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Preliminary regionalization and susceptibility analysis for landslide early warning purposes in Norway

Graziella Devoli
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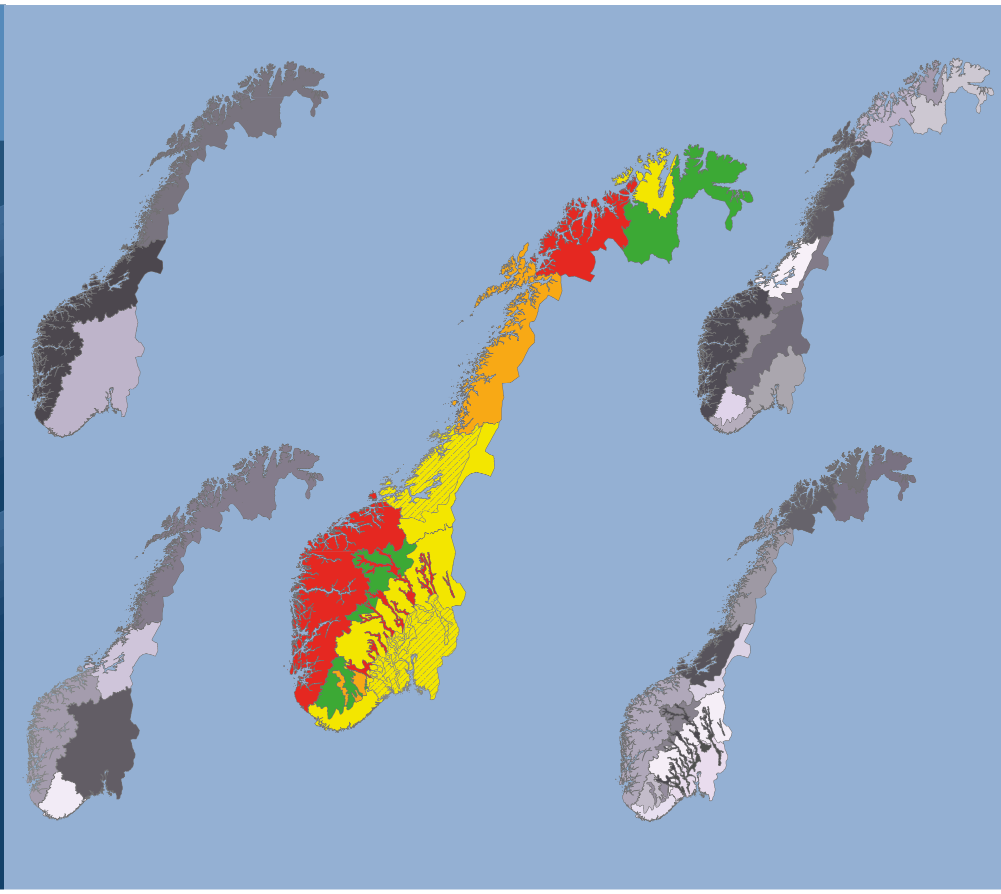

RAPPORT

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Preliminary regionalization and susceptibility analysis for landslide early warning purposes in Norway

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Abstract: In the development of national landslide early warning system it can be useful to divide the country into homogenous regions/zones with similar topography, geomorphology, precipitation pattern and susceptibility to debris flows and debris slides. In this study an expert knowledge based-approach was used and a multi-resolution qualitative analysis was done at national scale and four proposals of regionalization for early warning purposes are presented.

Key words: Warning regions, Debris flow, debris slide

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Preface

The Norwegian Water Resources and Energy Directorate (NVE) has developed an early warning for debris flows and debris slides which have been operational since October 2013. The development of the warning system requires the division of the country into homogenous regions/zones that can be used as warning zones in the daily landslide warning evaluation or to set spatial priorities in related investigation projects. This document proposes a preliminary regionalization of Norway based on topography, hydrology, climate geomorphology and geology and landslide activity. We thank Bernd Etzelmüller from the University of Oslo that provided digital landform data, Svein Olav Krøgli from the Norwegian Forest and Landscape Institute for discussions about landscape regions, Knut Stalsberg from the Geological Survey of Norway (NGU), Wai Kwok Wong and Monica Sund from NVE for comments and the revision of the document.

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Summary

In the development of national landslide early warning systems it can be useful to divide the country into homogenous regions/zones with similar topography, geomorphology, precipitation pattern and susceptibility to debris flows and debris slides. The regions can be used as warning zones in the daily landslide warning evaluation or to set spatial priorities in related investigation projects. In this study an expert knowledge based-approach was used and a multi-resolution qualitative analysis was done at national scale and four proposals of regionalization for early warning purposes are presented. For the analysis a number of thematic maps with different resolution like topography and relief, hydrographic map and watershed boundaries, map of climate type, annual precipitation, geomorphologic units and landforms as well as a landslide inventory map were acquired. Of the four proposals the "Regionalization 4" was used to show preliminary susceptibility levels in different areas of the country and to indicate which landslide types are predominant based on the analysis of available data. This map provides very general information and must be updated when more detailed results from landslide susceptibility analyses are available.

Sammendrag

I utviklingen av en nasjonal jordskredvarslingstjeneste kan det være nyttig å dele landet inn i homogene regioner/soner med lik topografi, geomorfologi, nedbørfordeling og aktsomhetsnivå for jordskred. Regionene kan brukes som varslingssoner i det daglige varslingsarbeidet eller som veiledning i forskningsprosjekter om hvilke regioner som skal analyseres først. I dette studiet har en kunnskapstilnærming og en multi-skala kvalitativ analyse blitt utført på nasjonal skala og fire forslag til regionalisering blir presentert. En rekke temakart har blitt samlet og analysert. Dette gjelder blant annet topografiske og hydrografiske kart, kart over vassdrag, klimatyper, årlig nedbør, landskapstyper samt skredhendelseskart. Av fire forslag, ble "Regionalisering 4" brukt videre for å vise foreløpige aktsomhetsnivåer og en beskrivelse av dominerende skredtyper i de ulike regionene. Dette kartet gir svært generell informasjon, og må oppdateres når data fra mer detaljerte aktsomhetsanalyser for jordskred er tilgjengelige.

1 Introduction

Landslide early warning systems (EWS) are important components in the disaster risk reduction strategy of many countries. They enable governments at national/local level and communities to take appropriate action for saving lives and property in anticipation of a landslide event to occur. Examples of such action are evacuation, road and railway closure, or the realization of physical mitigation measures. Fast-moving landslides, like debris flows and debris slides, occur in a wide variety of environments throughout the world and are relatively frequent in mountainous steep terrain. Debris flows are particularly dangerous to life and property, because they move quickly and travel for a long distance, destroying all objects in their paths. Although official data are not available it is estimated that about 40 people have been killed by debris flows in Norway during the last century, and the most common type of economical loss are due to blocking or destruction of roads and railways.

As a preventive measure, an early warning system is operated by the Norwegian Water Resources and Energy Directorate (NVE) since October 2013. The EWS publishes daily warnings at www.varsom.no and distribute them to road and railway authorities, municipalities and emergency authorities (like police offices, county emergency offices), mass-media and public in general.

One important element of the EWS is the dissemination and communication of warning messages. The authority in charge of issuing warning must be able to communicate properly: *1) what kind of threats can be expected, 2) when and 3) where.* Beside written messages sent to emergency and local authorities, maps can be used as tools to visualize which areas or regions can be affected. A further step in the development of a national early warning system is to divide the country into homogenous regions concerning the occurrence of debris flows and debris slides. Climatic, orographic, hydrological conditions and administrative criteria can be used to establish these regions. A regionalization can be useful in understanding which areas have similar behavior in terms of landslide occurrence under intense rainfall or snowmelt episodes and high groundwater level. It can be used as guidance and to set priority in future investigations (i.e. establishment of regional thresholds) or to activate appropriate emergency response depending on the geographical context. The regions can be used as warning zones, which are herein defined as "a territory that has homogeneity to be used for warning purposes. By homogeneity, it is meant hydro-meteorological response to the outcome of a specific type of hazardous process", in this case a landslide. A preliminary landslide susceptibility[1] value can be assigned to each region. Susceptibility analyses are often performed at medium scale (1:50 000-1:500 000) especially for landuse purposes, representing a step between a landslide inventory and hazard map. Rarely have susceptibility analyses been done at national scale for early warning purposes. However simple qualitative susceptibility assessments at a national scale can be very useful in the first phase of a warning system because they can give information on what kind of susceptibility level and landslide type can be expected in a region.

[1] Susceptibility: It is the likelihood that a landslide will occur in an area on the basis of local terrain conditions.

In this study a multi-resolution qualitative analysis based on an expert knowledge approach has been performed with the purpose to divide Norway into preliminary regions with similar topography, geomorphology, precipitation pattern and landslide type for use in early warning. Specific objectives were: a) to propose different regionalizations: from very general to more detailed regions and b) to assign a preliminary qualitatively degree of exposure or landslide susceptibility to each region. The resulting map is thought as a tool to guide future investigations on debris flow and debris slide processes and is made for early warning purposes.

When not specified the word “landslide” is used in the present document as a general term to refer to both debris flows, debris slides/debris avalanches and soil slides in general.

2 Physical setting

Norway is divided into 19 counties and 428 municipalities with an area of 323,800 km^2. It has an elongated shape over 1800 km from latitude 58°N to 71°N. Approximately 30 % of the total land area consists of mountains where the highest peaks reach up to 2500 m a.s.l. Steep slopes over 30° cover 6.7 % of the country (Fig. A-3 and A-4 in Appendix A).

Caledonian orogenesis and later recurring glaciations have created an alpine fjord landscape along most of the Norwegian Atlantic coast. The overall development of the gross-geomorphology can be summarized as one of erosion and planation during the late Palaeozoic and Mesozoic, major uplift during the Cenozoic with maximum uplift in the western areas and glacial erosion during the Pleistocene (Etzelmüller et al., 2007). The Norwegian relief and landforms can be classified in 10 main units based on different topographic characteristics (i.e. elevation, slope angle, surface inclination) such as coastal plains, hills, plateaux and glacially scoured low mountains and valleys (Etzelmüller et al., 2007) (Fig. 1 and A-5 in Appendix A). The country can also be divided into 45 landscape regions and 444 sub-regions based on six landscape components: major landform, minor terrain form, water and catchment area, vegetation, agricultural land and built-up areas/technical installations (Fig. A-6 in Appendix A) (Puschmann, 2005 and http://kilden.skogoglandskap.no/map/kilden/index.jsp.).

Commonly the country is divided into 4 physiographic regions:

1. Eastern and Southern Norway (Østlandet and Sørlandet) contains extensive areas with forest, gentle valleys and rich arable land. This region is mostly hilly, but also contains some very large areas of lowland surrounding the Oslofjord. Østlandet is dominated by valleys. In the eastern part these valleys are directed north - south while further west, valleys have a more northwest - southeast direction and congregate on to the Oslofjord. The longest valleys in the country, Østerdalen and Gudbrandsdalen are located in this region as well as the longest river and watercourses, Glomma and the biggest lake, Mjøsa.

2. Western Norway (Vestlandet) is mountainous and the landscape is characterized by deep fjords penetrating 200 km inland or more, into the heart of the country where glaciers are located.

3. Central Norway (Trøndelag) comprises of a gentle landscape with rounded hills and mountains. The region also contains extensive lowland areas with valleys congregating on the Trondheimsfjord, where they open up and form a larger lowland area.

4. The landscape of Northern Norway (Nord-Norge) consists of a mixture of valleys, numerous fjords, alpine mountains extending all the way to the coast and many large islands. The interior part of the region, is characterized by large and wide north - south directed fjords and is dominated by the large plateau Finnmarksvidda with an altitude mostly below 400 m.

From a geological point of view, Norway is situated along the western margin of the Baltic shield with a cover of Caledonian nappes in the west. The bedrock of the Baltic shield is dominated by Precambrian basement rocks (e.g. granites, gneisses, amphibolites and meta-sediments) in the southern and south-eastern part of the country. The Caledonian nappes are dominated by Precambrian rocks and metamorphic Cambro-Silurian sediments in the central and western parts of the country. Cambro-Silurian sedimentary and Permian volcanic rocks occur within the Oslo Graben (Etzelmüller et al., 2007). Continuous till deposits cover large areas of the valley sides and floors, although fluvial and glaciofluvial deposits as well as marine clays are widespread. The Fennoscandian igneous rocks are quite resistant to weathering whereas regions of sedimentary or metamorphic rocks are more susceptible to weathering, and the presences of overlying weathering soil will vary accordingly (Stalsberg et al., 2012) (Figs. A-11, A-12, and A-13 in Appendix A).

Because of the large latitudinal range and the varied topography, the country has different climatic areas. Along the coast, the climate is influenced by the North Atlantic Current, whereas the inland experiences a more continental climate. Based on the Köppen climatic classification, the Norwegian climate is classified in 3 main types: warm temperate humid climate, cold temperate humid climate and polar climate (Fig. A-7 in Appendix A). The highest annual temperatures can be found in coastal areas of the southern and western parts of the country while the coldest area throughout the year is the Finnmarksvidda (Fig. A-9 in Appendix A). Precipitation types can broadly be divided into three categories: frontal, orographic and showery. The largest annual precipitation amounts are found near the coast of Western Norway from the Hardangerfjorden to the Møre area. Thus, Brekke in Sogn og Fjordane county has an annual precipitation of 3575 mm. In contrary, the inner parts of Østlandet, Finnmarksvidda, and some smaller areas near the Swedish border, are all lee areas in relation to the large weather systems mainly coming from the west. Common for these areas is the low annual precipitation and that showery precipitation during summer is the largest contributor. Øygarden (Oppland) has the lowest annual precipitation with 278 mm (Fig. A-8 in Appendix A).

Large variation in topography and climate also results in different hydrological regimes. Rivers are relatively short and steep in Western Norway, Nordland and Troms, while they are long and gently sloping further south as well as in Trøndelag and Finnmark. Norway is divided into 262 watersheds that can be further divided into 5 types based on their hydrological regime: a) glacier watersheds, b) mountain watersheds, c) interior land watersheds, d) transitional watersheds and e) coastal watersheds. This differentiation is based on differences in runoff during the year, which is related also to rainfall and temperature (Fergus et al., 2010) (Fig. A-2 in Appendix A).

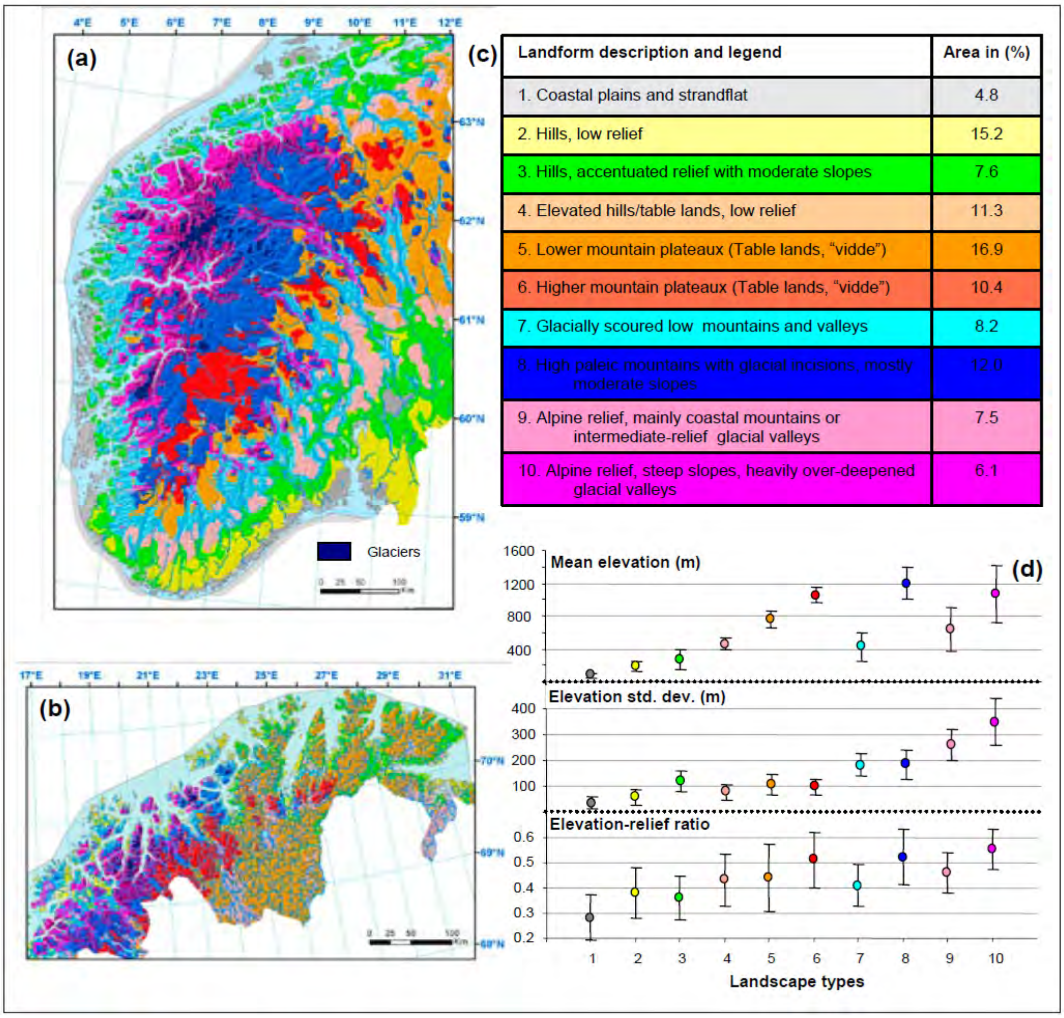

Fig. 1. Division of the Norwegian landscape into 10 major landform types as proposed by Etzelmüller et al. (2007)

3 Methodology

The analysis was done at national scale and results are presented at 1: 6 000 000 grid resolution. For raster maps the resolution varies from 25 m to 1000 m. For vector maps the scale varies from 1: 250.000 to 1:50.000.

Four main steps were followed in the analysis:

1. Verifying regionalizations already available and used for forecasting weather and snow avalanches.
2. Aquisition of thematic maps
3. Definition of criteria for regionalization and proposals of regionalization.
4. To assign a degree of exposition or susceptibility to each region based on historical landslide data.

3.1 Verifying regionalizations already available

A number of regionalizations are already in use for weather and snow avalanche forecasting (see figures in Appendix B). These can be found at the Norwegian Meteorological Institute (MET Norway) and at NVE. Other regionalizations (i.e. precipitation regions, run-off regions and regions showing future precipitation changing patterns) have been proposed in previous research projects (i.e. www.geoextreme.no). These regionalizations were also collected and evaluated for potential use in landslide early warning.

MET Norway uses different divisions of the country for either weather forecasting or climatic description purposes (B-1 to B-4 in Appendix B). Two regionalizations divides the country into three and five areas, respectively. Other are more detailed regionalizations (division in up to 16 regions). All of these regionalizations are used for meteorological forecasting purposes. At regional and local level the meteorological institute further divides the country into: coastal areas and interior land.

For early warning of snow avalanches NVE has preliminary divided the mountain areas of Norway into 25 warning zones (see figure B-5 in Appendix B).

A regionalization based on precipitation pattern was proposed by Hanssen-Bauer and Førland (1994 and 1998) and Hanssen-Bauer and Nordli (1998) and a regionalization showing seasonal distribution of streamflow runoff (Førland et al., 2000) is also available, see figures B-6 and B-7 in Appendix B.

3.2 Aquisition of thematic maps

For the purpose of this study, maps of parameters containing important conditioning and triggering factors for landslides (i.e. topography, rainfall, geology) were collected. The thematic maps herein analyzed were collected from NVE archives, the Norwegian Mapping Authorities (Statens Kartverk) and the Geological Survey of Norway (NGU) (www.ngu.no/kart). Information on weather and climate was obtained from the

Norwegian Meteorological Institute (MET) (www.met.no). Information on geomorphology, landforms and landscape at national scale was obtained from Etzelmüller et al. (2007) and from the Norwegian Forest and Landscape Institute (Skog og landskap) (http://kilden.skogoglandskap.no/map/kilden/index.jsp and Puschmann 2005). Information about past landslide events was collected from the national landslide database (www.skrednett.no).

The following thematic maps were collected, and visualized in the appendix A:

- Administrative boundaries (A-1)
- Hydrography and watershed boundaries (A-2)
- Digital elevation model (resolution: 25m) from which topography, relief and slope angle were derived (A-3 and A-4)
- Geomorphologic units, landforms and landscape regions (A-5 and A-6)
- Climate type, annual precipitation, annual temperature and annual runoff (A-7 to A-10)
- Geology: bedrock map, Quaternary deposits, marine clays boundaries (A-11 to A-13)
- Landslide events and previous preliminary landslide susceptibility analyses close to inhabited areas at national level (Bargel et al., 2011) (A-14 and A-15)

3.3 Definition of criteria to subdivide the country for landslide warning purposes

Subdivision of the landscape for hydro-meteorological warning purposes is quite commonly performed in many countries, but is often based only on meteorological, orographic, hydrographic and administrative criteria (i.e. www.protezionecivile.gov.it). However, for the zonation proposed herein we have also taken into account other criteria more specific for landslide prevention: geological conditions and landslide history. Thus the following criterias were considered:

- Climatic criteria: identification of areas with homogeneous climate and precipitation pattern.
- Orographic criteria: the country was separated in regions based on the physical geography; landform and distinguishing between flat areas and mountains, and between steep and gentle slopes.
- Hydrological criteria: limits of main catchment area and runoff areas
- Administrative criteria: observation of the different political administrative boundaries.
- Geological criteria: type of bedrock and alterated/weathered bedrock, type and distribution of loose deposits, marine clays boundaries
- History of past landslides

4 Analysis and proposal of regionalizations

A multi-resolution qualitative analysis was performed in several steps, based on an expert knowledge approach. The analysis started with recognition of the main conditioning and triggering factors for debris flows and debris slides. Table 1 synthesizes the main factors considered significant in the occurrence of landslides and their related categories.

Rainfall and the combination of rainfall and snowmelting is the main triggering landslide factor. In this study not only the total annual rainfall but also its spatial distribution was taken into account in the subdivision of regions. Topography and relief are important conditioning factors for landslide activity. Landslides occur both in the alpine fjord landscape along the Atlantic coast and further east where the topography is somewhat smoother (Stalsberg et al., 2012). Particularly significant for debris slide occurrence are slope angles between 25-30°. However, in some areas debris slides also occur on gradients as low as 20-25º, (rarely even 15-20°). Such events particularly occur on slopes without vegetation or with thin cover of loose deposits or where human activities have been undertaken, like in cuts and fillings for rural road construction. Debris flows usually initiate on slope angles between 25° and 45° depending if they start as debris slides or as normal erosion process of fine material along a channel. Experience shows that type and distribution of lithologies and loose quaternary deposits on the slopes, such as till or talus, is decisive for landslide occurrence. The bedrock type largely defines the weathering type and intensity, thus influencing the loose sediment availability, type and grain sizes, which in turn controls the distribution of debris flows and debris slides. Steep valley sides covered with thick deposits of till, colluvium and weathered bedrock act as starting zones for shallow slides and subsequent debris flows (Stalsberg et al., 2012). In association with floods, shallow soil slides can occur because of erosion along river channels, especially in glacial and fluvial deposits. Landforms more prone to landsliding are glacially scoured low mountains and valleys; alpine relief, steep slopes, heavily over-deepened glacial valleys, and alpine relief, mainly coastal mountains or intermediate-relief glacial valleys.

Table 1. Factors important in the occurrence of landslides and the weighting proposed. The symbol ++ means highly significant and + means low-medium significant for landslide occurrence. For all categories a weight from low (1) to very high (4) was used.

Elevation (m) ++	Weight
0-200	1
200-500	2
500-800	3
800-1100	4
1100-2463	3
Slope angle (°) ++	
0°-5°	1
5°-10°	1
10°-15°	2
15-25°	3
25°-45°	4
>45°	3

Climate +	Weight
Polar climate	2
Cold-Temperate Climate	3
Warm -Temperate Climate	3
Precipitation (mm) ++	
<250	1
250-500	2
500-1000	2
1000-1500	2
1500-2000	3
2000-2500	3
2500-3000	4
3000-4000	4
>4000	4

Landforms ++	Weight
Coastal plains and strand flats	1
Hilly	1
Upland hilly terrain and table lands	1
Upland mountains with moderate slopes	2
Glacially-scoured low mountains andvalley	3
Alpine relief or glacial relief	4
Landscape regions +	
Glaciers (Breene)	0
Highland plateaux and plains (Viddebygedene, Finnmarksvidda, Varangervidda)	1
Coastal districts and fishing villages (Kystbygdene og Skagerak coast, Nordlandsværran)	1
High alpine mountains (Høyfjellet, Gaissane i Finnmark, Lofoten)	1
Low alpine mountain range (Lågfjellet)	1
Fjord districts (Fjordbygdene, Oslofjorden, Ytre fjordbygdene; Jæren and Lista)	2
Lake and Silurian districts (Innsjøbygdene)	2
Northern boreal forest (Fjellskogen)	2
Farming districts and Clay soil districts (Jordbruksbygdene, Leirjordsbygdene)	3
Interior valleys , inner and central fjord districts (Innlandsbygdene, Midtre bygdene, Indre bygder)	3
Forest districts (Skog bygdene, Dalsland, Heibygdene, Skogtraktene)	3
Valley and highland districts and lowland valleys (Dal- og fjellbygder, Østerdalene, Dalbygdene)	4

Quaternary deposits ++	Weight
Bedrock	1
Humus	1
Peat deposit	1
Eolic deposits	1
Glacier deposit	1
Artificial fylling	2
Marine deposit	2
Bedrock with shallow cover	2
Alluvial deposit	3
Colluvial deposits	3
Weathered and altered bedrock	4
Moraine	4
Till limits +	
Below	2
Over	4

In the initial phase, the possibility to use existing regionalizations was evaluated. Two zonations available for weather forecasting purposes were found to be suitable for this purpose. The first one (Fig. B-1) designated here the “3 regions” zonation divides the country into three areas (Northern Norway, Western and Central area, Eastern and South of Norway) while the second one (Fig. B-2) designated the “5 region” zonation divides the country into 5 regions.

The first regionalization (R1) was obtained using the “3 regions” zonation as a basic map, while the second proposition (R2) was obtained using the “5 region” zonation (Fig. 2). In both cases, hydrological criteria and in particular watershed limits were used to delineate the new zonation instead of using administrative boundaries (counties boundaries) as they were used in the existing zonations.

Because of the complex topography, rainfall regime and geomorphology, especially in Northern, Central and South-Eastern Norway, it was necessary to subdivide these regions to better reflect the topographic and meteorological homogeneity.

From the regionalization R2 a third regionalization (R3) was obtained by incorporating precipitation data, slope angle and elevation maps and spatial distribution of marine clay deposits (Fig. 3). The marine clay distribution was included to be able to distinguish between areas more prone to earth slides (in particular slides in clayed-silty soils and quick clay slides) from those more prone to debris flows and debris slides. In this phase, each region was analyzed separately for each factor using the respective categories proposed in table 1.

The final regionalization (R4) was obtained from combining R3 with landform and landscape data (Fig. 3). The difference with respect to R3 is mainly for the South-Eastern Norway (Østlandet) which was further divided into 4 subregions, and for Southern Norway (Agder) which was divided into 3 subregions. The regionalizations R3 and R4 are presented in Figure 4.

The cross-examination of the parameters listed in table 1 allowed 4 proposals of possible regionalizations, varying from a very general regionalization with few regions (R1 and R2) to a more detailed one with many subregions (R3 and R4), (Table 2).

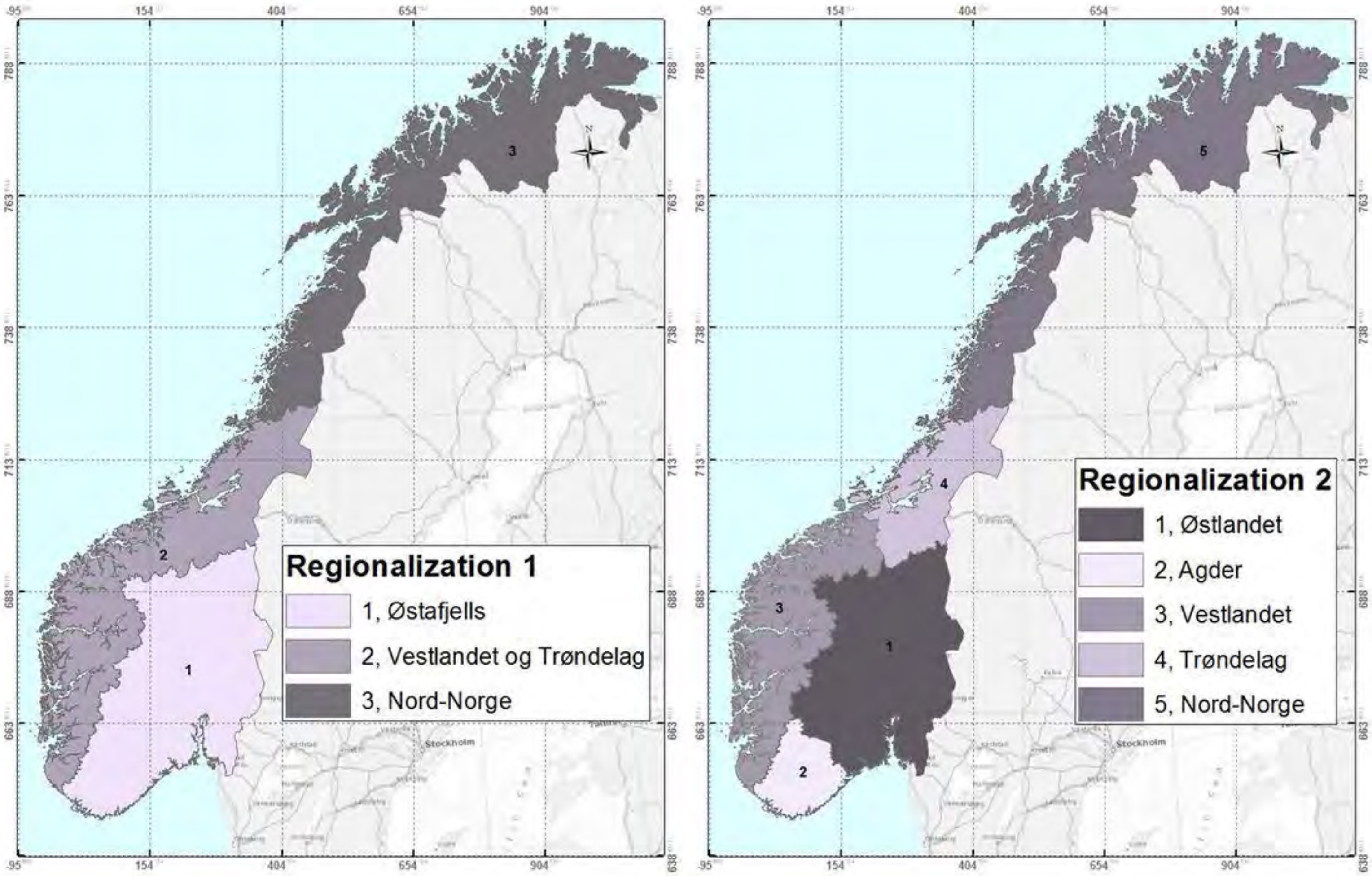

Fig. 2 Regionalizations 1 (R1) and 2 (R2)

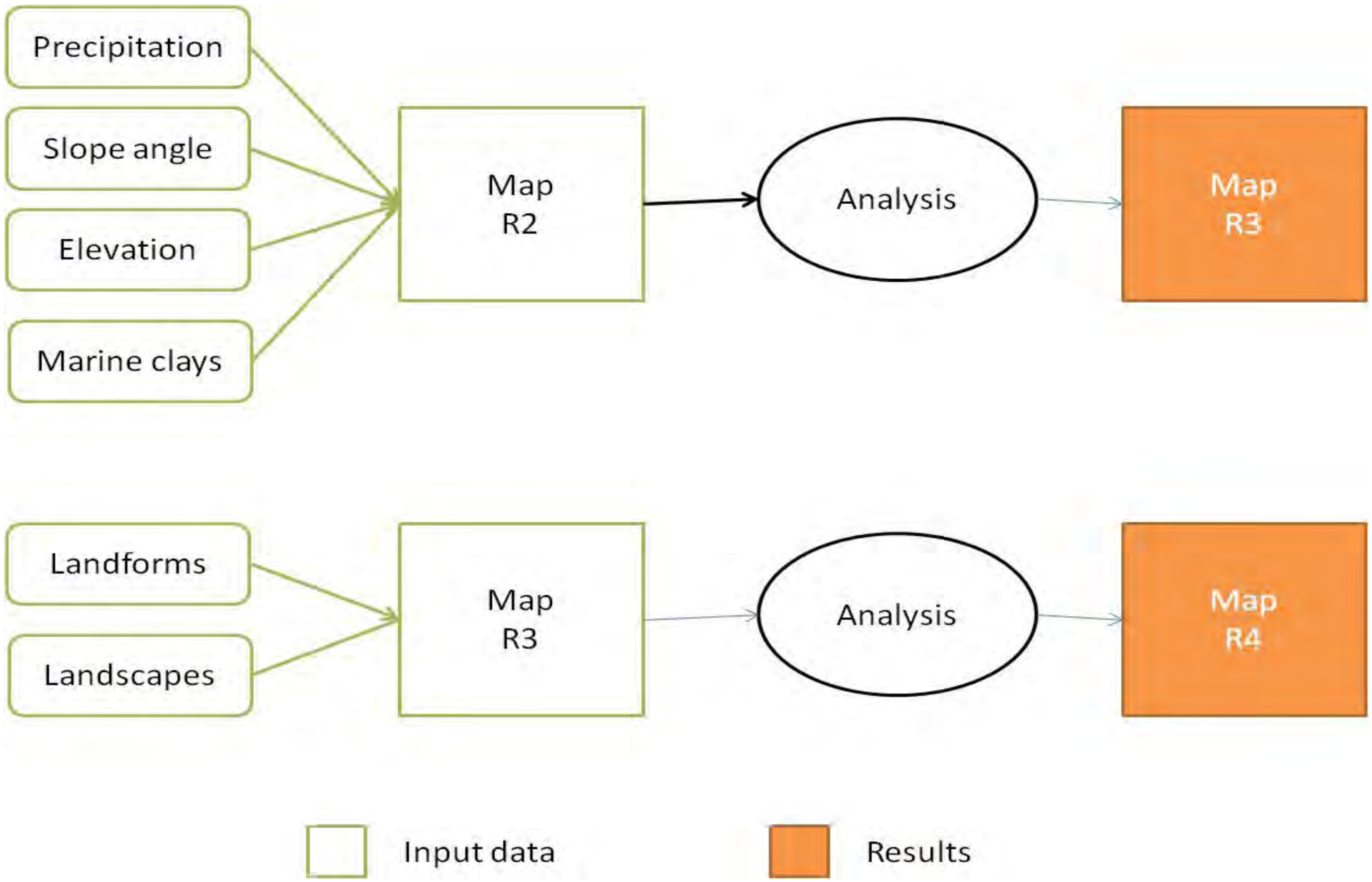

Fig. 3 Input data and analysis of parameter maps for regionalization 3 (R3) and 4 (R4)

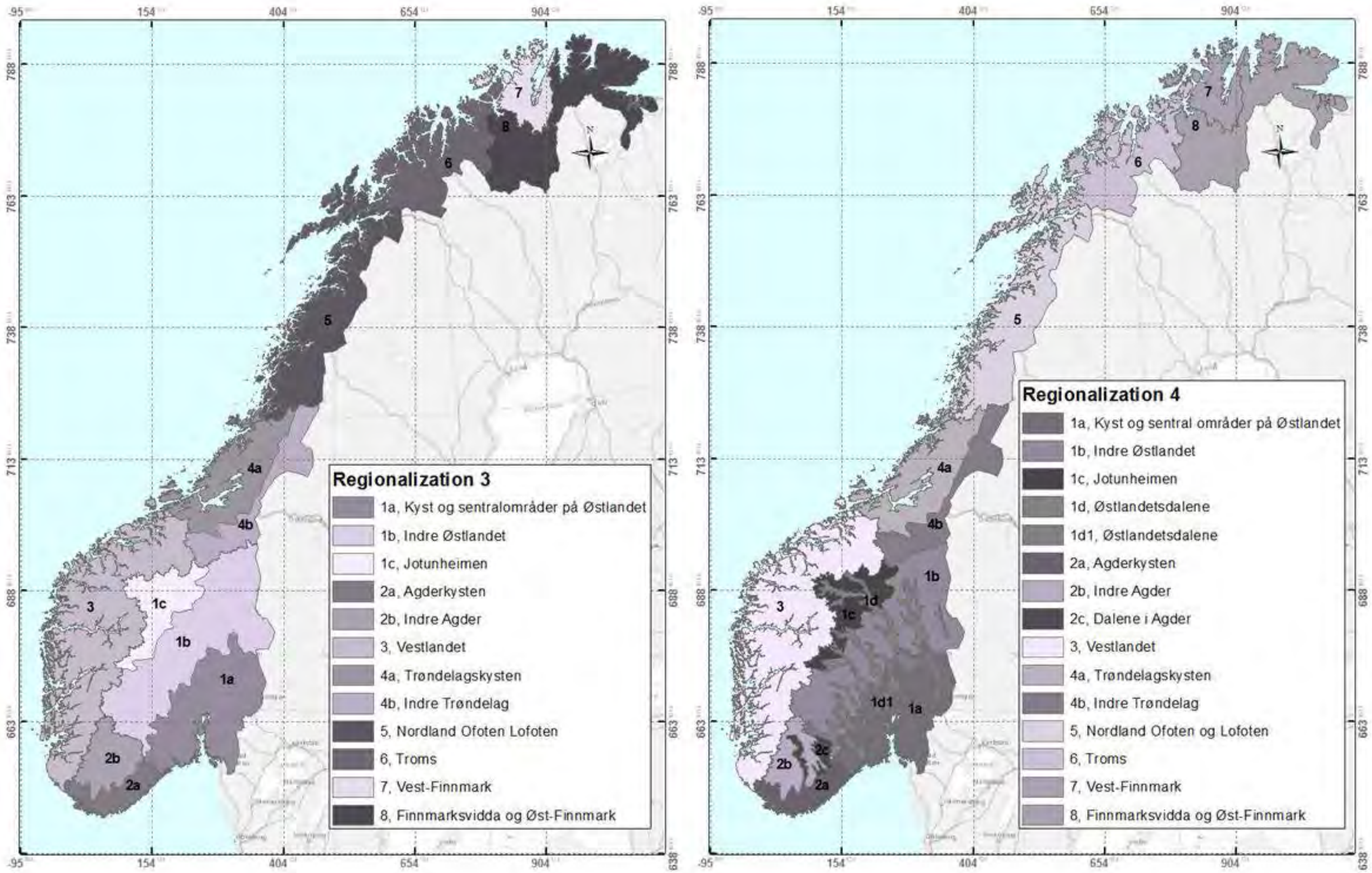

Fig. 4 Regionalization 3 (R3) and 4 (R4)

The proposed regionalizations shows regions that are hydro-meterological and orographic homogeneous at a regional scale and are thought to have similar behaviour in terms of landslide occurrence under intense rainfall or snowmelt episodes and high groundwater level. The regions are proposed based on the currently available information, and consequently they are preliminary. Therefore, they must be updated and eventually replaced when more detailed information or landslide susceptibility maps become available. All proposed regions presented herein can be used as warning zones depending on the specific weather conditions, or can be used as tools in to set priority in future related early warning investigations (i.e. indicating which regions should be studied or where models should be tested first).

Table 2. Summary of regionalizations and regions proposed.

	R1	**R2**	**R3**	**R 4**
Code and region names	1Østafjells (Østlandet, fjellet i Sør Norge, Agder) (South Norway)	1 Østlandet (South-Eastern Norway)	1a Kyst og sentralområder på Østlandet	1a Kyst og sentralområder på Østlandet
			1b Indre Østlandet	1b Indre Østlandet
			1c Jotunheimen	1c Jotunheimen
				1d og 1d1 Østlandesdalene
		2 Agder (Southern Norway)	2 Agderkysten	2a Agderkysten
			2b Indre Agder	2b Indre Agder
				2c Dalene i Agder
	2 Vestlandet og Trøndelag (Western and Central Norway)	3 Vestlandet (Western Norway)	3 Vestlandet	3 Vestlandet
		4 Trøndelag (Central Norway)	4a Trøndelagskysten	4a Trøndelagskysten
			4b Indre Trøndelag	4b Indre Trøndelag
	3 Nord-Norge (Northern Norway)	5 Nord-Norge (Northern Norway)	5 Nordland, Ofoten, Lofoten	5 Nordland, Ofoten, Lofoten
			6 Troms	6 Troms
			7 Vest Finnmark	7 Vest- Finnmark
			8 Finnmarksvidda og Øst-Finnmark	8 Finnmarksvidda og Øst-Finnmark

In the second phase of the study geological data (loose quaternary deposits distribution) and landslide information (spatial distribution, number and type of historical landslide events) were also included. The spatial distribution and number of recorded landslide events is important in the definition of susceptibility, because it indicates which area is more prone to landslides and which type of landslide phenomenon can be expected. National inventories can be used for this purpose. The analysis of records registered in the national database shows that landslides occur almost everywhere in the country. However, there is a very clear concentration of events and high spatial frequency in certain areas which suggests a strong control from relief, topography and geology. It is important to point out that the database can contain limitations in terms of data quality and lack of spatial records, but this was neglected for the scale and purpose of this study. In addition to landslide events, information from previous preliminary susceptibility analyses done at national level and close to inhabited area (Bargel et al., 2011) was also included.

In this phase R4 was used as input map and a preliminary susceptibility map was proposed following the process indicated in Figure 5. Conditioning and triggering factors received a weight as proposed in table 1. Landslide information received a weight as proposed in table 3. For each region it was observed which categories of conditioning and triggering were predominant and the correspondent weights were summarized.

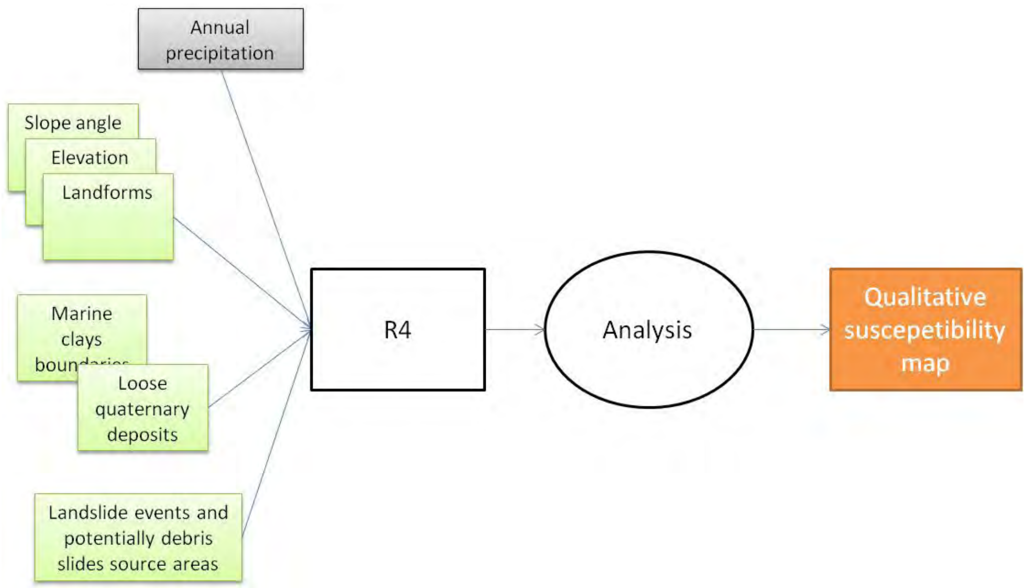

Fig. 5. Input data and process to obtain the preliminary susceptibility map.

Table 3. Weight assigned to the landslide information available

Presence of landslide events	**Weight**
Rare events and poorly documented	1
Few events or uncertain	2
Many events but not well documented	3
Many events and well documented	4
Presence of existing starting zone in inhabited areas*	
Low	1
Medium	2
High	3

* source areas for debris slides close to inhabited areas obtained from Bargel et al., 2011

The resulting map (Fig. 6) shows the assigned degree of susceptibility for each specific region. The degree of susceptibility varies from low to high. The explanation of the susceptible levels used is shown in Table 4. Note that the boundaries between regions are controlled mainly by spatial rainfall distribution, overall landforms, geology and catchment limits.

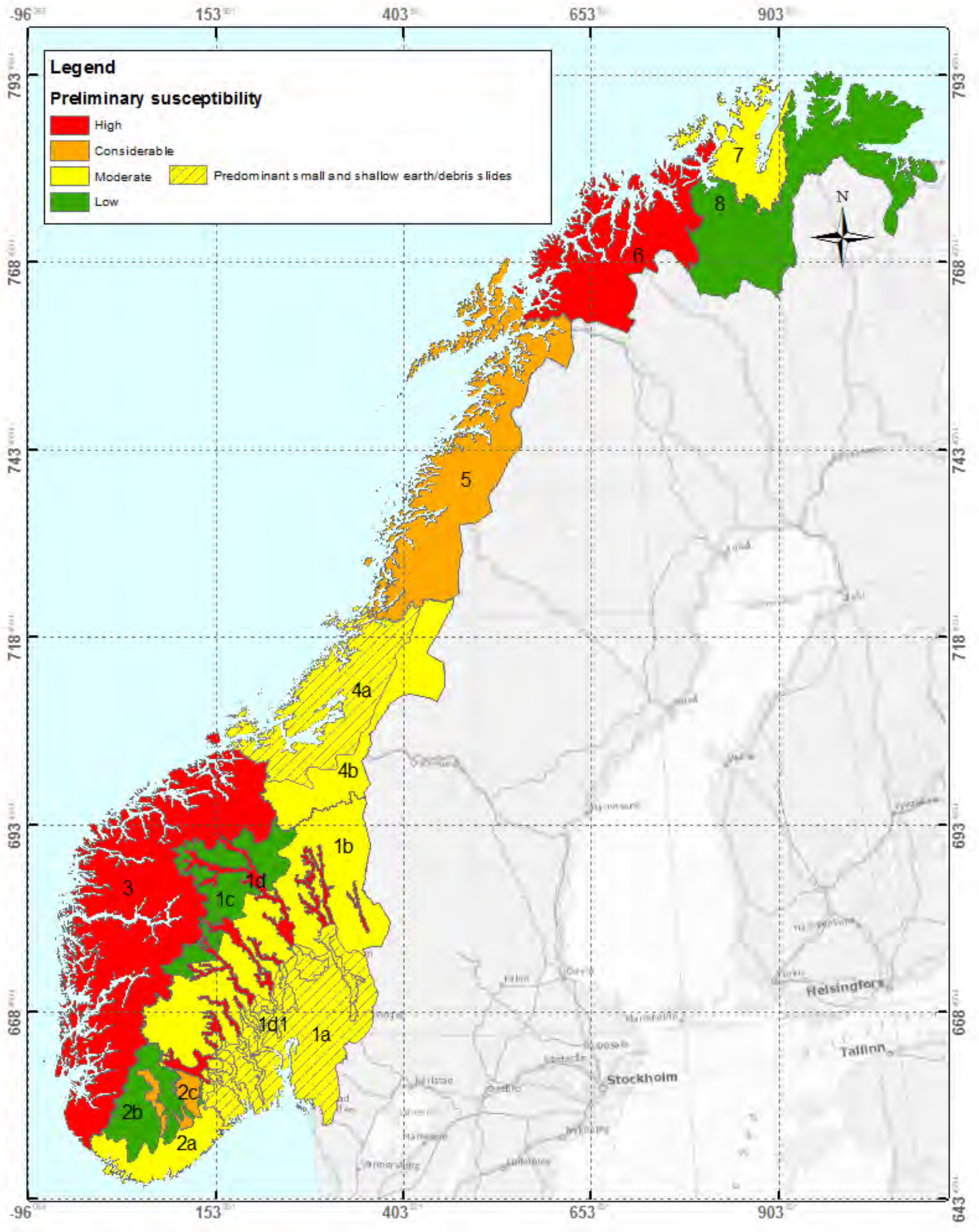

Fig. 6. Preliminary susceptibility level for the different regions.

Table 4. Explanation of the susceptibility levels used in Fig. 6

<table>
<tr><th colspan="2">Susceptibility levels</th><th colspan="3">Explanation</th></tr>
<tr><td>4</td><td>High</td><td colspan="3">Alpine relief or glacial relief, Glacially scoured low mountains and valleys, steep slopes (25-45° and >45°), many landslides events

- Region 1d, 3, and 6: Many debris flows and debris slides are expected to occur in the region as consequence of intense rainfall and snowmelt especially in loose moraine deposits, in addition to many shallow soil slides along roads, railways and rivers.</td></tr>
<tr><td>3</td><td>Considerable</td><td colspan="3">Upland hilly terrain and table lands, locally alpine relief and steep slopes (25-45° and >45°), many debris flows and debris slides.

- Region 2c and 5. Many debris flows and debris slides occur as consequence of intense rainfall and snowmelt especially in loose till deposits or weathered bedrock. Soil slide in artificial slopes (along roads, railways and rivers) are secondary landslide types in the regions.</td></tr>
<tr><td>2</td><td>Moderate</td><td>Upland hilly terrain and table lands, gentle slopes (<25° locally up to 45°), few debris slides and debris flows, some soil slides in artificial slopes and often lacking of detailed information, many not triggered by natural causes (i.e. rainfall/snowmelting) and occurring in days without rainfall.

- Region 1b, 2a, 4b and 7: Debris flows and debris slides are possible during episodes of intense rainfall or during snowmelt but mainly shallow soil slides in artificial slopes along roads, railways and rivers are expected.</td><td>2</td><td>Hills dominated by marine clay deposits, locally steep slopes (25-45°), many landslide events mainly in artificial slopes, but also in natural slopes. Here slides in clayed-silty soils are predominant.

- Region 1a, southern part of the 1d and 4a: Many soil slides in natural and artificial slopes (along roads, railways and rivers) occur during intense rainfall and high groundwater and soil saturation or during intense snow melting episode and high ground water and soil saturation.</td></tr>
<tr><td>1</td><td>Low</td><td colspan="3">Upland hilly terrain and table lands, Upland mountains with moderate slopes, gentle slopes (<25°, but locally 25-45°). No debris flows and debris slide events recorded, many uncertain events and often triggered by anthropic causes. Lack also of landslide records because of the low density population and transport communication lines.

- Region 1c, 2b and 8: Debris flows and debris slides are very rare in this region. Shallow soil slides along roads, railways and rivers can occur but often triggered by human causes and not by rainfall.</td></tr>
</table>

5 Conclusions

In this study a preliminary regionalization of Norway has been proposed for the purpose to be used in the landslide early warning system or in related investigation projects. The regionalization was done using orographic, hydrological, geological, climatic, and administrative criteria, as well as data on landslide activity. The analysis was performed at a national scale (1: 6.000.000) and a number of thematic maps with different resolution were acquired such as topography and relief, hydrographic map and watershed boundaries, map of climate type, annual precipitation, geomorphologic units, landforms and a landslide inventory map were acquired. Existing regionalizations used in weather-, snow avalanche- and flood forecasting were also collected and analyzed.

The country was divided into regions with similar topography, geomorphology, precipitation pattern and susceptibility to debris flows and debris slides. Four regions were proposed and vary from very general large regions to proposals with subregions. The proposed regionalizations are useful for understanding which areas have similar behaviour in terms of landslide occurrence during intense rainfall or snowmelt episodes and high ground water level. The regions can be used as warning zones in the daily landslide warning evaluation depending on specific weather conditions, or in to set priority in related future investigations. Among the regionalizations proposed, R4 is the one suggested to be most representative for debris flows and debris slides and probably the most appropriate to be used for early warning purposes. R4 is used to show preliminary susceptibility levels in different regions of the country in this report and to indicate which landslide types are predominant based on the analysis of available data. The proposed maps are available at xgeo.no as additional maps in warning evaluation.

It is stressed that the results are based on expert knowledge and on the available information, and may have some limitations, but on the other hand they are quite comprehensive for the scale and the purpose of the study. The regionalization provides very general and preliminary information and must be updated and eventually replaced when more detailed landslide susceptibility maps are available.

6 References

Bargel T., Fergus T.Å., Devoli G., Orvedal K., Peereboom I., Øydvin E.K., Stalsberg K.,Sletten K., Fischer L., Rubensdotter L., Eilertsen R. (2011) - Plan for skredfarekartlegging. Delrapport jordskred og flomskred. NVE Report nr 16/2011. Norwegian Water Resources and Energy Directorate, Oslo, Norway

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Stalsberg K., Fischer L., Rubensdotter L., Sletten K. 2012. Approaches to shallow landslide and debris flow—assessments in Norway. Landslides and Engineered Slopes: Protecting Society through Improved Understanding – Eberhardt et al. (eds) © 2012 Taylor & Francis Group, London, ISBN 978-0-415-62123-6

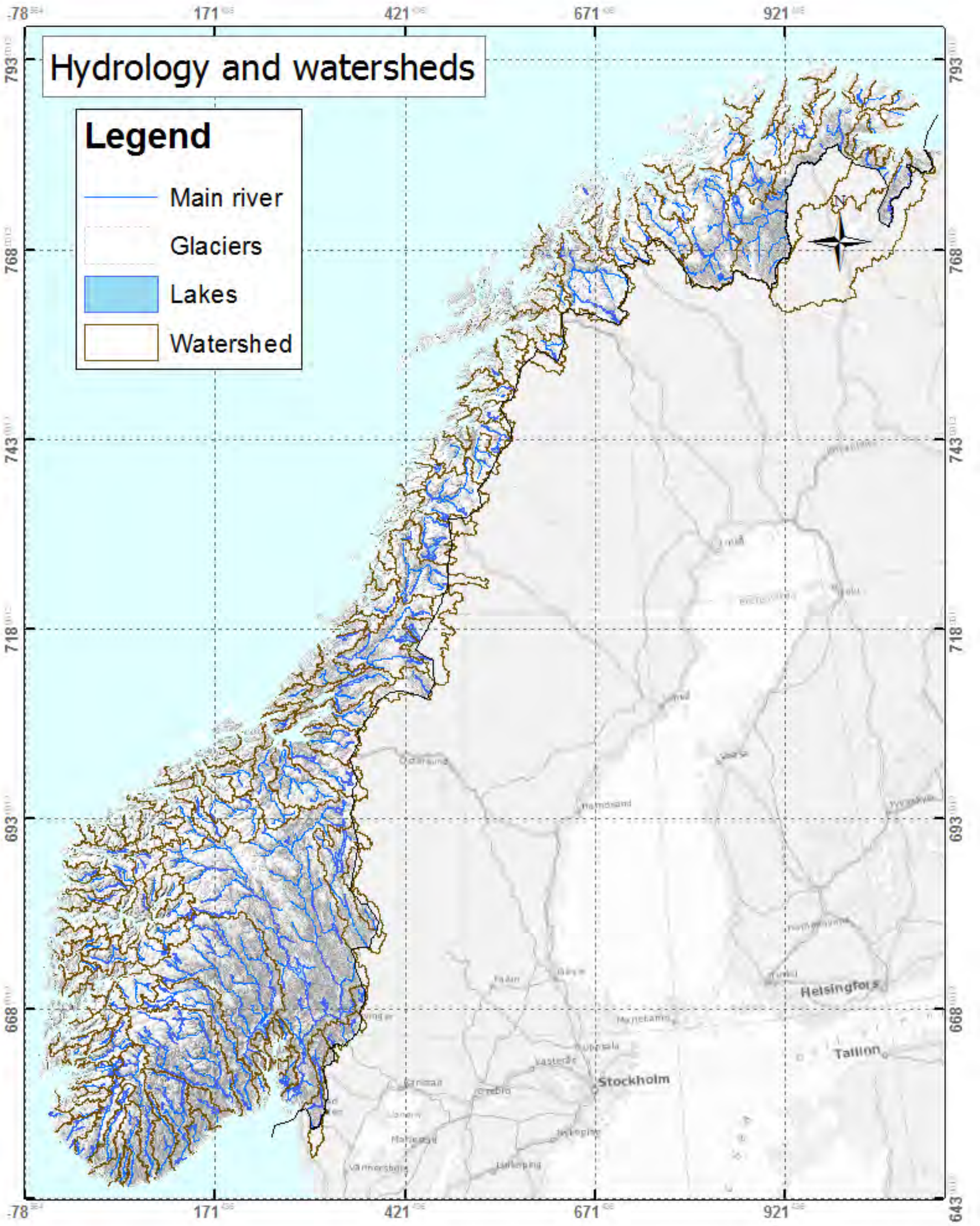
http://kilden.skogoglandskap.no/map/kilden/index.jsp.

Appendix A-Thematic maps

A-1

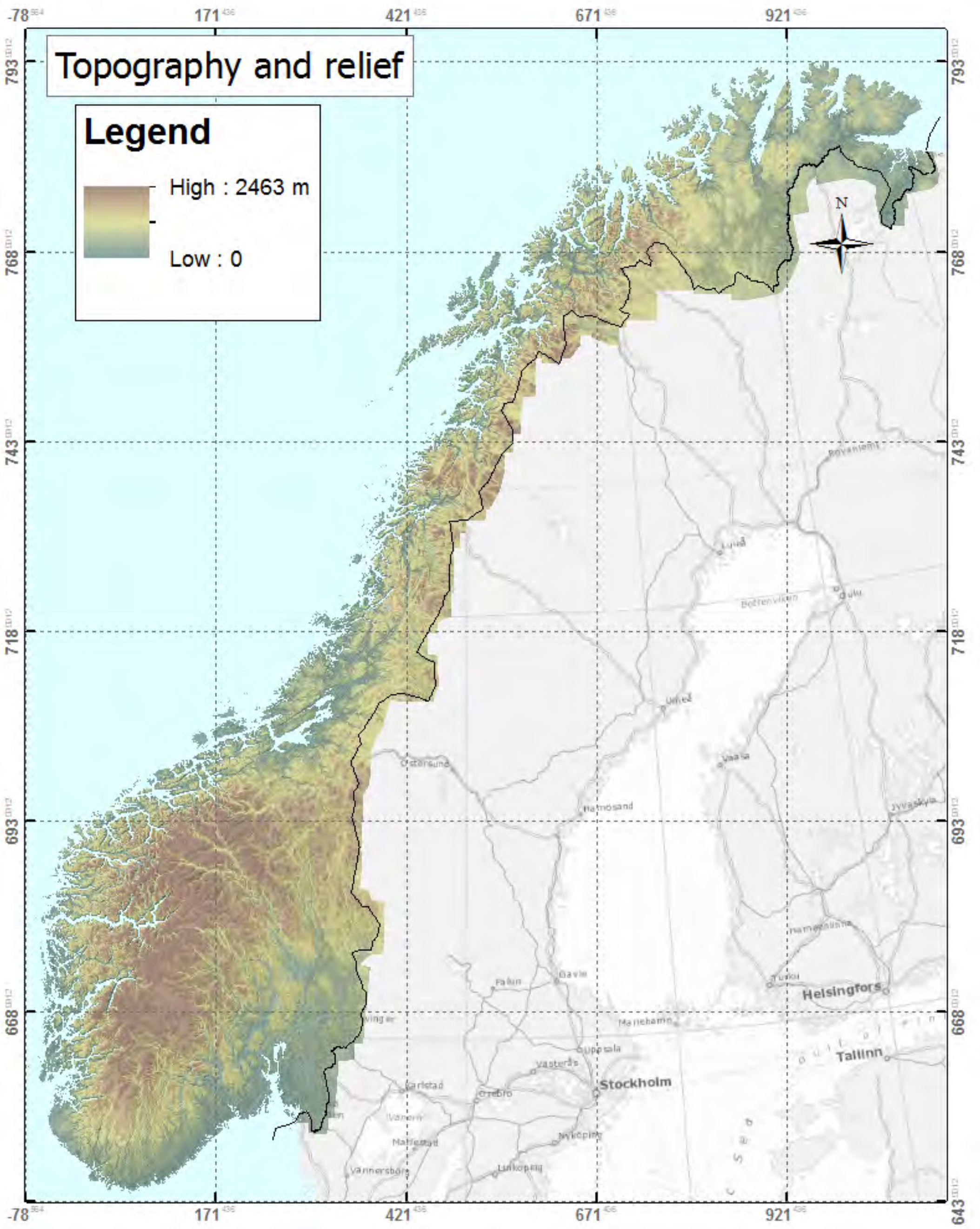
Source: Statens Kartverk

A-2

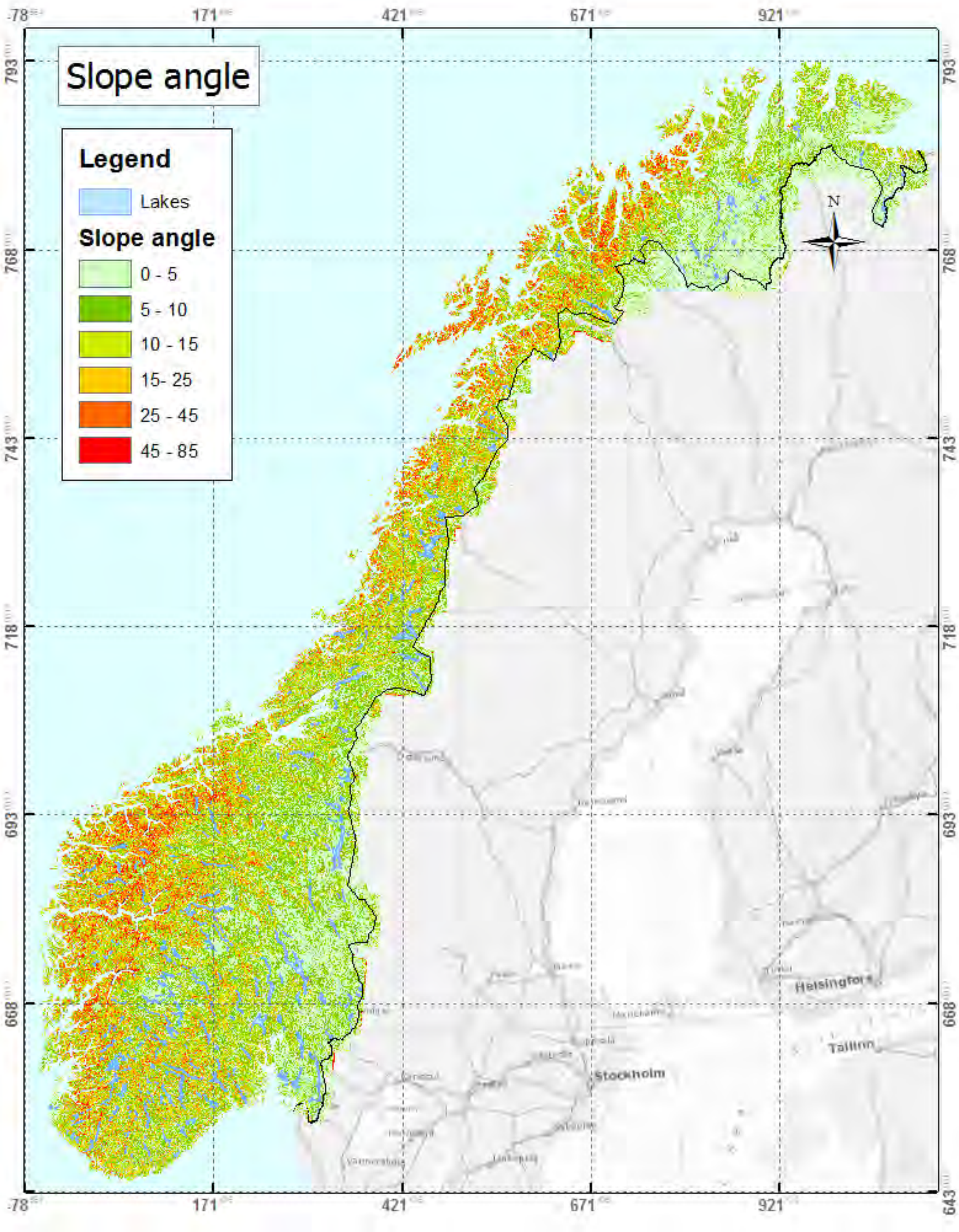


Source: NVE

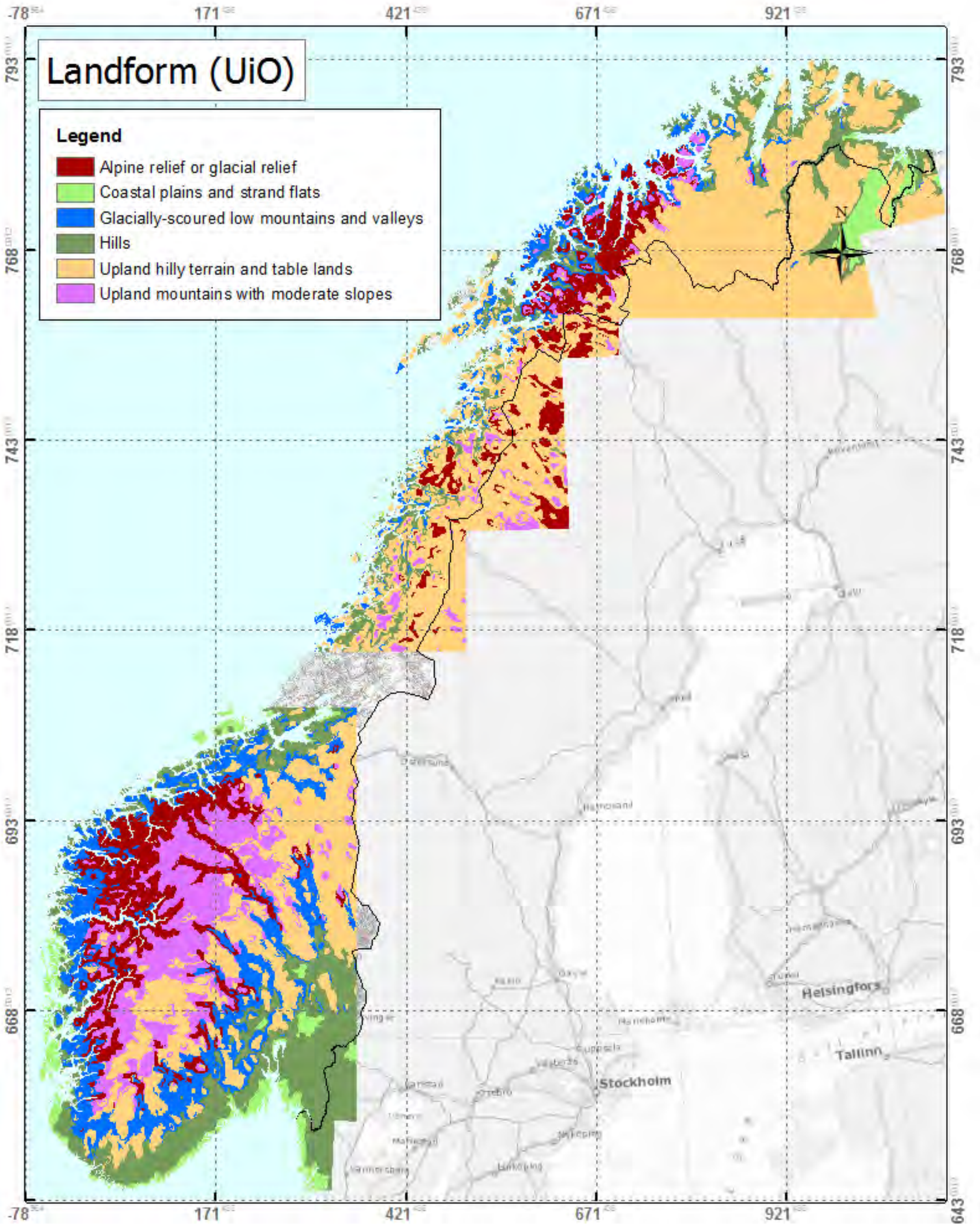
A-3



Source: Statens Kartverk

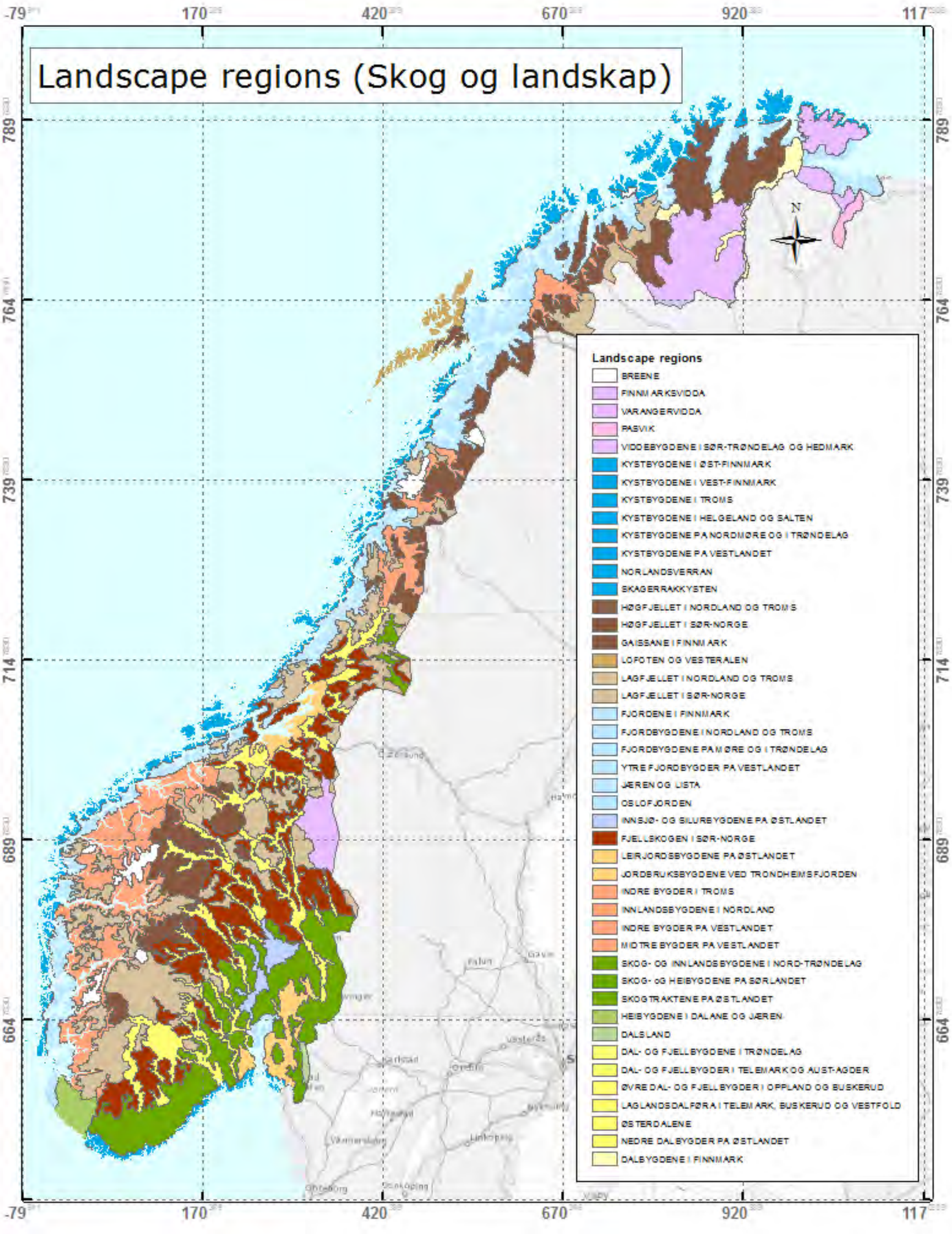


Source: modified from Statens Kartverk



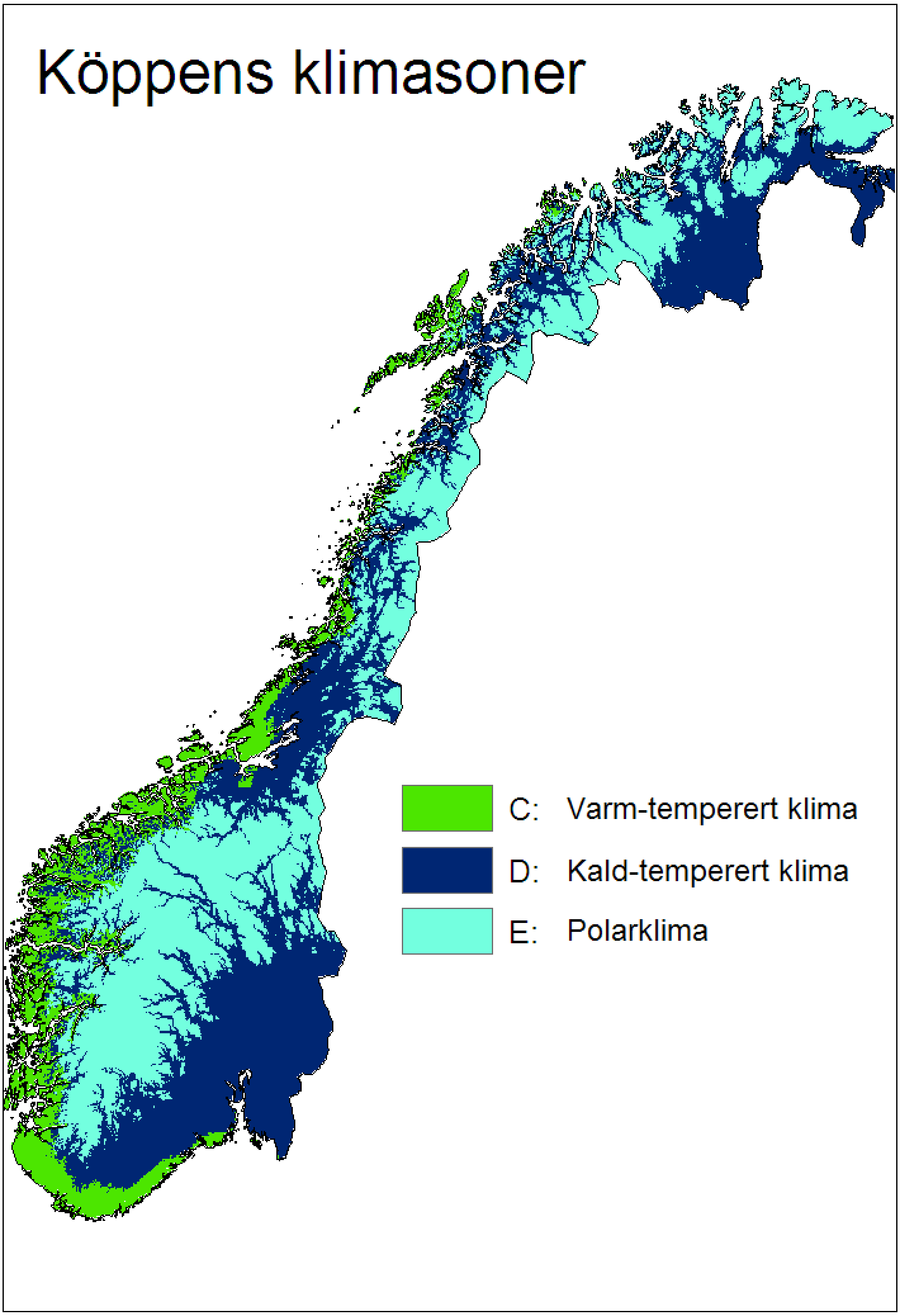
Source: Modified from Etzelmüller, B., Romstad, B., Fjellanger, J., 2007. Automatic regional classification of topography in Norway. Norwegian Journal of Geology 87, 167–180.

A-6



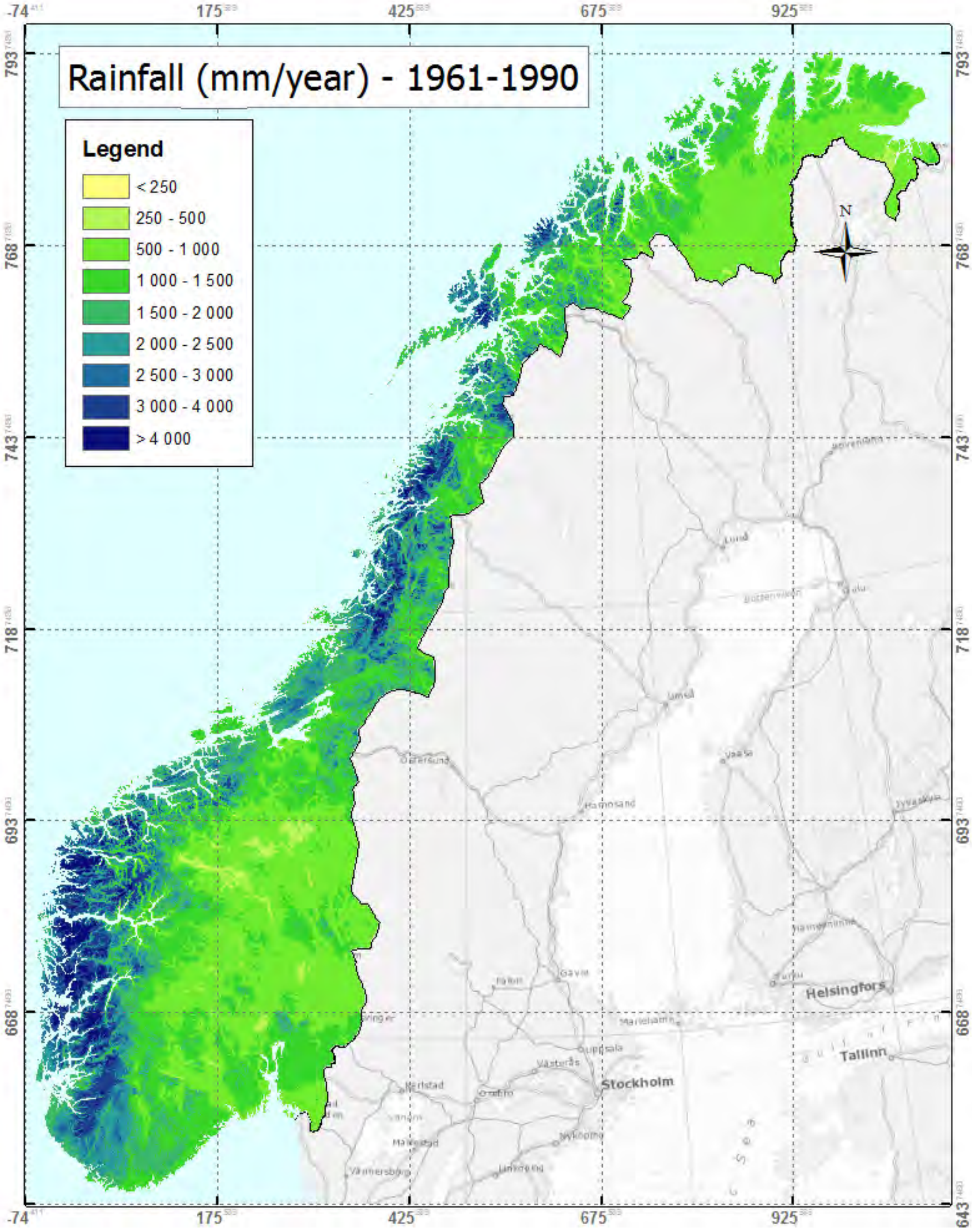
Source: Modified from http://kilden.skogoglandskap.no/map/kilden/index.jsp.

See table 1 for English names of landscape regions.

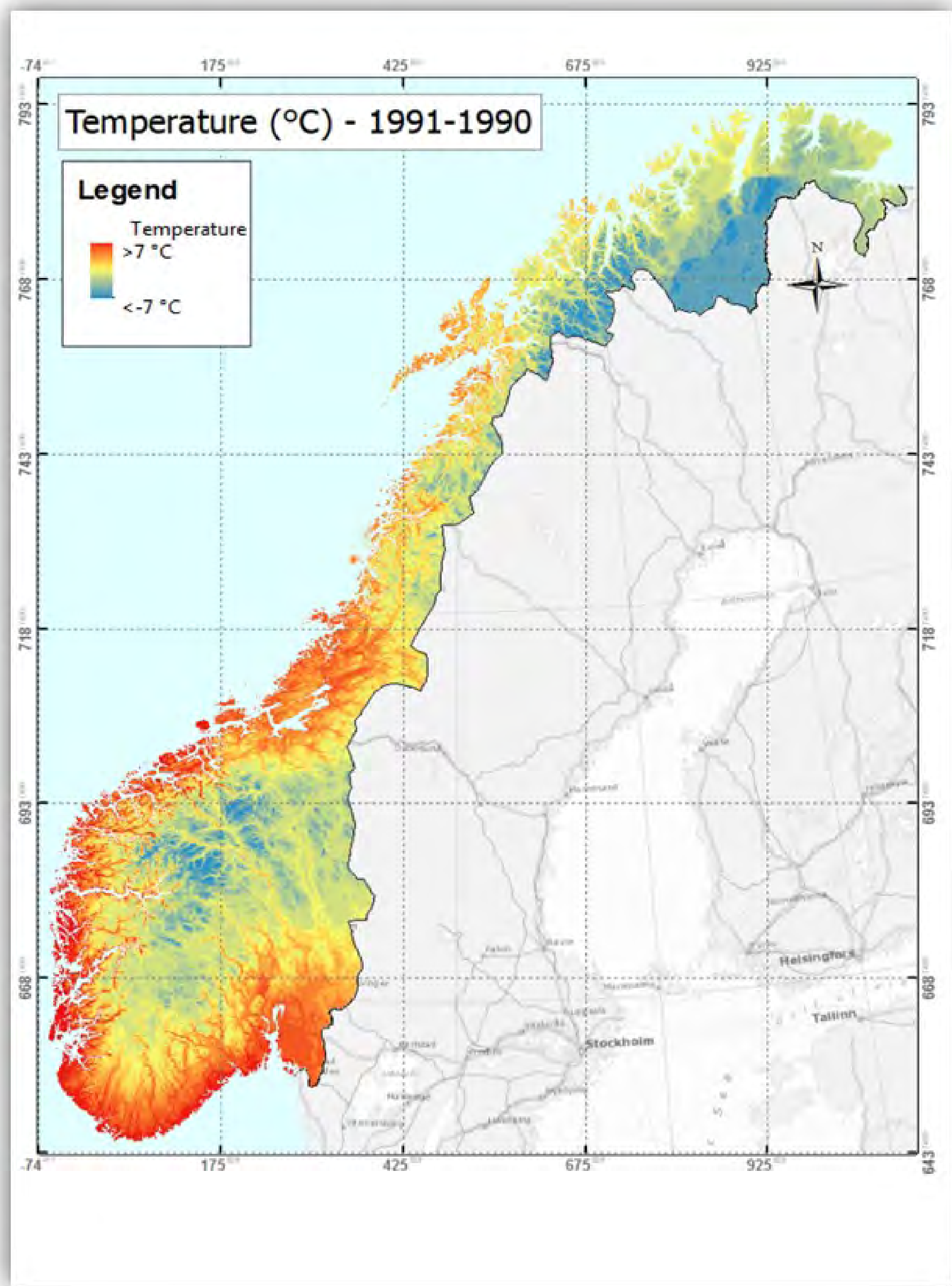


Climatic regions based on Köppen classification. Source: www.met.no

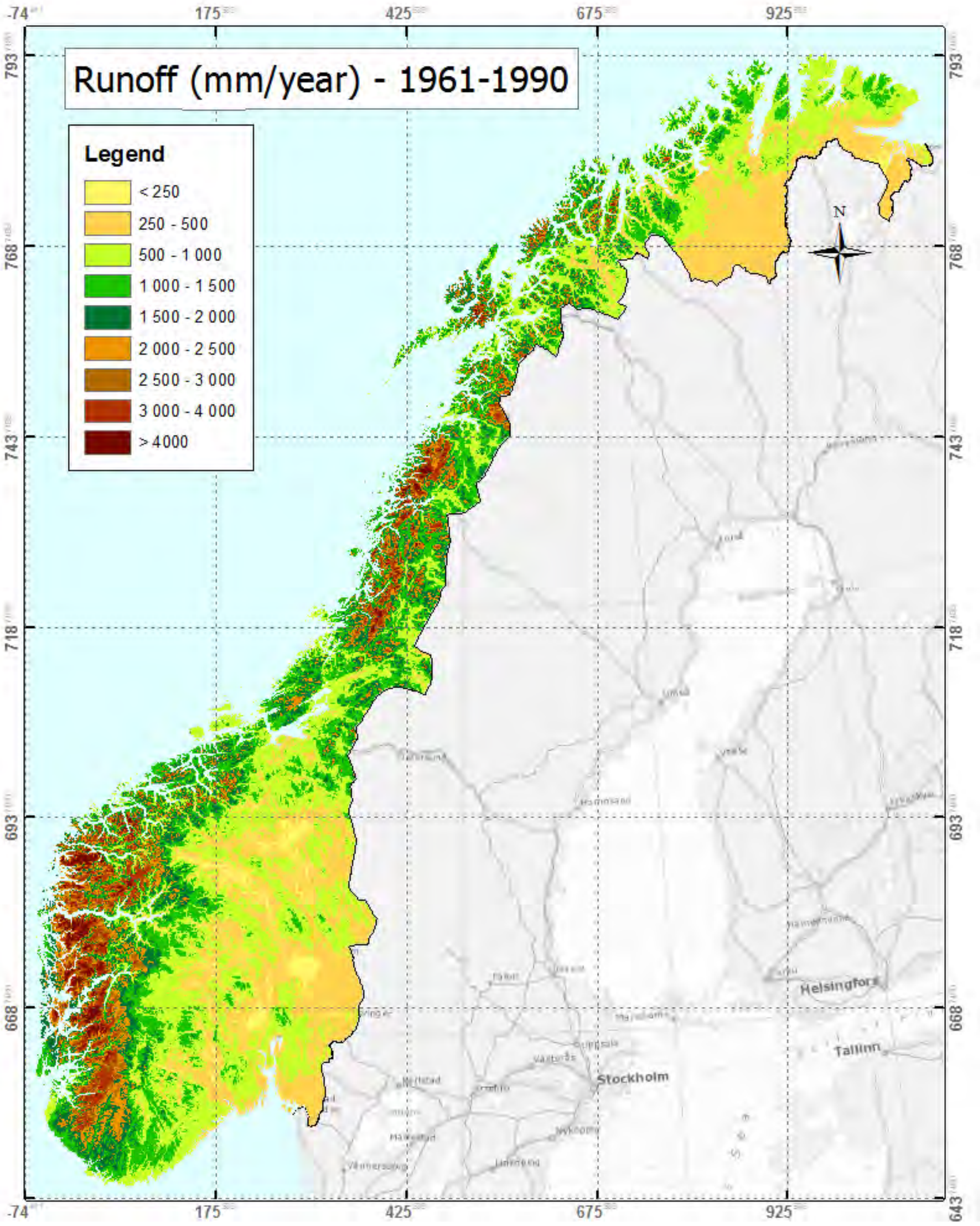
(English legend: C: Warm-Temperate Climate; D: Cold-Temperate Climate E: Polar Climate)



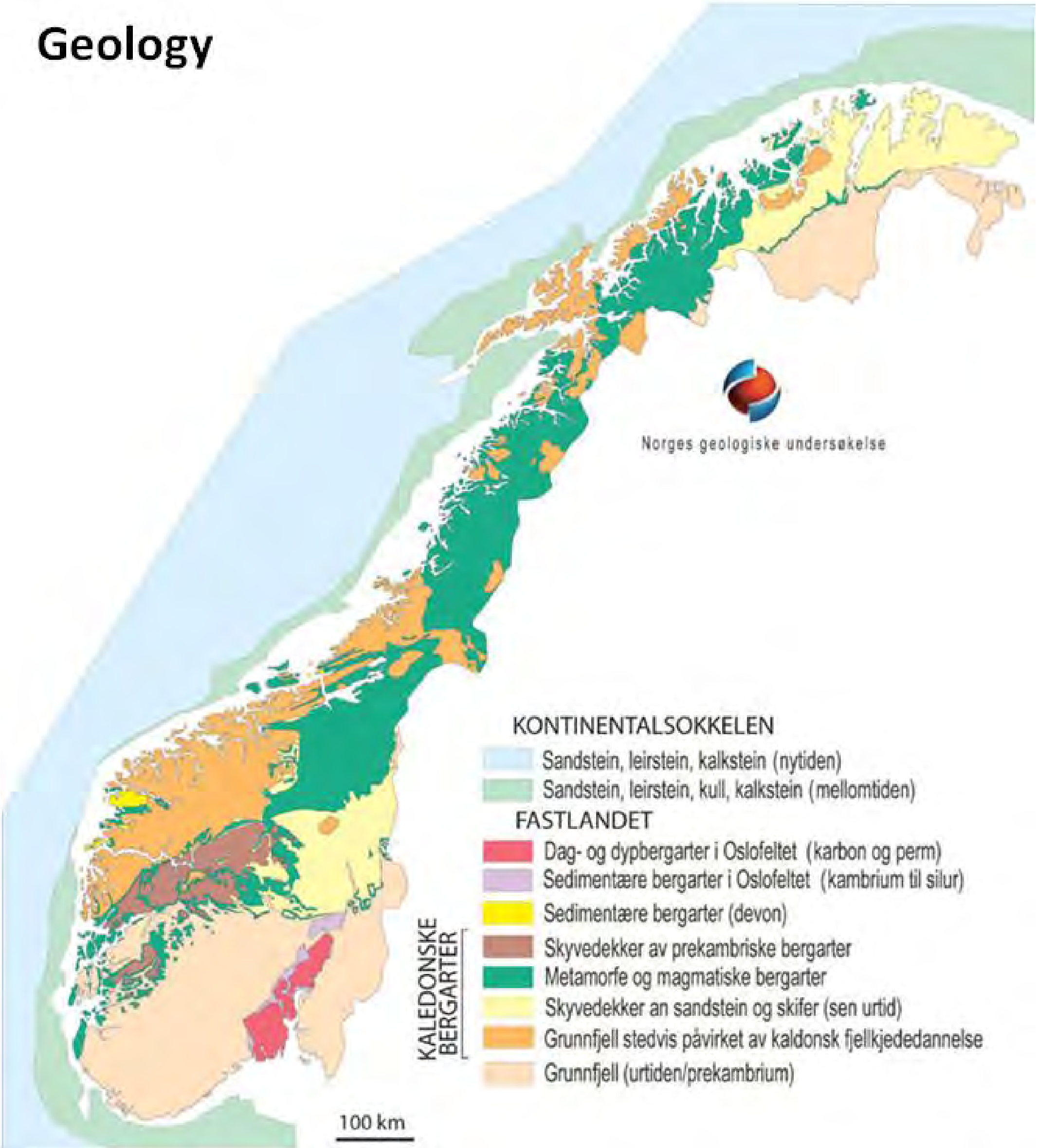
Source: www.met.no and senorge.no



Source: www.met.no and senorge.no

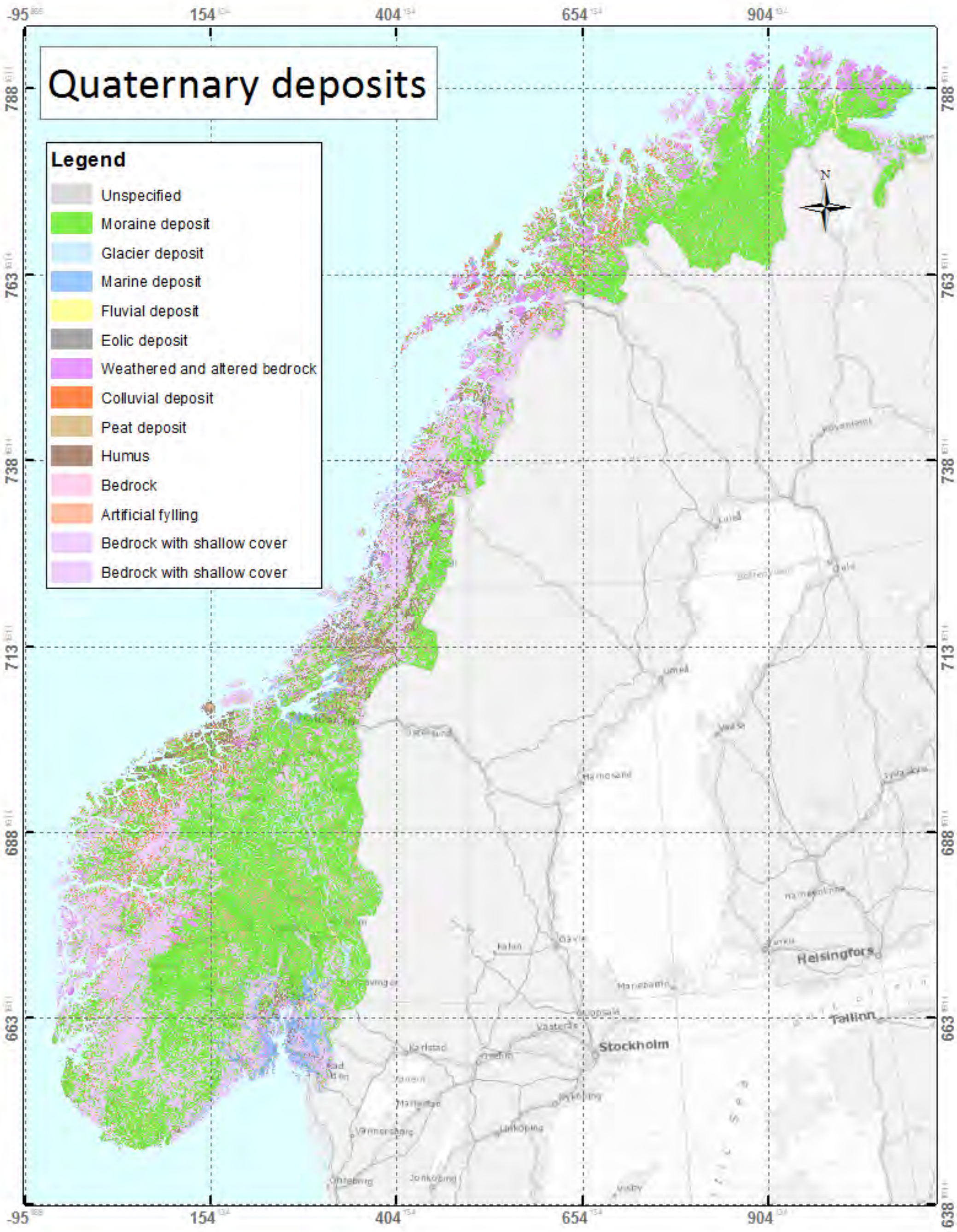


Source: www.nve.no



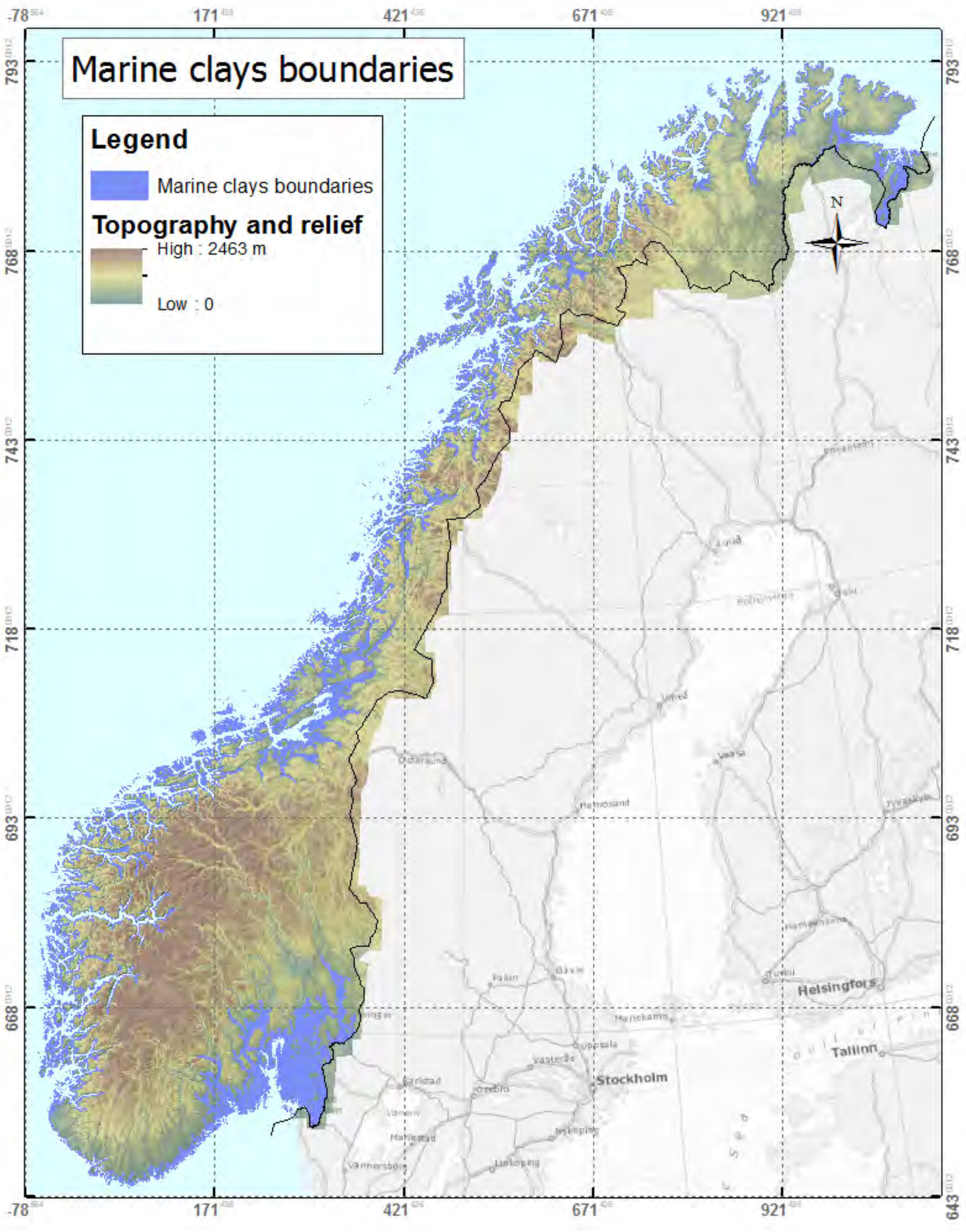
Simplified geological map. Source: www.ngu.no

A-12

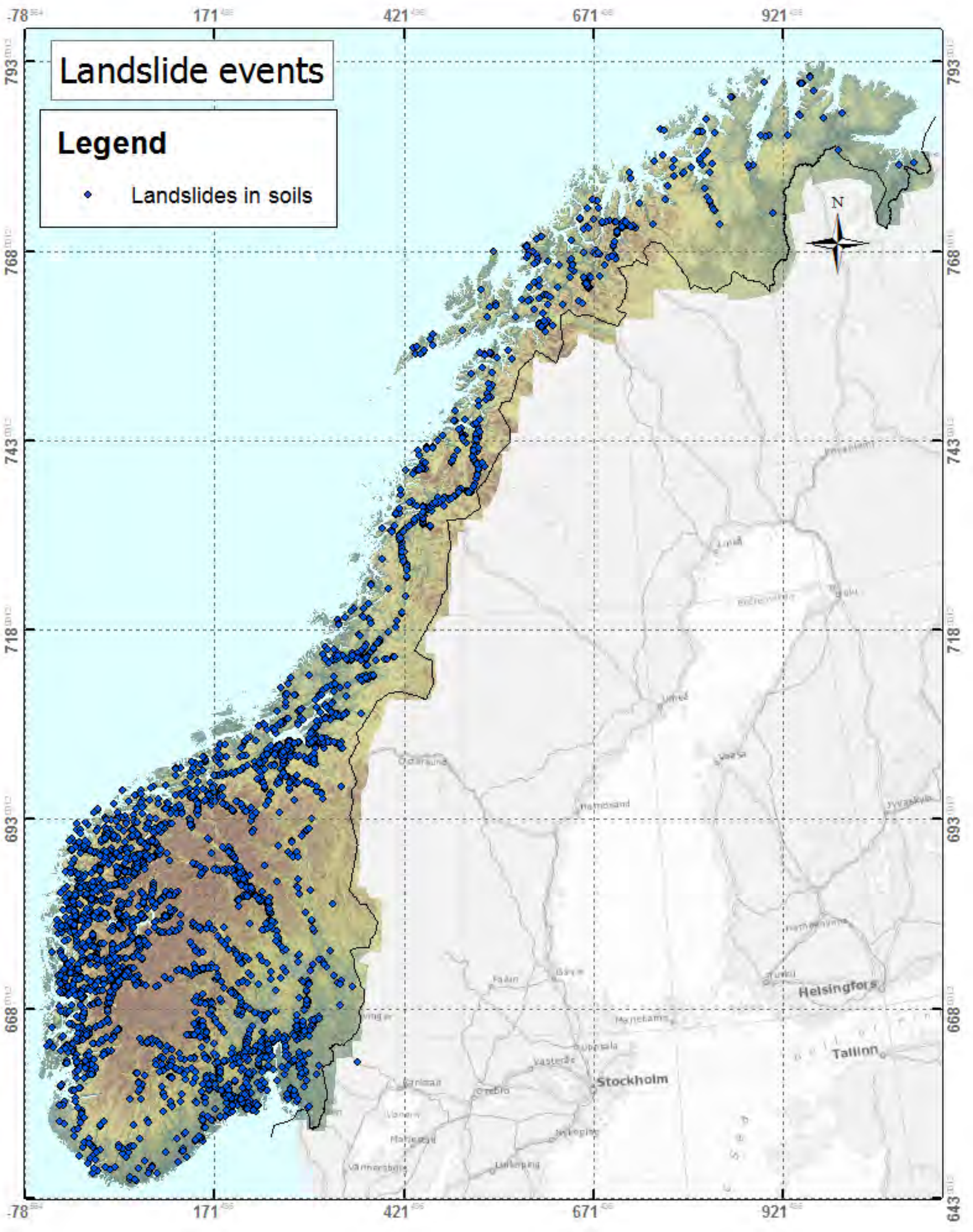


Source: modified from www.ngu.no

A-13

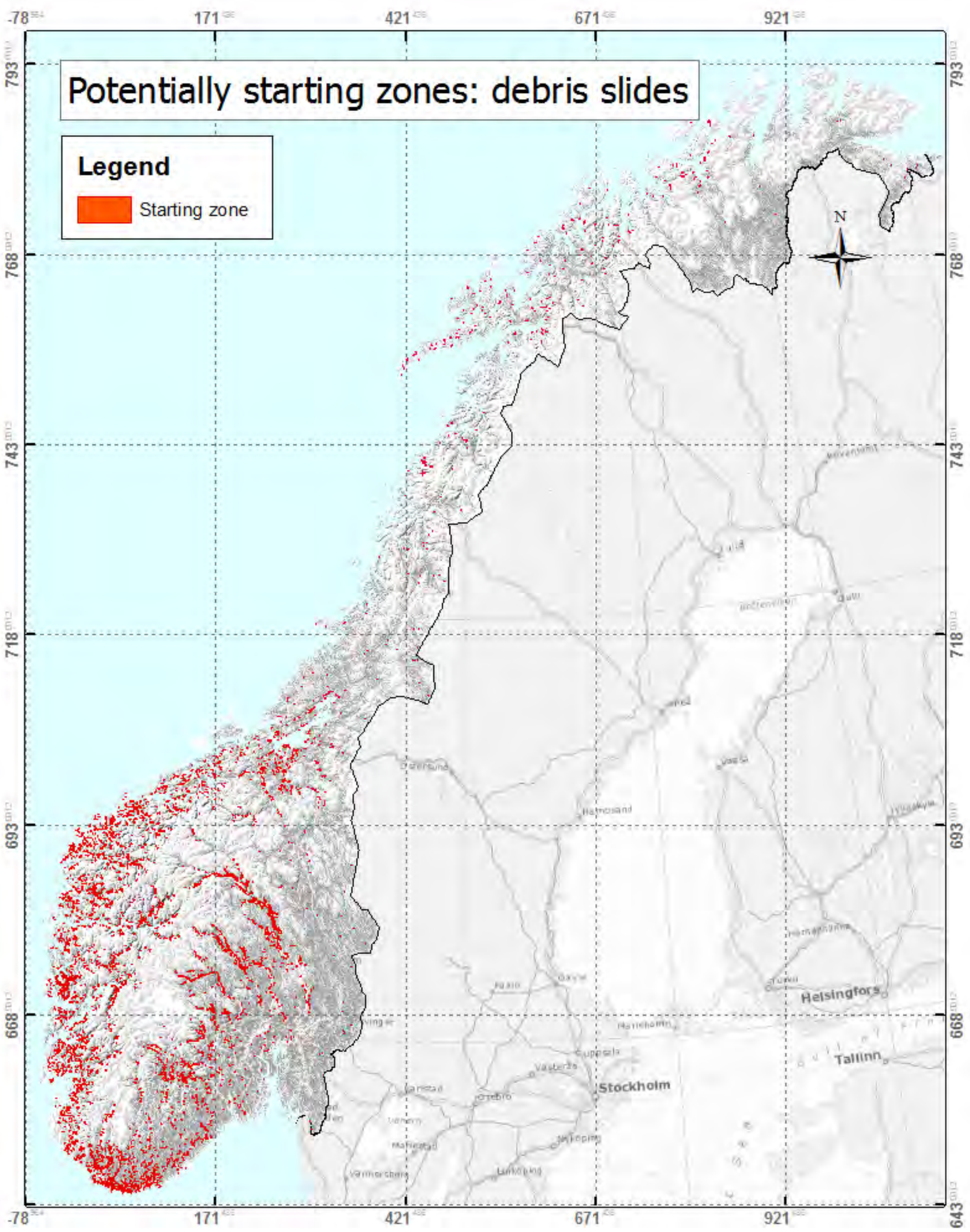


Source: www.ngu.no



Source: modified from www.skrednett.no

A-15

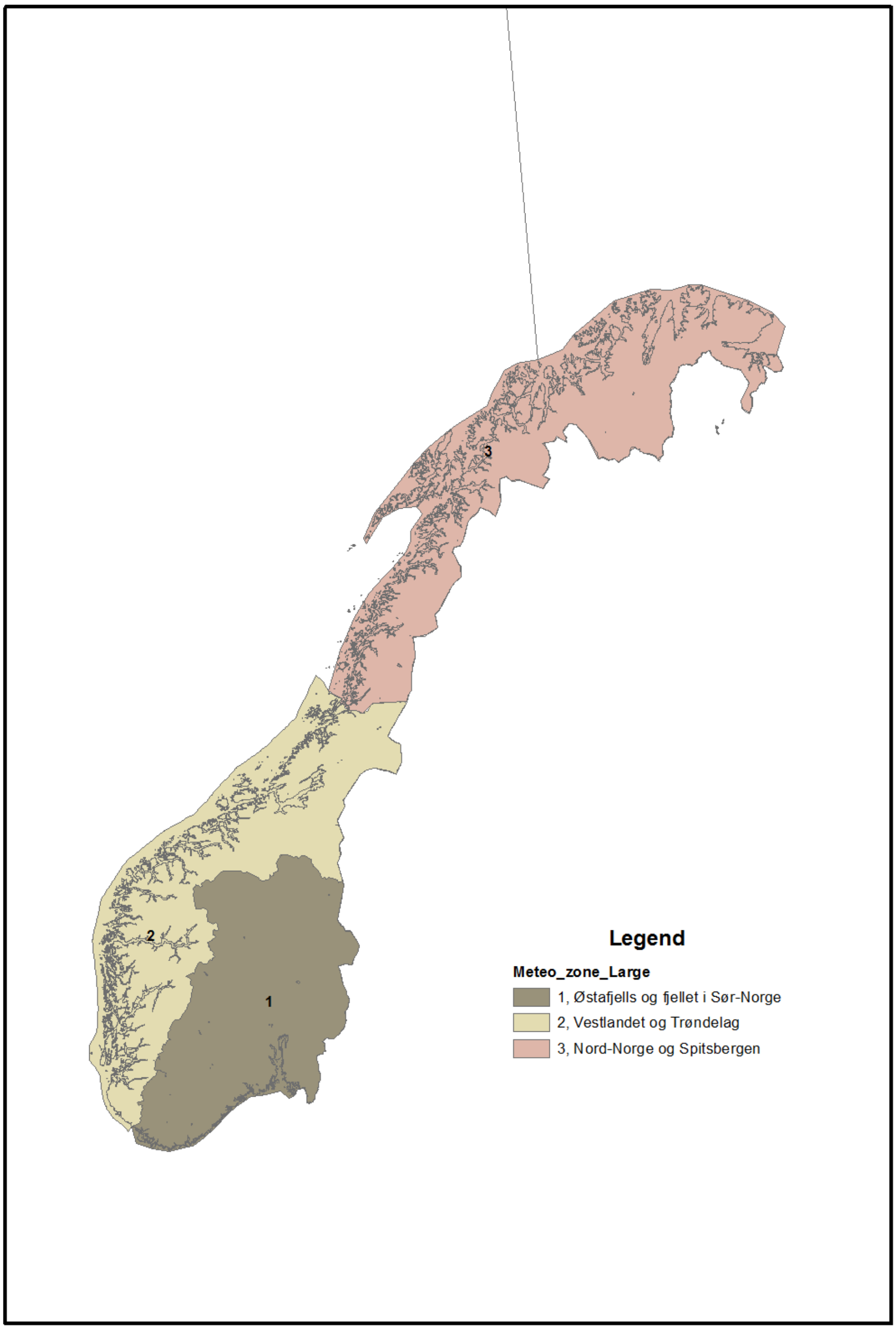


Preliminary landslide susceptibility analyses close to inhabited areas at national level.

Source: Bargel T., Fergus T.Å., Devoli G., Orvedal K., Peereboom I., Øydvin E.K., Stalsberg K.,Sletten K., Fischer L., Rubensdotter L., Eilertsen R. (2011) - Plan for skredfarekartlegging. Delrapport jordskred og flomskred. NVE Report nr 16/2011.

Appendix B - Existing regionalizations

B-1

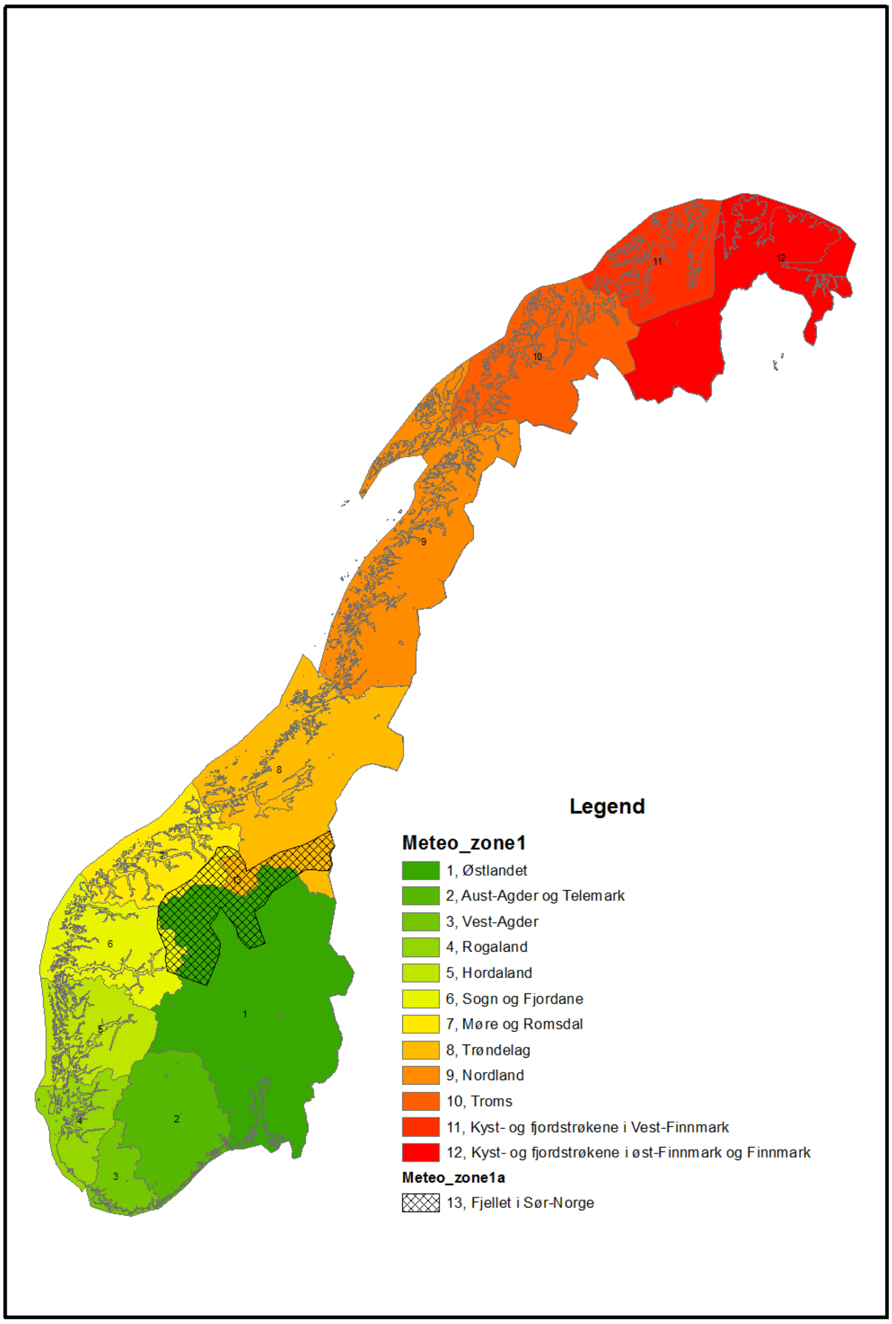


Regionalization for meteorological purposes. 3 regions. This division visualized the areas of 3 main offices of the Meteorological institute (Blinder, Bergen and Tromsø) responsible for weather forecasts. Prepared during the project Geoextreme in 2005 (www.geoextreme.no)

B-2

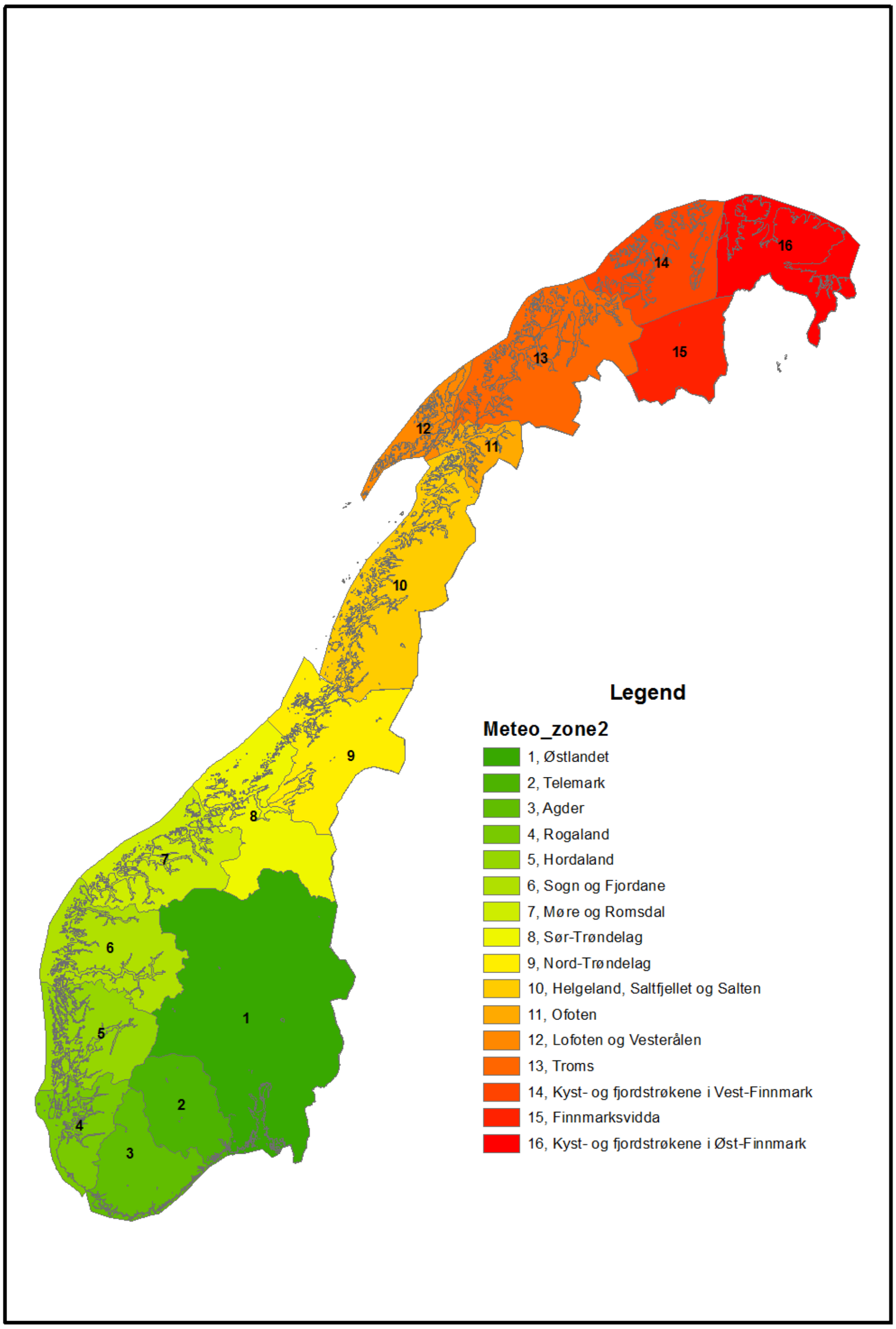
Regionalization for meteorological purposes. 5 regions

Source: www.met.no



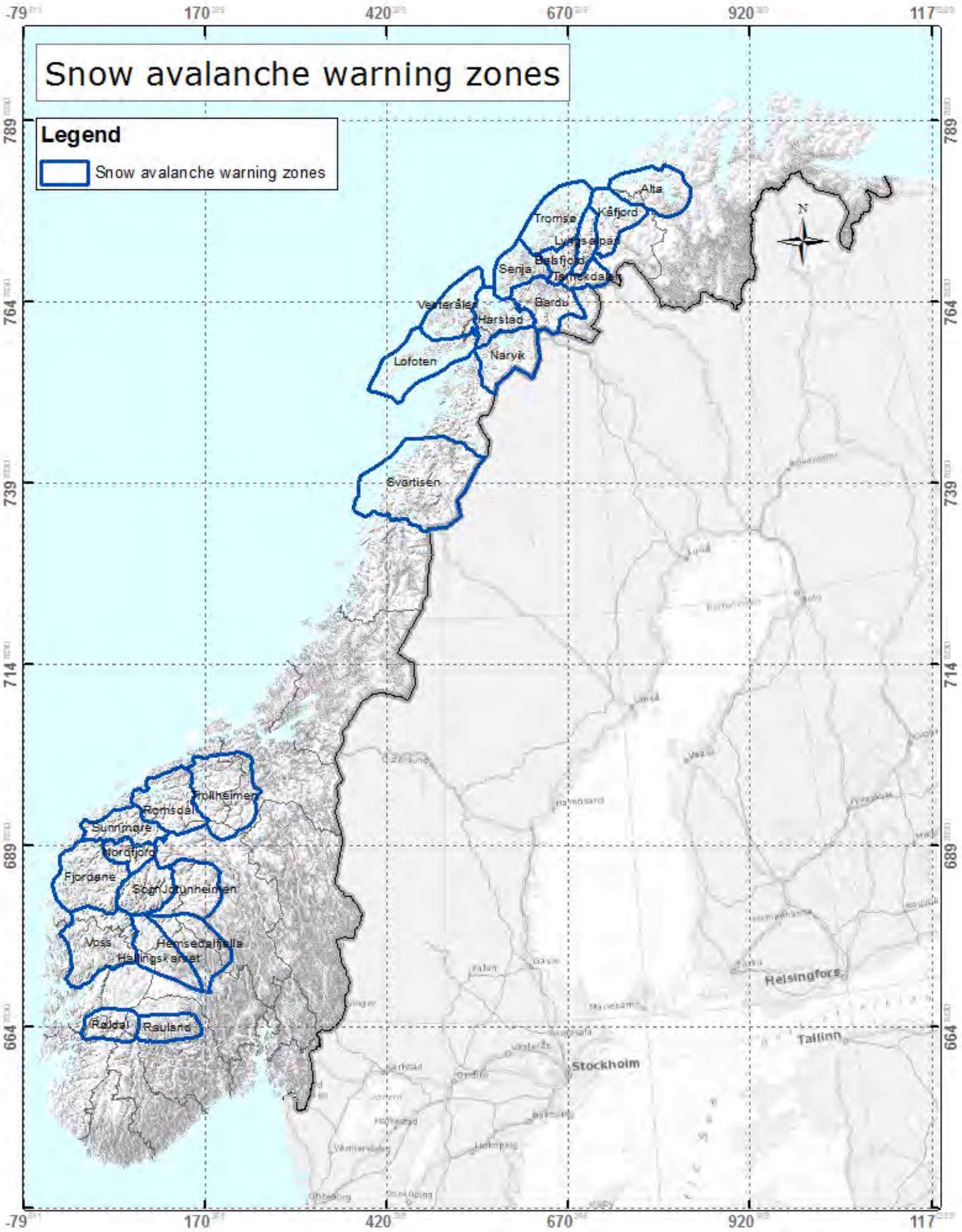
Regionalization for meteorological purposes. 13 regions.

Prepared during the project Geoextreme in 2005 (www.geoextreme.no)



Regionalization for meteorological purposes. 16 regions.

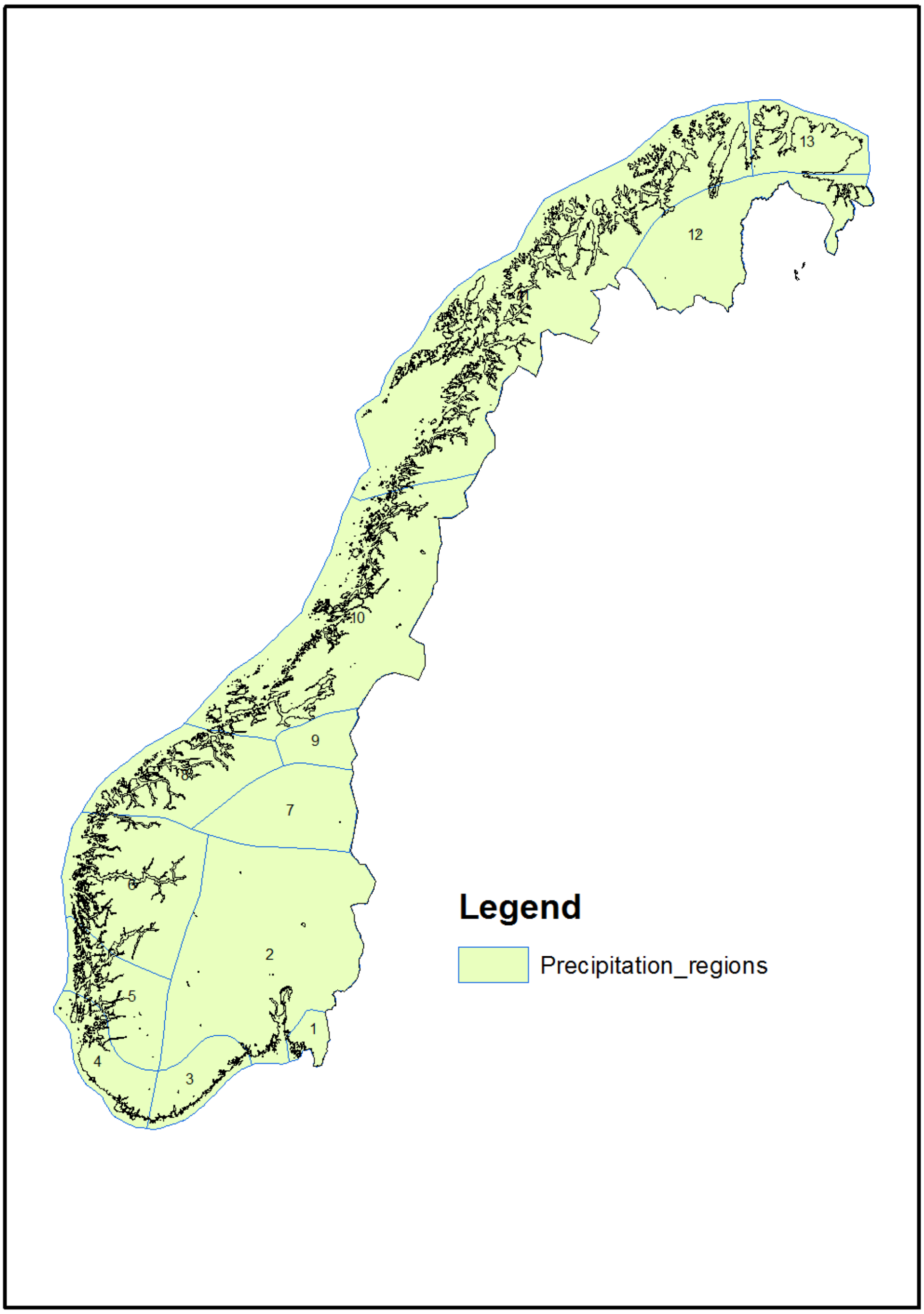
Prepared during the project Geoextreme in 2005 (www.geoextreme.no)



Warnings zones used for snow avalanche early warning

Source: xgeo.no; www.nve.no

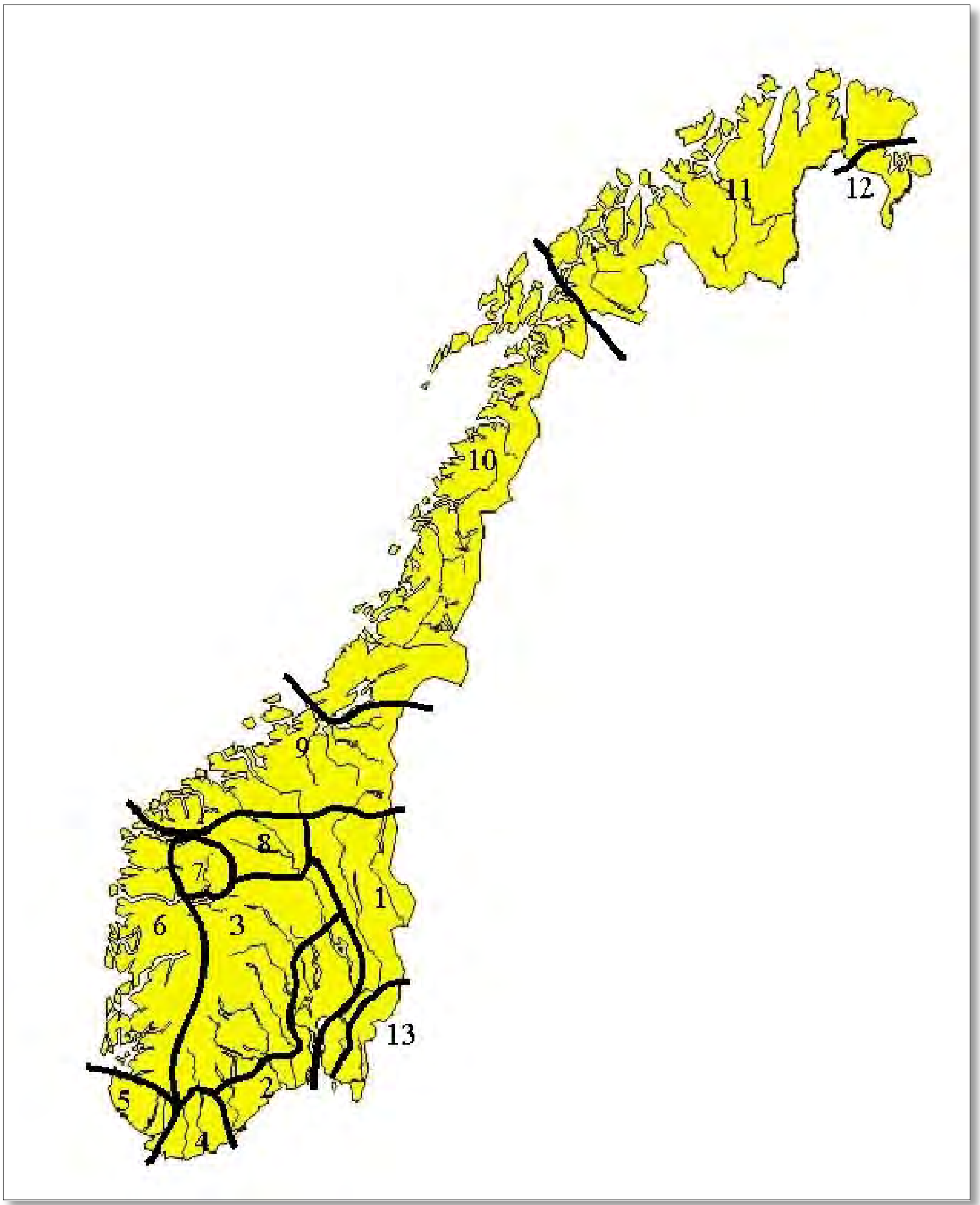
B-6



Precipitation regions

Souce: Hanssen-Bauer, I, and E. J. Førland, 1994: Homogenizing Long Norwegian Precipitation Series. J. Climate, 7, 1001–1013.

B-7



Runoff regions

Source: Førland. E.J., L.A. Roald, O.E. Tveito, & I. Bauer-Hanssen, 2000, Past and future variations in climate and runoff in Norway. DNMI Report no. 19/00 KLIMA

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