as applied to Northern, Eastern and Western Norway and Trøndelag were used: 70 %, 15 %, 12 % and 3% of the landslides in the susceptibility classes very high, high, moderate and low, respectively.

4 Results

4.1 Landslide inventory

In consistence with previous projects for modelling landslide susceptibility in Northern, Eastern and Western Norway and Trøndelag, only the landslide types 140, 142, 143 and 144 were selected and used in the assessment (140: Landslides in soils, unspecified; 142: Debris slide/Debris flow/Debris flood; 143: Clay slides; 144: Soil slide). This resulted in 274 debris flows, debris slides and soil slides within the study area (Fig. 1).

Due to spatial inaccuracies (described in chapter 3) one landslide point was deleted, so that the final landslide inventory contained 273 landslides, occurring in 152 REGINE units (Fig. 2, Fig. 3 and Fig. 4).

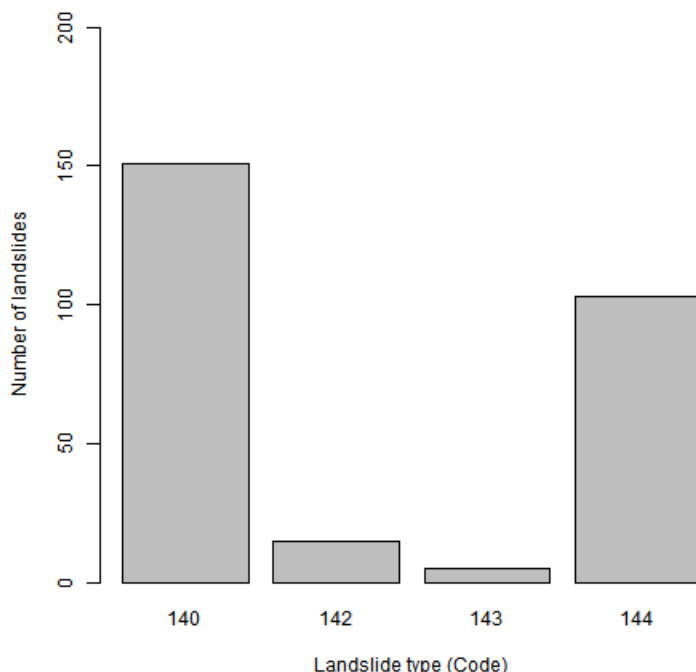


Figure 1 Distribution of different types of rapid landslides in the study area. (140: Landslides in soils, unspecified; 142: Debris slide/Debris flow/Debris flood; 143: Clay slides; 144: Soil slide. Source: Integrated national database for all types of rapid mass movements, www.skrednett.no)

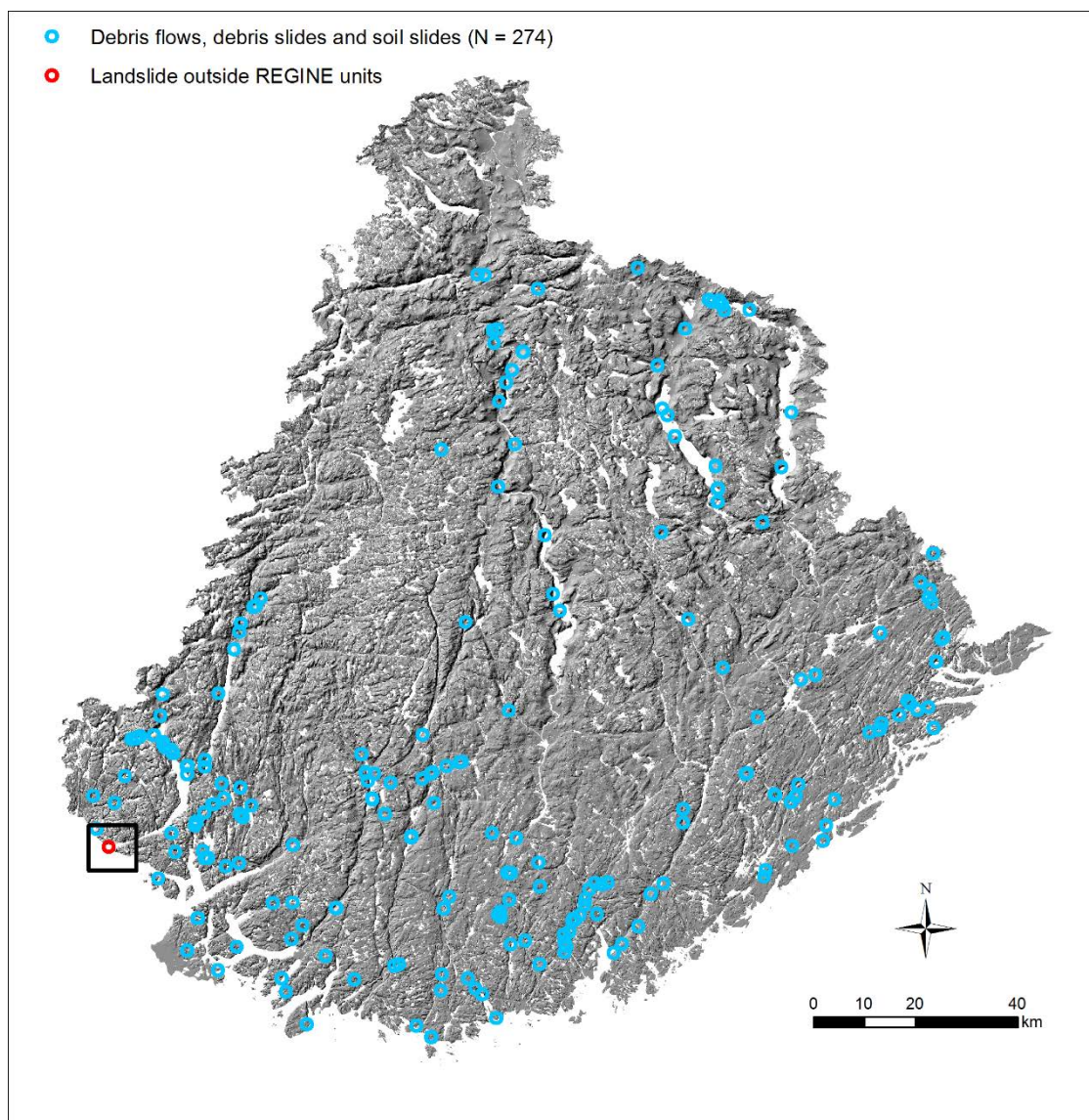


Figure 2 Location of landslides inside and outside of REGINE units. Note: One landslides is located outside of REGINE units due to spatial inaccuracies. The box indicates the location of the area shown in detail in Figure 3.

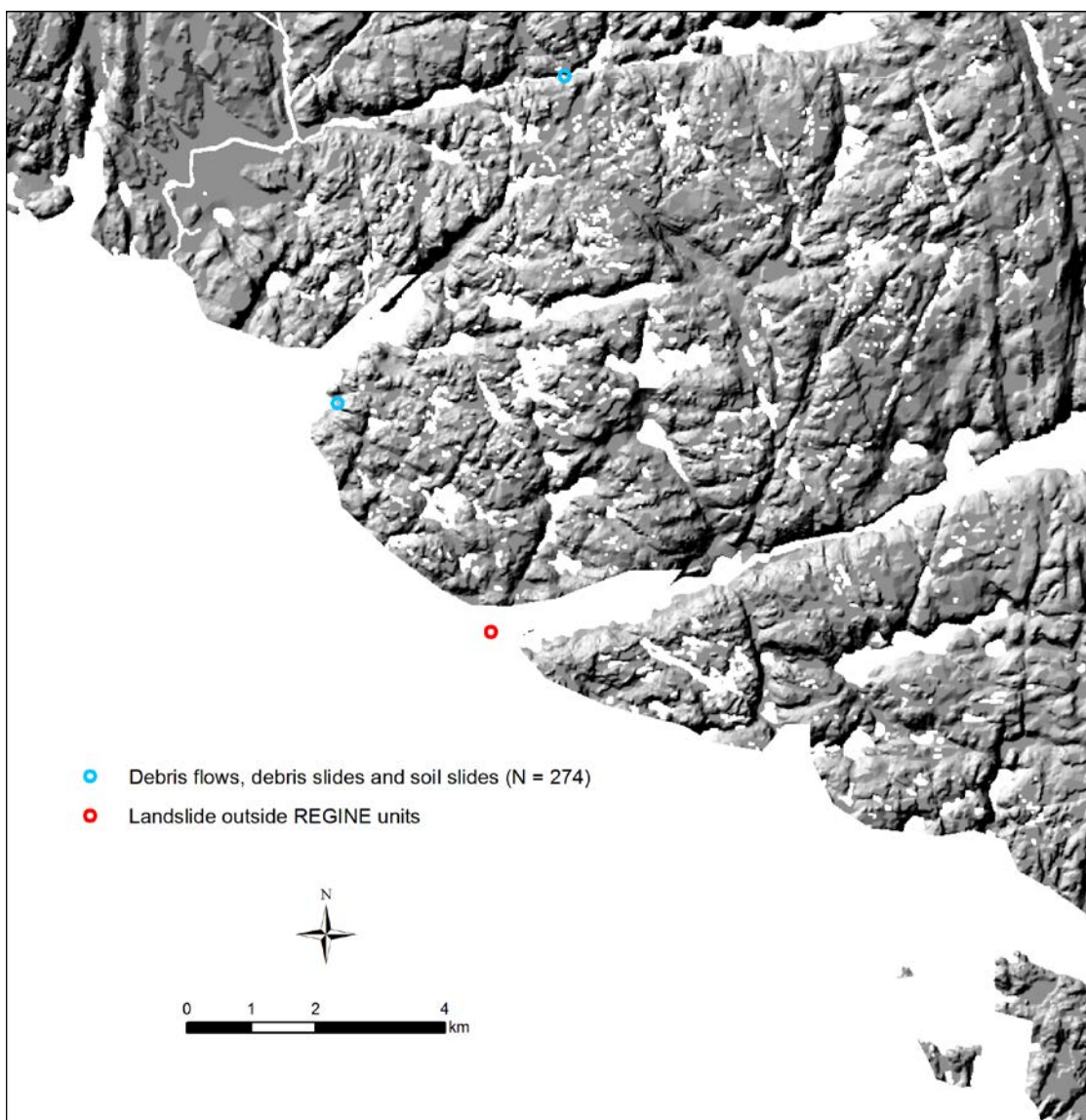


Figure 3 Location of the landslide outside of REGINE units which was deleted from the landslide inventory. Its location in the study area is given in Figure 2.

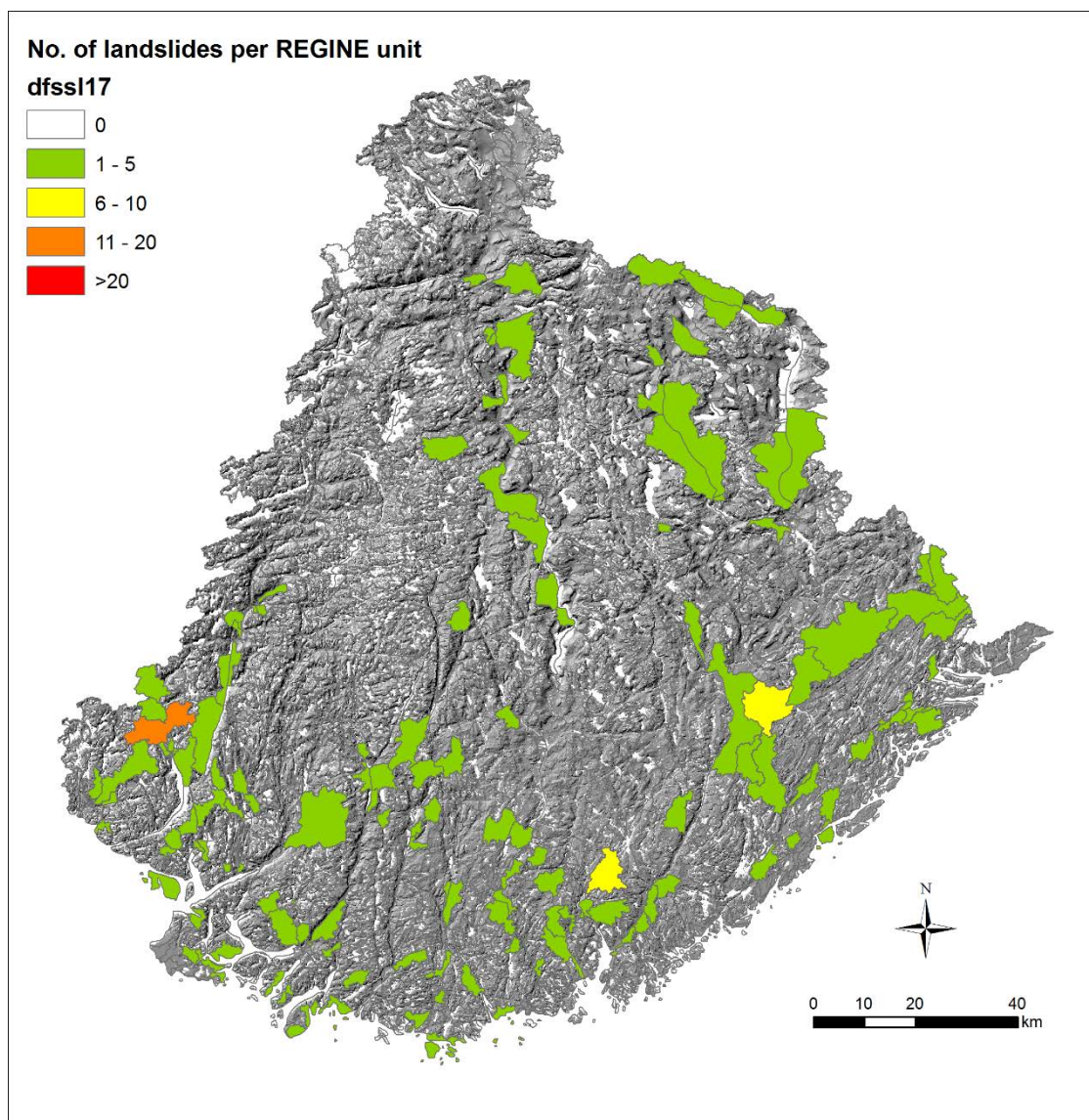


Figure 4 Distribution of debris flows, debris slides and soil slides per REGINE unit in the study area (dfssl17, N = 273)

4.2 Landslide susceptibility

Several hundreds of models were calculated (see chapter 3 for details). Finally, the following 6 models were selected using either 100% of the REGINE units with landslides or 50% of the REGINE units with landslides (Table 1). Half of the selected models were applied using GAM (model name contains “gam”), the other half using logistic regression (model name contains “logreg”).

Table 1 Variables finally used in the different models using 100% of the REGINE units with landslides (model name contains “dfssl17_1_”) or using only 50% of the REGINE units with landslides (model name contains “dfssl17_05_”) (s = applied with a smoother function, n = without smoother function, - = not selected; Note: Since the “logreg”-models were modelled using logistic regression, no smoother function was available).

No.	Code	Description	dfssl17_1_ gam_1	dfssl17_1_ gam_2	dfssl17_1_ logreg1	dfssl17_05_ gam_1	dfssl17_05_ gam_2	dfssl17_05_ logreg1
1	AREALENH	REGINE unit area (km ²)	s	s	-	s	s	n
3	AREALTOTAL	Total upstream area (km ²)	n	n	-	-	n	-
11	LMV11	Moraine material, continuous, locally thick (% of REGINE unit)	-	-	-	n	-	n
20	LMV22	Saddle-shaped glaciofluvial deposit (% of REGINE unit)				-	n	
25	LMV41	Marine and fjord deposits, continuous, locally thick (% of REGINE unit)	n	-	n	-	-	-
27	LMV43	Marine and fjord deposits, non-continuous/thin (% of REGINE unit)	s	-	n	-	-	-
28	LMV4143	LMV41 and LMV 43 combined	-	-	-	-	s	-
29	LMV414243	LMV41, LMV42 and LMV 43 combined	-	s	-	-	-	-
39	LMV81	Landslide material, continous, locally thick (% of Regine unit)	-	-	-	n	-	n
45	LMV130	Bare rock (% of REGINE unit)	n	n	n	-	-	-
47	DEM_RANGE	Elevation range in REGINE unit	n	n	n	n	n	n
48	DEM_MEAN	Mean elevation of REGINE unit	n	n	n	n	n	n
50	East_MEAN	Mean of eastern coordinates of REGINE unit	n	n	n	n	-	n
52	SL_MEAN	Mean slope of REGINE unit	n	n	n	n	-	-
56	RF_SUMrm	Sum of average yearly rainfall 1961-1990 in REGINE unit	-	-	n	-	-	-
60	C245ap	Heterogenous agricultural areas, mainly farmland and natural vegetation (% of REGINE unit)	-	-	-	n	-	n
62	C324ap	Transitional woodland-shrub (% of REGINE unit)	n	n	n	-	-	-

For the GAM models using 100% of the REGINE units with landslides, the transformation plots used by the models can be found in Appendix E.

The AUROC values for all 6 selected models indicate very good performance (AUROC greater than 0.8). The model “dfssl17_1_gam_1” turned out to be the best model since the AUROC value is slightly higher and the AIC values is slightly lower than the other models (Table 2). The random cross-validation using 50% of the REGINE units with landslides in the training sample and the other 50% in the independent testing sample led also to very high AUROC values (Table 3), which is a first indication that the models are rather stable. This is supported by the high AUROC values of the k-fold cross validations (Fig. 5).

Table 2 AUROC values for selected models. 100% of the REGINE units with landslides were used in the training sample. Therefore no independent testing samples could be prepared. In addition the AIC values are shown.

Model	AUROC (train1)	AIC
dfssl17_1_gam_1	0.86	304
dfssl17_1_gam_2	0.85	309
dfssl17_1_logreg_1	0.85	315

Table 3 AUROC values for the training samples “train05” and testing samples “test05” of the selected models. 50% of the REGINE units with landslides were used in the training sample and the other 50% in the independent testing sample. In addition the AIC values are shown.

Model	AUROC (train05)	AUROC (test05)	AIC
dfssl15_05_gam1	0.90	0.86	144
dfssl15_05_gam2	0.88	0.84	152
dfssl15_05_logreg1	0.89	0.83	146

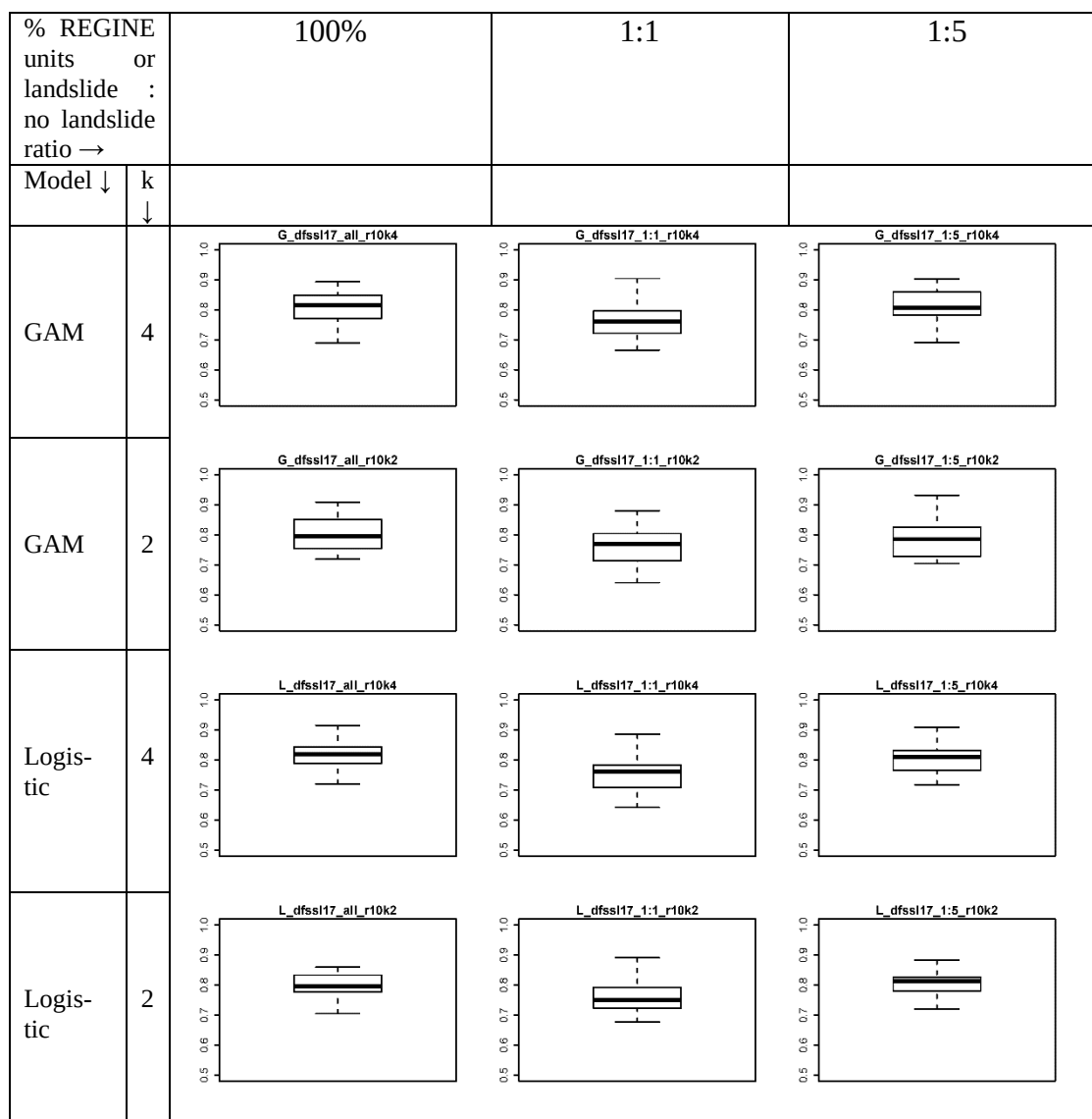


Figure 5 Results of 10-times ($r=10$) repeated k -fold ($k = 4$ or 2) cross validations using either GAM (“G”) or logistic regression (“L”) and the datasets dfssl17. The vertical axes of the boxplots show the range of the calculated AUROC values.

The strongest difference can be seen when the models are compared using a 1:1 relationship between REGINE units with landslides and those without landslides (Fig. 5). The results are rather similar comparing GAM models and logistic regression models.

Based on all three models using 100% of the REGINE units with landslides, landslide susceptibility maps were created using class thresholds defined by 70%, 15%, 12% and

3% of the landslides in the susceptibility classes very high, high, moderate and low, respectively (Table 4, Fig. 6 - 8).

Table 4 Landslide susceptibility thresholds for the different models using class thresholds defined by 70%, 15%, 12% and 3% of the landslides in the susceptibility classes very high, high, moderate and low, respectively. Class boundaries are probabilities (maximum possible range is from 0 to 1).

Model	Figure	low	moderate	high	very high
dfssl17_1_gam_1	6	0.0003 – 0.31	>0.31 – 0.47	>0.47 – 0.61	>0.61
dfssl17_1_gam_2	7	0.0004 – 0.31	>0.31 – 0.47	>0.47 – 0.60	>0.60
dfssl17_1_logreg_1	8	0.0002 – 0.33	>0.33 – 0.48	>0.48 – 0.61	>0.61

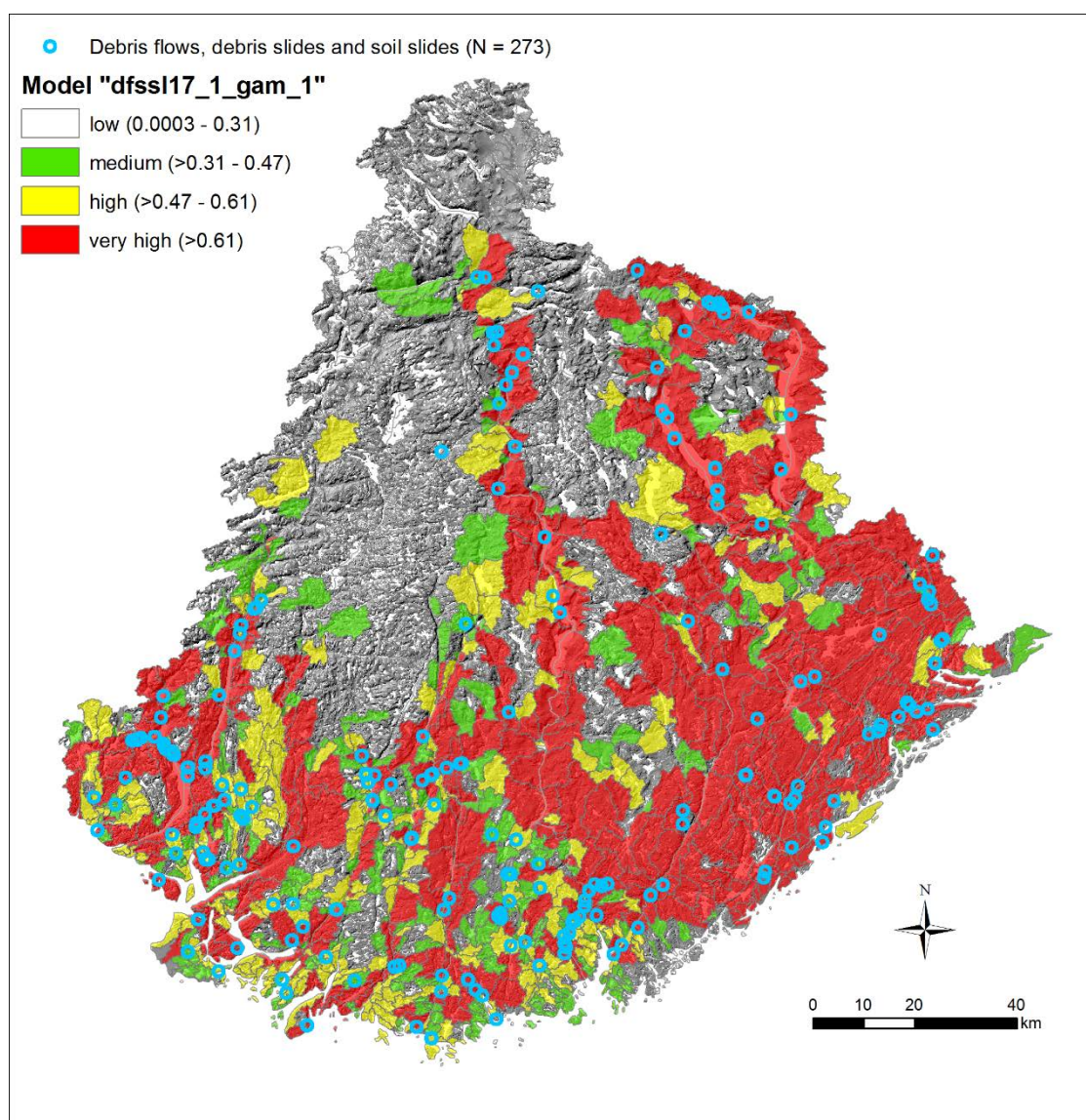


Figure 6 Landslide susceptibility in Agder, Model "dfssl17_1_gam_1".

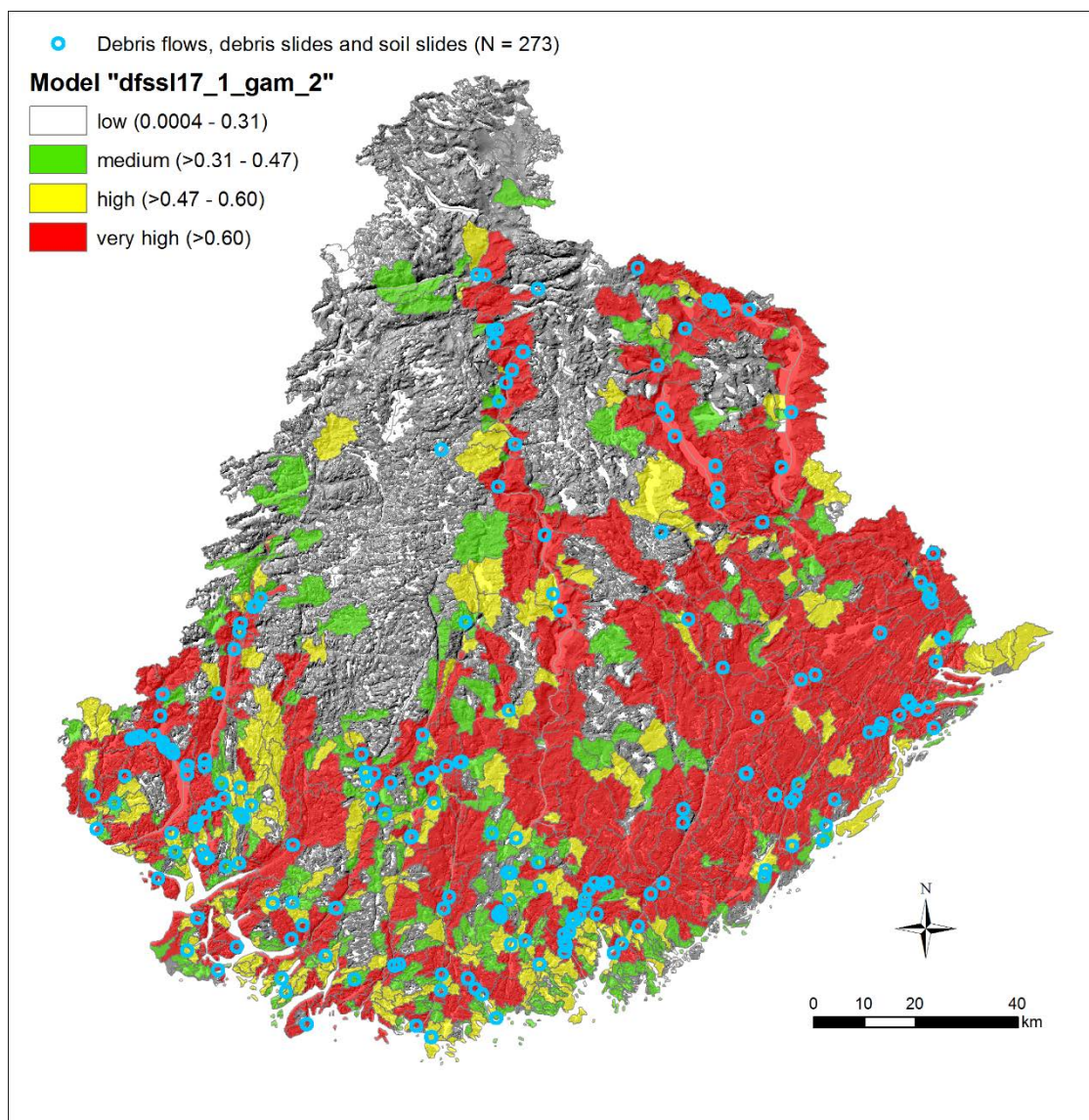


Figure 7 Landslide susceptibility in Agder, Model "dfssl17_1_gam_2".

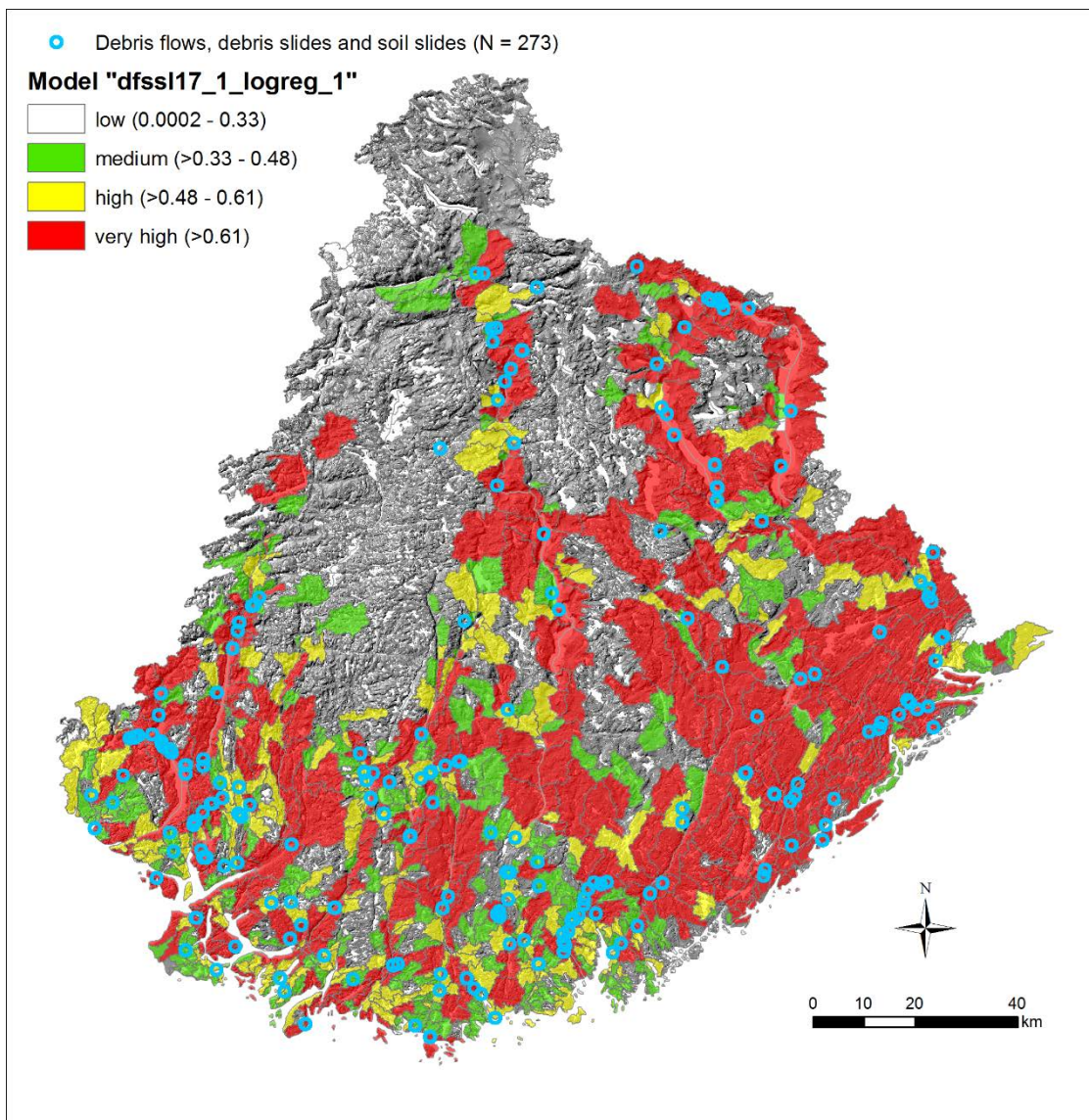


Figure 8 Landslide susceptibility in Agder, Model "dfssl17_1_logreg_1".

Fig. 9 shows the results of the best model in relation to landslide susceptibility in Eastern and Western Norway and Trøndelag.

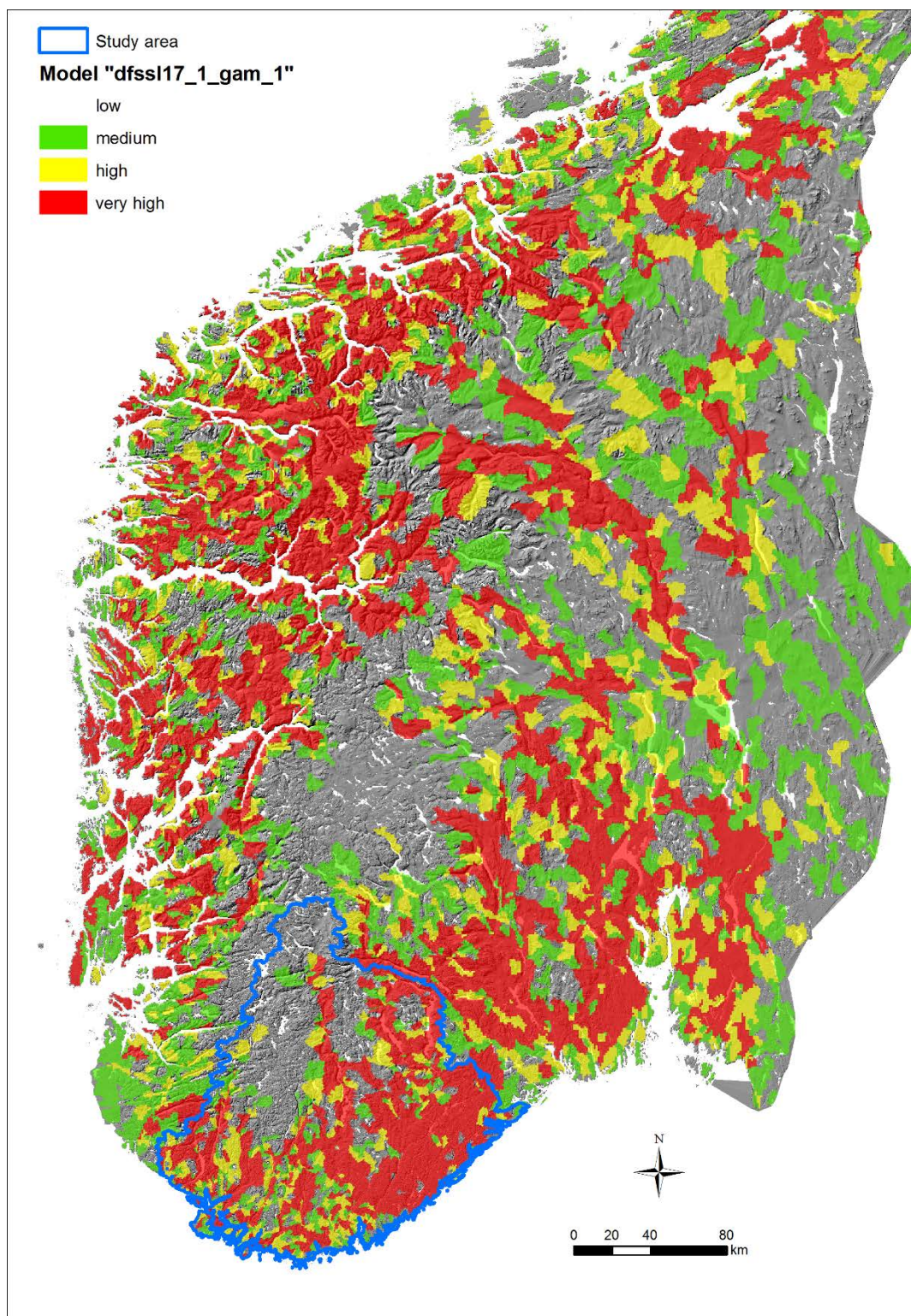


Figure 9 Landslide susceptibility in Agder, Model "dfssl17_1_gam_1" and landslide susceptibility for Eastern and Western Norway and Trøndelag.

5 Discussion

All models using 100% of REGINE units with landslides in the regression show very high AUROC values. Even within the k-fold cross validation step, the AUROC values remain high. This indicates that in all models the discrimination between the REGINE units with landslides and the REGINE units without landslides is good. There are only small differences in the AUROC values between the models. As found in the previous evaluations in Northern, Eastern and Western Norway and Trøndelag (Bell & Cepeda 2015, Bell & Cepeda 2014, Bell et al. 2014), the approach of modelling in REGINE units works very well especially given the unknown uncertainty of the spatial location of the landslide initiation areas. When modelling at REGINE unit level, it does not matter that most of the points are located where consequences were registered. It is sufficient that the registered landslide point and the actual initiation area are located within the same REGINE unit. In one case, the landslide point was located outside of the REGINE units, which could not be assigned to a specific REGINE unit. Thus, it was deleted.

The differences in the statistical performance are rather small. Even the resulting landslide susceptibility maps show a similar pattern with only minor changes. All models using 100% of REGINE units with landslides selected mainly topographic explanatory variables. The Quaternary map shows that 53 % of the study area is covered by bare rock, followed by 41 % of moraine material. Since for all categorical data the proportion of each class in the catchment was calculated and used as a variable during the regression of the model, it seems that there is not enough variation of Quaternary map layers across the REGINE units to explain the landslide distribution. An exception are the marine and fjord deposits. They cover less than 1% of the study area but are selected by all models using 100% of REGINE units with landslides.

Analysing the statistical validation criteria as well as the final landslide susceptibility maps (Fig. 6-8), we recommend to use model “dfssl17_1_gam_1” (Fig. 6). Although the differences are small, this model shows a slightly higher AUROC value and a slightly lower AIC value than the other models.

The final landslide susceptibility map can only be as good as the input data. Based on the available data, the resulting landslide susceptibility maps are of very good quality. The most important question is whether the landslide inventory is in general representative for all Agder. Fig. 10 shows that most of the 273 landslides are located along roads since most of the records are registered by the road and railway authorities. The maps also show large areas of low and moderate landslide susceptibility where no roads exist. Thus, the question is, whether landslides have actually occurred or not in these areas, the former situation likely due to the lack of registers associated with few exposed elements. So, the main limitation of the final landslide susceptibility map arises from the incompleteness of the landslide inventory. If landslides have occurred but were not registered, the final landslide susceptibility map might look different if unrecorded landslides were eventually used to re-evaluate the model. This should be a bigger issue

for areas of low and moderate susceptibility. In the other two susceptibility classes, information on high and very high susceptibility is statistically transferred from REGINE units with landslides to similar units for which so far no landslides have been recorded. However, some uncertainty also remains there.

Future efforts should focus on improving the landslide inventory. It might be worth trying to focus on selected areas of low and moderate susceptibility and check the completeness of the landslide inventory using remote sensing data (e.g. airborne laser scanning data, satellite images and aerial photographs). When a significantly improved landslide inventory is available, an updating of the modelling of landslide susceptibility should improve the predictive performance of the maps when used as part of a warning system.

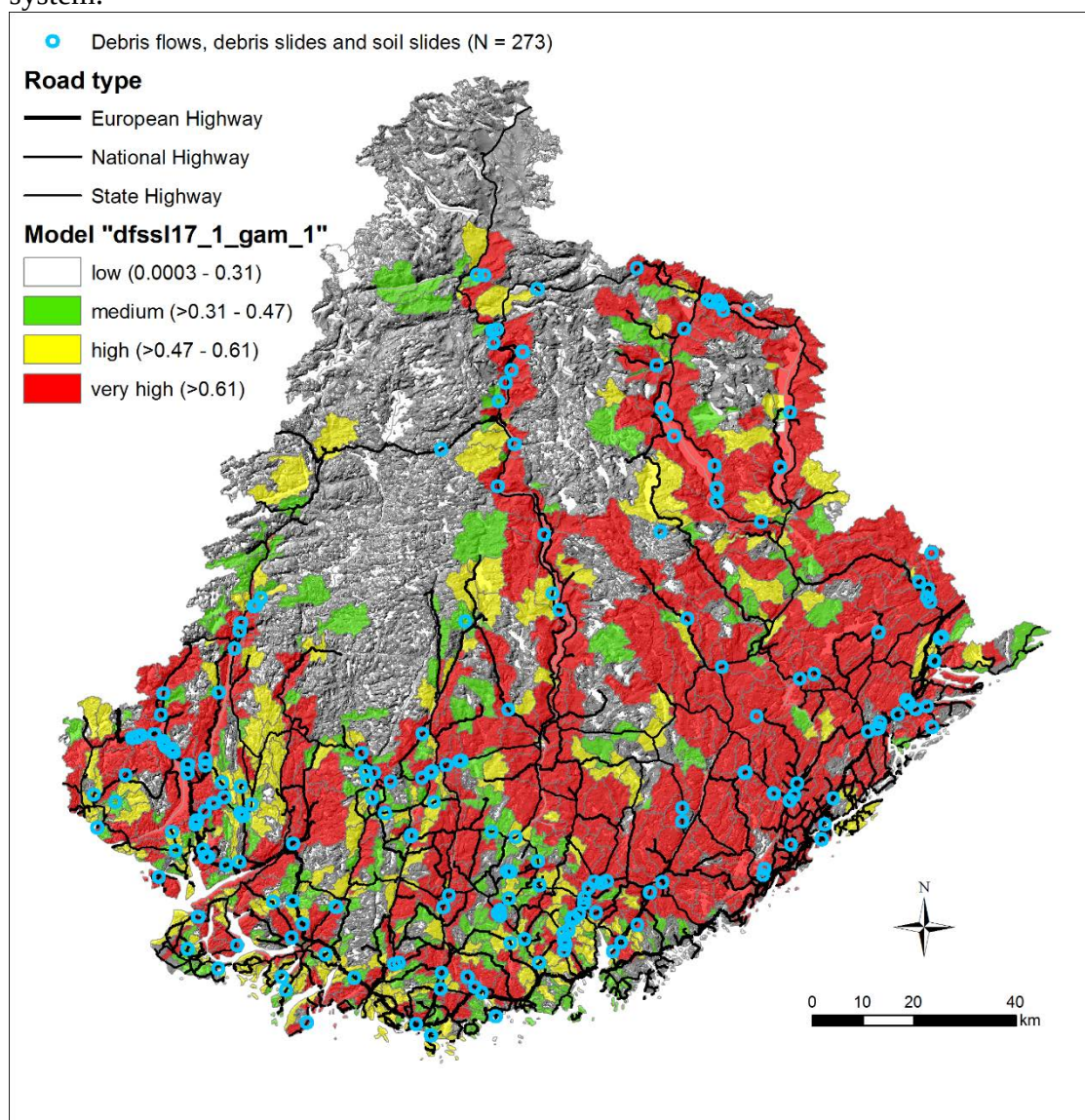


Figure 10 Landslides, landslide susceptibility and highways in Agder, Model "dfssl17_1_gam1".

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Appendix A

LIST OF VARIABLES

Contents

A1	List of variables
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2

A1 List of variables

No.	Code	Description
1	AREALENH	REGINE unit area (km ²)
2	TILSIGENH	REGINE unit runoff 1961-1990 (million m ³ per year)
3	AREALTOTAL	Total upstream area (km ²)
4	TILSIGTOTA	Total upstream runoff 1961-1990 (million m ³ per year)
5	AVR6190	Average runoff 1961-1990 (litre/second km ²)
6	AVR3060	Average runoff 1930-1960 (litre/second km ²)
7	SHAPE_AREA	Shape area
8	LMV0	not specified (% of REGINE unit)
9	LMV1	Soils/rocks under water, unspecified (% of REGINE unit)
10	LMV10	Moraine material, unspecified (% of REGINE unit)
11	LMV11	Moraine material, continuous, locally thick (% of REGINE unit)
12	LMV12	Moraine material, non-continuous/thin (% of REGINE unit)
13	LMV1112	LMV11 + LMV12
14	LMV13	Clay till, boulder clay, drift clay (% of REGINE unit)
15	LMV14	Ablation moraine (% of REGINE unit)
16	LMV15	Terminal moraine (% of REGINE unit)
17	LMV16	Drumlin (% of REGINE unit)
18	LMV20	Glaciofluvial deposit (% of REGINE unit)
19	LMV21	Glaciofluvial and fluvial deposit (% of REGINE unit)
20	LMV22	Saddle-shaped glaciofluvial deposit (% of REGINE unit)
21	LMV30	Glaciolacustrine deposit (% of REGINE unit)
22	LMV31	Glaciolacustrine and glaciofluvial deposit (% of REGINE unit)
23	LMV35	Lacustrine deposit (% of REGINE unit)
24	LMV40	Marine and fjord deposits, unspecified (% of REGINE unit)
25	LMV41	Marine and fjord deposits, continuous, locally thick (% of REGINE unit)
26	LMV42	Marine and fjord deposits, continuous (% of REGINE unit)
27	LMV43	Marine and fjord deposits, non-continuous/thin (% of REGINE unit)
28	LMV4143	LMV41 + LMV43
29	LMV414243	LMV41 + LMV42 + LMV43
30	LMV50	River and stream deposits, unspecified (% of REGINE unit)
31	LMV54	Floodplain deposits, continuous (% of REGINE unit)
32	LMV55	Floodplain deposits, non-continuous/thin (% of REGINE unit)
33	LMV60	Eolian deposits (% of REGINE unit)
34	LMV70	Weathered material, unspecified (% of REGINE unit)

35	LMV71	Weathered material, continuous, locally thick (% of REGINE unit)
36	LMV72	Weathered material, non-continuous/thin (% of REGINE unit)
37	LMV73	Block field (% of REGINE unit)
38	LMV80	Landslide material, not divided by thickness (% of REGINE unit)
39	LMV81	Landslide material, continuous, locally thick (% of REGINE unit)
40	LMV82	Landslide material, non-continuous/thin (% of REGINE unit)
41	LMV90	Peat and marshland (organic material) (% of REGINE unit)
42	LMV100	Humus blanket/thin peat blanket overlying bedrock (% of REGINE unit)
43	LMV101	Discontinuous or thin soil cover on bedrock (% of REGINE unit)
44	LMV120	Fill (anthropogenic material), unspecified (% of REGINE unit)
45	LMV130	Bare rock (% of REGINE unit)
46	LMV140	Bare rock/rock with patchy or thin cover (% of REGINE unit)
47	DEM_RANGE	Elevation range in REGINE unit
48	DEM_MEAN	Mean elevation of REGINE unit
49	DEM_MEDIAN	Median elevation of REGINE unit
50	East_MEAN	Mean of eastern coordinates of REGINE unit
51	north_MEAN	Mean of northern coordinates of REGINE unit
52	SL_MEAN	Mean slope of REGINE unit
53	SL_STD	Standard deviation of slope of REGINE unit
54	SL_MEDIAN	Median slope of REGINE unit
55	RF_MEAN	Mean of average yearly rainfall 1961-1990 in REGINE unit
56	RF_SUMrm	Sum of average yearly rainfall 1961-1990 in REGINE unit
57	C1ap	Artificial surfaces (% of REGINE unit)
58	C211ap	Arable land, not irrigated (% of REGINE unit)
59	C231ap	Pastures (% of REGINE unit)
60	C245ap	Heterogeneous agricultural areas, mainly farmland and natural vegetation (% of REGINE unit)
61	C322ap	Moors and heath land (% of REGINE unit)
62	C324ap	Transitional woodland-shrub (% of REGINE unit)
63	C339ap	Open space with little or no vegetation (% of REGINE unit)
64	C4ap	Inland marshes, peat bogs and intertidal flats (% of REGINE unit)
65	c316ap	Forests (% of REGINE unit)

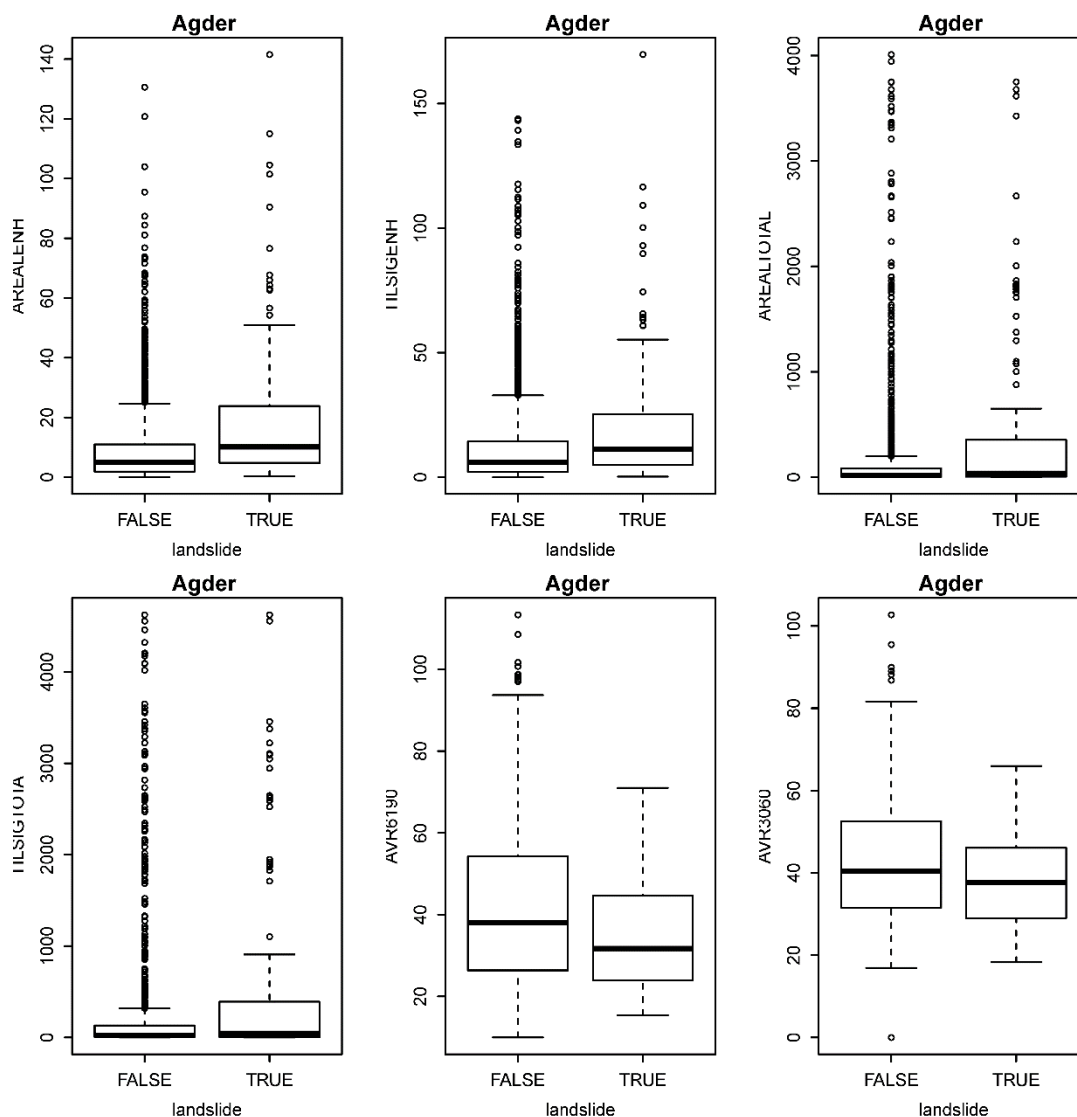
Appendix B

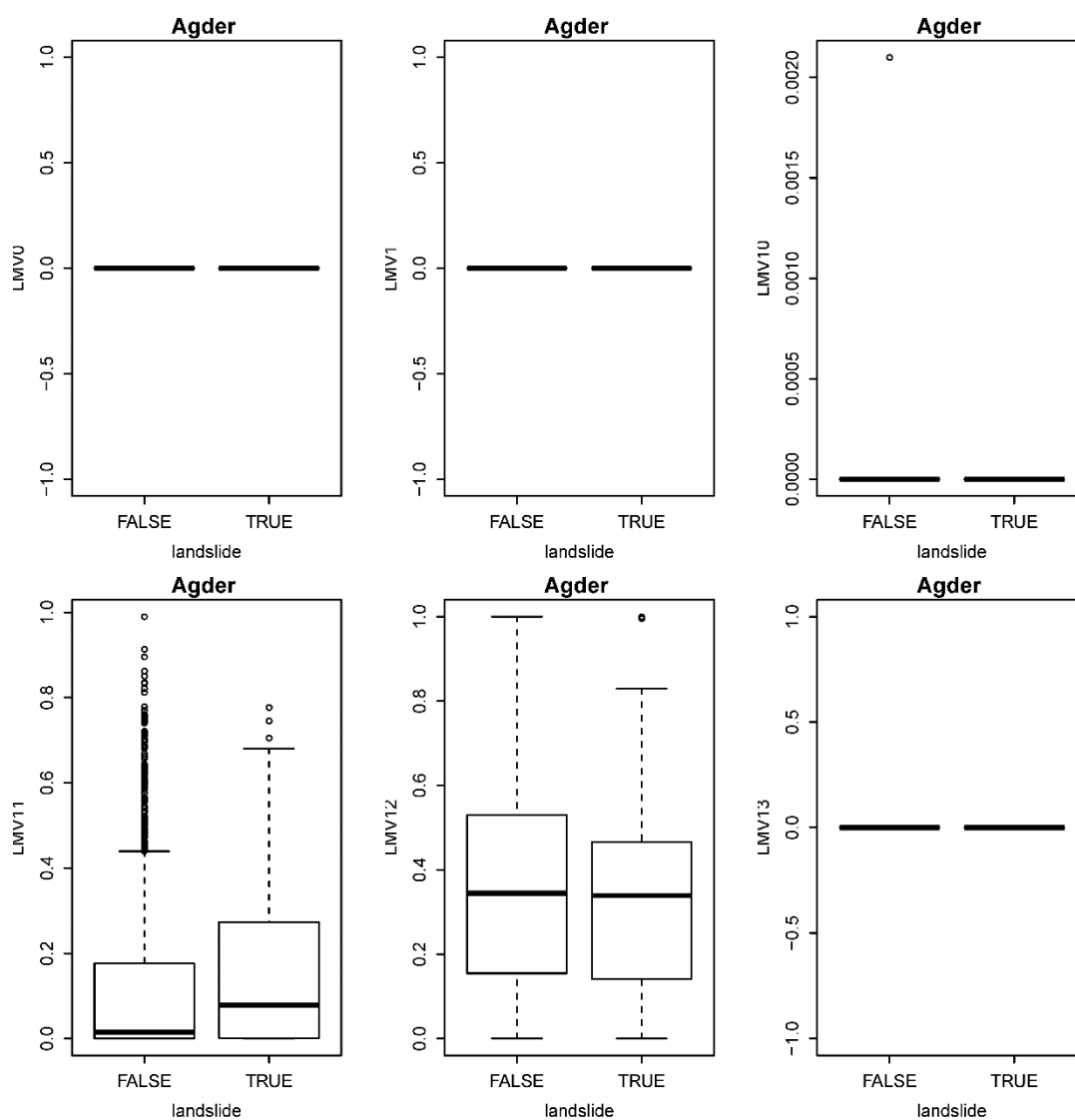
BOXPLOTS OF VARIABLES

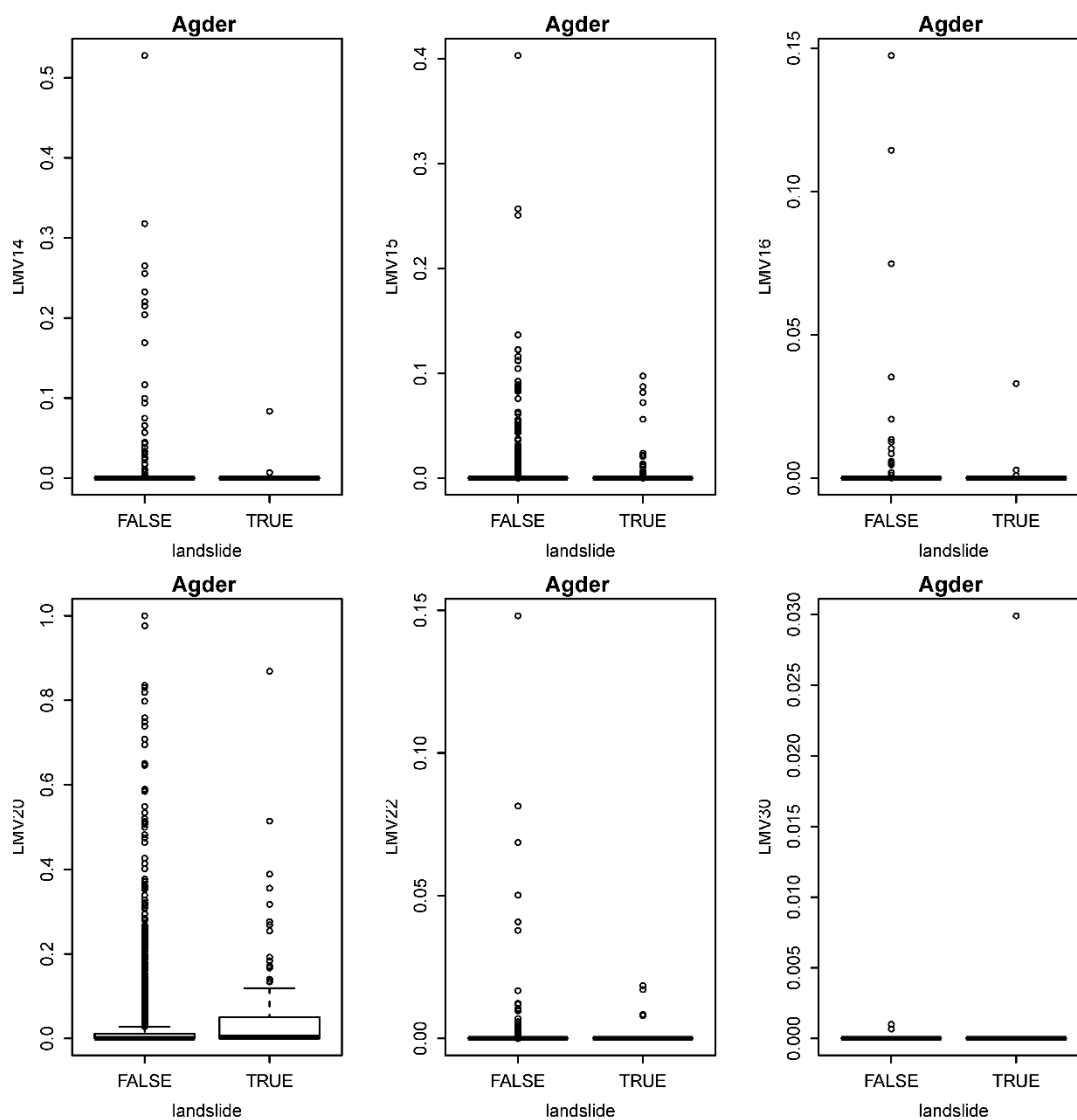
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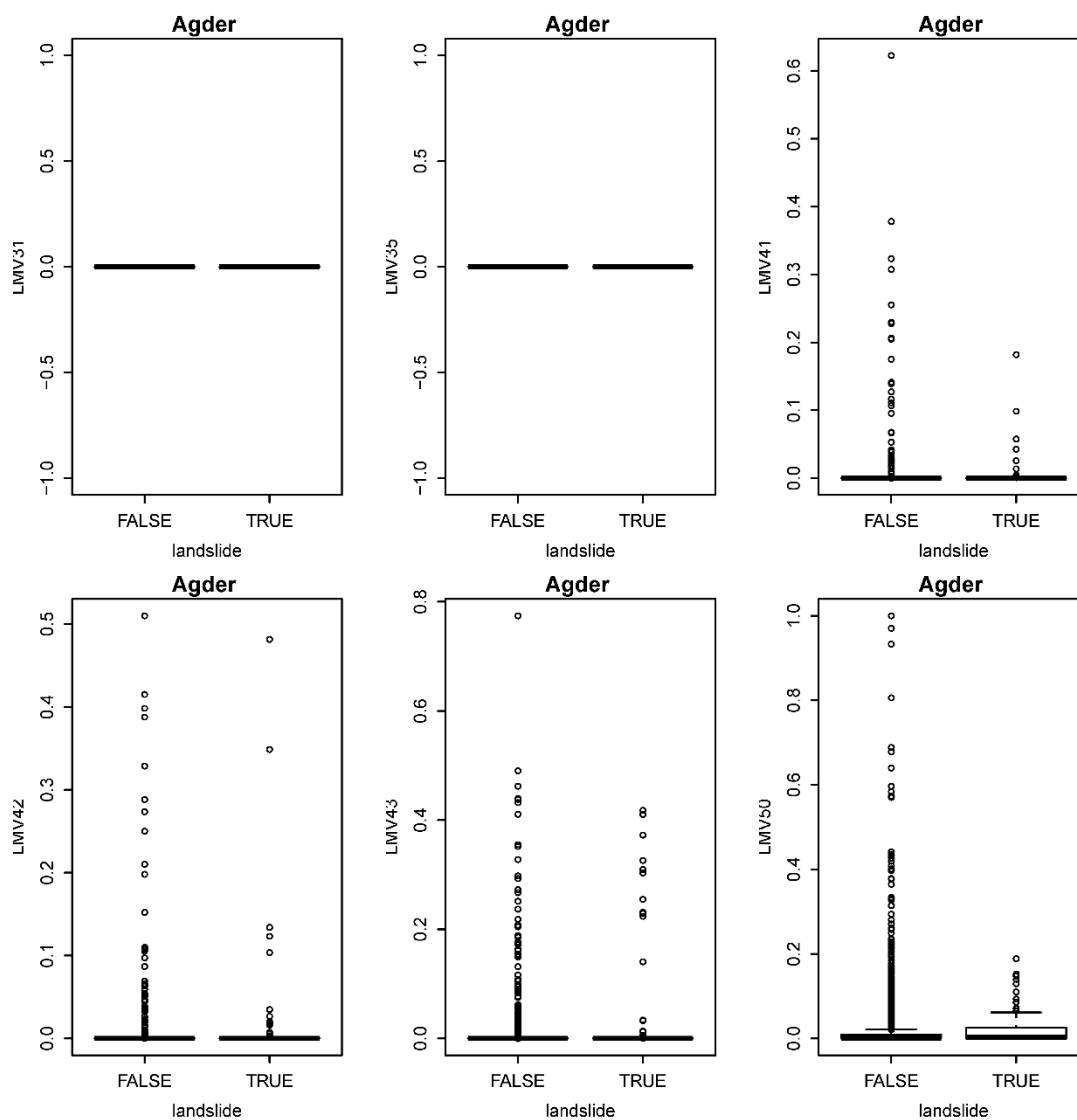
B1	Boxplots of variables in REGINE units with and without landslides	2
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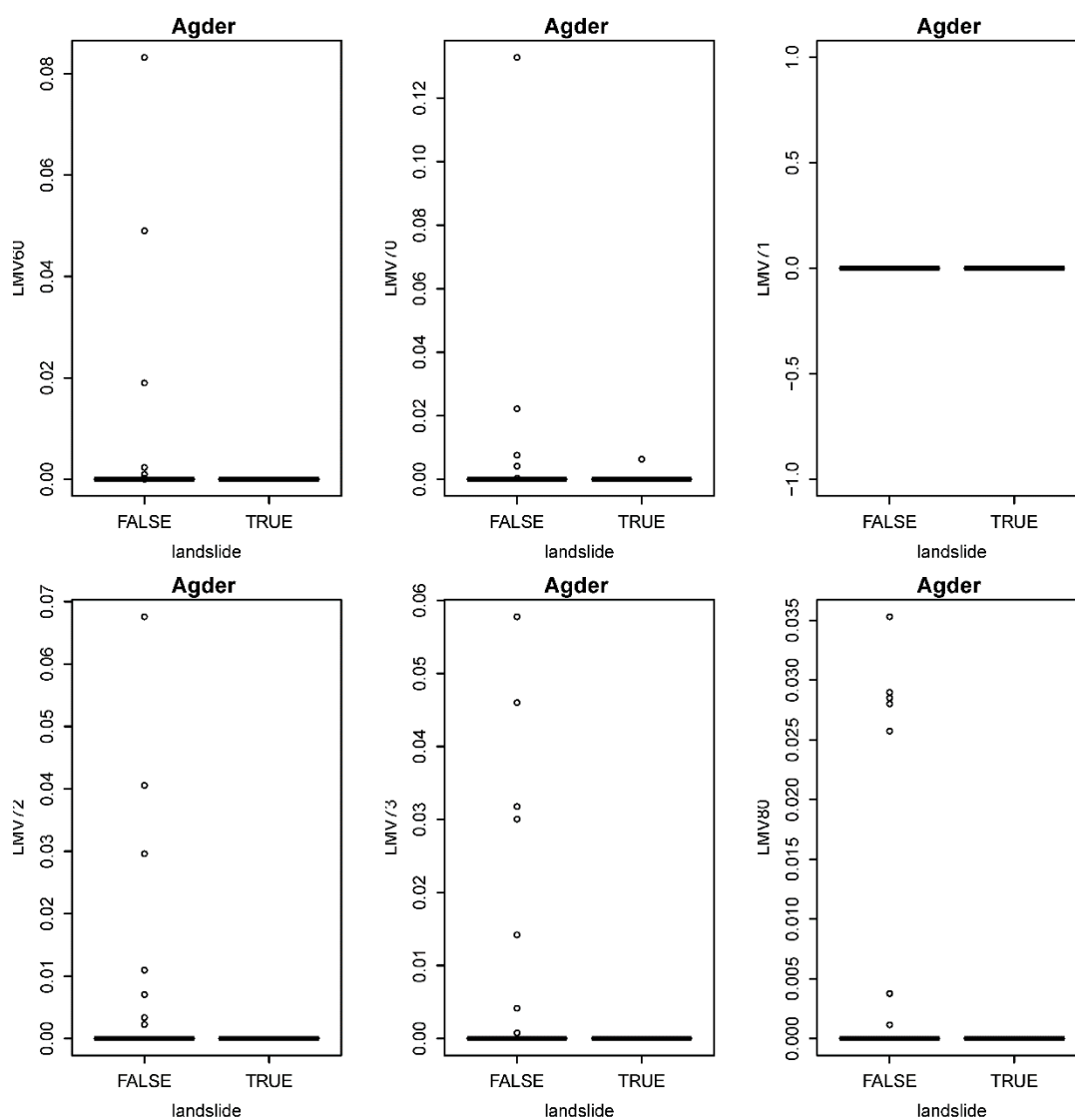
B1 Boxplots of variables in REGINE units with and without landslides

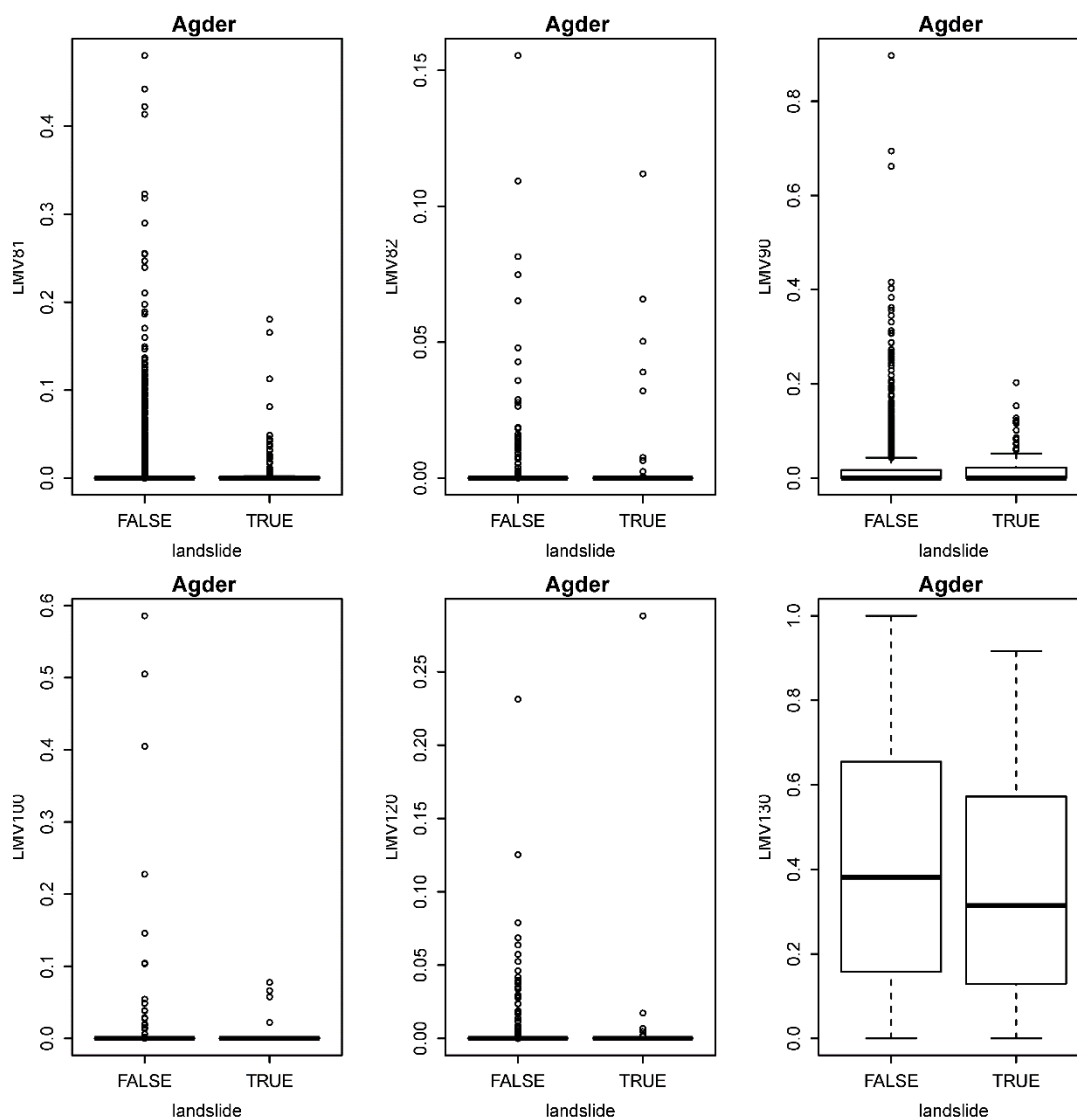


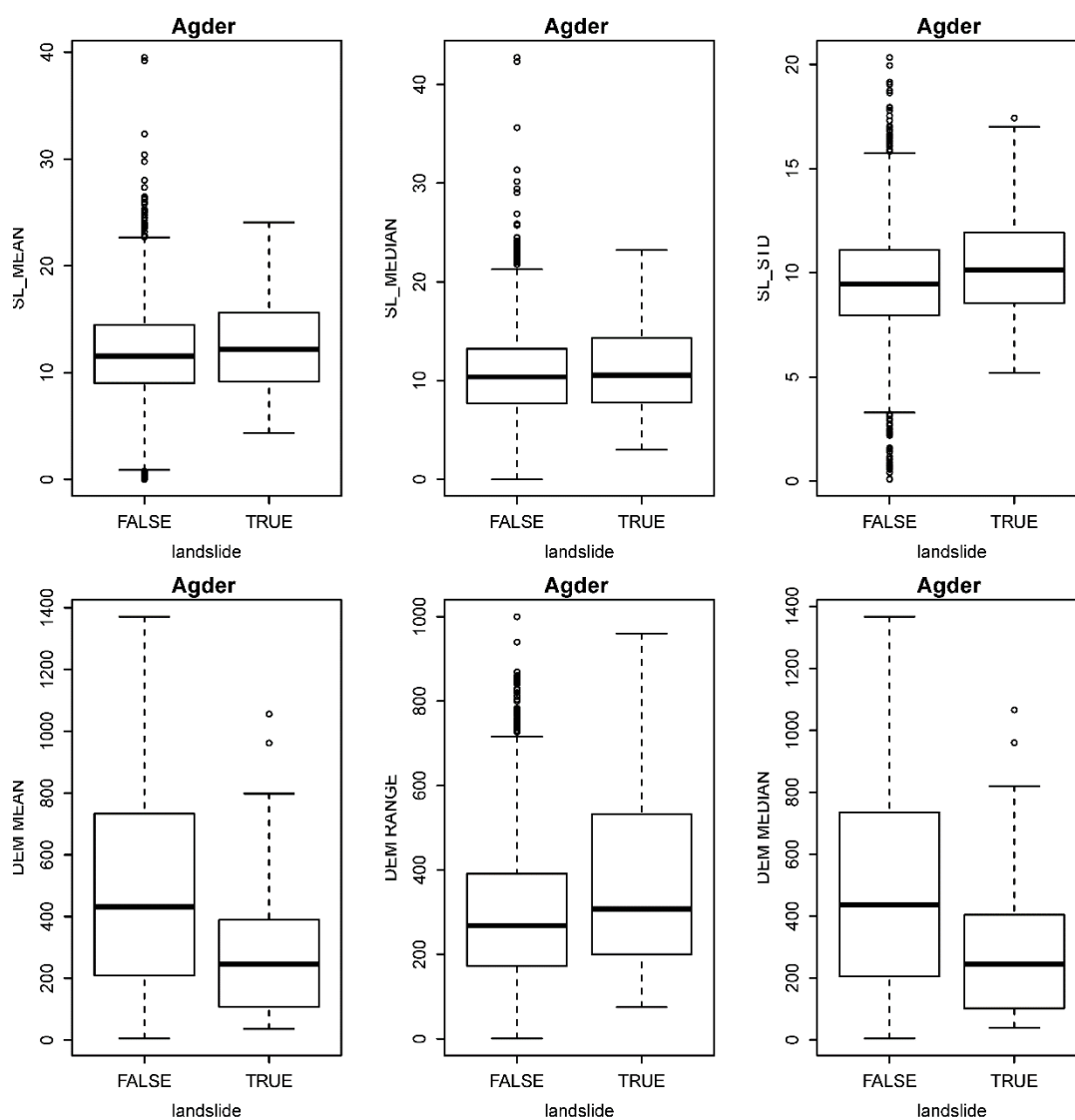


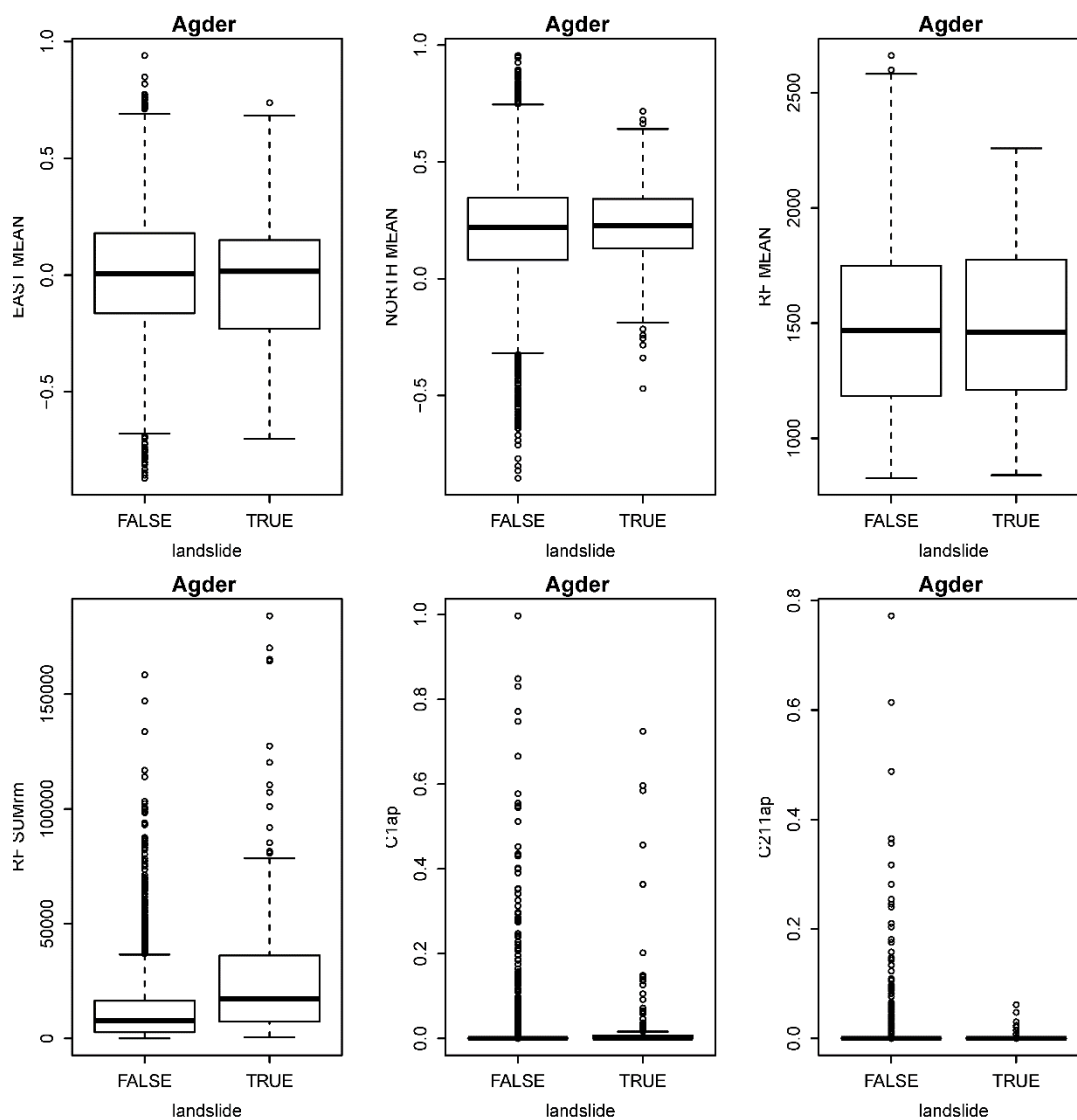


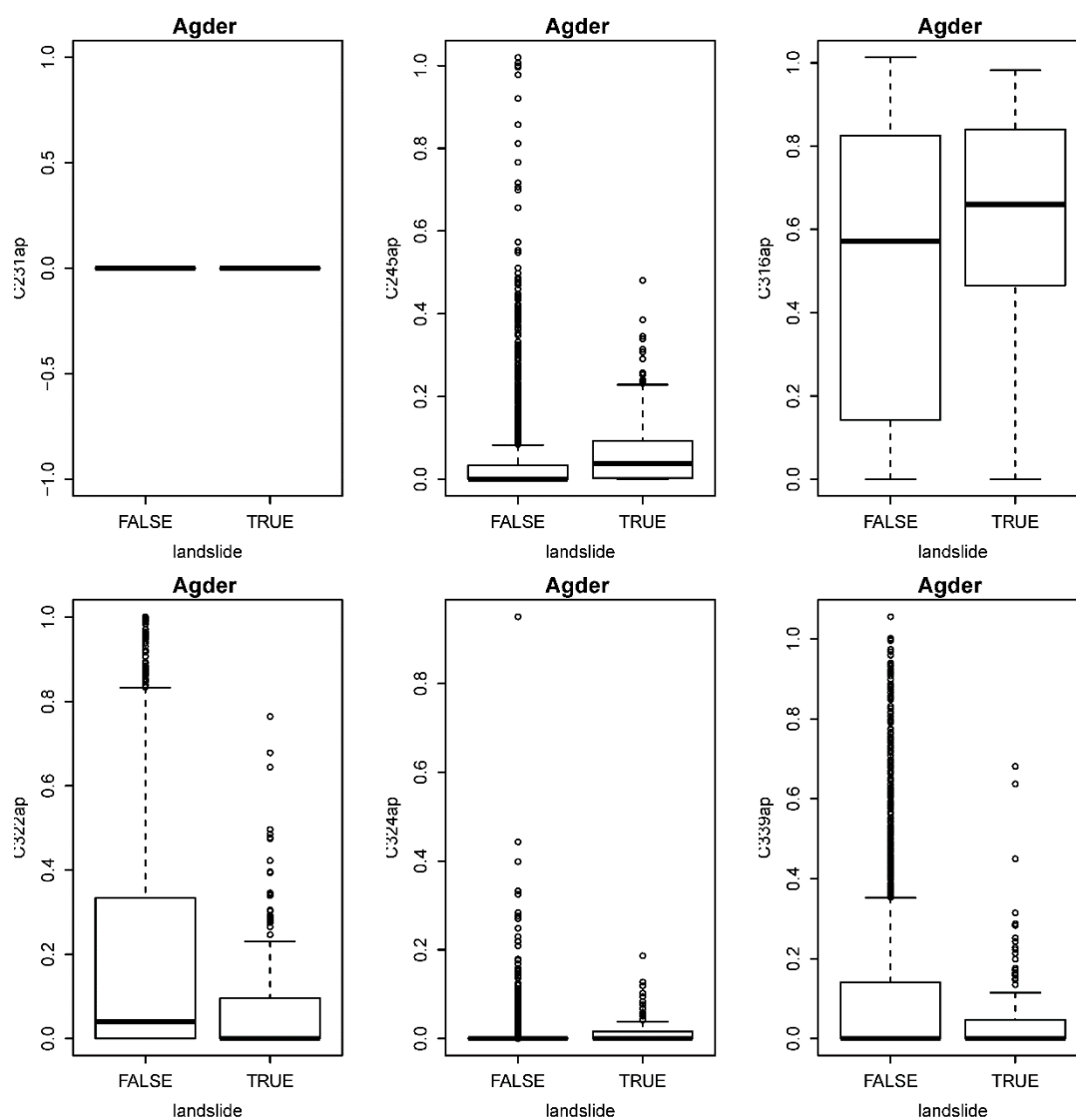


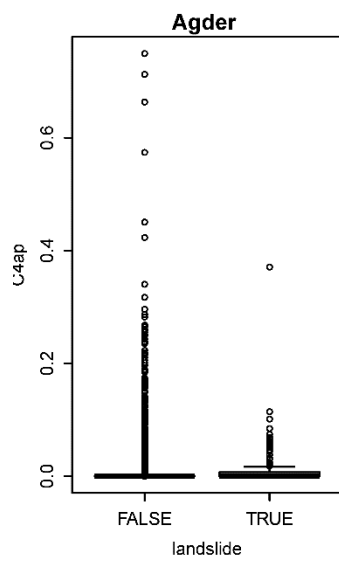












Appendix C

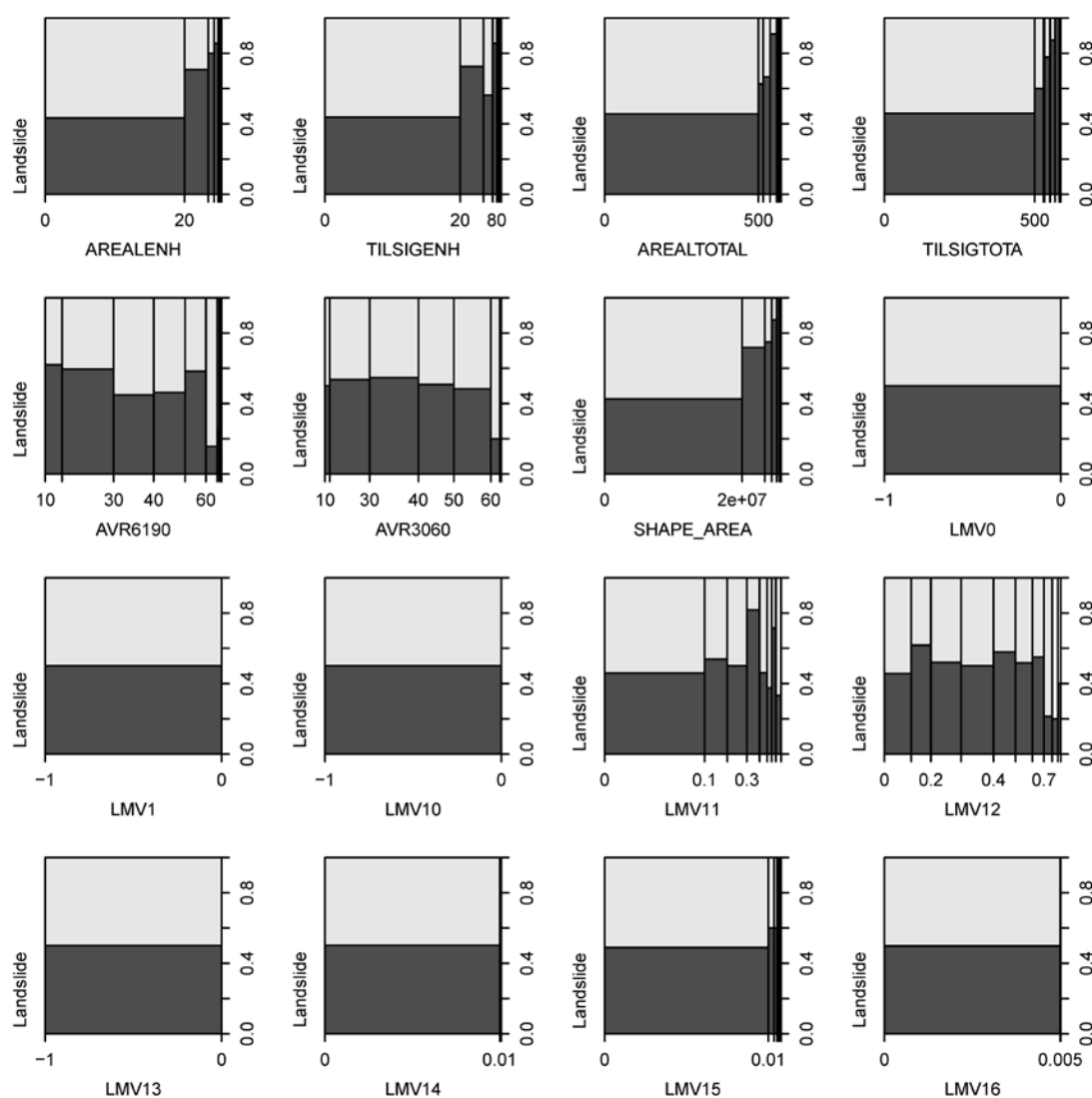
SPINEPLOTS OF VARIABLES

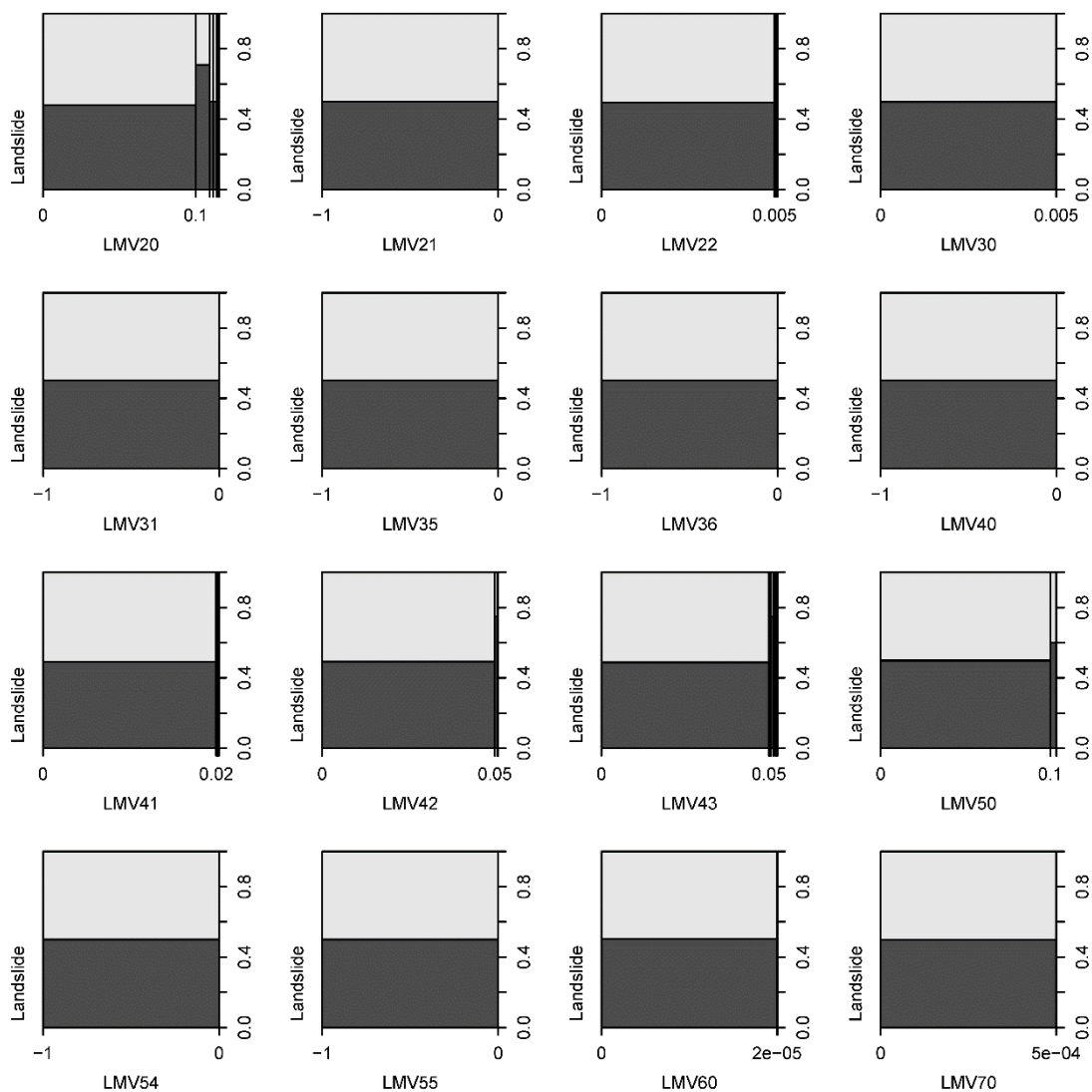
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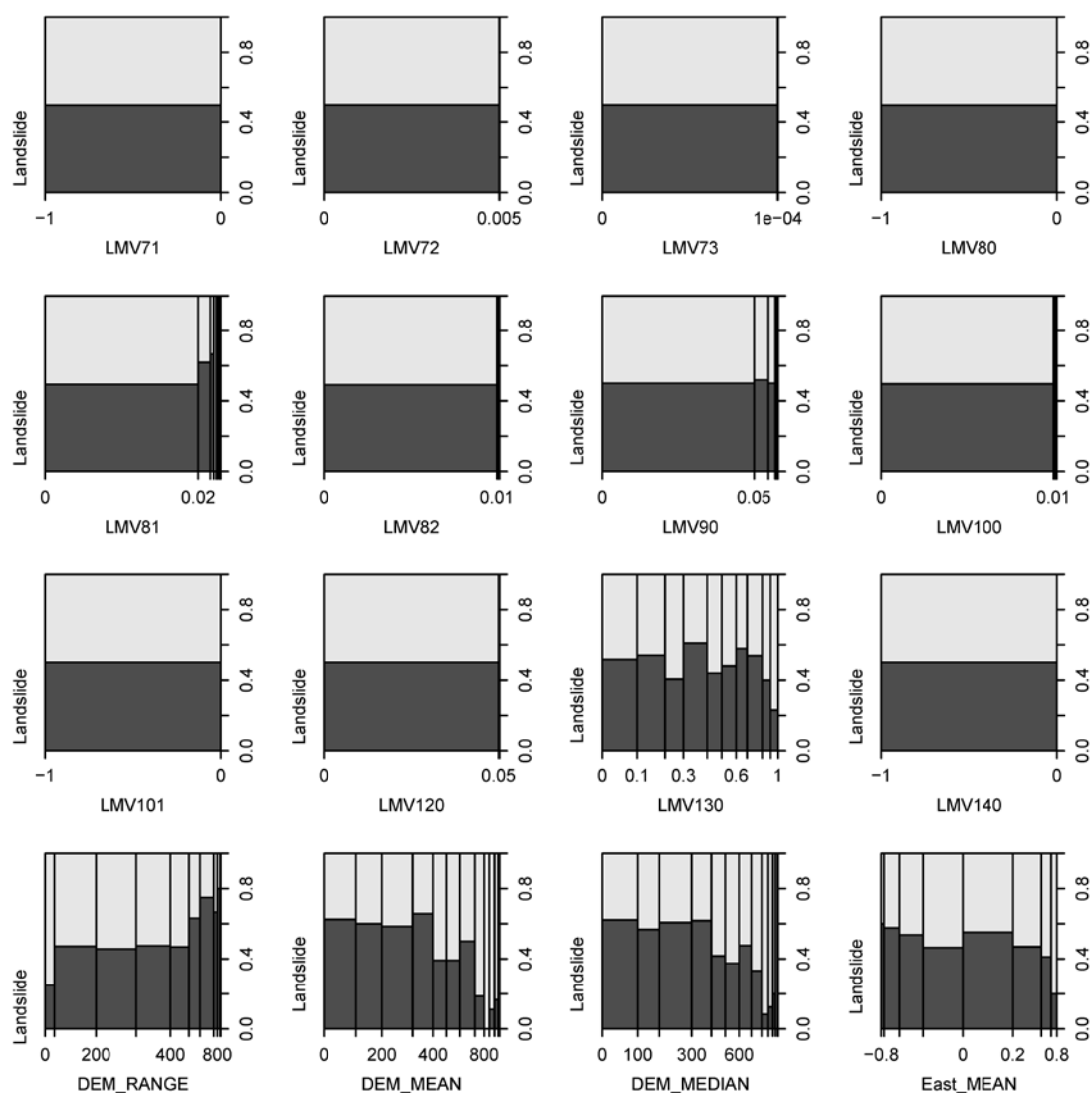
C1	Spineplots of variables	2
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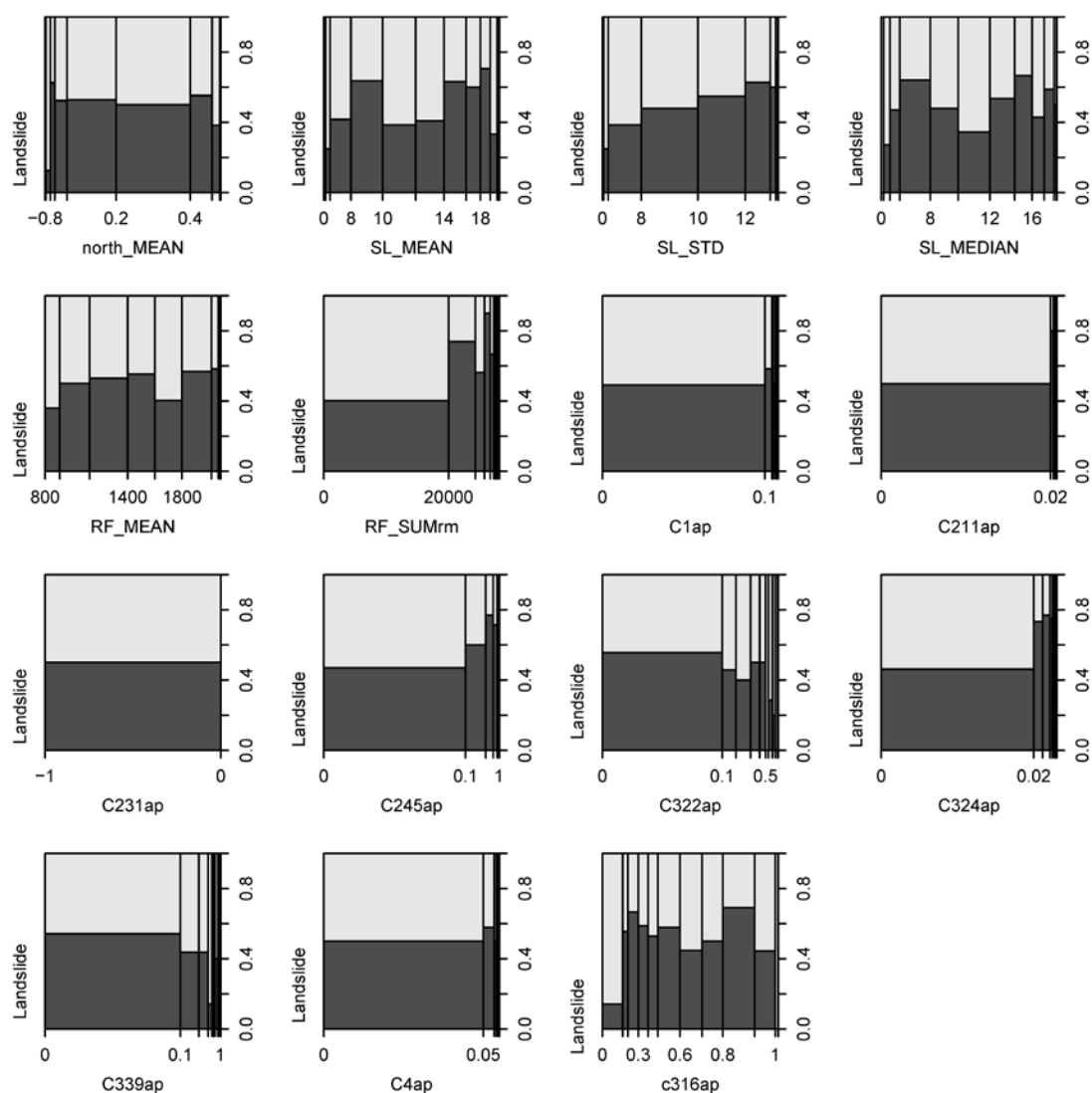
C1 Spineplots of variables

The spineplots shown here are simultaneously plotting the empirical frequency of landslide occurrence conditional on a predictor variable and the empirical frequency of that variable. Bar widths in the spineplots are proportional to the empirical frequency of the given interval of predictor values.









Appendix D

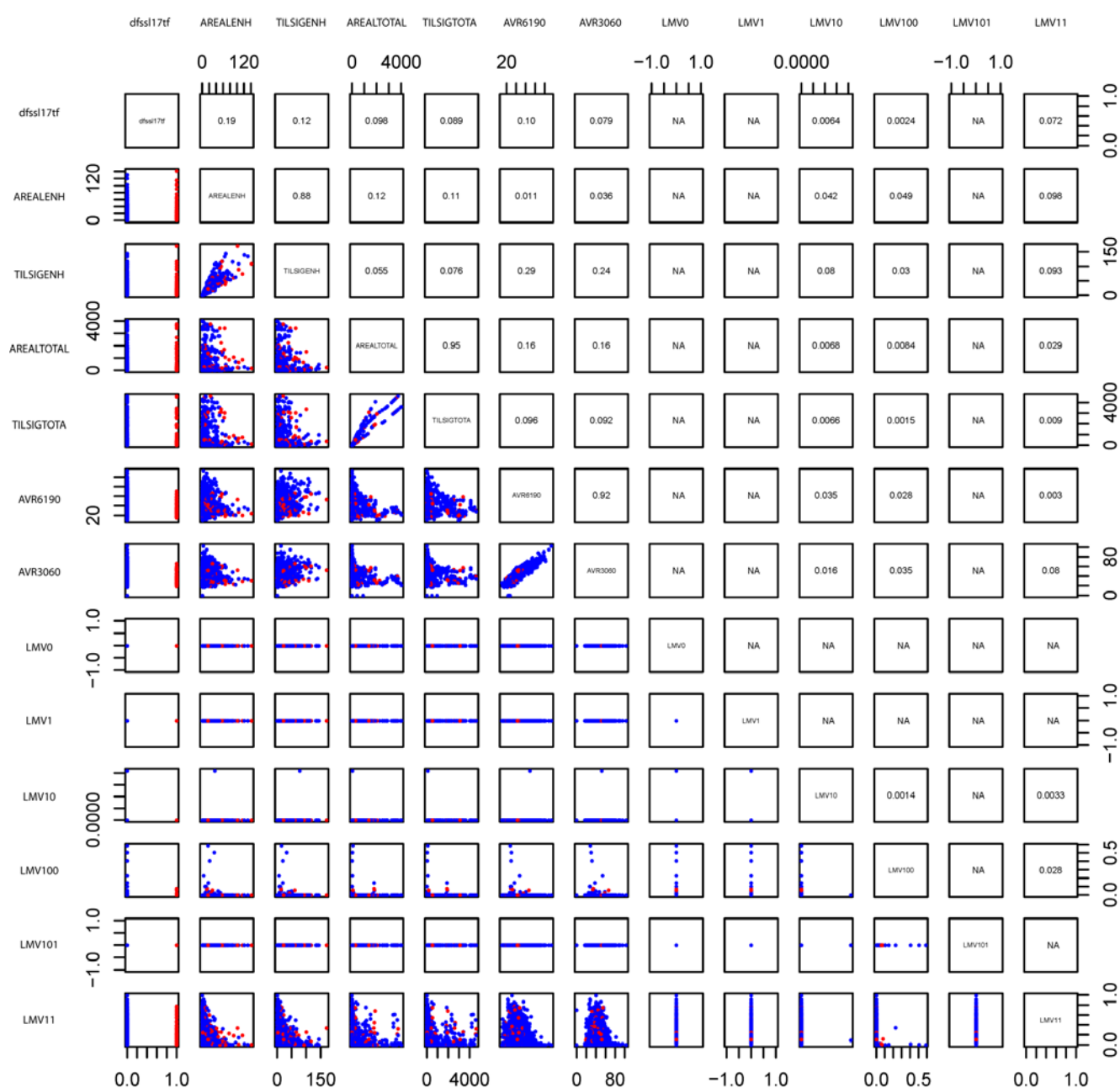
CORRELATION MATRICES OF VARIABLES

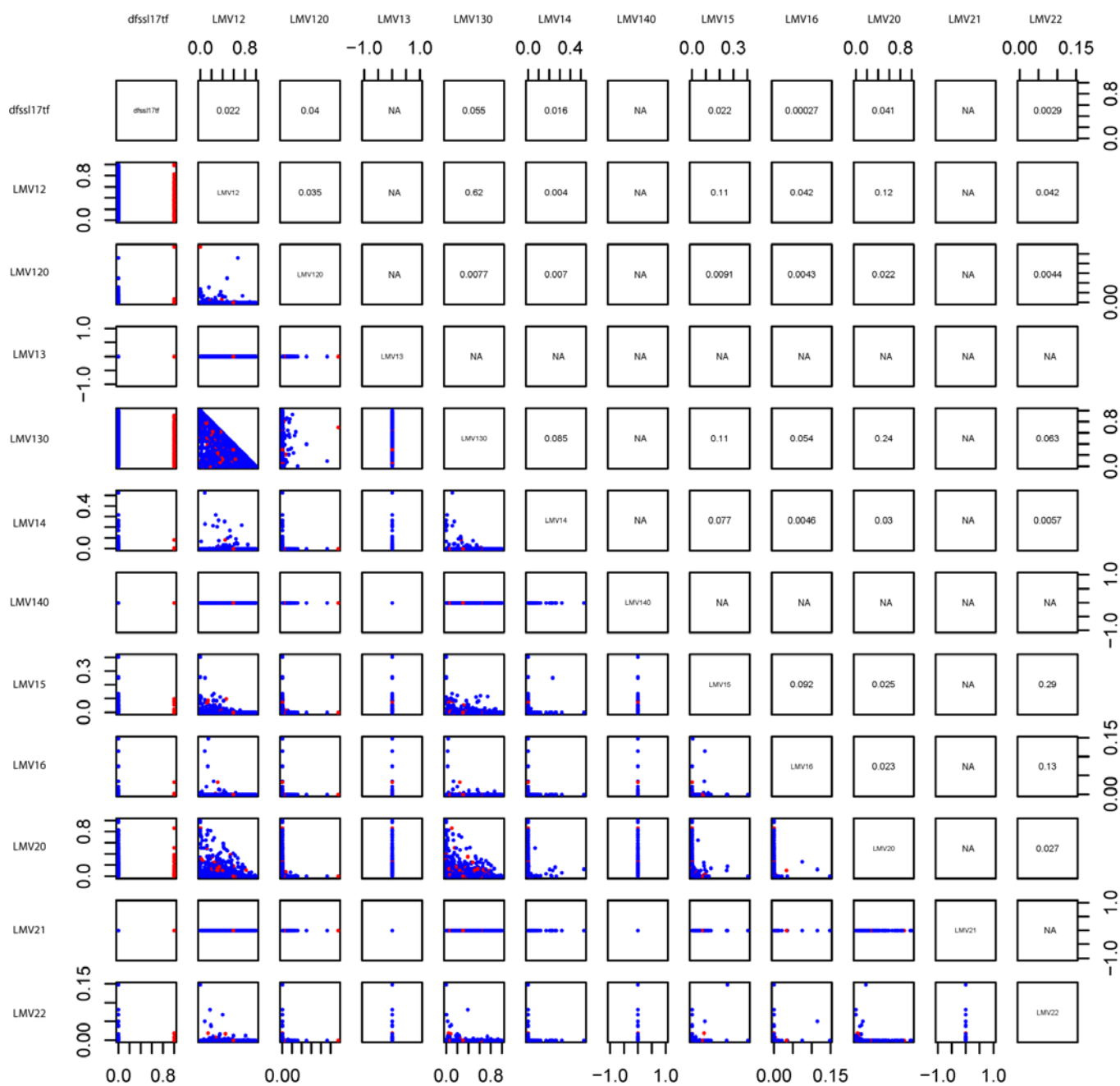
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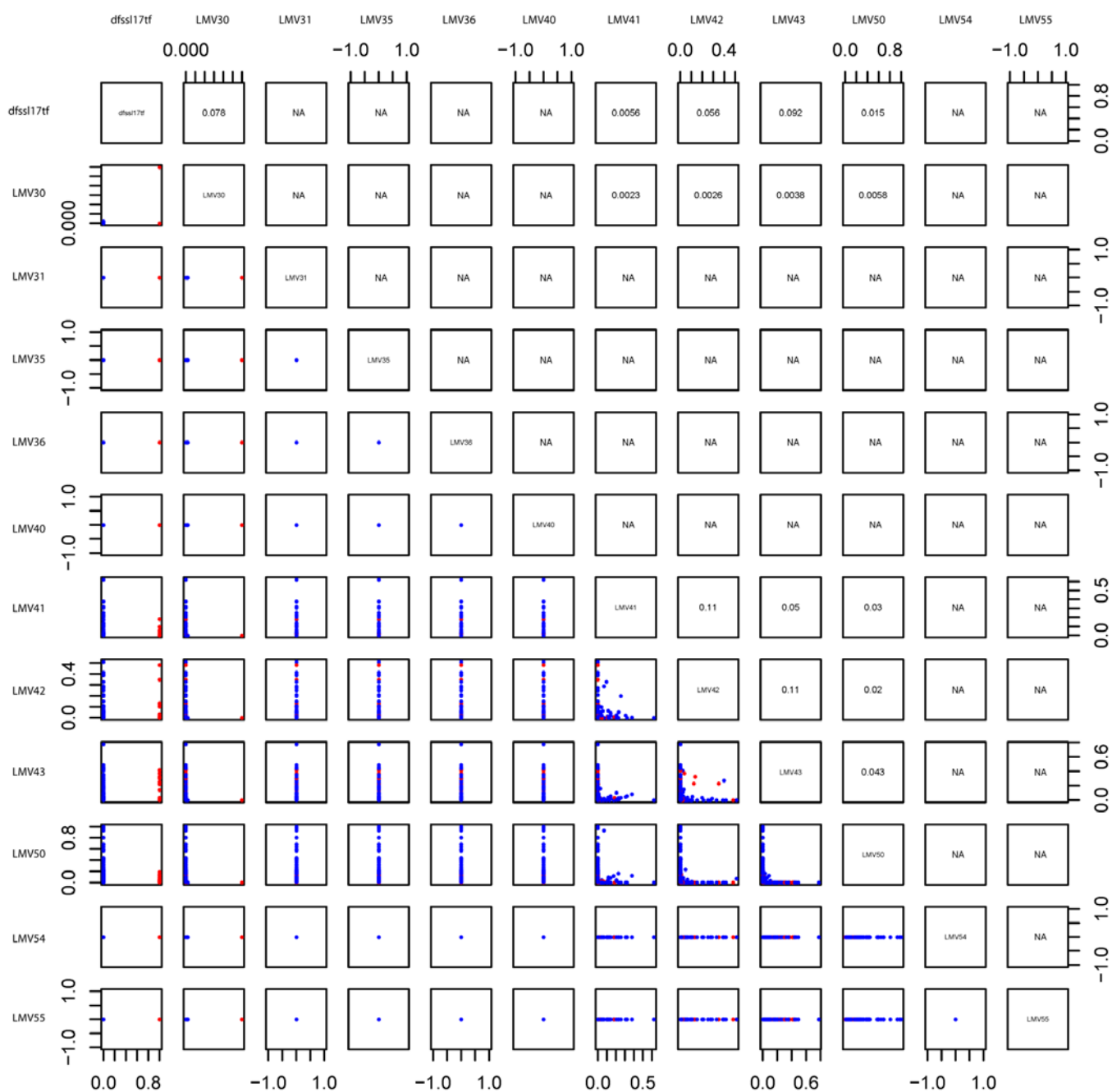
D1	Correlation matrices of variables	2
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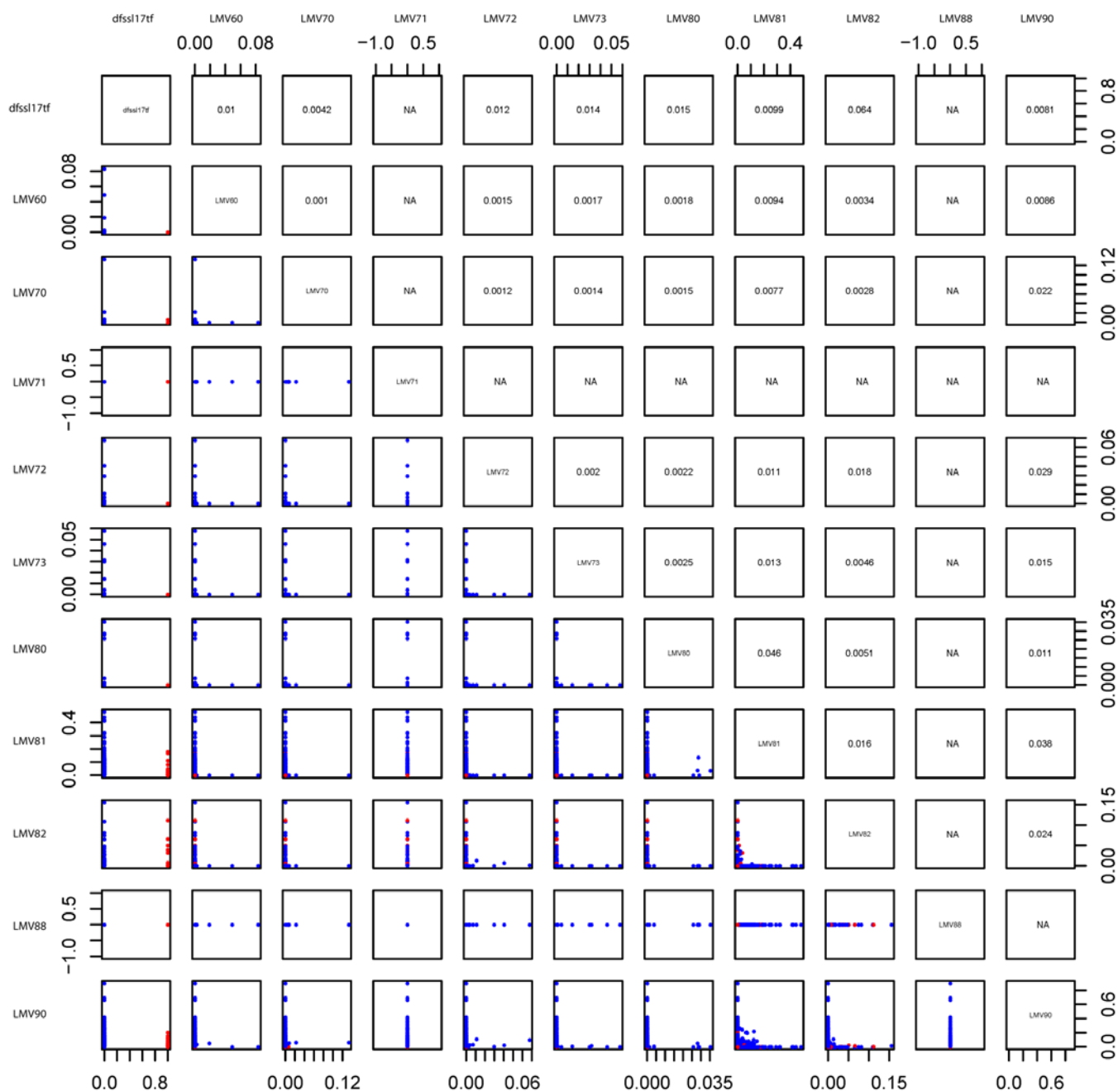
D1 Correlation matrices of variables

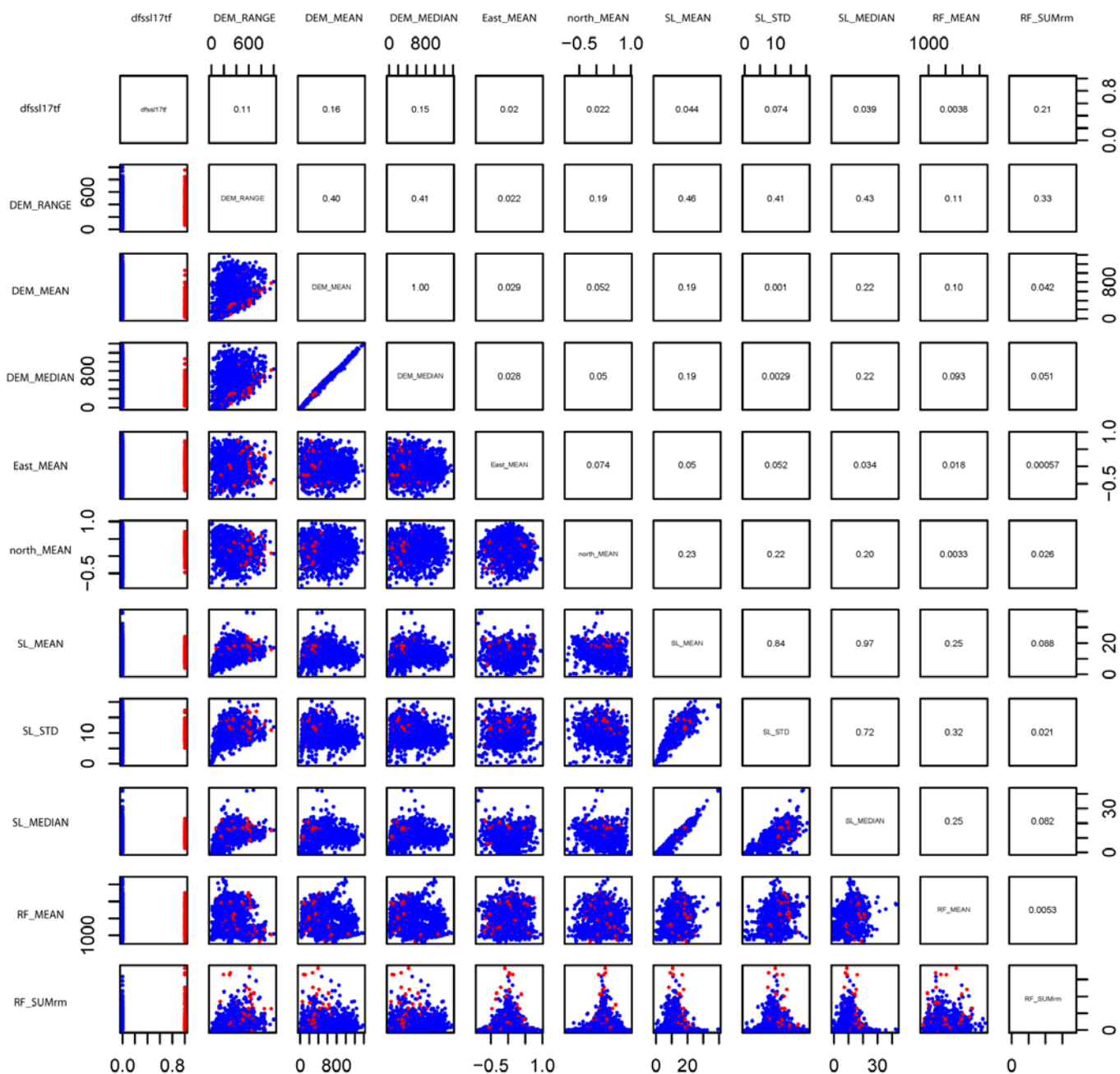
The axes labels are given in the diagonal cells in the middle from upper left to lower right. The cells in the lower left part of the matrices are showing the distribution of landslide (red) and non-landslide (blue) points for each pair of variables. The cells in the upper right part of the matrices show the correlation coefficients between each pair of variables.

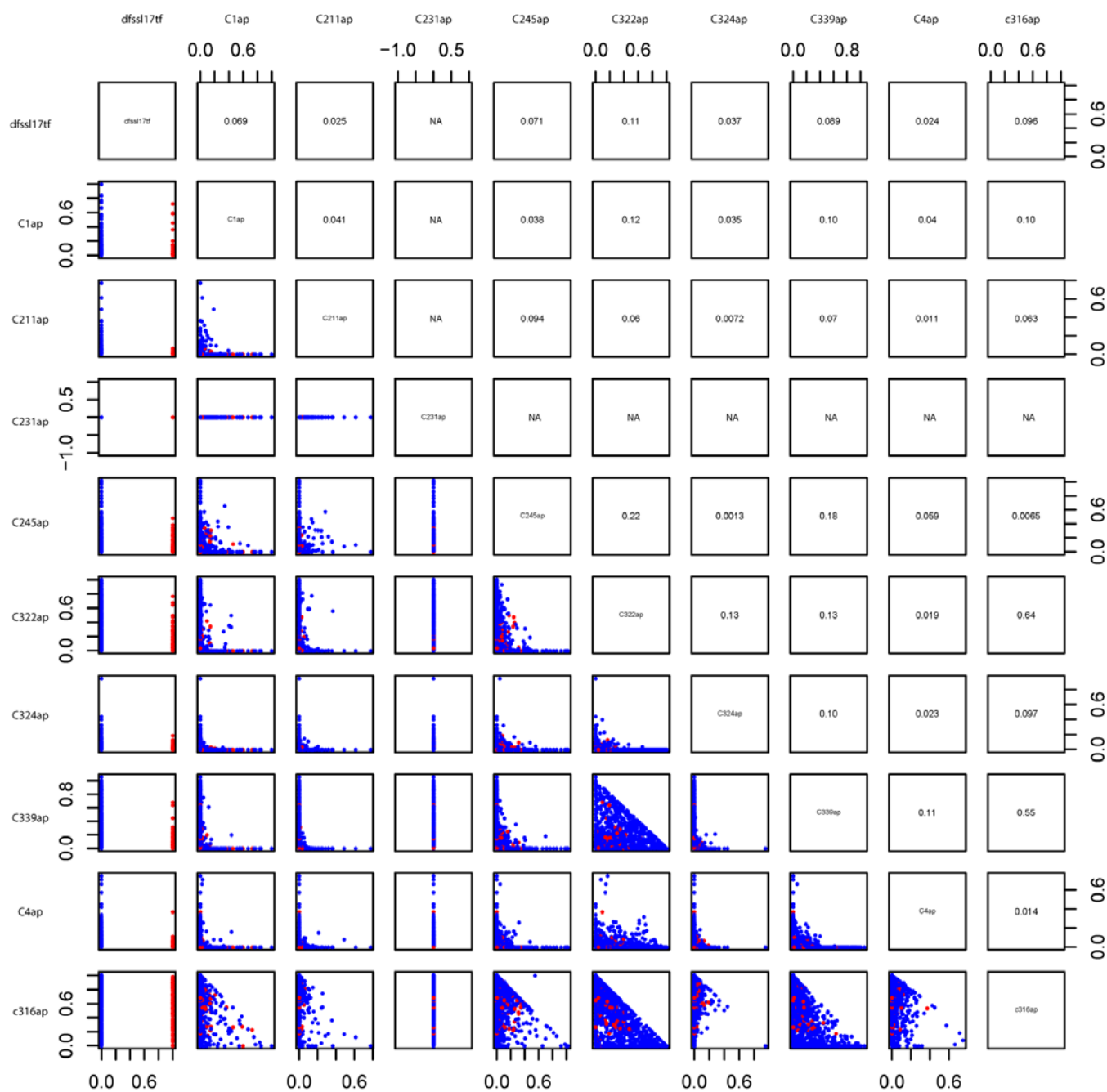












Appendix E

TRANSFORMATION PLOTS OF PREDICTOR VARIABLES

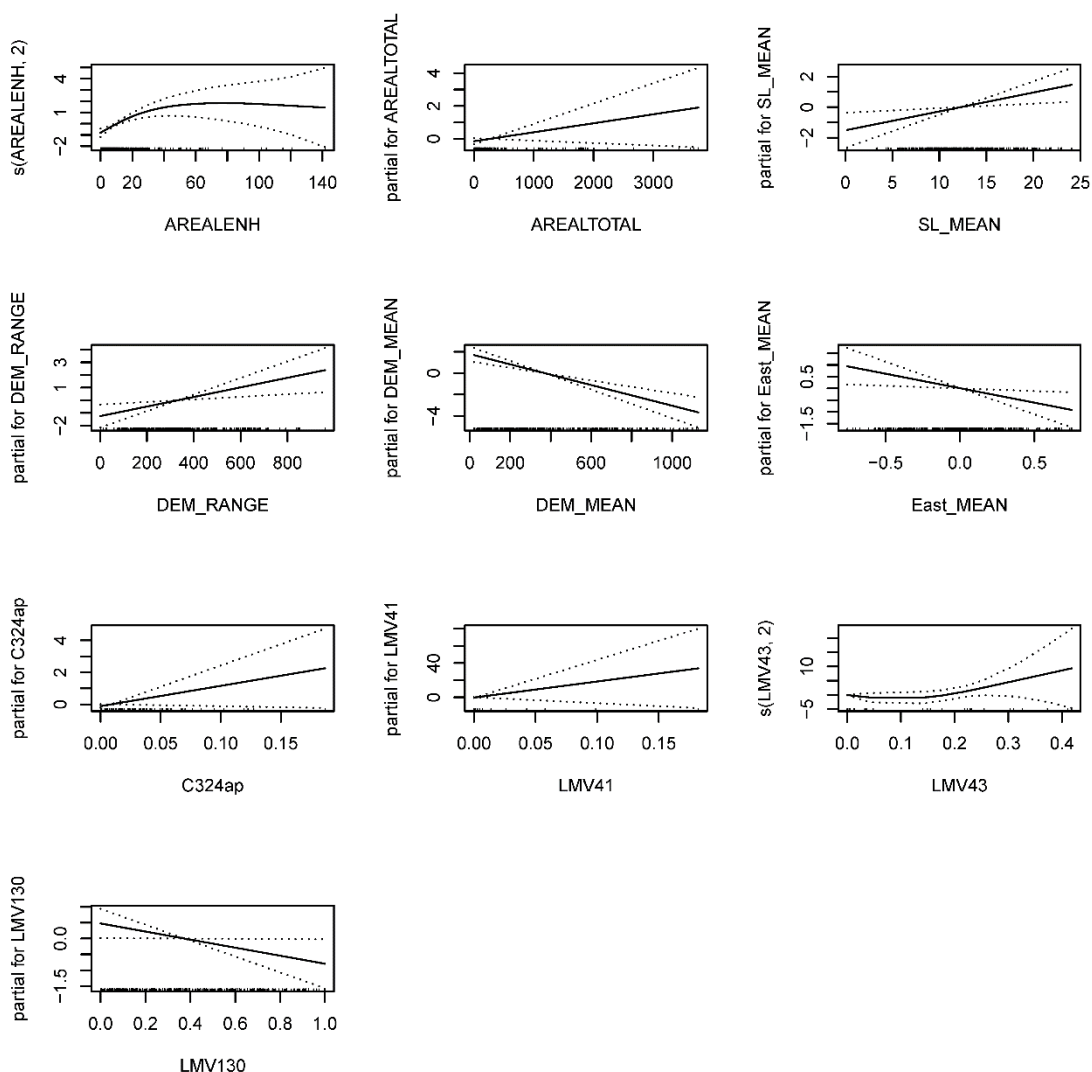
Contents

E1	Transformation plots of predictor variables	2
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E1 Transformation plots of predictor variables

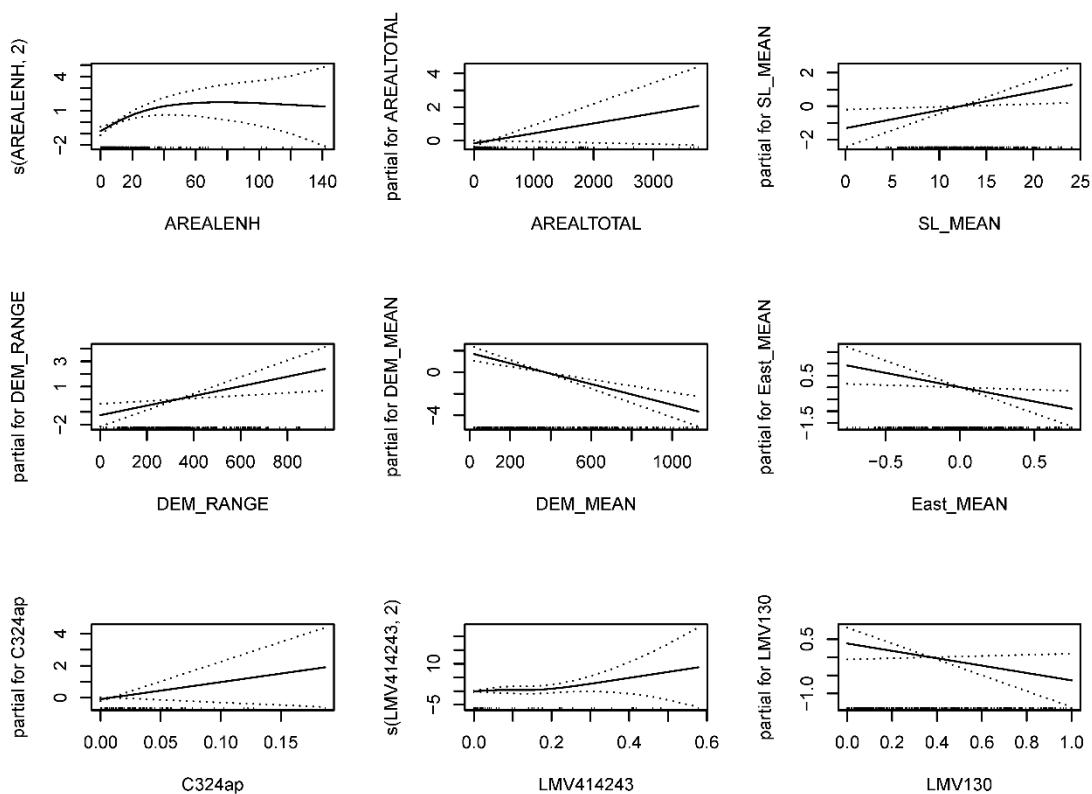
Transformation of predictor variables in the Generalized Additive Model “dssl17_1_gam_1”. A spline function for non-parametric smoothing of the variable, $s(\text{variable})$, indicates a nonlinear transformation. The dotted lines represent confidence bands.

Model “dssl17_1_gam_1”



Transformation of predictor variables in the Generalized Additive Model “dssl17_1_gam_2”. A spline function for non-parametric smoothing of the variable, $s(\text{variable})$, indicates a nonlinear transformation. The dotted lines represent confidence bands.

Model “dssl17_1_gam_2”



Dokumentinformasjon/Document information		
Dokumenttittel/Document title Susceptibility map for debris flows, debris slides and soil slides in Trøndelag		Dokumentnr./Document no. 20150747-01-TN
Dokumenttype/Type of document Teknisk notat / Technical note	Oppdragsgiver/Client NVE	Dato/Date 2017-12-22
Rettigheter til dokumentet iht kontrakt/ Proprietary rights to the document according to contract NGI		Rev.nr.&dato/Rev.no.&date 0 /
Distribusjon/Distribution BEGRENSET: Distribueres til oppdragsgiver og er tilgjengelig for NGIs ansatte / LIMITED: Distributed to client and available for NGI employees		
Emneord/Keywords Landslide susceptibility, precipitation-induced landslides, debris flows, debris slides, soil slides		

Stedfesting/Geographical information	
Land, fylke/Country Norge, Nord Trøndelag og Sør Trøndelag	Havområde/Offshore area
Kommune/Municipality	Feltnavn/Field name
Sted/Location	Sted/Location
Kartblad/Map	Felt, blokknr./Field, Block No.
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Dokumentkontroll/Document control					
Kvalitetssikring i henhold til/Quality assurance according to NS-EN ISO9001					
Rev/ Rev.	Revisjonsgrunnlag/Reason for revision	Egenkontroll av/ Self review by:	Sidemanns- kontroll av/ Colleague review by:	Uavhengig kontroll av/ Independent review by:	Tverrfaglig kontroll av/ Interdisciplinary review by:
0	Original document	2017-12-18 Rainer Bell	2017-12-22 José Cepeda	<i>Select control date</i> Type your name	<i>Select control date</i> Type your name

Dokument godkjent for utsendelse/ Document approved for release	Dato/Date 22 December 2017	Prosjektleder/Project Manager José Cepeda
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