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Using local monitoring data for regional forecasting of weather-induced landslides in Norway

Utilisation de données de surveillance locales pour la prévision régionale de glissements de terrain provoqués par les conditions météorologiques en Norvège

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ABSTRACT: Since 2013, a national early warning system addressing weather-induced landslides in soils is operational in Norway. The system is based on real-time hydro-meteorological measurements used as input to a spatially distributed precipitation-runoff model covering the whole country with 1 km by 1 km grid. The warning thresholds are defined considering relative water supply and relative groundwater conditions. This study presents a methodology aiming at integrating the adopted warning model with monitoring data collected at local scale, specifically pore water pressure measurements. Preliminary analyses of the temporal and spatial distribution of the landslide events in relation to the modelled territorial data and the local monitoring data are conducted within a test area, highlighting the additional contribution of local measurements for early warning purposes. The results of the research may be considered as a first attempt to integrate regional and local monitoring data within a warning model for landslides.

RÉSUMÉ: Depuis 2013, un système d'alerte précoce national traitant des glissements de terrain dans les sols liés aux conditions météorologiques est opérationnel en Norvège. Le système est basé sur des mesures hydro-météorologiques en temps réel utilisées comme entrée dans un modèle de précipitations et de ruissellement réparti dans l'espace couvrant l'ensemble du pays avec une grille de 1 km sur 1 km. Les seuils d'avertissement sont définis en tenant compte de l'approvisionnement relatif en eau et des conditions relatives des eaux souterraines. Cette étude présente une méthodologie visant à intégrer le modèle d'alerte adopté aux données de surveillance collectées à l'échelle locale, en particulier aux mesures de pression d'eau interstitielle. Des analyses préliminaires de la distribution temporelle et spatiale des événements de glissements de terrain en relation avec les données territoriales modélisées et les données de surveillance locales sont effectuées dans une zone de test, mettant en évidence la contribution supplémentaire des mesures locales à des fins d'alerte précoce. Les résultats de la recherche peuvent être considérés comme une première tentative d'intégration de données de surveillance régionales et locales dans un modèle d'alerte pour les glissements de terrain.

Keywords: Risk; hazard; LEWS; monitoring strategies; warning models

1 INTRODUCTION

Landslide early warning systems (LEWS) are being increasingly applied in recent years as non-structural risk mitigation measures. Two categories can be distinguished on the basis of the scale of design and operation: “local” systems and “territorial” systems (Pecoraro et al., 2018; Piciullo et al., 2018). Territorial LEWS typically deal with weather-induced landslides over appropriately defined warning zones, through the monitoring and forecasting of meteorological variables (Calvello and Piciullo, 2016). However, meteorological monitoring alone does not allow to account for critical soil conditions controlling the triggering process (Staley et al., 2012).

This paper deals with the national LEWS operational in Norway since 2013 (Devoli et al., 2018). The warning model used therein is based on the monitoring and modelling of hydro-meteorological conditions potentially triggering slope failures. This study introduces a conceptual framework for designing a multi-scalar warning model aimed at integrating local observations and regional gridded data employed in the Norwegian national LEWS. To this aim, preliminary results from a first application to a selected case study will be presented and discussed.

2 BACKGROUND

2.1 Norway’s physical setting

Norway covers an area of ~ 385,000 km^2 on the western and northern part of the Scandinavian Peninsula. The mainland is characterized by a very elongated shape which stretches from latitude 58°N to more than 71°N. Approximately 30% of the land area consists of mountains and 6.7% of the country is covered by steep slopes (Jaedicke et al., 2009). The Norwegian landscape has been largely formed during the Quaternary period, especially by the actions of glaciers which eroded and transported sediments (Fredim et al., 2013).

The latitudinal elongation, the rugged topography and partial exposure to the Atlantic lead to large climatic differences and to a non-uniform precipitation regime throughout the country.

Annual precipitation may exceed 5000 mm in the mountain areas along the western coast, while some valleys receive less than 300 mm of rainfall in the Eastern regions (Krøgli et al., 2018).

Steep slopes, various climatic properties and loose sediments provide a basis for the triggering of weather-induced landslides in loose soils, such as debris flows, slush flows, and shallow landslides (Piciullo et al., 2017). Haque et al. (2016) reported that 42 people died in the country in the period 1995-2016, as a consequence of 25 landslide events. Economic consequences due to landslides are significant mainly due to the disruption of the road and railway networks.

2.2 Norwegian national LEWS

The Norwegian national landslide early warning system (LEWS) was officially launched in 2013, as a joint initiative of the Norwegian Water Energy and Directorate (NVE) and other public agencies (Piciullo et al., 2017). The system can be classified as a “territorial” LEWS, according to the scheme proposed by Calvello (2017).

Figure 1 shows the scheme of the procedures scheduled for the daily landslide hazard assessment and the sources of information.

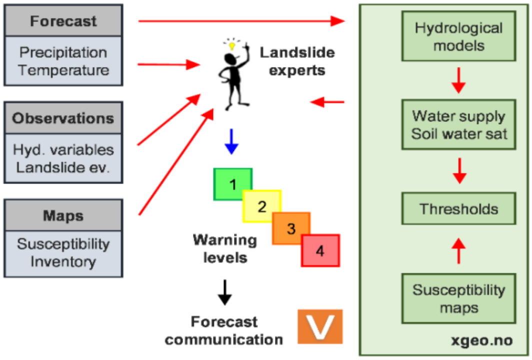

Figure 1. Conceptual framework of the national LEWS (modified from Piciullo et al. 2017)

Warning thresholds were statistically derived by cross-checking the time of past landslide events with modelled hydro-meteorological variables obtained from a distributed 1 km by 1 km grid version of the HBV model (Beldring et al., 2003). The thresholds currently used were proposed by Colleuille et al. (2010) combining water supply (rainfall and snow melt) and soil water content (both expressed as relative values normalised to annual averages and maxima over a 30-year reference period, respectively). Setting of daily warning levels is supported by two different susceptibility maps, which include information on landslide-prone areas within first-order catchments and on potential source areas (Bell et al., 2014; Fischer et al., 2012).

To issue one of the 4 warning levels adopted by the model, from level 1 (i.e. no warning) to level 4 (i.e. very severe warning), every day a landslide expert qualitatively performs a nationwide assessment of landslide hazard using all the available information (Krøgli et al., 2018).

3 METHODOLOGY

The methodology adopted for defining a multiscalar warning model which integrates local observations and regional gridded data comprises three successive phases: selection of the territorial units, events correlation, and definition of the warning model (Fig. 2).

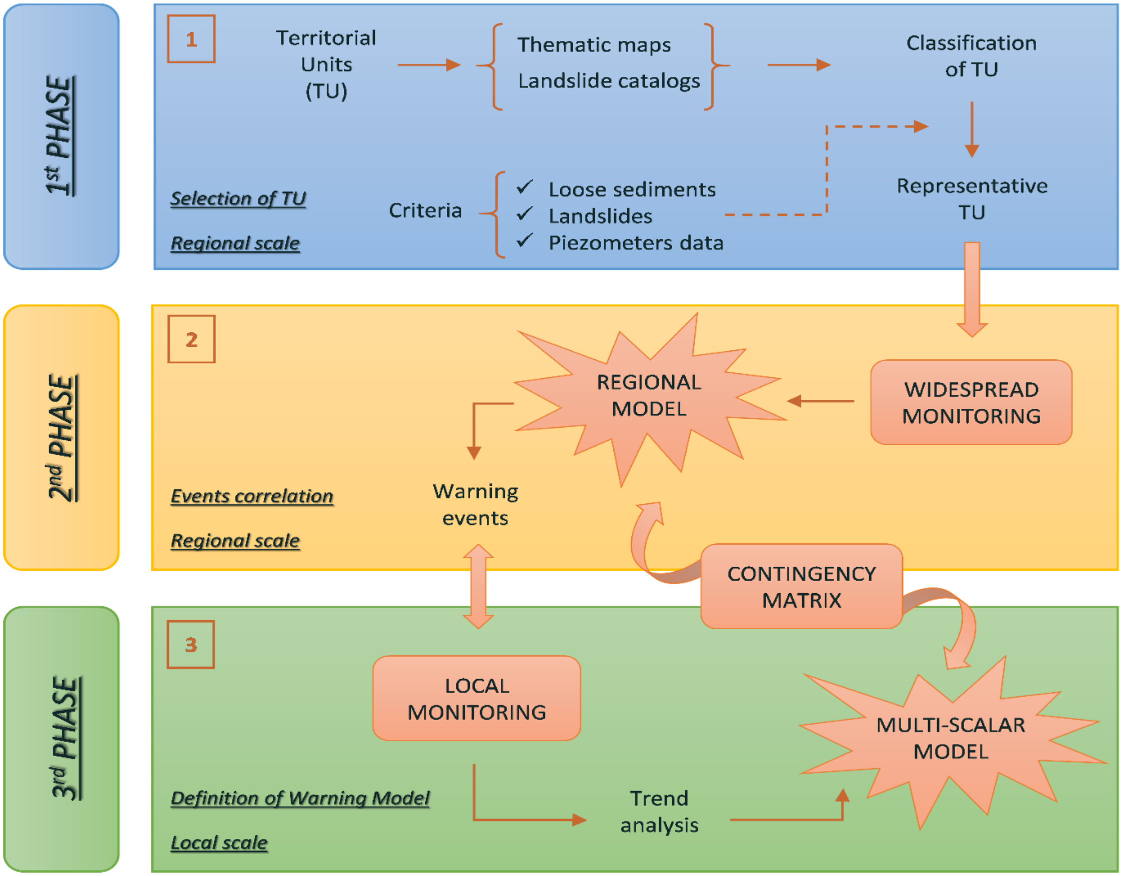

Figure 2. Methodology adopted for integrating local and regional monitoring data within a warning model at regional scale.

In the first phase, the minimum territorial units have been defined and classified for identifying potential test areas in relation to landslide density and availability of monitoring data in the period of analysis. In the second phase, one of the selected territorial units has been analysed through the regional warning model implemented within the national LEWS. Therefore, the combinations of relative soil water supply and relative soil water content have been compared to the warning levels for identifying the warning events. In the third phase, the alerts issued have been assessed considering the trends of the pore water pressure observations available within the area of analysis.

Finally, the performance of the two warning models—regional and multi-scalar—has been compared by means of a 2 by 4 contingency table (Tab. 1) relating the presence or absence of landslides with the level of the warning: level 1 "no warning", level 2 "moderate warning", level 3 "severe warning", and level 4 "very severe warning".

Table 1. Contingency table and performance criteria adopted to relate the presence of landslides with the warning levels (W1 to W4). Legend: MA=missed alerts; TN=true negatives; CA=correct alerts; FA=false alerts

	W1	**W2**	**W3**	**W4**
Landslides	MA	CA	CA	CA
No landslides	TN	FA	FA	FA

4 RESULTS

4.1 Selection of the territorial units

The Norwegian hydrological basins have been identified as the most appropriate minimum territorial units for testing the adopted multi-scalar warning model for weather-induced landslides. Indeed, the catchment scale is an intermediate scale of analysis for which pore water pressure measurements may provide useful additional information.

Following the framework proposed in Figure 2, the territorial units have been classified according to three criteria.

The first criterion is the presence of loose sediments in the shallow soil layers covering weathered and altered bedrock. Information on potentially unstable areas has been retrieved looking at a quaternary deposits map at 1:50,000 scale (www.ngu.no). The second criterion is the occurrence of historical landslide events in recent years. Landslide records have been retrieved from a national database and containing more than 65,000 entries, most of them related to landslides that occurred in the last 20 years (www.skrednett.no). The last criterion is the availability of a relevant number of pore water pressure measurements in the shallow soil layers in the proximity of the landslide source areas. Piezometers data have been collected at local scale from boreholes installed by the Norwegian Geotechnical Institute (NGI) for a variety of geotechnical projects. According to these criteria, 30 territorial units have been selected as potentially useful for the analyses.

The results described herein refer to the Horvereidelva basin (Fig. 3), situated along the Atlantic coast in the central part of Norway and covering an area of ~ 14 km^2. The soil profile consists of loose sediments prone to landslides (55%), materials not prone to landslides (27%) and bare rocks (18%). From January 2013 to June 2017 (i.e. the period of analysis) the study area experienced 5 landslides, 4 of them can be classified as weather-induced landslides in soils.

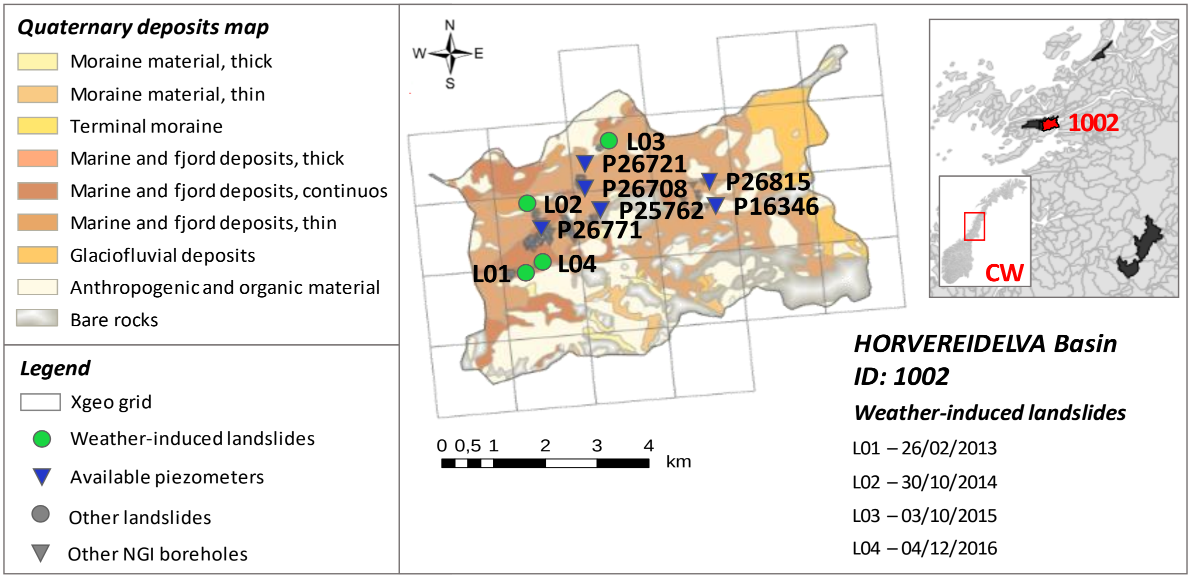

Figure 3. Quaternary deposit map, landslides and piezometers in the test area, i.e. Horvereidelva basin

4.2 Events correlation

The Horvereidelva basin comprises 25 1-km^2 grid cells, for which the daily forecasts of the hydro-meteorological variables are available (www.xgeo.no). The daily average values have been compared with the warning levels employed by the regional model, in order to identify the days with warnings as well as to define, in these cases, the level of the warning (Fig. 4).

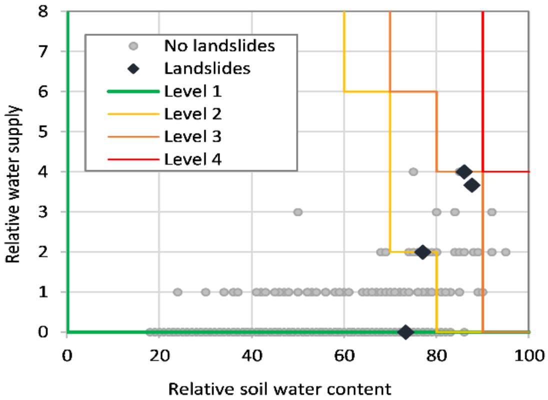

Figure 4. Results obtained applying the regional warning model employed in the national LEWS

Two of the four landslide events which affected the test area between January 2013 and July 2017 occurred when the warning model was in level 1, i.e. when no warnings were issued; in the two other occurrences the warning model was in level 2. On the other hand, in the period of analysis, 25 daily warnings have been issued: the majority being level 2 “moderate warnings” (18 events), with the rest of them being level 3 “severe warnings” (7 events). No “very severe warning” has been issued from January 2013 to June 2017.

4.3 Definition of the warning model

The 25 warning events issued by applying the regional model have been further scrutinized considering the local observations. Piezometer data come from 158 boreholes installed in the test area for projects carried out by NGI. In particular, six piezometers installed in shallow soil layers and in the proximity of the landslide events are herein considered, as they provide useful data in the period of analysis (Fig. 5).

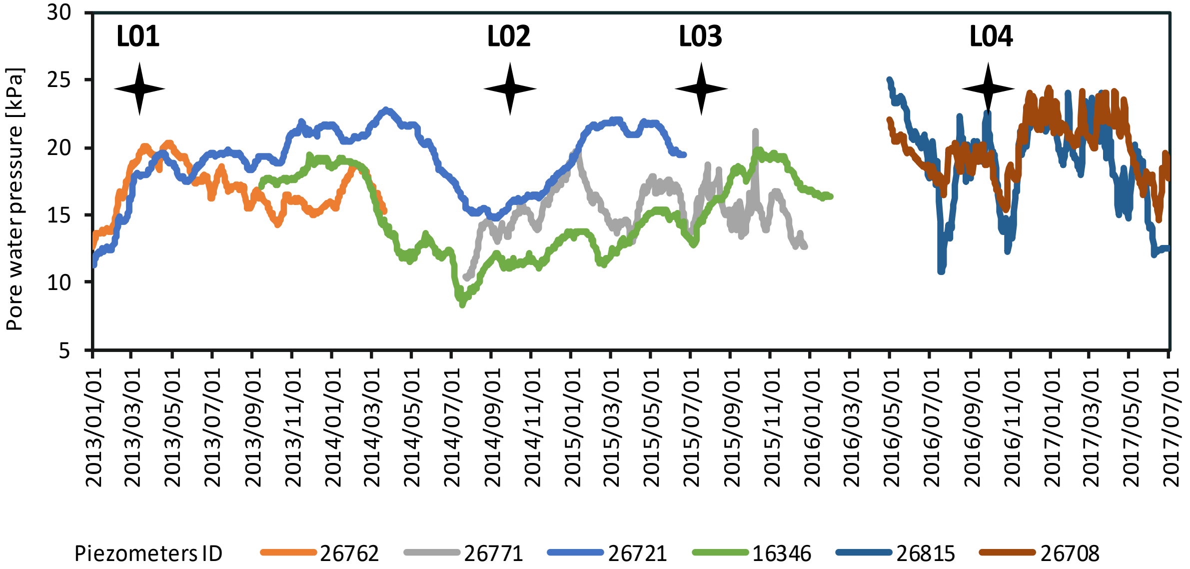

Figure 5. Pore-water pressures recorded in the 6 considered piezometers in the period of analysis (dates with landslides are indicated with cross marks)

The records are characterized by a significant short-term variability. Therefore, before being used they have been statistically processed in order to smoot the short-term fluctuations and to make the identification of potential trends possible.

To this aim, the simple moving average of the recorded pore water pressures at a given day (u_i) has been calculated using time periods (n) of 1, 2, 3, 4, 5, 6, 7, and 14 days, as follows:

$$u_i = \sum_{k=i-n+1}^{i} \frac{p_k}{n} \tag{1}$$

where p_k is the pore water pressure recorded at day k.

Then, two indicators of pore water pressure variations have been defined, as follows:

$$\Delta u_i = u_i - u_{i-n} \tag{2}$$

$$\Delta u_i^* = \frac{\Delta u_i}{\Delta u_{imax}} \tag{3}$$

where Δu_i is the difference between the simple moving averages calculated for n days before a warning alert and referring to days i and $i-n$; and Δu_i^* is the same difference normalized by the maximum difference observed in the dataset, Δu_{imax}.

A 2-step procedure has been developed that uses the above-defined indicators (Fig. 6). In the first step, the differences between the simple moving averages referring to days i and $i-n$ are evaluated. In case they do not show a clear trend, the warning level issued by the regional model is maintained. Otherwise, a second step is performed wherein the normalized simple moving average differences are compared with predefined thresholds.

Three final outcomes are possible: the maintenance of the same warning level issued by the regional warning model, an increase of the warning level, a decrease of the warning level. No more than two warning level increments are allowed.

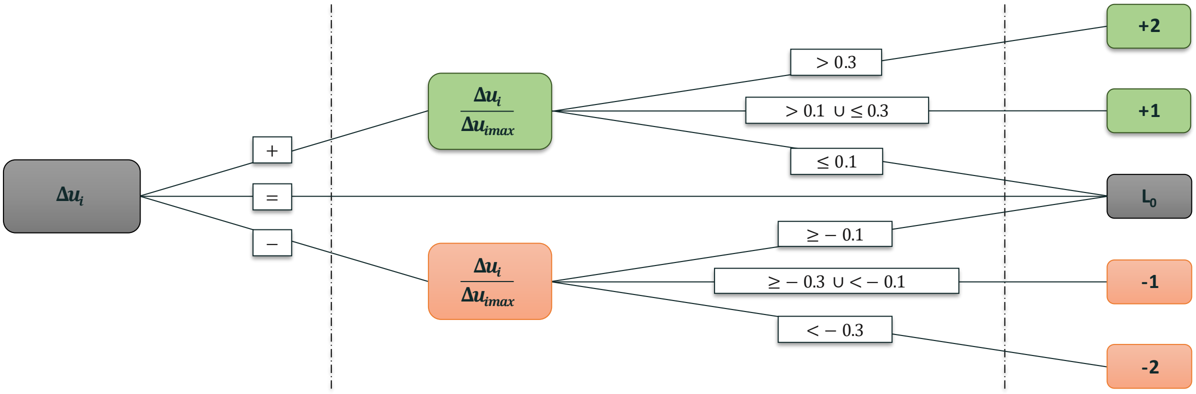

Figure 6. Scheme of the adopted multi-scalar warning model. The numbers on the right indicate the change in the original warning level (L_0) after updating with the pore-water pressure data.

The proposed model has been applied to the 25 warning events issued by the regional model using different values of n, and the best results have been achieved using a time period of 14 days (Tab. 2). The two correct alerts (CA) originally classified as level 2 “moderate warnings” (W2), have been raised to level 3 “severe warnings” (W3) and to level 4 “very severe warnings” (W4), respectively. Moreover, looking at the false alerts (FA), two of the 7 “severe warnings” false alerts have been decreased to “moderate warnings”, while 11 of the 16 “moderate warnings” false alerts have been no longer classified as alerts as they become true negatives (TN).

These preliminary results highlight the potential of using pore water pressure observations to improve the performance of the regional warning model.

Table 2. Comparison between regional (a) and multi-scalar (b) early-warning models

a)	**W1**	**W2**	**W3**	**W4**
Landslides	2	2	0	0
No landslides	1525	16	7	0

b)	**W1**	**W2**	**W3**	**W4**
Landslides	2	0	1	1
No landslides	1536	7	5	0

5 CONCLUSIONS

This work presented a methodology aiming at integrating local and regional monitoring data for early warning purposes. The multi-scalar warning model herein defined has been described and discussed through an application to a first case study.

Of course, this study is still in a preliminary phase and some issues need to be addressed, such as the influence of the numerosity and the distribution of the piezometers on the reliability of the results. However, the results achieved herein highlights a huge potential for the local geotechnical observations to complement widespread meteorological monitoring for a territorial early warning system addressing weather-induced landslides in Norway.

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