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Regional landslide forecasting in Piemonte (Italy) and in Norway: experiences from 2013 late spring

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Abstract. A few countries in the world operate systematically national and regional forecasting services for rainfall-induced landslides (i.e. shallow landslides, debris flows and debris avalanches), among them: Norway and Italy. In Norway, the Norwegian Water Resources and Energy Directorate (NVE) operates a landslide forecasting service at national level. A daily national hazard assessment is performed, describing both expected awareness level and type of landslide hazard for a selected warning region. In Italy, each administrative region has its own regional environmental agency (Regional Agency for Environmental Protection, ARPA) that is responsible of the daily landslide hazard assessments and emission of landslide warnings for one or more catchments within the region. One of these agencies, the ARPA Piemonte, is responsible for issuing landslide warnings for the Piemonte region, located in Northwestern Italy. Both services provide regular landslide hazard assessments founded on a combination of quantitative thresholds and daily rainfall forecasts together with qualitative expert analysis. Daily warning reports are published at http://www.arpa.piemonte.gov.it/rischinaturali and www.varsom.no.

On spring 2013, the ARPA Piemonte, and the NVE issued warnings for hydro-meteorological hazards due to the arrival of a deep and large low-pressure system, called herein “Vb cyclone”. This kind of weather system is known to produce the largest floods in Europe. Less known is that the weather type can trigger landslides as well. In this study, we present the experiences acquired in late spring 2013 by NVE and ARPA Piemonte.

From 27th April to 19nd May 2013, more than 400 mm rain in Piemonte caused severe floods and diffused landslides. In Norway, the same weather type lasted from 15th May to 2nd June 2013 and brought warm winds with high temperatures that caused intense snow melt over a large area, and brought a lot of rain in the Southeastern Norway, initiating large flood along Glomma river and several landslides. Floods and landslides produced significant damages to roads and railways along with buildings and other infrastructure in both countries.

1 Introduction

The Sendai Framework (UN, 2015) clearly emphasizes the need for enhancing multi-hazard early warning systems, preparedness, response, recovery, rehabilitation and reconstruction, in order to prevent new and reduce existing disaster risk. Furthermore, response actions must be focused within and across sectors, by States, at local, national, regional and global level. One of the target proposed, in the framework, is to increase substantially the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030 (UN, 2015). Many countries have started to move toward the realization of this task, some of them already long before 2015.

The spatial occurrence of certain types of landslides (especially rainfall- and snowmelt-induced landslides) could be forecasted in advance, through combined regional and local early warnings in certain regions, given our understanding of the interactions between precursors and triggers. Early warning systems (EWS) for rapid mass movements have become essential elements of integral risk management worldwide and an overview of the existing systems is available in Stähli et al. (2015) and Calvello (2017). EWS can be divided in local and territorial (Calvello, 2017) or in three main categories: (i) alarm, (ii) warning and (iii) forecasting (Stähli et al., 2015). Most of them, have been designed to forecast rapid mass movement, mainly rainfall- and snowmelt induced landslides that, annually, cause significant economic damages. Many local early warning systems exist at specific sites where extensive monitoring instrumentation provides detailed information, while a few countries systematically operate national/territorial early warning systems for landslides (mainly constrained to shallow landslides).

Rainfall- and snowmelt induced landslides (i.e. shallow slides, debris avalanches, debris slides, debris flows and slushflows) cause dramatic impacts on society, and these could be potentially enhanced under a changing climate (Stoffel et al., 2014; Gariano and Guzzetti, 2016). Norway and Italy have a long tradition of flood forecasting, but only in relatively recent years, they have spent efforts to design, develop and operate landslide forecasting services, often in synergy with flood and/or snow avalanche forecasting. The ARPA Piemonte landslide warning system start to be operational in 1994, while the Norwegian landslide forecasting service, since 2013. Both services use different spatial scales and technologies, but they have a main purpose to alert people to imminent hazards and allow them to get to safety.

Other European countries are developing local or regional warning systems and they are dealing with the same challenges, however little collaboration or exchange of experience exist among groups. Quite often each forecasting service focuses on the analysis of the climatic and meteorological conditions in their own region, forgetting that the precipitation can be part of larger processes that can affect many countries at the same time. Rainfall-induced landslides are not necessary isolated events or restricted to a specific country, but they may have a regional distribution. As example, we can mention the landslides triggered by Hurricane Mitch in 1998 across the Central America countries (i.e. Bucknam et al., 2001; Cannon et al., 2002) or the landslides triggered by the storm Desmond the 4th and 5th December 2015 in UK and in Norway (Dijkstra et al., 2016; Boje et al., 2016). The purpose of this study is to present the landslide forecasting experiences from Northwestern Italy and Norway under the same meteorological condition, in order to better understand the meteorological process and the associated secondary hazards like floods and landslides and promote the exchange of knowledge and collaboration during future similar events.

2 The Vb cyclones

Floods and landslides are important secondary effects of high-impact weather events, like tropical and extra-tropical cyclones, as they are accompanied by extremely strong winds and heavy precipitations. In particular is Central Europe and the northern Alpine region a source of high-impact events associated to the Vb cyclones (Messmer et al., 2015). This type of cyclone was mentioned by Köppen (1881) and later defined by Van Bebber (1882; 1891), who proposed a cyclones classification based on the main storm circulation trajectories in Europe (Messmer et al., 2015; Roald, 2008). One of the trajectory described was named Vb. This track is called "Vb-tief" by Roald (2008). In latter classifications like the GWL/SVG classification proposed by James (2007) this synoptic weather regime is known as 11 TM «Tief Mitteleuropa=Low (Cut-Off) over Central Europe», while in the GWT classification is known as "TME Central European low" (Jørandli, 2016).

The origin of Vb cyclones is either the Bay of Biscay, the Balearic or the Ligurian Sea, where moisture uptake occurs. The cyclone moves eastward over the southwestern part of France and over the Mediterranean Sea, where it refills with moisture and energy. Then, Vb cyclones move across Northern Italy and the Adriatic Sea before they turn northward to the Black Sea or Saint Petersburg and later North-West (**Fig. 1**). They are characterized by very warm and humid air masses from the central Atlantic and Mediterranean streaming around the eastern parts of the Alps, towards northwest, with cold air masses linked to depressions further west forming a quasi-stationary front with extremely heavy rainfall. The synoptic configuration is linked to blocking anticyclones in the North Atlantic and over Finland or the Kola Peninsula. This type of weather is typical in July or August, but in recent years it was observed in late spring (May, June).

The Vb cyclones have been studied by many authors and some of these works have been summarized in Messmer et al. (2015). Most of these studies have presented case studies of floods induced by Vb cyclones, and focusing on analyzing the source of moisture, while few studies focus on analyzing the decrease or increase of number of cyclones. A description of the basic climatology of this weather type is provided in Messmer et al. (2015), given insight into the Vb cyclones variability and investigating their physical mechanisms.

These cyclones transport large amounts of atmospheric moisture to the central Europe and northerly side of the Alps, thus triggering extreme precipitation events (Messmer et al., 2015). The potential of transporting extreme precipitations to central Europe is especially high if these cut-off low systems are positioned in the northern or eastern parts of the Alps (Awan and Formayer, 2016). There is agreement among authors on the large-scale dynamics of Vb events, which indeed seem to determine whether a Vb cyclone delivers high precipitation or not (Messmer et al., 2015). Even if they are rare events, 2.3 per year (Messmer et a., 2015), the Vb cyclones are highly relevant for Europe because of their potential to produce extensive precipitation and subsequent floods, particularly, during the warm season, and often in Austria, Switzerland, Germany, Poland and the Czech Republic. The Vb cyclones are well known, among hydrologists and meteorologists, to have caused most of the largest floods in Central Europe, in the Elbe, Danube, or the Rhine catchments and in the Alpine area, like the: "1000-year flood" in 1342 in rivers Elbe, Danube, and Main; the Oder flood in July/August 1997; the flood in Elbe and Danube in August 2002; the floods in Austria and Switzerland in August 2005. Less mentioned in international literature is the fact that this type

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of weather is responsible of extensive floods events and of triggering landslides also in the southern sector of the Alps and in Norway. Roald (2008; 2013, 2015) documented many flood events caused by Vb cyclones in southeastern Norway, like the July 1789 Storofsen flood, the 1860 flood and the Pinseflom flood in June 2011, among others. A recent study by Jørandli (2016) and Devoli et al (2017) also confirmed that Vb cyclones are the most typical weather type capable of triggering landslides in the southeastern Norway, often in association with large floods.

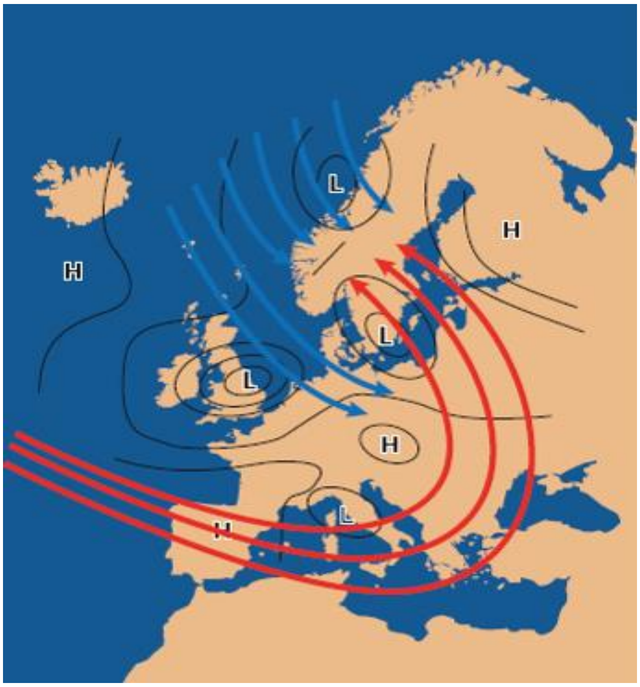


Fig. 1: Southern type of weather: Vb trajectory. Where "H" is high-pressure and "L" is low-pressure.

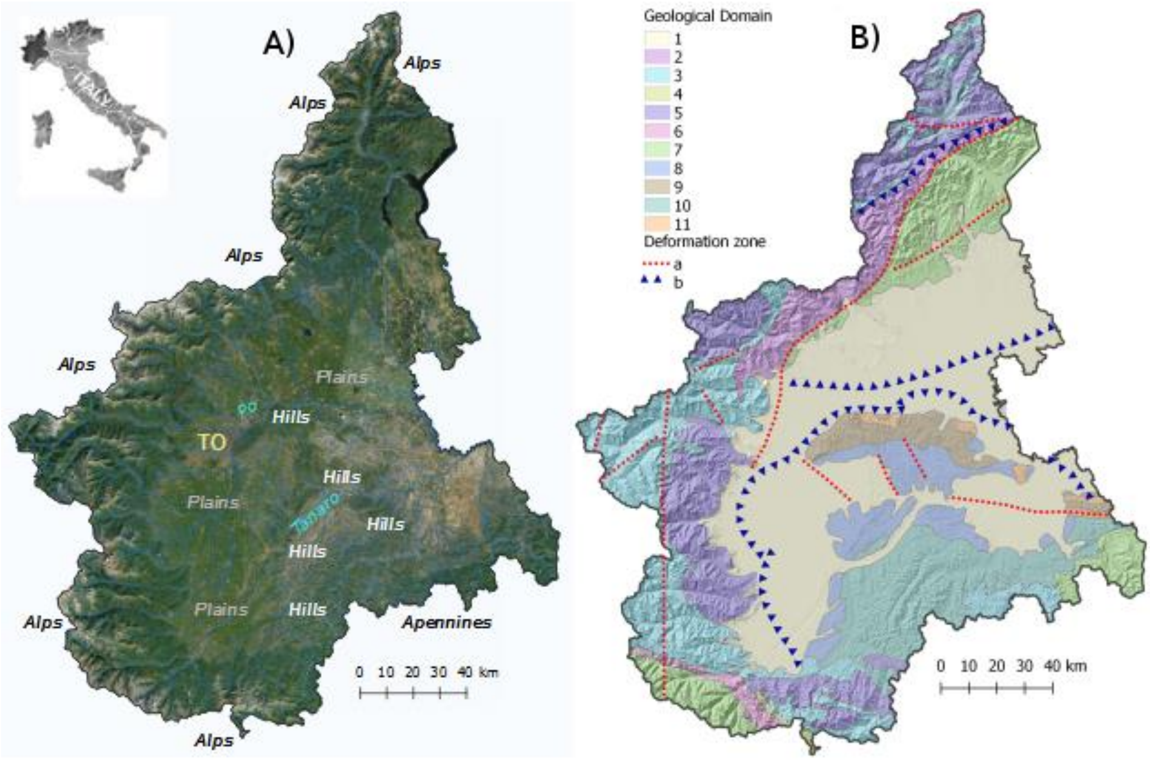
3 Study area

In this study, we analyze the effect of the Vb condition in two areas in Europe: Piemonte region, in northwestern Italy, and Østlandet region in southeastern Norway.

3.1 Piemonte region, Italy

Piemonte region is complex from a geomorphological and geological point of view. Its territory is shaped by mountain environments (Western Alps and subordinate Apennine with a peaks ranging from 1000 to 4800 m asl), hills (Torino Hill, Monferrato hills and Langhe with an elevation range of 400-700 m asl), and alluvial plains (200-300 m asl), surrounded by the Alps and Apennines on three sides (**Fig. 2a**). The Western Alps are characterized by a complex double-verging structure with asymmetrical transversal cross-section (Roure et al., 1990, 1996; Pfiffner et al., 1997), subdivided into three main structural sectors. (1) Southalpine domain characterizes the Internal sector (the collisional system upper plate consists in Hercynian and pre-Hercynian bedrock formed by lower continental and upper mantle rocks). (2) Helvetic–Dauphinois domains constitute the External sector, representing the European foreland zone, formed by Hercinian intrusive massifs system and Mesozoic flysch cover. (3) frontal thrust of Pennidic domain and the Insubric front (Malusà and Vezzoli, 2006) bound the Axial sector formed by Hercynian and pre-Hercynian continental rocks and Hercynian metasedimentary formations, oceanic lithosphere rocks and ocean fronting continental boundaries and orogenic flysch units. During the Quaternary, wide glaciers occupied alpine valleys and modeled by glacial pulsations. Locally, glacial landforms and deposits were modified by Holocenic fluvial/torrential processes, associated with widespread landslides (Soldati et al., 2006).

The geology of hilly environment is mainly formed by Oligocenic-Miocenic sedimentary strata, originated during the Tertiary Piemonte Basin where the lowest term of sedimentary sequence is formed by shallow-sea deposits, while deep marine environment (turbidite deposits up to 4 km thickness) represents the upper part of the sedimentary sequence. The stratigraphic succession is due to Oligocene marine transgression made by the alternation of marls, sandstones and shales (about 5-50 cm thickness); strata dipping NW with 8°-15° inclination. Sin-sedimentary tectonics controlled the thickness and lateral interdigitations of the stratigraphic successions. The northward movement of the Padan thrust belt (Falletti et al. 1995) caused the progressive uplifting of the basin followed since Langhian. The sedimentary sequence lies on alpine metamorphic units by unconformity (Biella et al. 1987, 1992; Gelati and Gnaccolini 1988). Appennine units are poorly represented within the borders of Piemonte, mainly represented by Ligurian, Subligurian and Epiligurian units (**Fig. 2b**).



Figu. 2: A) Physiography of Piemonte; B) Geological/structural sketch map of Piemonte: 1. Quaternay; *ALPS*: 2. Austroalpine domain (pre-Alpine crystalline basement and Palaeozoic cover); 3. Pennidic domain (Permian–Mesozoic–Tertiary metamorphic cover; 4. Pennidic domain (Helminthoid Flysch Units); 5. Penninic domain (pre-Triassic crystalline basement); 6. Helvetic domain (Permian–Mesozoic cover); 7. Helvetic domain (pre-Alpine crystalline basement and Carboniferous cover); *APENNINE and HILLS:* 8. Internal margin foredeep deposits; 9. Epiligurian Sequences (episutural basins deposits unconformably covering the Ligurian units); 10. Epiligurian Sequences (“Oligo-Miocene” of Langhe); 11. Ligurian and Subligurian Units (nappes, locally ophiolitic-bearing); a. Front of tectonic units (limits of different paleogeographic domains); b. Neotectonic deformation zones.

The spatial distribution of annual rainfall shows high precipitation in the northern areas with more than 2,100 mm per year, and low in the eastern part of the plains with less than 700 mm per year (**Fig. 3**). The monthly distribution of precipitations in Piemonte shows a bimodal distribution, with two highs during spring and fall, and two minimums, during winter and summer. Four rainfall regimes (three continental ones and one Mediterranean) can be distinguished;

- Prealpine: dry season during winter, main maximum during spring and secondary maximum during fall;
- Subcoastal: dry season during summer, main maximum during fall and a secondary maximum during spring;
- Subalpine: dry season during winter, main maximum during fall and secondary maximum during spring;
- Subcontinental: dry season during winter, main maximum during fall and a secondary maximum during summer.

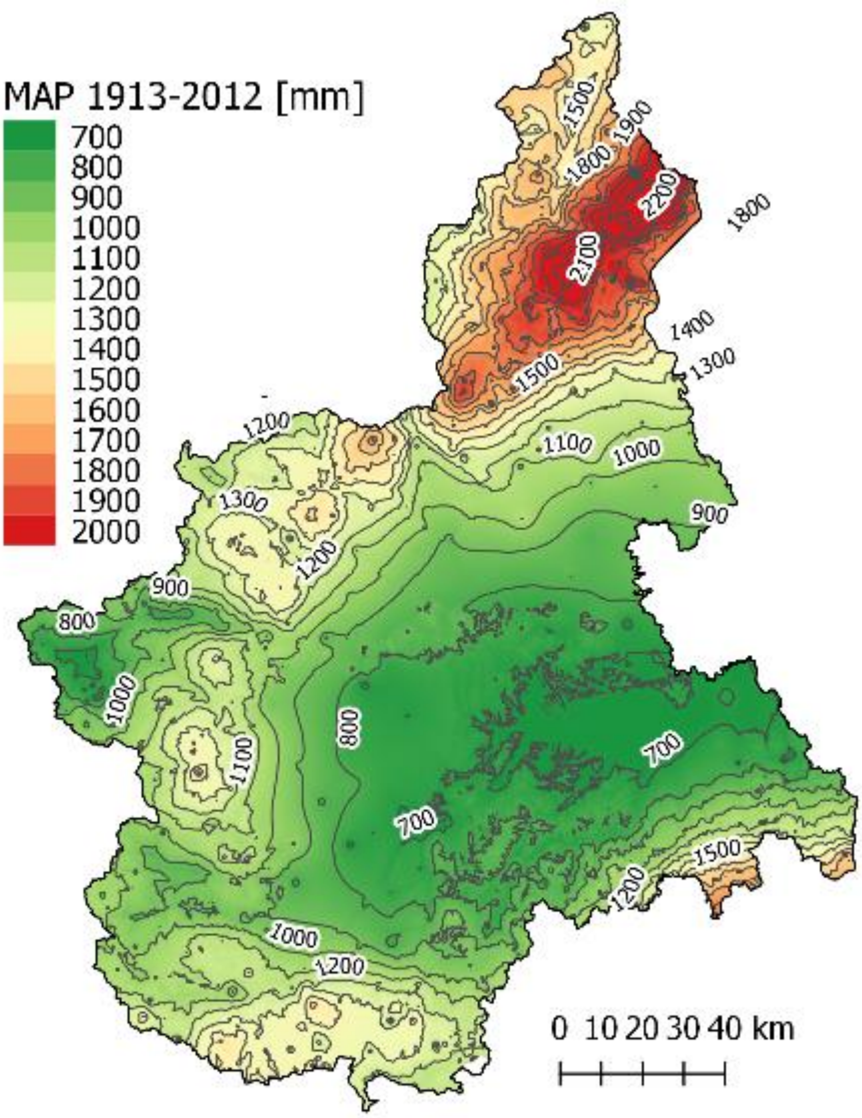


Fig. 3: Mean Annual Precipitation (MAP) in Piemonte from 1913 to 2012 (source: Arpa Piemonte).

3.2 Østlandet region, Norway

The herein so-called Østlandet region in southeastern Norway has also a complex geomorphological and geological setting. The region includes eight administrative counties (**Fig. 4a**). The highest mountains are located in the northern and western part of the area with maximum elevations up to 2469 m. asl, observed in the Jotunheimen area. The region is mostly hilly, with dominant landforms represented by glacially scoured valleys directed N-S in the eastern sector, while NW-SE in the western sector that congregate on to the Oslofjord. The valleys Østerdalen and Gudbrandsdalen are the longest in the country. The region contains also some very large areas of lowland surrounding the Oslofjord. The longest river and watercourses, Glomma, and the biggest lake, Mjøsa, are also located in this region (Devoli and Dahl, 2014). Southeastern Norway contains extensive areas with forest and rich arable land. From a geological point of view, this region is dominated by bedrock of the Baltic shield, characterized by Precambrian basement rocks (e.g. granites, granodiorite, gneisses, amphibolites, rhyolite, gabbro, diorite and meta-sediments). In the northern sector rocks within the Caledonian orogen (e.g. sandstone, schist, amphibolite, micaschist, phyllite conglomerate) prevail. Cambro-Silurian sedimentary rocks (e.g. shale, limestone, phyllite) and Permian volcanic rocks (syenite, granite monzonite, porphyritic rocks and basalt) occur within the Oslo Graben (Solli and Nordgulen, 2006). Quaternary deposits that cover the bedrock are mainly left by glacial processes. Continuous till deposits cover large areas of the hilly mountains and valley sides and floors, with a variable thickness from 0.5 to a couple of meters. The bottom of the valleys is mainly covered by thick fluvial and glaciofluvial deposits. Till deposits have a large heterogeneity in terms of granulometry and composition. The amount and the composition varies as function of the bedrock, in some places the till deposits are covered by landslide deposits occurred after glaciation. Most of the rainfall-induced landslides in the region occur in till deposits, especially where there is a large clay mineral that reduce the water infiltration and provide more surficial runoff. Marine clay deposits are observed in the southern sector of the region, where quick clays slides may form triggered mainly by human activities.

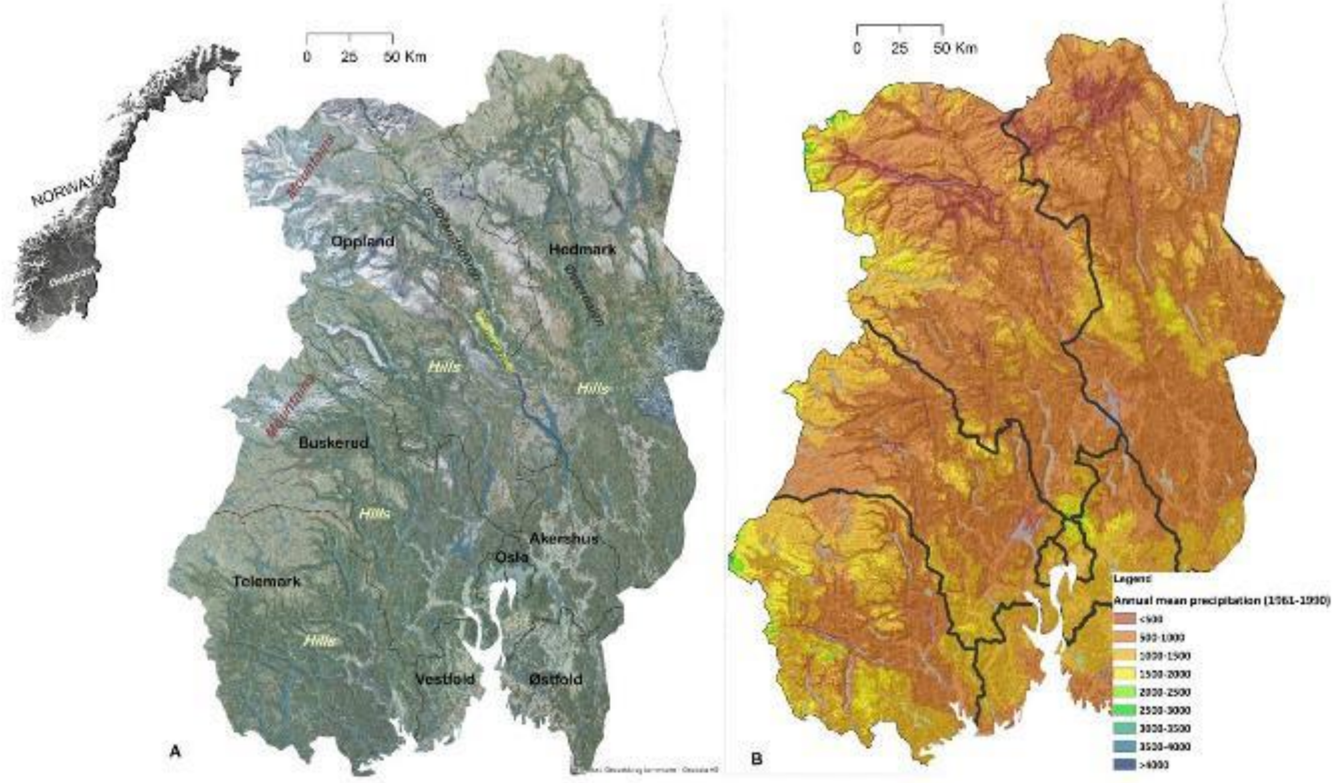


Fig. 4: Østlandet region: A) Physiography; B) Mean Annual Precipitation.

Based on Köppen classification, the climate of the region is varying from a Tundra type (ET) in the Northwestern part, to Subartic (Dfc) in the central part. The Warm-summer humid continental type (Dfb) and Oceanic type (Cfb) are mainly observed in the southern sector and along the southern coastline. In this region, the climate is mainly characterized by cold winter and warm summer. The amount of precipitation in form of rainfall and snow varies depending on the area (i.e. valley floor and mountain), but in general this area is the driest of Norway with low precipitation and mostly during summer. Deficit of precipitation are observed at Skjåk where the annual precipitation is of about 317 mm (water equivalent) or Biri with 754 mm annual precipitation. The area has a normal stable snow cover during winter, with normal annual maximum (1971-2000) around 1000 mm in the mountain. The annual medium temperature ranges from -7°C in the mountain area to 7°C in the coastal area.

4 The landslide forecasting services in Piemonte region and in Norway

Both services are classified as "territorial EWS" by Calvello (2017) and based on Stähli et al. (2015), they can be classified as "Forecasting-type" services because they predict the level of danger of a rapid mass movement processes, typically at the regional scale, focusing on predict the occurrence of multiple landslides over a warning area and at regular intervals. In contrast to warning systems, the data interpretation is not based only on a threshold and it is conducted on a regular basis, e.g., daily. Experts analyze sensor data and consult models to forecast the regional danger levels, which are communicated widely in a bulletin. The main goal of the services is to save lives, reduce landslide risk for roads, railways and settlements, also increasing safety and predictability. In addition to contributing to a better foundation for emergency preparedness at local level, the service provides continuous information on the situation and expected development to national and regional authorities and the public.

4.1 Piemonte's landslide forecasting service

The Regional Warning System for Geo-Hydrological hazards of ARPA Piemonte includes three slope phenomena early warning systems (EWSs) based on empirical rainfall thresholds, designed *ad hoc* for different typology slope processes, whose triggering is generally determined by precipitation with different intensity over different accumulation periods and duration:

- DEFENSE (*DEbris Flows triggEred by storms – Nowcasting SystEm*) is operated to forecast channelized debris flows occurrence in small alpine basins. DEFENSE works by the intersection in GIS environment between alpine catchments, classified by the Clay Weathering Index, and instantaneous rainfall intensity (mm/h) provided by the weather radars using a storm-tracking algorithm (Tiranti et al., 2014).

- SMART (*Shallow landslides Movements Announced through Rainfall Thresholds*) is operated to forecast shallow landslides in mountain area (zone 1) and hilly environments (zone 2) Thresholds equations in the two zones are:

$$I = 25 \cdot D^{-0.45} \quad \text{Zone 1} \tag{1}$$

$$I = 40 \cdot D^{-0.65} \quad \text{Zone 2} \tag{2}$$

Where *I* is the rainfall mean intensity (mm/h) and *D* is the rainfall duration (h). More details are reported in Tiranti and Rabuffetti (2010).

- TRAPS (*Translational/Rotational slides Activation Prediction System*) is operated to forecast deep-seated translational and rotational slides in the hilly environment. TRAPS analyses the 60-days antecedent precipitation measurement including water deriving from snow melting (Tiranti et al., 2013).

ARPA Piemonte daily evaluates EWSs response to issue a regional warning to Civil Protection municipalities and citizens on slope processes occurrence. All the EWSs responses are displayed and managed through a WebGIS interface **(Fig. 5**) that allows a real-time estimation of hazard scenarios induced by observed and forecasted weather conditions. All the EWSs are operative 24h/7d and an automatic warning is issued by e-mail and SMS to experts when the threshold is reached and/or exceeded.

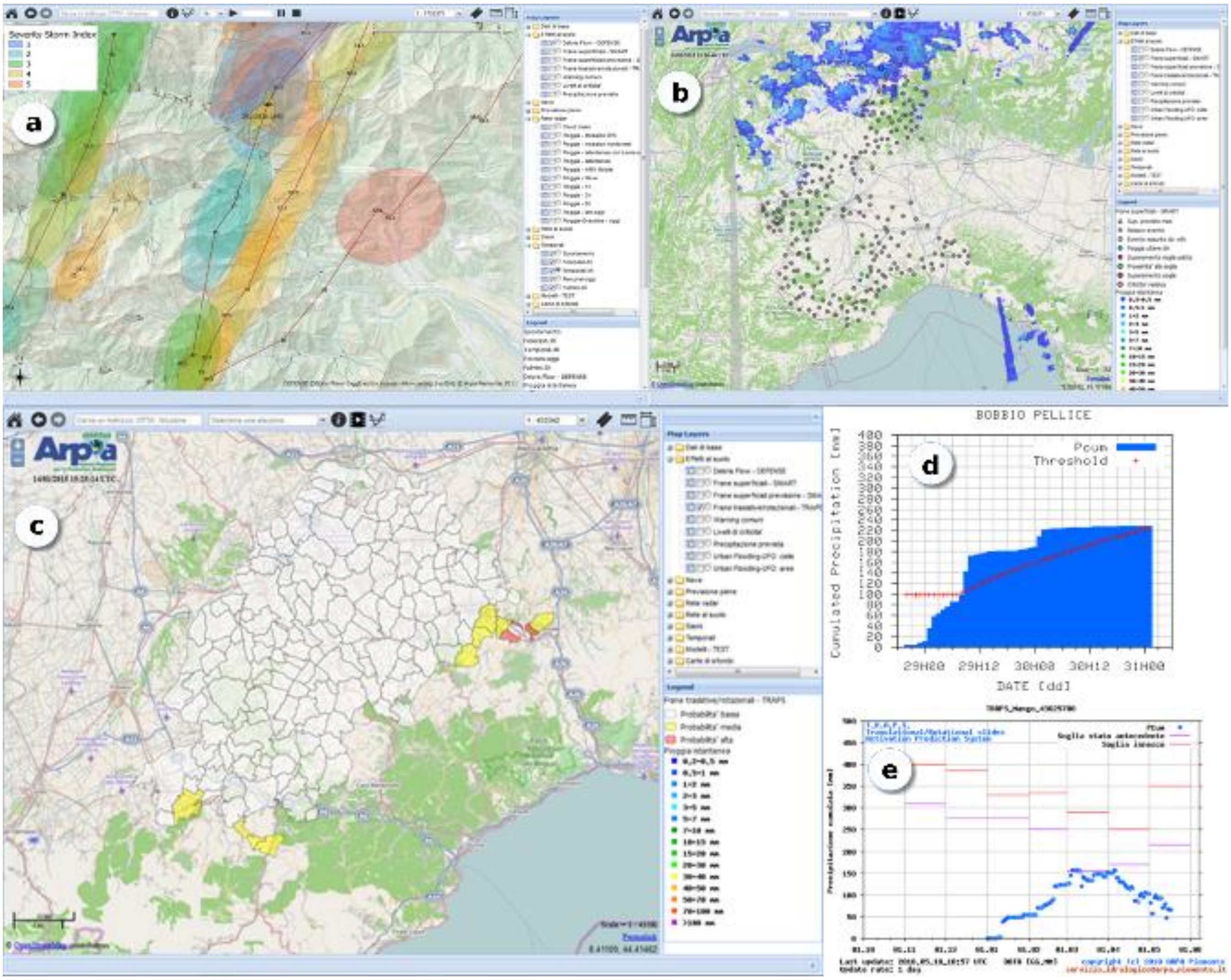


Fig. 5: Examples of EWSs WebGIS interface. a) DEFENCE: storm's cells are ellipses, lines are storms' path, yellow polygon is the catchment affected by debris flow triggering rainfall intensity; b) SMART: dots represent the rain gauges linked to shallow landslides triggering thresholds; c) TRAPS: polygons represent the areas characterized by different probability for translational landslides activation (white = low/null probability; yellow = medium probability; red = high probability); d) an example of SMART thresholds (red dashed line) representation related to accumulated rainfall (blue area) recorded by rain gauges; e) an example of TRAPS diagram: blue dots are the antecedent precipitation values accumulated over previous 60 days, red lines are the month triggering threshold value and purple lines are the monthly predisposing thresholds (thresholds indicating the high probability of early instability) (source: Arpa Piemonte).

4.2 The Norwegian forecasting service

The Norwegian Landslide Forecasting Service at NVE is designed to forecast the occurrence of shallow slides, debris avalanches, debris flows and slushflows (Colleuille et al., 2017). The daily assessment is built on landslide hazard thresholds, real-time hydrometeorological observations and landslide events, but also on historical landslide inventory and susceptibility maps. Meteorological data, such as air temperature and precipitation, are daily used to simulate runoff, snow conditions, soil water content and other hydro-meteorological variables, through hydrological models. The different modeled hydro-meteorological variables have been combined and cross-checked with the time of previous landslides to identify the relationship that best describes the landslide occurrence and to statistically derive thresholds for different regions of the country (Colleuille et al., 2010, Boje et al., 2014; Boje, 2017). The best performance is obtained when the simulated water supply (e.g. rain and snowmelt) and the simulated soil water saturation degree are combined (**Fig. 6a, 6b and 6c**). The main principle is that a landslide hazard bulletin is issued when a combination of the threshold values is exceeded. The service uses a unique threshold for all different types of landslides. The threshold is called Hydmet (stand for "hydrometerological index"). The threshold shows that landslide may occur in Norway for values of water supply lower than 8% of the mean annual precipitation and for soil saturation higher than 60%. The thresholds can be visualized in form of raster data (with 1-km^2 resolution) at link xgeo.no, a web portal that assist experts in the daily forecast of floods, snow avalanches and landslides (**Fig. 6d**). Here, prognosis and simulated parameters are daily published for the next 6 days (Devoli et al., 2014). In addition to landslide thresholds and real-time observations of hydrological variables (discharge, snow, groundwater level, soil water content and frozen soil), expert knowledge is fundamental in the daily landslide hazard assessment. A daily national landslide hazard assessment is issued by the personnel on duty that describes both expected awareness level and type of landslide hazard at a regional level. The warning area is not a fixed zone but can be a single county, a group of counties or a group of municipalities. The landslide forecasting team consists of people with different backgrounds, such as geologists, geophysicists, hydrogeologists and physical geographers. The service is operative 7 days a week, throughout the year. The Landslide Forecasting Service delivers continuous updates on the current situation and development to national and regional stake-holders and the public. Assessments and updates are published at least twice day and contain the prognosis for the three coming days. The forecast is valid from 7AM the day of publication to 7AM the following day (8AM to 8AM Daylight Saving Time). The assessment is done by utilizing observations and prognoses developed by the Norwegian Meteorological Institute (MET

Norway), and the service has daily communication with the meteorologist on duty. The service also works closely with the Norwegian Flood Forecasting Service and the assessment of slushflows is carried out with support from the Norwegian Avalanche Centre. The service is established in cooperation with the Norwegian Public Road Administration (NPRA) and the Norwegian Railway Administration (Bane NOR) (Colleuille et al., 2017).

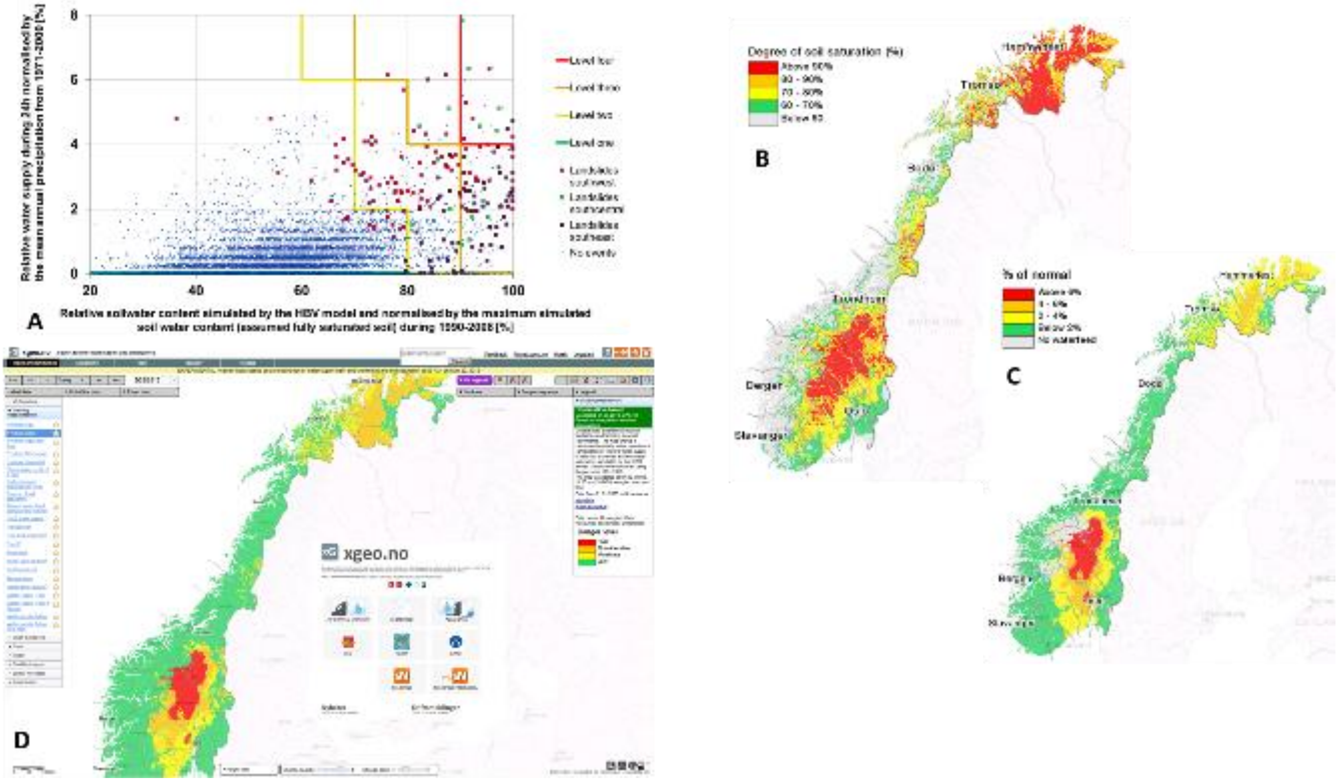


Fig. 6: Landslide thresholds and WebGIS interface xgeo.no. a) national landslide thresholds based on simulated degree of soil saturation and water supply obtained from HBV model; b) Map of simulated degree of soil saturation. The percent describes the relationship between todays soil water storage compared to the maximum soil water storage simulated with the HBV-model in the reference period 1981-2010; c) Map of simulated water supply (rain and snowmelt) the last 24 hours as percent of yearly normal water supply in the period 1981-2010, and is the product of simulated snow melt and interpolated precipitation; d) The web interface xgeo.no with the Hydmet map in the background. The map is the cartographic representation of the national thresholds presented in a) and, obtained combining the maps in b) and c). The maps in b), c) and d) are examples from the 22nd May 2013 and extracted from xgeo.no.

5 Meteorological conditions in late spring 2013

5.1 Antecedent conditions

The analysis of the initial conditions shows that the winter 2012/2013 was cold and dry in both countries with temperature lower than normal. The period March to May was still cold in Piemonte, but wetter than in Norway. Antecedent conditions in Piemonte were characterized by rainfall above normal with +30% on March and heavy precipitation on the end of April. Between 27th April and 1st May 2013 several rain gauges in northwestern Piemonte recorded more than 200 mm in 120 hours. At the end of the spring the recorded anomaly in precipitation was +65%, resulting the second wettest season in Piemonte since 1900.

In southeastern Norway, the winter 2012-2013 was cold, especially on January and March, and characterized by cool air from North (Roald, 2015 Stranden and Sund, 2013). The spring arrived late. The period January-April was characterized by precipitation deficit in many areas. The snow depth was lower than normal and thus ground frost deeper than normal. In May, the warm air from south and south-east initiated snow melt in the mountains. **Fig. 7** shows the snow distribution in Norway during April-May 2013. By the middle May there was still snow at elevation higher than 700m asl and more snow than normal in the western part of the area. On May the precipitation was +200-500% above average, especially in the western parts of the Østlandet region (Sund, 2014).

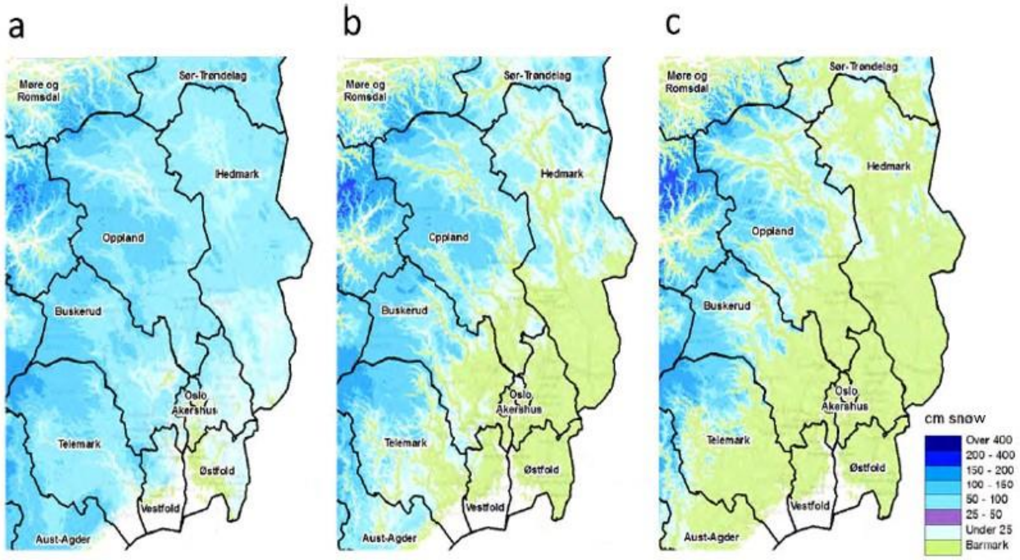


Fig. 7: Snow distribution a) middle of April, b) end of April and c) middle May, Norway (source: xgeo.no)

5.2 Meteorological conditions during the period analysed

In retrospect, it could be observed that the Vb weather regime was relatively easy to follow across the Mediterranean Sea. The first significant impacts in form of strong winds up to 120 km/h and sandstorms were observed in Malta and southern Italy (particularly in Sicily and Calabria region) the 15th and 16th May 2013 (Meteoweb, 2013 and G. Devoli personal communication).

5.2.1 Piemonte

From 15th May 2013 to 19th May 2013, an intense cold front affected Piemonte, causing abundant precipitations, a general increase of rivers discharge and vast areas of Piemonte affected by floods and landslides.

On 15th May 2013, a trough blunder on Western Europe conveyed warm and wet flows from south towards Piemonte, causing widespread precipitations that intensified especially in the Northern Piemonte and on the border areas with Liguria. Fig. 8 shows the mean sea level pressure analysis by ECMWF on 16th May at 00:00 UTC. The main low-pressure system is centered over the North Sea, while a secondary low one is near North Africa coasts: the isobars determine intense southern humid air-flow from Mediterranean Sea towards Scandinavian Peninsula.

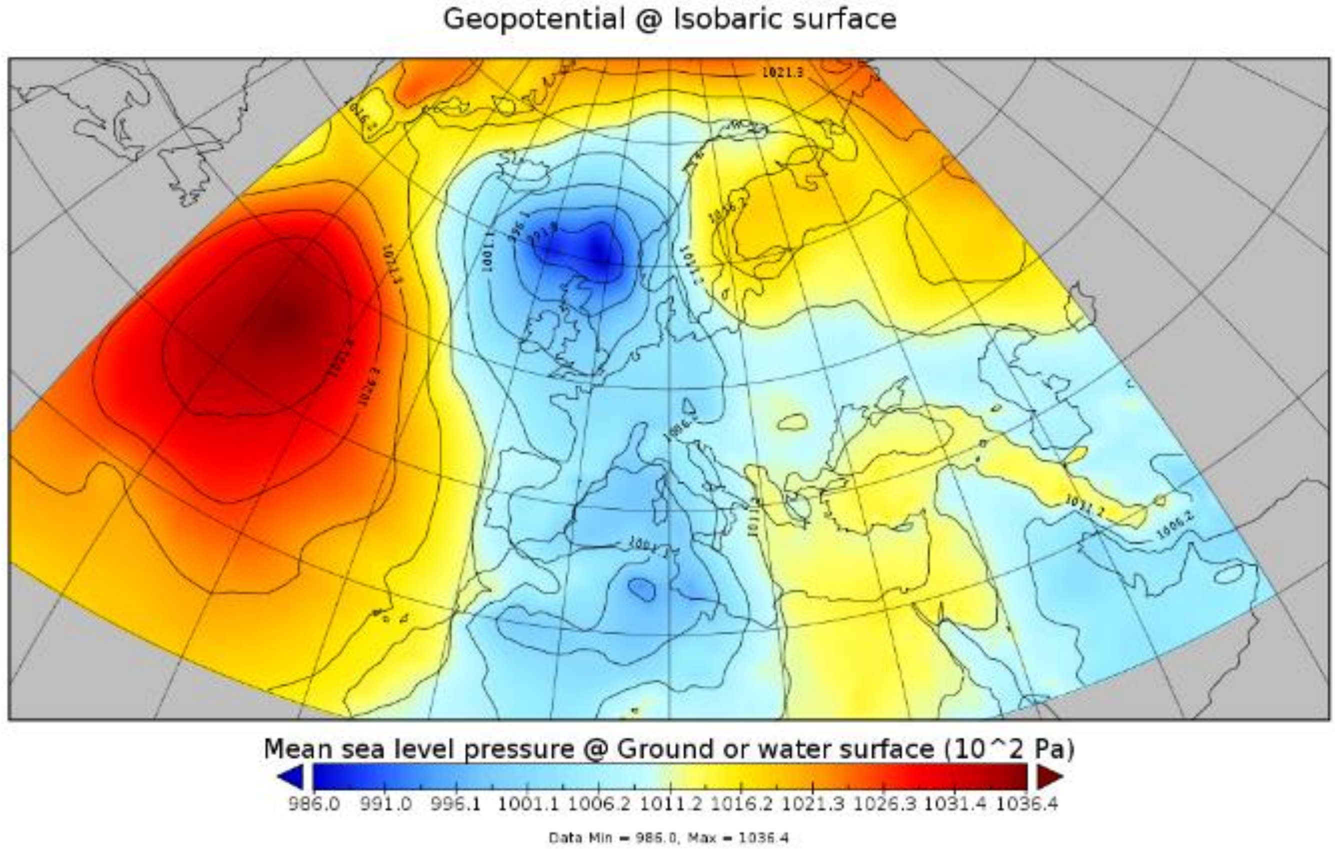


Fig. 8: ECMWF mean sea level pressure analysis over Europe on 16th May 2013 at 00:00 UTC (source: Arpa Piemonte).

Widespread, moderately strong local precipitations affected Piemonte during night. In the Po valley were recorded on average 30 - 40 mm rainfall with 45.6 mm maximum. About 20-25 cm fresh snow were recorded in the Alps above 2000 m asl. On 16th May 2013, the low-pressure area, responsible for severe weather, gradually moved towards Biscay Bay, continuing to convey wet and unstable air over Piemonte. However, an increase of atmospheric pressure in Ligurian Gulf caused an attenuation of meridional flows and a general attenuation of precipitations. In the late evening, the cold front associated with the low-pressure crossed Piemonte, causing instability and convective rainfall, more intense over the north-western footpath. Close to Turin (TO in **Fig. 2a**), the Po river reached the alarm level meanwhile downstream the river approached warning thresholds. The minor hydrographic network reached also warning levels close to Turin and in the southern catchments (Tanaro in **Fig. 2a**). On 17th May afternoon, the cold sector, which affected Piemonte over past 48 hours passed, favoring a general attenuation in the rainfall. However, atmospheric post-frontal instability caused sparse and thunderstorms, particularly on the western foothills, where the interactions between southern flows and alpine foothills caused strong connection with abundant hail: hourly precipitation rates reached 40 mm. Discharges of minor hydrological network increased as result of severe thunderstorms. On 18th May 2013, the occluded front passed Piemonte from west to east. The wet airflow remained intense from the south resulting in convergence close to the northwestern foothills, with further intensification of rainfalls. During the night discharges of major hydrological network grew, but staying below warning thresholds. Significant increases of the minor hydrologic network, particularly in near Turin, and the high part of Tanaro catchment in the south Piemonte.

On 19th May 2013 morning, the sea level pressure increased, favoring the precipitation exhaustion except for northern Piemonte where rainfall terminated during central hours. The rainfalls between Saturday and Sunday resulted in significant increases in rivers discharge both in northern and southern basins. Attention levels of were reported on secondary hydrological network, particularly in the basins near Turin. In the upper part of Tanaro catchment also attention levels were recorded. Po river levels stabilized around attention levels upstream and downstream Turin in the morning and in the downhill sections in the afternoon. Over the entire period, more than 300 mm fell in northwestern areas with peaks of 350 mm in 96 hours (**Fig. 9**). The return period for 3-6 hours rainfall accumulation were about 20 years. Finally, considering rainfall accumulations since 1st March 2013 to mid-May, several catchments recorded more than 600 mm.

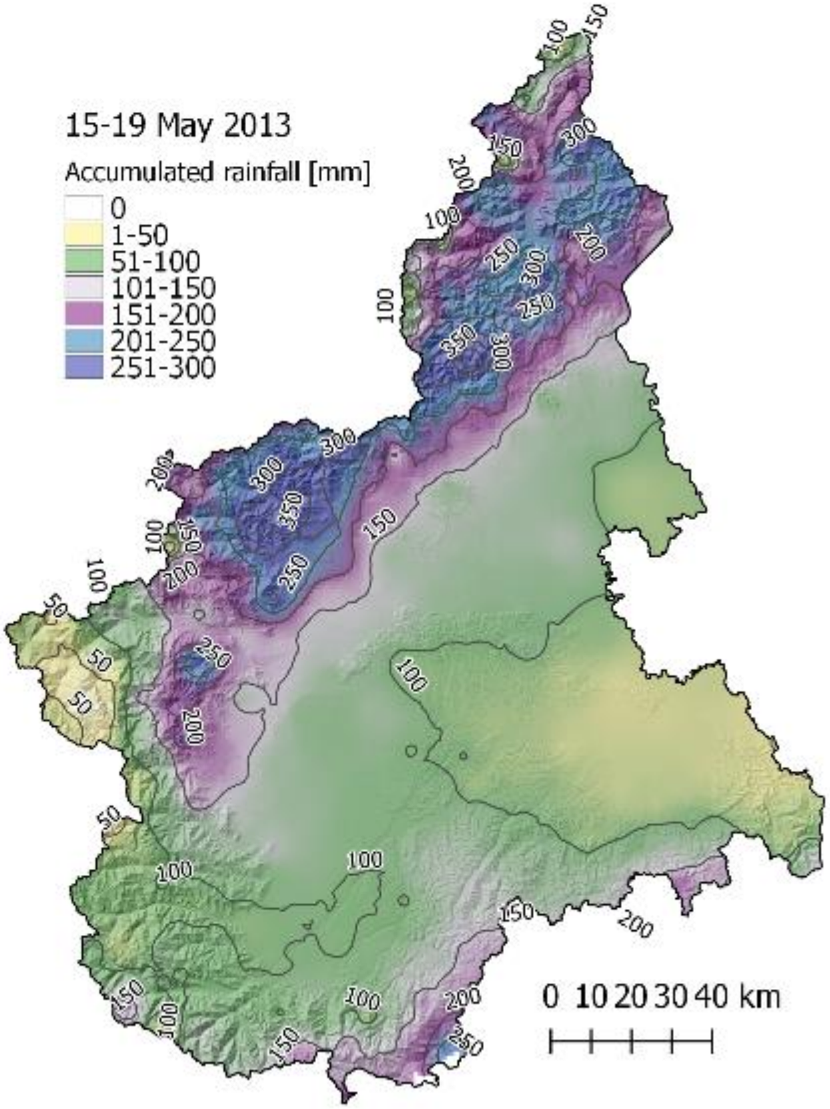


Fig. 9: Accumulated rainfall from 15th May to 19th May 2013 (source: Arpa Piemonte).

5.2.2 Norway

It is well known, in Norway, that Vb cyclones can produce the largest floods during spring (Roald, 2008). Therefore, the flood forecasting service at NVE, pays attention, each year, to these weather conditions in southern Europe. The arrival of the Vb cyclone on May 2013 was forecasted with some weeks in advance by mentioning the possible arrival of a warm weather system from south (as it was indicated in a “situation report” published the 3rd May). The temperature starts to increase around the 5th May in the mountain area, starting the snow melt process. A short decrease in temperature was observed on 14th -15th May and 22nd May before and in correspondence of the two main rainfall episodes. The temperature reached the highest peak on 18th and 19th May, causing significant snow melting in the area. Due to the arrival of several warm air fronts the temperature continued to increase constantly until the end of May.

The first rainfall arrived on 15th -16th May and most of in the easterly counties of Telemark and Buskerud (**Fig. 10a**). In Eggedal station were measured 60 mm in 24 hours. In this area, many hydrologic stations reach the flood level (**Fig. 10b**) and in Eggedal the water discharge was the fourth highest since registration started in 1972, resulting in a big flood.

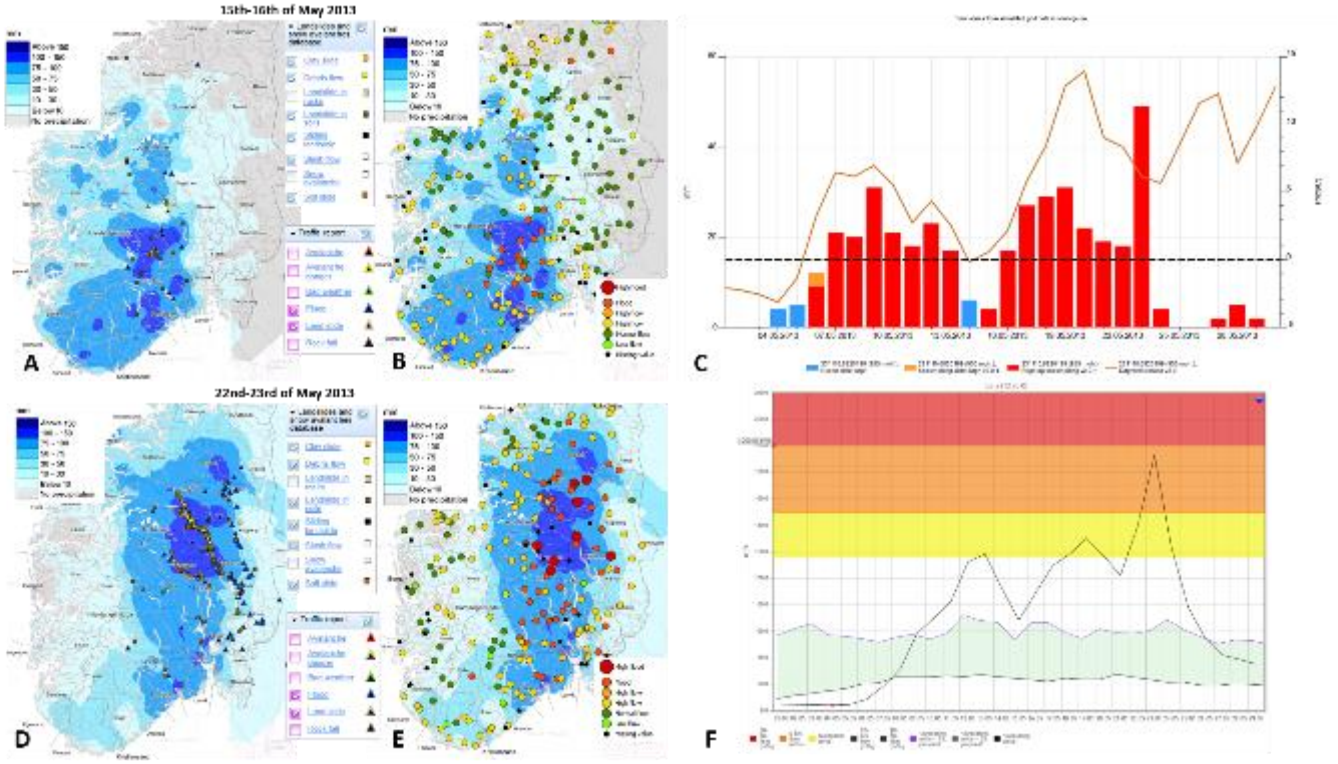


Fig. 10: The 15th-16th May and the 22nd May events. A) Rainfall measurement the 15th and 16th May and landslide events; B) Rainfall measurement the 15th and 16th May and water discharge level; C) Rainfall and temperature distribution during May in the Gudbrandsdalen area (red: rainfall; blue: new snow, orange line: temperature); D) Rainfall measurement the 22nd and 23rd May and landslide events; E) Rainfall measurement the 22nd and 23rd May and water discharge level; F) Water discharge at Etna station during May 2013 (source: xgeo.no).

Precipitation started in the western counties, moving eastward. A second and more significant rainfall episode occurred on the 22nd and 23rd May affecting mainly the Glomma and Østerdalen catchments in the eastern sector of the region (Figure 10d). In Østerdalen were measured 50-60 mm that day, while in Gudbrandsdalen values ranged from 50 mm to 93 mm. An overview of the rainfall and temperature distribution during May 2013 in the Gudbrandsdalen area is presented in Figure 10c. The two rainfall episodes, in addition to the incoming snowmelt, were responsible for the increase of groundwater in the region and to produce high water discharge in many of the rivers in the area (Figure 10e). In Folla river a 100-year return period was measured, while in Numedalslågen and Skien catchments a 30-year return period flood was observed (Roald, 2015). In Drammen river at Begna, Etna and Dokka station the flood reaches the 50-year return period (Figure 10e). At Gausdal and Gudbrandsdal river the flood was estimated to be between 50 and 100-year return period. The Vb situation persisted from 15th May – 2nd June and caused also intense rainfall and urban flood in the capital Oslo on the 2nd of June.

5.3 Warning levels

The warning levels indicates the landslide hazards and generally the mitigation measures a recipient should undertake to reduce potential damages. Both services at ARPA Piemonte and NVE use four levels symbolized by the typical traffic lights colors, summarized in the **Tab. 1**. Even if the numbering of the levels is different, the meaning of the warning is similar. Emergency response authorities should be prepared to implement emergency plans, mitigation measures, carry out evacuations and other contingency responses. Hazard and risk maps are mandatory to help local authorities to prioritize the implementation of measures.

Tab. 1 – Warning levels in use in Italy and Norway, with their respective local names.

Warning level	**Italy**	**Norway**	**Explanation**
Red	**3**	**4**	Very high landslide hazard. Several large landslides may occur; their long runout and extent may result in damage to settlements and infrastructure. Red awareness level is an extreme situation that occurs very rarely. Safety measures such as closed roads and evacuations can occur on short notice. Pay attention to the media and follow recommendations from the authorities.
Orange	**2**	**3**	High landslide hazard. Large landslides that disturb infrastructure and roads may occur. Exposed roads may be closed off. Emergency authorities should increase vigilance related to landslides and be prepared for incidents that can impact infrastructure and roads. Mitigation measures should be carried out. Pay attention and follow recommendations from the authorities
Yellow	**1**	**2**	Moderate landslide hazard, primarily shallow slides on artificial slopes that may affect roads, railways or along river embankments. Sparse debris avalanches or debris flows may also occur causing damage to infrastructure, but primarily on a local scale. Emergency authorities should pay attention to weather conditions, prognoses. Preventive measures are recommended.
Green	**0**	**1**	Generally safe conditions. Debris avalanches, debris flows, shallow slides and slushflows are not expected at this level. However other landslide types (like rock falls, and in Norway clay slides and quick clay slides) may occur, caused by slow response processes, such as erosion, freeze-thaw weathering or human activity, such as deposition, digging or blasting. These incidents may occur at all awareness levels.

In Norway, warning levels are updated two times a day. The warning messages are sent from 66 h to a few hours ahead.

On 15th May 2013 the first warnings in Northwestern Alps and in central hilly areas about possible debris flows and landslides were issued by ARPA Piemonte **(Fig. 11**). Then, according to observed precipitations and updated NWP outputs, the warning levels remained stable over Alps, while alerted hilly areas reduced. According to observed rainfall occurred during 18th May and the first hours on 19th May 2013, warning for local floods, debris flows and landslides was newly issued for central Piemonte.

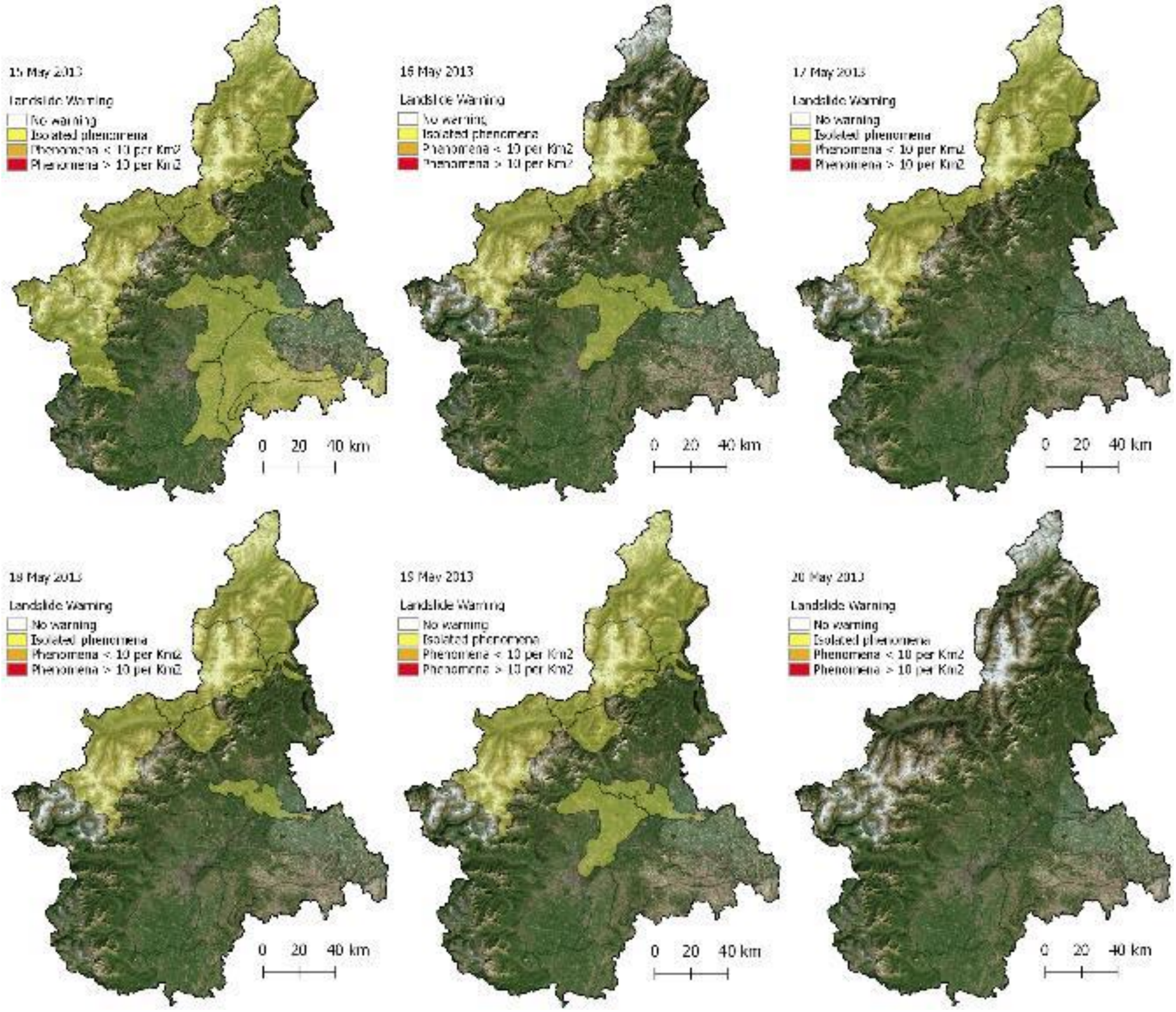


Fig. 11: Landslide warnings issued from the 15th to the 20th May 2013 in Piemonte region (source: Arpa Piemonte).

A first flood warning was sent in Norway the 14th May 2013, followed by a first landslide warning (orange level) on 15th May, for parts of the southeastern region. A yellow level was kept from 16th to 20th May. On 21st May the level was increase to orange and on 22nd May was also added a red warning level (**Fig. 12**). Different landslide warnings were issued every day until the end of May as shown in the **Fig. 12**. From 16th May until the end of May a yellow warning was also sent for Northern Norway.

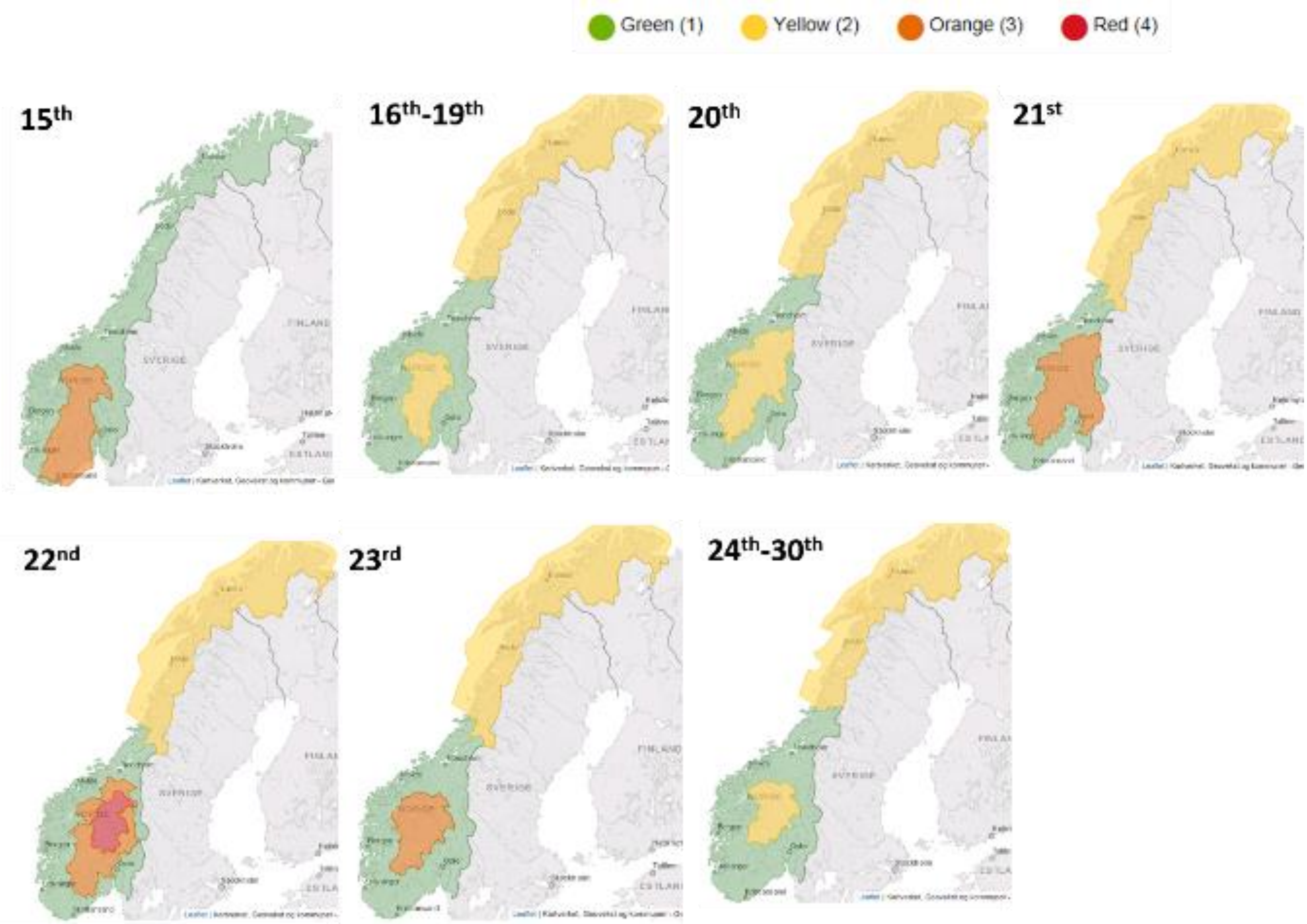


Fig. 12: Landslide warnings issued from the 15th to the 30th May 2013 in Norway (source: varsom.no).

The severity of the rainfall and snowmelt episode that occurred on 22nd May was clearly detected with some days in advance when the Hydmet map shows that landslide thresholds would be exceeded (**Fig. 13**).

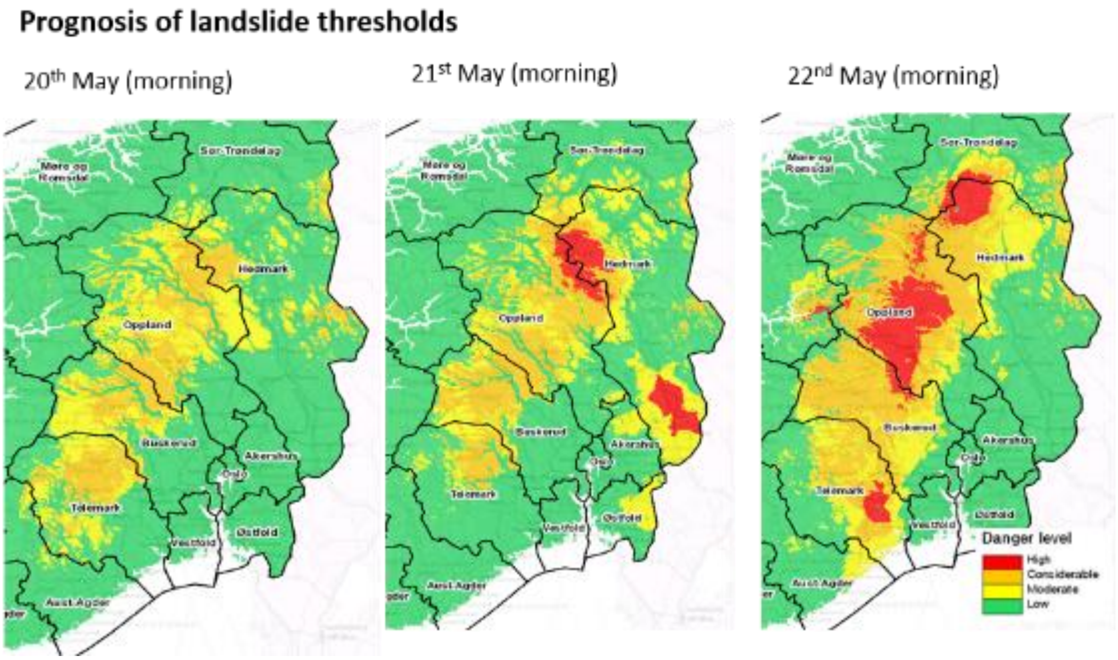


Fig. 13: Prognosis of landslide thresholds (source: xgeo.no).

6 Type of landslides and economic consequences

In Piemonte, after these rainfall events, about 320 slope phenomena have been reported (300 landslides and 20 channelized debris flows) (**Fig. 14**). The main landslide types occurred were wide shallow landslides, deep-seated rotational slides in alpine and hilly areas, and subordinated reactivation of some translational slides in hilly environment. The territory hit by slope and flood processes (**Fig. 15**) covers an area of 3,700 km^2 with about 420,000 inhabitants. In affected areas, important connecting routes are sited, including international ones. Due to severe phenomena occurred, numerous cases of traffic interruptions by landslides and flood were reported, as well as flooding of buildings, deposition of coarse alluvial sediments on roads, bridges jammed by debris flows, roadside walls collapse, erosion of roads surface, urban flooding and people trapped in cars. Rainfall event caused wide discomforts and damages to the community, both in relation to normal social cohabitation and economic wealth.

Fig. 14: Some examples of slope phenomena recorded during rainfall event. a) Road interrupted by a debris flow; b) a building hit by small rotational slide; c) shallow landslides on a road (source: Regione Piemonte).

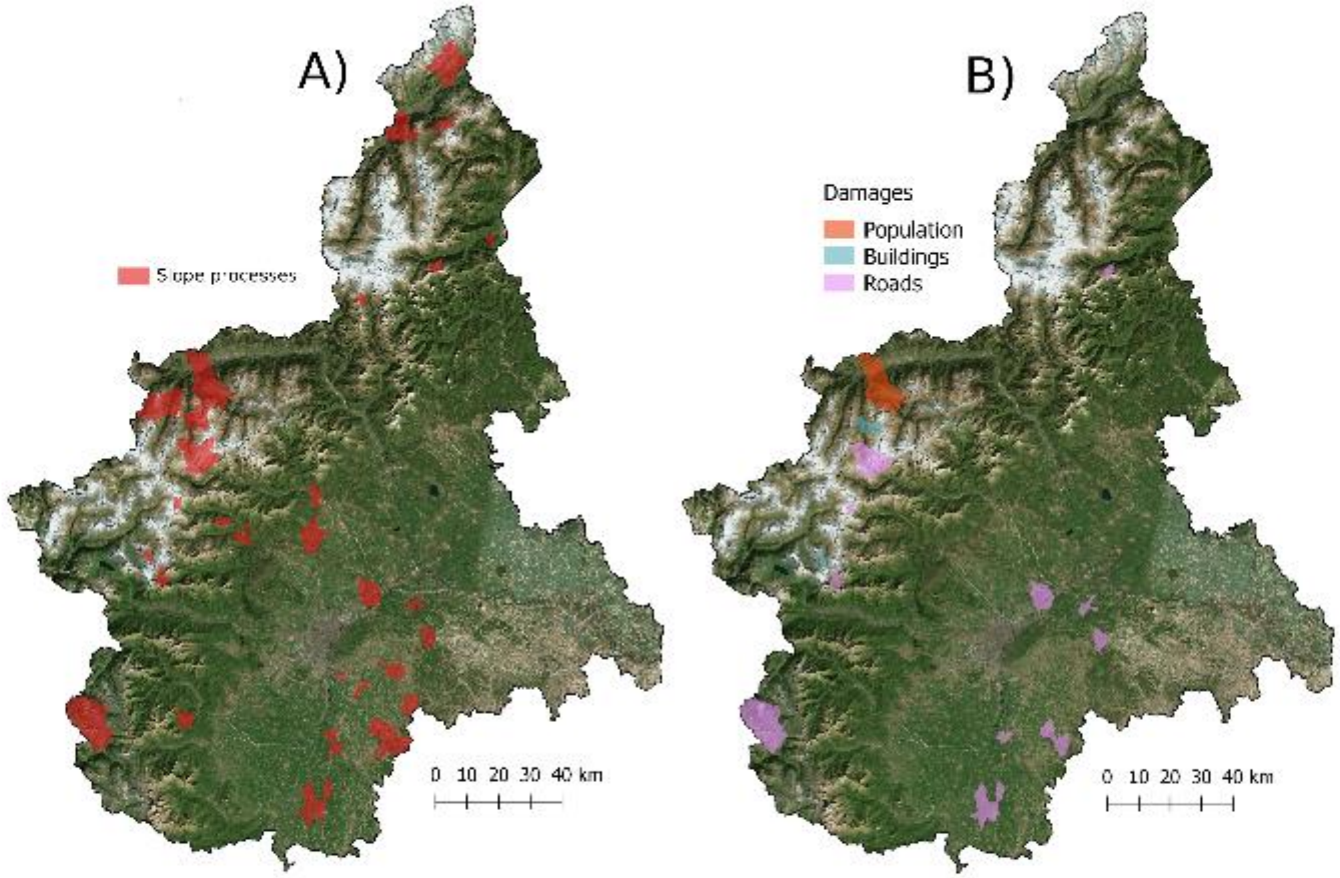


Fig. 15: A) Landslide processes occurred during the rainfall event. B) Reported landslide damages (source: Arpa Piemonte).

In Norway, more than 100 landslides were recorded in the database (www.skredregistrering.no) in this region between 15th May and 7th June. Mainly the events that reached roads and railway were recorded, but we believe that many more have occurred, but they have not been reported due to their location in less inhabited areas. **Fig. 10a** shows the spatial distribution of landslides during the first rainfall event and **Fig. 10d** shows the landslides occurred during the second rainfall event. In both figures are also indicated the areas where the road was blocked because of flood. The landslides observed were mainly debris flows and a combination of debris slides and debris flows, however most of them have been reported generically as landslides in soil (**Fig. 16**). There were many shallow slides in artificial cuts, mainly translation of small dimensions or along river sides. A few slushflows were also reported, especially in the northern sector of the region in the mountains. The landslides events and floods produced significant damages to roads, railway and private buildings and the economic losses were estimated around ~170 MI € (~1.5 bill NOK) for 22nd May. Many places were evacuated for several days. There were 350 cases of damage and 23 municipalities asked for mitigation measures in Hedmark and Oppland. The same system triggered landslides and floods in Northern of Norway, but these events are not described in this paper. More details can be founded in Stranden and Sund (2013).

Fig. 16: Flood and landslides at Kvam, Nord Frøn, Oppland county 22nd May 2013. A) and B) Flood and flood damages at Kvam; C) Debris slide at Ringebu; D) debris flow at Veikleåadalen E) shallow debris slide and debris flow deposits at Kvam; F) Debris flow at Veikleaådalen (Source: NVE).

7 Conclusions

In this study, we presented how the landslide forecasting services are operating in Norway and in Piemonte (Italy) and how they can predict in advance landslide events, using expert knowledge combined with quantitative thresholds, regular rainfall forecasts and real-time observations.

We presented a case study of successful forecasted landslide events triggered by the same large synoptic system, the Vb cyclone that occurred across Europe on May 2013. This extreme weather type triggered flood and hundreds of landslides, mainly debris flows, debris slides and shallow slides in Piemonte, Northwestern Italy, and in Østlandet region, Southeastern Norway, producing severe damages to infrastructure and buildings. Even if the forecasting services worked separately they could emit accurate warning messages at regional level that were extremely useful for road and railway administrations and municipalities. Based on these messages, the stakeholders could prepare the implementation of emergency plans, mitigation measures, carry out evacuations and other contingency responses before the event.

Other important outcomes from this study are also:

- Vb cyclones are not only responsible of large flood across Europe, but they can trigger landslides in those countries that are susceptible to that. However, there is not available literature describing landslides as natural hazards associated to Vb cyclones in Europe.
- Vb cyclones can produce floods and landslides not only in central Europe but also at higher latitudes, like Norway and in the southern sector of the Alps.
- The back analysis of the event showed that large synoptic systems can produce different type of natural hazards across Europe, like sandstorm at low-latitudes, and flood and landslides when the system move across the mountain regions. They can be predicted with some days in advance and even weeks, for the case of Norway. It is important that the different forecasting services follow the system since the initial stage to be better prepared.
- Even if they are rare phenomena, and probably expecting to decrease in frequency in the future (Messmer et al., 2015), Vb cyclones are serious challenges for forecasting services and emergency response authorities, during spring, because they are large systems that can affect the area for a long period and produce large floods and hundreds of landslides.
- The type of landslides triggered by the described event were similar in both countries, typical rainfall-induced landslides like debris flows, debris slides and relatively shallow slides, not particularly large in term of volume, but in large amount and largely spread all over the regions, causing significant damages to infrastructure or isolating communities because of blockage of roads and railways.
- As presented herein the predictability of Vb cyclones is quite good, however, they are very large synoptic systems and damages cannot be completely reduced, therefore society and operational services must be prepared. For forecasting services, this situation is also demanding, because require a lot of personal on duty at the same time for both flood and landslide forecasting.
- In several occasions, we have observed that landslides are not always isolated and very localized processes, but rainfall-induced landslides can have a large spatial distribution across European countries when they are triggered by large synoptic systems. Therefore, international collaborative efforts are necessary among natural hazards prediction centres operating in different countries, because they can help to understand and better predict natural hazards associated to large synoptic systems and to improve forecasting services effectiveness.

This study is the result of an inter-institutional and international collaboration across Europe, initiated and promoted in 2016 by the Norwegian Water Resources and Energy Directorate (NVE) in two ways:

a) creating a network of experts working in the prevention of rainfall-induced landslides that were gathered together during an international workshop in Oslo in October 2016 to establish a forum for exchange of knowledge, challenges and best practices among those working with operational forecasting services for rainfall-induced landslides (Devoli, 2017);

b) promoting collaborations with specific institutions to study specific events: besides the one described herein with ARPA Piemonte, NVE is collaborating with the British Geological Survey to compare forecasting experiences and to better understand "westerly" synoptic systems, that move across the Atlantic in the autumn, causing landslides in UK and in Norway (like the storm Desmond, the 4th and 5th December 2015, described in Dijkstra et al., 2016 and Boje et al., 2016).

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