Replies to comments of Reviewers #1 and #2

Submission ID: nhess-2017-24

We would like to thank the Editor and the Reviewers for their careful review and their valuable comments, which have been constructive and useful to improve the quality of the manuscript.

Our replies to general and specific comments of Reviewers #1 and #2 are listed below.

Anonymous Referee #1

General comment / remark:

The early warning system (EWS) in Norway described in this paper is based on realtime observation of hydro-meteorological condition, landslide occurrence, pre-defined hazard threshold levels, landslide inventory and susceptibility maps. The system provides daily regional alerts and warnings on landslide throughout the country to the public through website (http://www.varsom.no/en/). Its performance during the operation period from 2013 to 2014 was evaluated and the results indicated that the performance was generally good with high rate of correct prediction and low rate of false alarm or missed events. Room for improvement in operation has also been identified and proposed. This EWS can be a good reference/example for other parts of the world where rainfall-induced landslide warning system is needed and respective datasets, viz. real-time rainfall and landslide observation, susceptibility maps, landslide inventory are present.

R: We thank Reviewer #1 for his/her positive comment to our paper.

Specific comments:

1. Some figures are unclear and difficult to read. Please improve the legibility of the figures as far as possible.

R: According to the comment, figures 4, 5, have been updated and improved as suggested. Thank you.

2. Currently, the warning levels are updated twice per day. Given that heavy rainstorms can develop rapidly, suggest to update at shorter time interval in some situation such that appropriate warning levels can be issued in time before landslide occurrence.

R: The warning levels are updated minimum twice per day based on weather forecast. The system manager, NVE, receives weather forecast updates 4 times per day and, using this information, sends the warnings as early as possible from 66 hours to few hours ahead. This information was added to the manuscript to better clarify this point. Thank you.

3. Some tables and figures are incorrectly referred in the text (e.g. "Table 2" in line 427 should read Table 4). Suggest the author to review all table and figure numbers.

R: We checked all the figures and tables. Thank you.

4. "R" in lines 168 and 173 should read "Red".

R: We modified as suggested. Thank you.

5. "Tab." and "Fig." through the manuscript should read "Table" and "Figure".

R: According to the comment, we modified “Tab." and "Fig." through the manuscript. Thank you.

6. The "Probability of serious mistakes" as one of the performance indicators in Table 4 has not been evaluated in subsequent sessions.

R: We thank the Reviewer for his/her comment, however the “Probability of serious mistakes” has been evaluated in the performance analysis but was erroneously omitted in table 11. Figure 12 was also revised due to a different error we found in the position of the bars.

Anonymous Referee #2

General comment / remark:

This manuscript assesses the performance of a national early warning system for regional landslide occurrence that was established recently in Norway. To this end, a performance-evaluation method EDuMaP (originally developed in Italy) was adapted to the case of Norway where spatial warning units are not constant but variable in space from case to case. While overall the landslide early warning system (LEWS) seems to perform quite well, this study also revealed that such a performance analysis strongly depends on the criterion selection. Assessing the performance of such a country-wide LEWS is of great interest to NHESS readers as such warning systems are still new and not well-established yet. The manuscript provides a good description of the warning system and shows an interesting approach how it can be evaluated in a systematic manner. In that sense, I see a substantial potential for publication in this journal.

R: We thank Reviewer #2 for his/her interest in our manuscript. We carefully revised the manuscript according to the many valuable comments and recommendations provided by both Reviewers.

On the other hand, I have a number of major questions and comments that, I think, deserve some further work:

1) The analyzed data set (both the number of warnings and observed landslides) is limited. It includes only warnings of three warning classes (green, yellow and orange) and a relatively low number of landslide observations (in particular for case B) without any landslide event classified as "large" (line 388). So one of my main question is: why was this analysis restricted to Vestlandet only and not performed for whole Norway? And why does it only include data from two years? I'm afraid that with this limitation (in particular with the missing of red warnings) the performance analysis is not comprehensive enough to draw strong conclusions.

R: We thank Reviewer #2 for this comment that gives us the possibility to better explain the reasons of choosing this case study and dataset. The "Vestlandet" region was chosen as it is one of the areas most prone to landslides in Norway. Moreover, for this area the landslide database is more reliable and complete than in the rest of Norway. As the second most populated area of the Nation, more information on landslides are available.

The Norwegian national landslide early warning system (LEWS) is a realtively new system that became operational in 2013. The analyses presented in this manuscript started in 2015 and only data for 2013-2014 were available at that time. A large work of collection and checking of landslide information from different sources (NVE, rails and roads Authority, other databases, media) was carried out, with the aim of avoiding repetitions and providing a reliable dataset. However, to answer this comment, we checked the number of warning issued in 2015-2016 in Vestlandet. There were only few days with Orange warnings and no one with Red warnings. The table below shows the number of warnings and the warning levels issued in Vestlandet in the period 2013-2016.

Warning levels	**yellow**	**orange**	**red**
2013	21	0	0
2014	34	5	0
2015	20	2	0
2016	21	0	0

As shown, the red level would still be missing even if we considered the period 2015-2016. According to the meaning of warning levels presented at http://www.varsom.no/en, the red level defines "an extreme situation that occurs very rarely, it requires immediate attention and may cause severe damages within a large extent of the warning area". Concluding, incorporating these data would not change the results of the performance analysis and would not add anything significant towards the main aim of the paper, i.e. proposing an extension of the EDuMaP method for the performance evaluation of LEWSs issuing warnings over zones characterised by a variable size. Finally the title of the paper has been modified in "*Adapting the EDuMaP method to test the performance of the Norwegian early warning system for weather-induced landslides*", for better clarifying the aim of the paper and avoiding confusion in the reader.

2) Coming from another research field than "performance analysis" I had substantial difficulties to understand the extended EDuMaP-method (section 3.3). In particular, I was missing the "rationale" behind this method. In simple words: What's the rationale behind the assumption that an issued warning was successful or less successful. For example, is it more important that the location of an issued warning is correct than its intensity? Or is it most important that an warning is issued for day 1 even if the location and intensity is somewhat over- or underestimated? I suggest that the authors very clearly explain their rationale behind their technical assumptions.

R: The EDuMaP method comprises three successive steps: identification and analysis of landslide and warning Events (E), from available databases; definition and computation of a Duration Matrix (DuMa), and evaluation of the early warning model Performance (P) by means of performance criteria and indicators. The parameters needed to carry on the events analysis (E) are ten. Among them, there is the spatial discretization adopted for warnings, $\Delta A(k)$, which describes if the warning zone is fixed or variable. For instance, the LEWS employed in Rio de Janeiro considers fixed warning zones, on the contrary the system adopted in Norway uses variable warning zones. In earlier studies, the EDuMaP method has been applied to analyse the performance of regional landslide EWSs adopting a fixed spatial discretization for warnings. When the landslide EWS employs variable warning zones, this characteristic significantly influences the first two steps of the EDuMaP method.

Section 3.3 was rewritten for increasing the comprehensibility of the methodology. It explains how to define landslide events (LEs) and warning events (WEs) and how to compute the duration matrix in case of variable warning zones. The landslides are grouped in LEs as a function of the warning zone in which they occur. A warning zone can be seen as an area alerted with the same level of warning (i.e., green, yellow, orange, red). The EDuMaP method evaluates the duration of each level of warning (i.e., green, yellow, orange, red) and the class of landslide event (i.e: the number of landslides) occurred over the time in a warning zone. In the EDuMaP method, a warning can be considered successful as a function of both the level of warning issued and the number of landslide occurred in the zone alerted. The number of landslides expected for each warning level often is defined by the LEWS managers, otherwise can be evaluated considering a landslide density criterion, $L_{den(k)}$.

3) I'm missing a benchmark for this performance evaluation. Is this landslide early warning system successful or not in comparison with other early warning systems worldwide? On lines 66 to 70 the authors mention a number of other such early warning systems – some of them are regional, others are local – and, in addition, there are also many flood early warning systems worldwide. I'm sure some of them have been evaluated in a similar way than this one. For the reader, it would be important to know (as a conclusion from this work) how the performance of this EWS compares with others.

R: Among LEWSs at a regional scale, the performance of the system is evaluated principally by computing the joint frequency distribution of landslides and alerts. Empirical evaluations are often carried out by simply analyzing the time frames during which significant high-consequence landslides occurred in the test area (Keefer et al., 1987; Aleotti, 2004; Cheung et al., 2006; Baum and Godt, 2010; Capparelli and Tiranti, 2010). Alternatively, the performance evaluation is based on 2 by 2 contingency tables computed for the joint frequency distribution of landslides and alerts, both considered as dichotomous variables (Yu et al., 2003; Cheung et al., 2006; Godt et al., 2006; Restrepo et al., 2008; Tiranti and Rabuffetti, 2010; Kirschbaum et al., 2012; Martelloni et al., 2012; Peres and Cancelliere, 2012; Staley et al., 2013; Lagomarsino et al., 2013, 2015; Greco et al., 2013; Segoni et al., 2014; Gariano et al., 2015; Stähli et al., 2015). The performance of the systems operational in Norway and Rio de Janeiro was analysed applying the EDuMaP method considering: the possible occurrence of multiple landslides in the warning zone; the duration of the warnings in relation to the time of occurrence of the landslides; the level of the issued warning in relation to the landslide spatial density in the warning zone; the relative importance system managers attribute to different types of errors.

In general it's difficult to compare the performance of LEWSs, especially if it has been evaluated with different methods. The values to evaluate the statistical indicators derive from different reasoning, for example, on what is considered as false, missed or correct alerts. Substantial differences may be observed among a 2x2 contingency table and a $n \times m$ duration matrix. The latter compares the n levels of warning in relation to the m classes of landslide events. The EDuMaP method evaluates the performance of a LEWS considering the number of warning levels and the classes of landslide events, thus, warnings and landslides are not considered as dichotomous variables as it is for contingency tables.

A benchmark could be defined, but it would require a separate analysis and a comparison of a relatively high number of different LEWSs evaluated with the EDuMaP method. Because system managers of LEWSs may attribute a relative importance to different aspects (i.e.: missed alerts, false alerts, purple errors, correct alerts, greens, the level of warning issued, classes of landslide, etc..). As a consequence, different performance criteria are needed to be chosen in order to consider the system managers choices and to carry on the performance analysis. Currently the authors are still working on a comparison among the performance evaluation of different LEWSs in order to provide "functioning standards".

4) Fig. 9b seems to omit the category "no warning issued – no event observed" while Fig. 9a seems to include this category (True Negatives). Is this mentioned somewhere? On what basis did you do this? As a result, the green category (in Fig. 9b) seems to be underrepresented. Yellow seems to dominate (but this is only for cases with either a warning or an observed landslide.) I think this gives different messages if you include or exclude the category "no warning issued – no event observed". From Fig. 9b the authors conclude that for Case B the EWS performs slightly better than for Case A. I would say the difference is very small . . . and I wouldn't over-interpret Fig. 9.

R: We thank the Reviewer for giving us the possibility to clarify some important concepts of the duration matrix, that erroneously we have neglected to mention in the manuscript. The component d11 ("no warning issued – no event observed") of the matrix expresses the number of hours when no warnings are issued and no landslides occur. Both criteria (1 and 2) purposefully neglect element d11, whose value is typically orders of magnitude higher than the values of the other elements of the matrix because it also includes all hours without rainfall, for which a LEWS is not designed to deal with, specifically. Thus, d11 component is neglected in our analysis in order to avoid an overestimation of the performance and to allow a more useful relative assessment of the information located in the remaining part of the duration matrix. So, in figure 9 a, b (currently figure 6 a,b) the d11 component of the duration matrix is neglected.

According to the suggestion provided we have modified the description for figure 9. Here are the new sentences: "In terms of criterion 2, Case B shows slightly higher values of Green (14%) than

Case A (7%). This means that considering the reduced set of landslides (Set b), there is a slightly better correspondence between the LE classes and corresponding warning levels issued". However, it doesn't mean a better performance for Case B, because figure 9 (currently figure 6) shows only preliminary results. With the EDuMaP method the performance is evaluated through the evaluation of statistical indicators (fig. 12 and tab. 11- currently fig. 9 and tab. 9).

5) That brings me to another issue: is it really necessary (and of added value) to conduct the performance analysis for the two cases? Why don't you show only results for Case B (as you seem to distrust the data from Case A that you omit in Case B). Again – as stated above – I would suggest to extend the analysis to the entire country and to the entire period of the warning system, but exclude those landslide observations that you distrust.

R: The dataset B is composed by a catalogue of landslides with a known typology. On the contrary the dataset A includes also landslides in soil of unknown typology that can be, anyway, classified as rainfall-induced landslides. For this reason we decided to keep both the datasets. Finally, the results coming from the two datasets were compared to evaluate the differences in terms of performance indicators arising from uncertainties in the landslide database.

6) The list of references includes many reports . . . some of them in Norwegian . . . please check which of these reports are really important for the understanding of this paper. (for example, do we really need all these references on geology and landforms?). On the other hand, I'm missing references to other authors (than Calvello and Piciullo) on performance evaluation of warning systems. There must be some of them!

R: According to the suggestion all the references in Norwegian have been cancelled because considered not useful to improve the comprehension of the manuscript.

In literature two main approaches can be distinguished for the evaluation of the performance of LEWSs at a regional scale: empirical evaluations and 2x2 contingency tables. As already mentioned in the answer to comment No. 3, the firsts are often carried out by simply analyzing the time frames during which significant high-consequence landslides occurred in the test area (Keefer et al., 1987; Aleotti, 2004; Cheung et al., 2006; Baum and Godt, 2010; Capparelli and Tiranti, 2010). The latter are computed for the joint frequency distribution of landslides and alerts, both considered as dichotomous variables (Yu et al., 2003; Cheung et al., 2006; Godt et al., 2006; Restrepo et al., 2008; Tiranti and Rabuffetti, 2010; Kirschbaum et al., 2012; Martelloni et al., 2012; Peres and Cancelliere, 2012; Staley et al., 2013; Lagomarsino et al., 2013, 2015; Greco et al., 2013; Segoni et al., 2014; Gariano et al., 2015; Stähli et al., 2015). The EDuMaP method is a different approach taking into account: the possible occurrence of multiple landslides in the warning zone, the duration of the warnings in relation to the time of occurrence of the landslides, the level of the issued warning in relation to the landslide spatial density in the warning zone and the relative importance system managers attribute to different types of errors. A comparison between the EDuMaP method and other methodologies for the evaluation of the performance lies outside the scope of the paper, which is focused on the definition of an original approach, to be implemented in the EDuMaP method, for the computation of the elements of the duration matrix in the case of early warning models issuing alerts on variable warning zones. Many references to different approaches for the performance evaluation were presented in Calvello and Piciullo 2016, and Piciullo et al., 2016.

Minor comments:

The abstract is not well balanced between introduction (background) and results (conclusions). There is too much background and introduction about the EWS. I suggest to shorten that substantially.

R: According to the suggestion, the abstract has been rewritten. The description of the Norwegian LEWS was too long and has been shortened. Now is less than half compared to the introduction and conclusions. Thank you.

Line 47: “which are increasing with climate change”; I would say: “which are expected to increase with cc”

R: We modified as suggested.

On line 75 the authors mention for the first time the fact that the Norwegian EWS issues “variable” warning zones. It is very important that the authors clarify what they mean with “variable”. I suggest to write “warning zones with a variable extent (or: area)”.

R: The sentence has been modified in:” Daily alerts are issued throughout the country in variable size warning zones".

Line 110: “In contrary” should be “On the other hand,”

R: Corrected as suggested.

Line 216: “are observed described”; either observed or described

R: observed has been deleted.

The authors use the term “precipitation episodes” several times in the text. I’m not sure “episodes” is the correct term here. I would rather suggest “events”.

R: We changed in “precipitation events”. Thank you

Line 254: “are shown” (not “are showed”)

R: Corrected. Thank You

Table 3 is not necessary because all this information is given in the text already.

R: Table 3 was cancelled.

Line 331: “the some” should be “the same”

R: Corrected. Thank You

Line 335: “in Day 1” should be “on Day 1”

R: Corrected. Thank You

Line 335: “appears” should be “appear”

R: Corrected. Thank You

Tables 5 and 6 are not necessary because all this information is given in the text already

R: Table 5 was cancelled whereas table 6 is useful to summarize all the information on number of landslides, landslides, warning events issued and warning zones alerted in 2013-2014 in the area of analysis.

Line 427: “Tab.2” should be “Tab. 4”

R: Modified. Thank You

I’m not sure all of the Figures are really needed. Please carefully reconsider which of Figs. 1 to 6 (on the EWS and its application) are really needed.

R: We accepted the comment and decided to cancel figures 1, 3 and 6 because judged as not useful to fulfill the main aim of the paper. Thank you

Title

Adapting the EDuMaP method to test the performance of the Norwegian early warning system for weather-induced landslides

Authors

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Abstract

The Norwegian national landslide early warning system (LEWS), operational since 2013, is managed by the Norwegian Water Resources and Energy Directorate and has been designed for monitoring and forecasting the hydro-meteorological conditions potentially triggering slope failures. Decision-making in the EWS is based upon rainfall thresholds, hydro-meteorological and real-time landslide observations as well as on landslide inventory and susceptibility maps. Daily alerts are issued throughout the country considering variable size warning zones. Warnings are issued once per day for the following 3 days and can be updated according to weather forecasts and information gathered by the monitoring network. The performance of the LEWS operational in Norway has been evaluated applying the EDuMaP method, which is based on the computation of a duration matrix relating number of landslides and warning levels issued in a warning zone. In the past, this method has been exclusively employed to analyse the performance of regional early warning model considering fixed warning zones. Herein, an original approach is proposed for the computation of the elements of the duration matrix in the case of early warning models issuing alerts on variable size areas. The approach has been used to evaluate the warnings issued in Western Norway, in the period 2013-2014, considering two datasets of landslides. The results indicate that the landslide datasets do not significantly influence the performance evaluation, although a slightly better performance is registered for the smallest dataset. Different performance results are observed as a function of the values adopted for one of the most important input parameters of EDuMaP, the landslide density criterion (i.e. setting the thresholds to differentiate among classes of landslide events). To investigate this issue, a parametric analysis has been conducted; the results of the analysis show significant differences among computed performances when absolute or relative landslide density criteria are considered.

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Keywords: EDuMaP method, rainfall-induced landslides, warning zones, alert, landslide density.

1. Introduction

In the last decades, natural hazards caused an increased number of consequences in terms of economic losses (Barredo, 2009) and fatalities throughout Europe (European Environment Agency, 2010; CRED, 2011). Most natural disasters are related to extreme rainfall events, which are expected to increase with climate change (Easterling et al., 2000; Morss et al., 2011). The European Commission, following an increase in human and economic losses due to natural hazards, developed legal frameworks such as the Water Framework Directive 2000/60/EC (2000) and the Floods Directive 2007/60/EC (2007), to increase prevention, preparedness, protection and response to such events and to promote research and acceptance of risk prevention measures within the society (Alfieri et al., 2012). Among the many mitigation measures available for reducing the risk to life related to natural hazards, early warning systems (EWSs) constitute a significant option available to authorities in charge of risk management and governance.

Within the landslide risk management framework proposed by Fell et al. (2005), landslide EWSs (LEWSs) may be considered a non-structural passive mitigation option to be employed in areas where risk, occasionally, rises above previously defined acceptability levels. According to Glade and Nadim (2014), the installation of an EWS is often a cost-effective risk mitigation measure and in some instances the only suitable option for sustainable management of disaster risks. Rainfall-induced warning systems for landslides are, by far, the most diffuse class of landslide EWS operating around the world. LEWSs can be employed at two distinct scales of analysis: "local" and "regional" (ICG 2012; Thiebes et al. 2012; Calvello et al. 2015, Stähli et al., 2015). EWSs at a regional scale for rainfall-induced landslides have become a sustainable risk management approach worldwide to assess the probability of occurrence of landslides over appropriately-defined wide warning zones. In fact during the last decades, several systems have been designed and improved, not only in developing countries (UNISDR 2006; Chen et al., 2007; Huggel et al., 2010; among others) but also in developed countries (NOAA-USGS, 2005; Badoux et al., 2009; Baum and Godt, 2010; Osanai et al., 2010; Lagomarsino et al., 2013; Tiranti and Rabuffetti, 2010; Rossi et al., 2012; Staley et al., 2013; Calvello et al., 2015; Segoni et al., 2015). As a recent example, the Norwegian landslide EWS was launched in autumn 2013 by the Norwegian Water Resources and Energy Directorate (NVE). The regional system has been developed for monitoring and forecasting the hydro-meteorological conditions triggering landslides and to inform local emergency authorities in advance about the occurrence of possible events (Devoli et al., 2014). Daily alerts are issued

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throughout the country in variable size warning zones. The evaluation of the alerts issued, i.e., the performance of the early warning model is not a trivial issue, and regular system testing and performance assessments (Hyogo Framework for Action, 2005) are fundamental steps.

The performance analysis of LEWSs can be an awkward process, particularly for systems employed at regional scale, because many aspects are important for the analysist to consider. Most typically, the performance evaluation is based on 2 by 2 confusion matrices computed for the joint frequency distribution of landslides and alerts, both considered as dichotomous variables, and the evaluation of statistical indicators (e.g., Cheung et al., 2006; Godt et al., 2006; Martelloni et al., 2012; Staley et al., 2013; Segoni et al., 2014; Lagomarsino et al., 2015; Gariano et al., 2015; Stähli et al., 2015). The method employed herein, which is called EDuMaP (Calvello and Piciullo, 2016), allows to consider aspects peculiar to territorial LEWSs that are not considered by the joint frequency distribution approach. In particular, the EDuMaP method takes into account: the occurrence of concurrent multiple landslides in the warning zone; the duration of the warnings in relation to the landslides; the issued warning level in relation to the landslide spatial density in the warning zone; the relative importance attributed, by system managers, to different types of errors. Up to now, this method has been applied exclusively to evaluate the performance of regional warning models designed for issuing alerts in fixed warning zones (Calvello and Piciullo, 2016; Piciullo et al., 2016a,b; Calvello et al., 2016). In the present study the EDuMaP method has been adapted to evaluate the performance of the alerts issued for variable size warning zones. To this purpose, the procedure has been tested on the Norwegian landslide EWS in the period 2013-2014. The Western Norway is the area most prone to landslides in Norway and it has been chosen as test area because the landslide database was more reliable and complete than for the rest of Norway.

2. The national landslide early warning system for rainfall-and snowmelt-induced landslides in Norway

2.1 Physical setting

Norway covers an area of ~ 324,000 km^2. With its elongated shape of 1800 km, the country reaches from latitude 58°N to 71°N. Approximately 30% of the land area are mountainous, with the highest peaks reaching up to 2500 m. a.s.l and slope angles over 30 degrees covering 6,7% of the country (Jaedicke *et al.*, 2009). In geological terms, Norway is located along the western margin of the Baltic shield with a cover of Caledonian nappes in the western parts of the country (Etzelmüller *et al.*, 2007; Ramberg *et al.*, 2008). The Caledonian nappes are dominated by Precambrian rocks and

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metamorphic Cambro-Silurian sediments, while the bedrock in the Baltic shield is dominated by Precambrian basement rocks. Cambro-Silurian sediments and Permian volcanic rocks are found in the Oslo Graben (Ramberg *et al.*, 2008).

Recurrent glaciations, variations in sea level and land subsidence/uplift, as well as weathering, transport and deposition processes have created the modern Norwegian landscape (Ramberg *et al.*, 2008). Thus, dominating quaternary deposits include various shallow (in places colluvial) soils, as well as moraine and marine deposits.

Because of the latitudinal elongation and the varied topography, the Norwegian climate displays large variations. Along the Atlantic coast, the North Atlantic Current influences the climate whereas the inland areas experiences a more continental climate. Based on the Köppen classification scheme, the Norwegian climate can be classified in three main types: warm temperate humid climate, cold temperate humid climate and polar climate. Precipitation types can be divided into three categories: frontal, orographic and showery. The largest annual precipitation values are found near the coast of Western Norway (herein also called Vestlandet) with up to 3575 mm/year. On the other hand, the driest areas receiving <500 mm/year are found in parts of South-Eastern Norway (Østlandet) and Finnmark county.

Steep landforms in combination with various soil and climatic properties provide a basis for several types of shallow landslides in non-rock materials. These slope failures include slides in various materials, debris avalanches, debris flows and slush flows. Landslides are mostly triggered by rainfall, often in combination with snowmelt. Some events are also triggered from/initiated as rockfall or slush flows, developing into, for example, debris flows as they propagate downslope. Shallow landslides constitute a substantial threat to the Norwegian society. According to Furseth (2006), at least 230 people have been killed by such slope failures during the latest approximately 500 years. In the period 2000-2009, road authorities registered more than 1800 shallow landslides along Norwegian roads.

2.2 The national landslide early warning system

In order to mitigate the risk from shallow landslides, a national EWS has been developed at the Norwegian Water Resources and Energy Directorate (NVE) as part of the national responsibility on landslide risk management. The system is established to warn about the hazard of debris flows, debris slides, debris avalanches and slush flows at regional scale. The EWS, operative since 2013, has been developed in cooperation with the Norwegian Meteorological Institute (MET), Norwegian Public Road Administration (SVV) and the Norwegian National Rail Administration (JBV).

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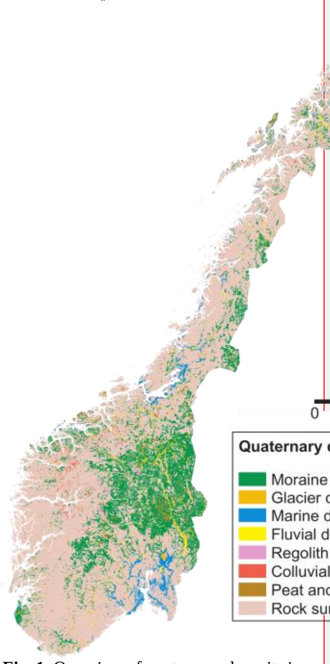

Fig. 1. Overview of quaternary deposits in Norway. Modified from NGU, (2012).¶
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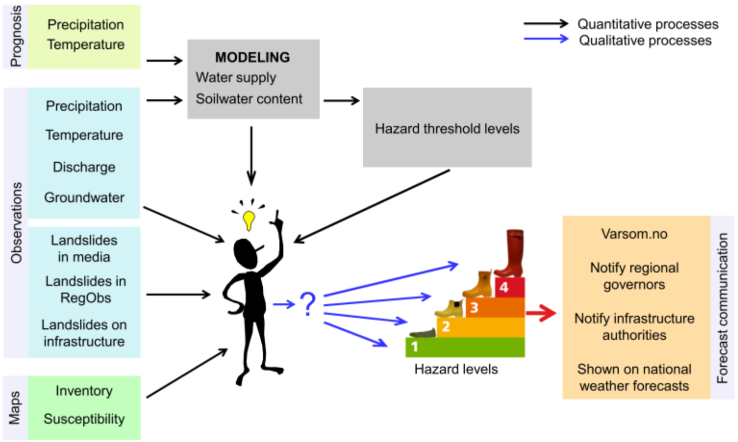

Figure 1. Organization of the landslide early warning system in Norway.

Decision-making in the EWS is based upon hazard threshold levels, hydro-meteorological and real-time landslide observations as well as landslide inventory and susceptibility maps (**Fig. 1**). In the development phase of the EWS, hazard threshold levels have been investigated through statistical analyses of historical landslides and modelled hydro-meteorological parameters. Daily hydro-meteorological conditions such as rainfall, snowmelt, runoff, soil saturation, groundwater level and frost depth have been obtained from a distributed version of the hydrological HBV-model (Beldring *et al.*, 2003).

Hazard threshold levels presently used in the EWS were proposed by Colleuille *et al.* (2010). The thresholds, combining simulations of relative water supply of rain or snowmelt and relative soil saturation/groundwater conditions, were derived from empirical tree-classification using 206 landslide events from different parts of the country. Later analyses, summarized by Boje *et al.* (2014), confirm the good performance of combining soil water saturation degree and normalised rainfall and snowmelt.

Two different landslide susceptibility maps are used as supportive data in the process of setting daily warning levels. One map indicates initiation and runout areas for debris flows at slope scale (Fischer *et al.*, 2012), while another indicates susceptibility at catchment level, based upon Generalized Additive Models (GAM) statistics (Bell *et al.*, 2014).

Susceptibility maps, hazard threshold levels and other relevant data are displayed in real-time in a webpage, www.xgeo.no, which is used as decision expert tool to forecast various natural hazards (floods, snow avalanches, landslides). Landslide hazard threshold levels and hydrometeorological

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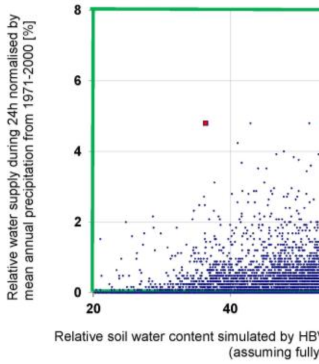

Fig. 3. Hydrometeorological hazard thresholds used in the Norwegian EWS.¶
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forecasts are displayed as raster data with 1 km^2 resolution, whereas susceptibility maps, landslide information (historical and real-time) and hydrometeorological observations are shown as either raster, polygon or point data.

A landslide expert on duty (as member of a rotation team) uses the information from forecasts, observations, maps and uncertainty in weather forecasts to qualitatively perform a nationwide assessment of landslide warning levels (**Fig. 1**). Four warning levels are defined: green (1), yellow (2), orange (3), and red (4) showing the level of hazards, or more exactly the recommended awareness level (**Tab. 1**). The warning period follows the time steps of quantitative precipitation and temperature forecasts used to simulate other hydro-meteorological parameters, and thus lasts from 06:00 UTC to 06:00 UTC each day. Warning levels are updated minimum twice during the 24 hour warning period (morning and afternoon) as a function of the weather forecast. Weather forecast updates are received 4 times per day and warning messages are sent as soon as possible, from 66 hours to few hours ahead. Warning messages are published in a publicly accessible webpage (www.varsom.no). Yellow, orange and red levels of warning are also sent to emergency authorities (regional administrative offices, roads and railways authorities) and media. Warning zones are not static geographical warning areas. Instead they vary from a small group of municipalities to several administrative regions, depending on current hydro-meteorological conditions (**Fig. 2**). Thus, extent and position of warning zones are dynamic and change from day to day.

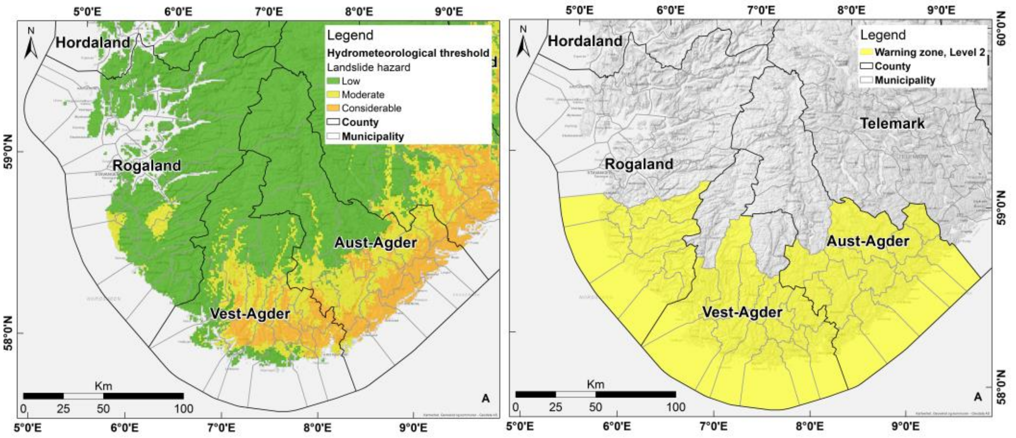

Figure 2. a) Hydrometeorological thresholds indicating potential landslide hazard in the counties of Rogaland, Vest-Agder, Aust-Agder and Telemark in South-Eastern Norway on 15.02.2014. b) The

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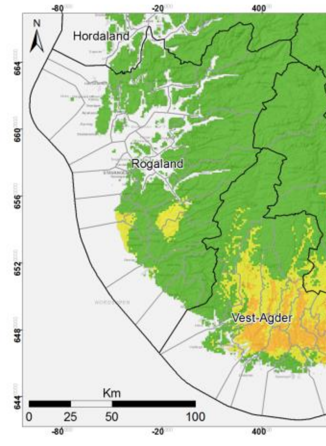

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resultant early warning zone, on warning level 2 (“yellow level”) issued on 15.02.2014 for the same area and including about 32 municipalities.

2.3 Current performance evaluation of the EWS

To evaluate the performance of a regional landslide early warning model, a comparison of warning levels issued and landslides occurred is carried out on a weekly basis. Event information is reported by Roads/Railways Authorities or municipalities, as well as obtained from media and from a real-time database to register observations. The latter has been designed as a public tool supporting crowd sourcing (Ekker et al. 2013), and is currently available to the public as a telephone application and a website (www.regobs.no). Categorization of issued warning levels into false alarms, missed events, correct and wrong levels is based on semi-quantitative classification criteria for each warning level. The principle behind the criteria is that rare hydro-meteorological conditions are expected to cause more landslides and possibly higher damages (**Tab. 1**). As an example, the warning level Red corresponds to an extreme situation that occurs very rarely. It requires immediate action and may cause severe damages within a large extent of the warning area. The criteria contain information on the expected number of landslides per area, as well as hazard signs indicating landslide activity. As seen in **Table 1** the ranges chose for the number of expected landslides and the size of the hazardous areas at each warning level are quite wide. This choice is due to the fact that the EWS is relatively new and still in a phase of continuous development.

Table 1. Criteria for evaluating daily warning levels in the Norwegian EWS.

Warning level	Classification criteria
4 (Red)	> 14 landslide (per 10-15.000 km2) Hazard signs: Several road blockings due to landslides or flooding Extreme situation that occurs very rarely, requires immediate action and may cause severe damages within a large extent of the warning area. This level corresponds to a >50 years return period flood warning.
3 (Orange)	6-10 landslides (per 10-15.000 km2) Hazard signs: Several road blockings due to landslides or flooding Severe situation that occurs rarely, require contingency preparedness and may cause severe damages within some extent of the warning area. This level corresponds to 5-50 years return period flood warning
2 (Yellow)	1-4 landslides (per 10-15.000 km2) Hazard signs: flooding/erosion in streams Situation that requires monitoring and may cause local damages within the warning area. Expected some landslide events, certain large events may occur
1 (Green)	No landslides 1-2 landslide caused by local rain showers 1 small debris slide if in area with no signs of elevated warning level

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Hazard signs: Several road blockings due to landslides or flooding
Eliminato: **3 (Orange)**
Eliminato: 6-10 landslides (per 10-15.000 km2)¶
Hazard signs: Several road blockings due to landslides or flooding
Eliminato: **2 (Yellow)**
Eliminato: 1-4 landslides (per 10-15.000 km2)¶
Hazard signs: flooding/erosion in streams
Eliminato: **1 (Green)**
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Man-made events (from e.g. leakage, deposition, construction work or explosion)

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3. Performance evaluation of the LEWS in Western Norway for the period 2013-2014

3.1 Study area and landslide data

The study area includes the four administrative regions of Møre og Romsdal, Sogn og Fjordane, Hordaland and Rogaland located on the Norwegian west-coast. A common name for the entire area is Vestlandet (i.e. Western Norway). The area is dominated by narrow fjords and steep mountainsides reaching from sea level to 1000 m a.s.l. or more, and high annual precipitation of up to ~3500 mm. Shallow quaternary deposits cover locally weathered and altered bedrock of mainly precambric and Caledonian metamorphic and magmatic origin. As a result, Vestlandet is highly prone to landslides, in particular, debris avalanches, debris flows and slush flows.

Vestlandet is the rainiest area of Norway with many annual precipitation events bringing high amounts of rain and/or snow. Precipitation patterns and spatial distribution display large variations within the study area. The precipitation patterns are described based on the main spatial distribution:

a) NNW precipitation only in the region of Møre og Romsdal;

b) NW precipitation mainly in the regions of More og Romsdal and Sogn og Fjordane, or sometimes in the northern part of Hordaland;

c) WNW precipitation in the entire study area;

d) W precipitation distributed mainly in Sogn og Fjordane, Hordaland and Rogaland;

e) SW precipitation distributed mainly in Rogaland and Hordaland, or sometimes also in Sogn of Fjordane;

f) SSW precipitation only in Rogaland, or sometimes in Hordaland and rarely in the southern part of Sogn og Fjordane;

g) S and SE with precipitation mainly in South-Eastern Norway (in summer) and not in the study area, however because of size of the systems, precipitation can spread to Møre og Romsdal or to eastern Sogn og Fjordane or Hordaland, depending on trajectory;

h) Local showers (mostly in summer), with clusters of maximum precipitation distributed randomly within the study area;

i) Southern Norway, with precipitation distributed in the entire southern part of the country and consequently in the entire study area.

During the years 2013 and 2014 more than 70 precipitation events, i.e. rain and/or snow records with more than 30 mm/24h, were registered, with some episodes bringing more than 75-150

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1-2 landslide caused by local rain showers
1 small debris slide if in area with no signs of elevated warning level
Man-made events (from e.g. leakage, deposition, construction work or explosion)

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mm/24h of rain/snow to the entire study area or part of it, following the patterns indicated above. Duration of precipitation events ranged from 1 day to 14-18 consecutive days, particularly during autumn.

Landslide early warnings higher than green level were issued for 49 days during the two-year period (**Tab. 2**). Most of these were at yellow level, however five warnings at orange level were issued in 2014 in 3 consecutive days. In 12 cases, the yellow warnings issued during the morning evaluation was downgraded to green later the same day. The most significant precipitation events recorded in 2013-2014 are 11 and occurred in the following days: 14-15/04/13, 12-13/08/13, 7/10/13, 22/10/13, 15/11/ 13, 28/12/ 13, 23/02/ 14, 20/03/14, 14/07/14, 18-19/08/14, 27-28/10/14.

Table 2. Significant rainfall, number of days with at least one warning, number of warnings and landslides in the period 2013-2014.

	2013	**2014**	**tot**
Precipitation events, i.e. rainfall and/or snow > 30 mm/24h	41	32	73
Number of days with at least one warning	20	29	49
Number of warnings	21	39	60
red warnings	0	0	
orange warnings	0	5	
yellow warnings	21	34	
Number of landslides	204	181	385

Examples of warnings issued during 2013 and 2014 are shown in **Figure 3**. Most of the alerted warning zones were completely included in the study area (**Fig. 3 c, d, f**). However, some warnings were mainly issued for neighboring areas to the 4 regions chosen as case study (**Fig.3 a, b, e**). The examples of **Figure 3** also illustrates the diversity in having variable instead of fixed size warning zones.

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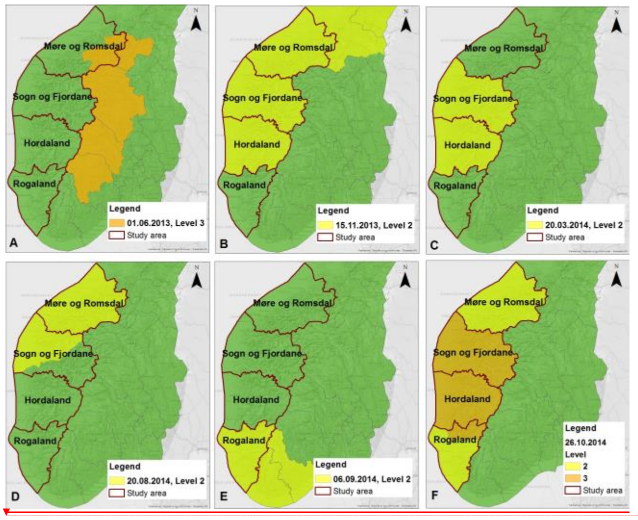

Figure 3. Examples of early warning areas and levels during 2013-2014.

Within the study area, for the period 2013-2014, the Norwegian national landslide database (www.skrednett.no) lists 476 landslides in soils and/or slush flows. Due to errors and double registration, 385 of these slope failures were considered valid for the current analyses; 249 (65%) are categorized as landslide in soil, not otherwise specified due to lack of further documentation; 65 (17%) are categorized as debris avalanches, following Hungr et al. (2014), in many cases initiated as small debris slides; 27 (7%) are classified as debris flows, following Hungr et al. (2014); 20 (5%) are soil slides in artificial slopes (cuts and fillings along roads or railway lines); 19 (4%) are slush flows and the remaining 5 (1%) are rock falls developing into debris avalanches.

The EDuMaP method was applied to two different sets of phenomena: Set A and Set B. The first set includes all 385 slope failures, while the second included only 131 phenomena, as “landslide in soil not specified” and “rock fall/debris avalanches” were removed from this dataset. The removal of non-specified landslides was due to the questionable quality of these registrations in the national landslide database, while the exclusion of rock falls inducing debris avalanches was due to uncertainty on whether precipitation can indeed be considered their triggering cause.

3.2 The EDuMaP method

The paper proposes the evaluation of the performance of the landslide early warning system operational in Norway by means of the “Event, Duration Matrix, Performance (EDuMaP) method” (Calvello & Piciullo, 2016). This method has been principally employed to analyse the performance of regional early warning model considering fixed warning zones for issuing alerts. The method

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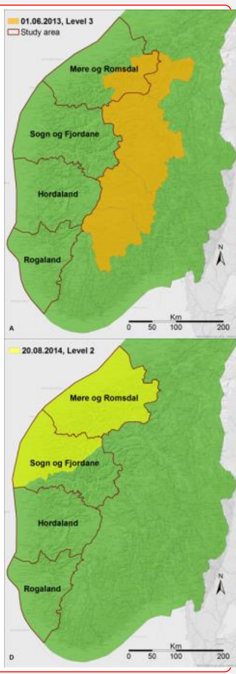

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comprises three successive steps: identification and analysis of landslide and warning Events (E), from available databases; definition and computation of a Duration Matrix (DuMa), and evaluation of the early warning model Performance (P) by means of performance criteria and indicators.

The first step requires the availability of landslides and warnings databases for the preliminary identification of "landslide events" (LEs) and "warning events" (WEs). A landslide event is defined as one or more landslides grouped on the basis of their spatial and temporal characteristics. A warning event is defined as a set of warning levels issued within a given warning zone, grouped considering their temporal characteristics. The parameters which need to be defined to carry on the events analysis are ten: 1) warning levels, W_{lev}; 2) landslide density criterion, $L_{den(k)}$; 3) lead time, t_{LEAD}; 4) landslide typology, L_{typ}; 5) minimum interval between landslide events, Δt_{LE}; 6) over time, t_{OVER}; 7) area of analysis, A; 8) spatial discretization adopted for warnings, $\Delta A_{(k)}$; 9) time frame of analysis, ΔT; 10) temporal discretization of analysis, Δt. For more details see Calvello and Piciullo, 2016. The second step of the method is the definition and computation of a "duration matrix", whose elements d_{ij} report the time associated with the occurrence of landslide events in relation to the occurrence of warning events, in their respective classes. The element d_{11} of the matrix expresses the number of hours when no warnings are issued and no landslides occur (Fig. 4). The number of rows and columns of the matrix is equal to the number of classes defined for the warning and landslide events, respectively (**Fig. 4**). The final step of the method is the evaluation of the duration matrix based on a set of performance criteria assigning a performance meaning to the element of the matrix. Two criteria are used for the following analyses (**Fig. 4**), respectively indicated as criterion 1 and criterion 2. The first criterion employs an alert classification scheme derived from a 2x2 contingency table, thus identifying: correct predictions, CPs; false alerts, FAs; missed alerts, MAs; true negatives, TNs. The second criterion assigns a color code to the elements of the matrix in relation to their grade of correctness, classified in four classes as follows: green, G, for the elements which are assumed to be representative of the best model response; yellow, Y, for elements representative of minor model errors; red, R, for elements representative of a significant model errors; purple, P, for elements representative of the worst model errors. Both criteria purposefully neglect element d_{11}, whose value is typically orders of magnitude higher than the values of the other elements of the matrix because it also includes all hours without rainfall, for which a LEWS is not designed to deal with, specifically. Thus, d_{11} element is neglected in order to avoid an overestimation of the performance and to allow a more useful relative assessment of the information located in the remaining part of the duration matrix. A number of performance

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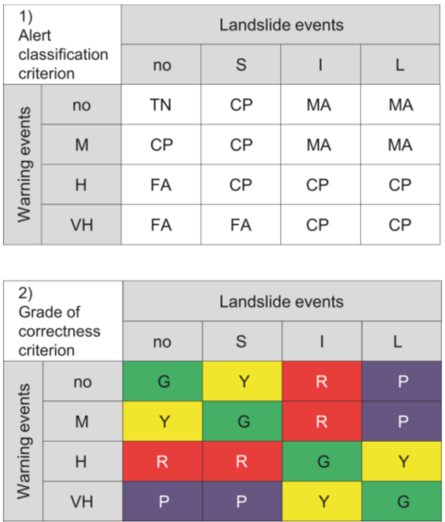
indicators may be derived from the two performance criteria described. **Table 3** reports the name, symbol, formula and value of the performance indicators considered herein.



1) Alert classification criterion		Landslide events			
		no	S	I	L
Warning events	no	TN	CP	MA	MA
	M	CP	CP	MA	MA
	H	FA	CP	CP	CP
	VH	FA	FA	CP	CP

2) Grade of correctness criterion		Landslide events			
		no	S	I	L
Warning events	no	G	Y	R	P
	M	Y	G	R	P
	H	R	R	G	Y
	VH	P	P	Y	G

Figure 4. Performance criteria used for the analyses performed herein (modified from Calvello & Piciullo, 2016). Four classes of warning events (key: no, no warning; M, moderate warning; H, high warning; VH, very high warning) and four classes of landslide events (key: no, no landslides; S, small event, few landslides; I, intermediate event, several landslides; L, large events, many landslides).

Table 3. Performance indicators used for the analysis.

Performance indicator	Symbol	Formula
Efficiency index	I_{eff}	$CP/\Sigma_{ij}d_{ij}$ (excluding d_{11})
Hit rate	HR_L	CP/(CP+MA)
Predictive power	PPW	CP/(CP+FA)
Threat score	TS	CP/(CP+MA+FA)
Odds ratio	OR	CP/(MA+FA)
Miss classification rate	MR	1- I_{eff}
Missed alert rate	R_{MA}	MA/(CP+MA)
False alert rate	R_{FA}	FA/(CP+FA)
Error Rate	ER	(Red&Pur)/ Σ_{ij} d_{ij} (excluding d_{11})
Missed and false alerts balance	MFB	MA/(MA+FA)
Probability of serious mistakes	P_{SM}	$Pur/\Sigma_{ij}d_{ij}$ (excluding d_{11})

3.3 Adaptation of the EDuMaP method to variable size warning zones

In earlier studies, the EDuMaP method has been applied to analyse the performance of regional landslide EWSs adopting a fixed spatial discretization for warnings. In contrast, the Norwegian landslide EWS employs variable size warning zones. This characteristic influences the first two phases of the EDuMaP method: identification and analysis of landslide and warning events from

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available databases; definition and computation of a duration matrix. This section explains how to define LEs and WEs and how to compute the duration matrix in case of variable size warning zones.

The Norwegian EWS adopts four warning levels. Daily warnings are issued throughout the country considering municipalities as the minimum warning territorial unit (TU). Hence, municipalities alerted with the same warning level define a warning zone of level *i* (e.g., green, yellow, orange, red in **Fig. 5**). Therefore, on a day of alert, up to four warning zones alerted with different warning levels can be issued (e.g., day 3 in **Fig. 5**). LEs are defined by grouping together landslides occurred within each warning zone. The class each LE belong to, as defined in **section 3.2**, depends on the landslide density criterion, $L_{den(k)}$, chosen for the analyses.

The duration matrix is evaluated for the whole area of analysis, A, in a period of analysis, ΔT, summing the $time_{ij}$ computed within the different warning zones, for each temporal discretization Δt. In particular, the values of $time_{ij}$, for variable size warning zones, are computed as follows:

$$time_{ij} = \sum_{\Delta t} \frac{(TUA_{ij})}{A} \qquad \textbf{(Eq. 1)}$$

where: Δt is the minimum temporal discretization adopted for warnings (for the Norwegian EWS, equal to 1 day); A is the area of analysis; TUA_{ij} is the extent of the territorial unit alerted with a warning level *i*, and class of the landslide event, *j*, per day of alert. Each element of the duration matrix, d_{ij}, is then computed, within the time frame of the analysis, ΔT, as follows:

$$d_{ij}=\sum_{\Delta T}(time_{ij}) \qquad \textbf{(Eq. 2)}$$

The evaluation of landslide and warning events and the definition and computation of a the duration matrix is herein exemplified for three hypothetical days (Fig. 8). For instance, on Day 1 two distinct LEs appear, containing 4 and 1 landslides, respectively. The first event belongs to the warning zone alerted with level 2 and the latter to the warning zone alerted with level 1. In Day 3 there are 4 warning zones, each one alerted with a different warning level and 4 distinct LEs can be identified, one per warning zone. A landslide density criterion, $L_{den(k)}$ in four classes has been considered for the example of **Figure 5**: 0 (no landslides), small (1-2 landslides), Intermediate (3-4 landslides) and Large (≥5 landslides); together with four warning levels, W_{lev}: green, yellow, orange and red. At "day 1" two different warning zones can be defined grouping together the TUs (blue boundary in **Fig. 5**) with the same warning level. The warning zones are composed by 10 and 8 TUs, and they are alerted with two different warning levels: green and yellow. In the two warning zones, a "small" LE and an "Intermediate" LE, respectively, are occurred. Once the warning levels and the LEs within each warning zone have been defined, $time_{12}$ and $time_{23}$ are evaluated for each TU using

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Equation 1. At “day 2” three warning zones and two “Small” LEs have been identified. At “day 3” LEs occurred in each of the four warning zones identified. Finally, the evaluation of elements d_{ij} of the duration matrix is carried out following **Equation 2**, over the time frame of the analysis, *ΔT*.

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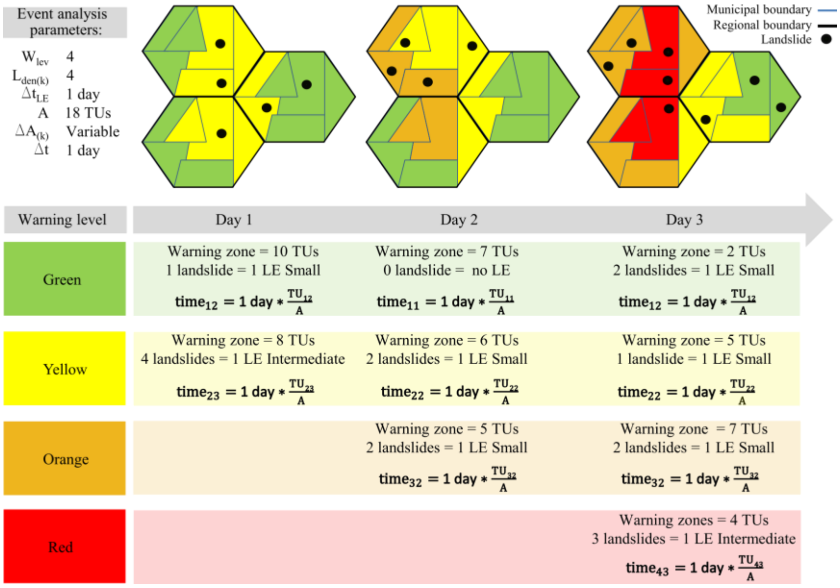

Warning level	Day 1	Day 2	Day 3
Green	Warning zone = 10 TUs 1 landslide = 1 LE Small $time_{12} = 1\ day * \frac{TU_{12}}{A}$	Warning zone = 7 TUs 0 landslide = no LE $time_{11} = 1\ day * \frac{TU_{11}}{A}$	Warning zone = 2 TUs 2 landslides = 1 LE Small $time_{12} = 1\ day * \frac{TU_{12}}{A}$
Yellow	Warning zone = 8 TUs 4 landslides = 1 LE Intermediate $time_{23} = 1\ day * \frac{TU_{23}}{A}$	Warning zone = 6 TUs 2 landslides = 1 LE Small $time_{22} = 1\ day * \frac{TU_{22}}{A}$	Warning zone = 5 TUs 1 landslide = 1 LE Small $time_{22} = 1\ day * \frac{TU_{22}}{A}$
Orange		Warning zone = 5 TUs 2 landslides = 1 LE Small $time_{32} = 1\ day * \frac{TU_{32}}{A}$	Warning zone = 7 TUs 2 landslides = 1 LE Small $time_{32} = 1\ day * \frac{TU_{32}}{A}$
Red			Warning zones = 4 TUs 3 landslides = 1 LE Intermediate $time_{43} = 1\ day * \frac{TU_{43}}{A}$

Figure 5: Computation of $time_{ij}$ elements as a function of warning levels and LEs occurred for each warning zone for three hypothetical days of warning.

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4. Results and discussion

4.1 Events analysis

As previously mentioned, the events analysis phase of the EDuMaP method depends on the values assumed by a series of well-identified parameters, which are defined to allow the analyst to make choices on how to select and group landslides and warnings.

The values of the ten input parameters, cf. section 3, for the two analyses carried out, i.e. case A and case B, are representative of the structure and operational procedures of the warning model employed in the Norwegian EWS. The period of analysis, *ΔT*, is 2013-2014, while Δt, is set to 1 day. Parameters t_{LEAD} and t_{OVER} are both set to zero. The four warning levels, W_{lev}, are: green (no warning), yellow (WL_1), orange (WL_2), red (WL_3). The landslides used for the analyses are grouped into landslide events considering a Δt_{LE} of 1 day. The four classes of LEs are defined employing a relative landslide density criterion, $L_{den(k)}$, as a function of both number of landslides and territorial

Eliminato: **Table 5** shows the values of the ten input parameters, cf. section 3, for the two analyses carried out, i.e. case A and case B.

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extensions. The values have been derived by the criteria for the daily warning levels evaluation in the Norwegian EWS (see **Tab. 1**). The only difference between case A and case B has to do with the type of landslides used for the analyses, which respectively refer to the datasets A and B.

Dataset A is composed by 385 rainfall- and snowmelt-induced landslides occurring within the study area. These slope failures have been grouped into 137 LEs. The majority of LEs belong to class "Small" (133 events), while the rest of them (4 events) belong to class "Intermediate"; no "Large" LEs have been recorded in the period of analyses (**Tab. 4**). For case B, the 131 considered phenomena have been grouped into 57 LEs, 54 "Small" and 3 "Intermediate" events (**Tab. 4**). A total of 60 warnings were issued in the period of analysis; none of these were "Red". Five warning zones received the level "Orange" and 55 zones received the warning level "Yellow". In the period of analysis 37 different warning zones have been alerted (**Tab. 4**).

Table 4: Number of landslides, landslides, warning events issued and warning zones alerted in 2013-2014 in the area of analysis.

	Case A	Case B
Landslide	385	131
Landslide events, LE	137	57
Small	132	54
Intermediate	5	3
Large	0	0
Warning events, WE	60	60
Warning zones alerted	37	37

4.2 Performance evaluation for the years 2013-2014

Two different sets of landslides have been considered in the performance of the Norwegian EWS for the Vestlandet area: Set A and Set B. The duration matrices obtained are shown in Table 5. Both cases refer to the years 2013-2014, thus, the sum of matrix elements is always equal to 730 days.

Table 5: Duration matrices for cases A and B, units of time expressed in days.

CASE A		**LE class**			
		1	2	3	4
WE level	1	600,48	107,62	0,00	0,00
	2	9,88	8,47	1,80	0,00
	3	0,00	1,16	0,58	0,00

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Tab. 5: Values of the EDuMaP input parameters for the two analyses: case A and case B¶

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	4	0,00	0,00	0,00	0,00

CASE B		**LE class**			
		1	2	3	4
WE level	1	671,55	36,56	0,00	0,00
	2	11,32	7,90	0,93	0,00
	3	1,16	0,00	0,58	0,00
	4	0,00	0,00	0,00	0,00

The duration matrices have been analysed considering two different performance criteria (see **Fig. 4**). The first one is derived by a contingency table scheme (criterion 1), the other one is based on a colour code assigning a grade of correctness to each matrix cell (criterion 2). The results obtained considering criterion 1 for both Case A and B (**Fig. 6 a**) show a very high percentage of correct predictions (CPs), over 96%, and around 1,5% of missed alerts (MAs). The amount of false alerts (FAs) are 1% and 2% respectively for Case A and B. Following criterion 2 (**Fig. 6 b**) differences, among Case A and B, can be observed in terms of greens (G), that are respectively equal to 7% and 14,5%, and yellows (Y) that are respectively equal to 91% and 82%. No P and just few R, equal to 2,3% and 3,6%, are observed in Case A and Case B, respectively. Following criterion 1, the differences among the two cases analysed are not significant. In terms of criterion 2, Case B shows slightly higher values of G (14%) than Case A (7%). This means that considering the reduced set of landslides (Set b), there is a slightly better correspondence between the LE classes and the corresponding warning levels issued.

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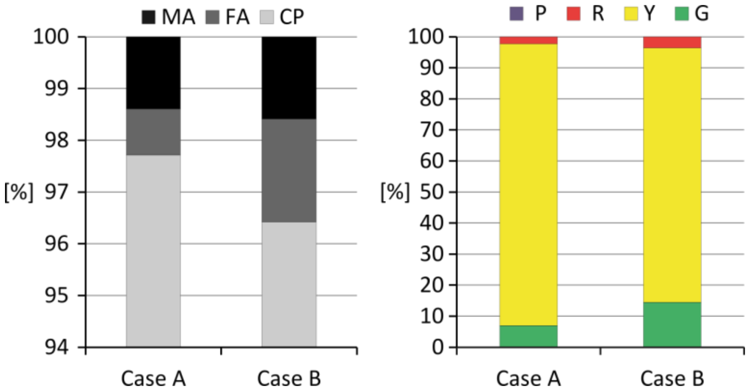

Figure 6: Duration matrix results in terms of: criterion 1 (a) and criterion 2 (b).

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The performance indicators used to analyse the duration matrices (**Tab. 3**) are grouped into two subsets of indicators, respectively evaluating success and error (**Fig. 7**). Excluding the odds rate

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(OR), the remaining success indicators have a percentage higher than 95% for both cases, due to the high value of CPs that is orders of magnitude higher than MAs and FAs. Therefore the OR, that indicates the correct predictions relative to the incorrect ones, assumes a very high value for both cases, although slightly higher for Case A (**Fig. 8**). The error indicators MR, ER, RMA and RFA assume very low values and the differences between the two cases are around 1% (**Fig. 7 b**). The MFB, which represents the ratio of MAs over the sum of MAs and FAs, is around 60% and 45% respectively for Cases A and B (**Fig. 8**).

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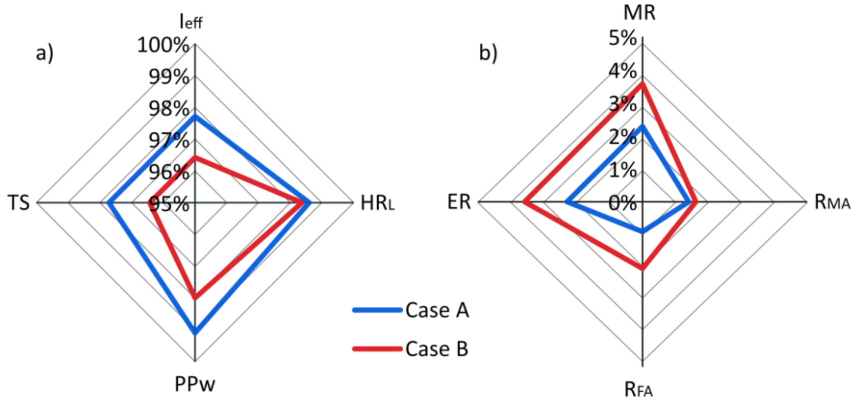

Figure 7: Performance indicators quantifying the landslide early warning performance of Case A (in blu) and Case B (in red) in terms of: success (a) and error (b).

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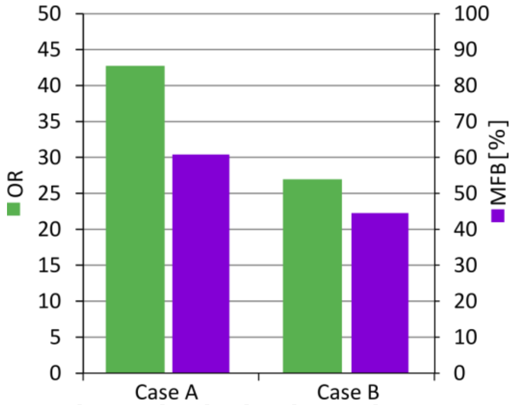

Figure 8: Odds Ratio (OR) and Missed and False alerts Balance (MFB) performance indicators, quantifying the landslide early warning performance of Case A and Case B.

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In this performance analysis the high value of I_{eff}, (>95%) and ORs, could be interpreted as an excellent result but, in contrast, the high value of MFB highlights some issues related to the duration of MAs in relation to the total duration of wrong predictions. In general, this could be a

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serious problem because MAs mean that no warnings or low level warnings have been issued during the occurrence of one or more LEs of the highest two classes (“Intermediate” and “Large”). In particular for Case A, 4 out of 5 LE of class “Intermediate” have to be considered MAs because they occurred when the warning was set to level 2. Following the previous considerations, Case B shows the best performance in terms of both success and error indicators, with a lower value of MFB and a high value of OR. Case B uses a landslide dataset composed of rainfall-induced landslides with a higher accuracy of information than Case A. As stated in Piciullo et al., (2016), the result of a performance evaluation is strictly connected to the availability of a landslide catalogue and to the accuracy of the information included in it.

Finally, it is important to stress the use of both success and error indicators to carry out a complete performance analysis. As in this case, dealing with some indicators neglecting others could cause a wrong evaluation of the early warning model performance. For instance, in the period of analysis, no LEs of class 4 and only few LEs of class 3 occurred. However, the majority of durations of these LEs have been missed. This means that the landslide early warning model was mostly able to predict LEs of class “Small”. A possible solution to obtain a better model performance, reducing MAs and simultaneously increasing CPs and G, could be to decrease the thresholds employed to issue the warning level “High”.

4.3 Parametric analysis: the landslide density criterion

A parametric analysis on the landslide density criterion, $L_{den(k)}$, has been herein conducted with a twofold purpose: to compare the performance of different early warning models, and to evaluate the effect of the choices that the analyst makes when defining landslide event (LE) classes on the performance indicators computed according to the EDuMaP method. The landslide density, $L_{den(k)}$, represents the criterion used to differentiate among n classes of landslide events. The classes may be established using an absolute (A) or a relative (R) criterion, i.e., simply setting a minimum and maximum number of landslides for each class or defining these numbers as landslide spatial density, i.e. in terms of number of landslides per unit area. Six landslide density criteria have been considered in the performed parametric analysis (**Tab. 6**) referring to the criteria used in the Norwegian EWS (**Tab. 1**). Two of them employ an absolute criterion using different numbers of landslides per LE class the other four simulations, obtained considering the relative criterion, vary as a function of both number of landslides and territorial extensions (10.000 km^2 and 15.000 km^2). Changing the definition of LE classes, the duration matrix and the performance indicators vary because of relocation of the d$_{ij}$ elements. In particular the time$_{ij}$ element, which is the amount of

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time for which a level i-th warning event is concomitant with a class j-th landslide event, may vary the j-th index causing a movement of the element along the i-th row. The parametric analysis has been performed using the landslide dataset A, which includes 385 landslides. **Table 7** reports the classification of the LEs in the 6 combination of landslide density criteria.

Table 6. Parametric analysis: landslide density criteria considered to classify the LEs.

LE class	Absolute criterion [No. of landslides] and number of LEs		Relative criterion [No. of landslides / Area] and number of LEs			
	$A_{0,14}$	$A_{1,18}$	R-15$K_{0,14}$	R-15$K_{0,10}$	R-10$K_{0,14}$	R-10$K_{0,10}$
0	0	1	0	0	0	0
SMALL	1 to 4	2 to 4	(1 to 4)/15'000 km^2	(1 to 4)/15'000 km^2	(1 to 4)/10'000 km^2	(1 to 4)/10'000 km^2
INTERMEDIATE	5 to 14	5 to 18	(5 to 14)/15'000 km^2	(5 to 10)/15'000 km^2	(5 to 14)/10'000 km^2	(5 to 10)/10'000 km^2
LARGE	> 14	> 18	> 14/15'000 km^2	> 10/15'000 km^2	> 14/10'000 km^2	> 10/10'000 km^2

Table 7. Classification of LEs for the 6 simulations reported in table 8.

LE class	Absolute criterion [No. of landslides] and number of LEs		Relative criterion [No. of landslides / Area] and number of LEs			
	$A_{0,14}$	$A_{1,18}$	R-15$K_{0,14}$	R-15$K_{0,10}$	R-10$K_{0,14}$	R-10$K_{0,10}$
SMALL	124	32	132	132	133	133
INTERMEDIATE	9	9	5	3	4	4
LARGE	4	4	0	2	0	0

As an example, the simulations R-15$K_{0,10}$ and R-15$K_{0,14}$ differ for the definition of both LE classes Large and Intermediate. By comparing the two respective duration matrices (**Tab. 8 a, b**) a movement of the durations from d_{24} and d_{34} to respectively d_{23} and d_{33} is evident. This behaviour is due to the increase of spatial density for LE class Large, in particular from 0,67 landslides per 1000 km^2 to 0,93 landslides per 1000 km^2 (**Tab. 6**), which causes a relocation of time$_{i4}$ along the rows.

Table 8. Duration matrix results for simulations R-15$_{0,10}$, R-15$_{0,14}$.

R-15$K_{0,10}$		**LE duration (h)**			
		1	2	3	4
WE duration (h)	1	600,48	107,62	0,00	0,00
	2	9,88	8,47	0,98	0,82
	3	0,00	1,16	0,00	0,58
	4	0,00	0,00	0,00	0,00

R-15$K_{0,14}$	**LE duration (h)**

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		1	2	3	4
WE duration (h)	1	600,48	107,62	0,00	0,00
	2	9,88	8,47	1,80	0,00
	3	0,00	1,16	0,58	0,00
	4	0,00	0,00	0,00	0,00

Changes within the duration matrix mean that the value of the performance indicators may change. **Table 9** presents a summary of performance indicators for all six simulations of the landslide density criteria used in the parametric analysis.

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Table 9 Performance indicators for the six simulations of landslide density criteria considered in the parametric analysis.

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Performance indicator	A$_{0,14}$	A$_{1,18}$	R-15K$_{0,14}$	R-15K$_{0,10}$	R-10K$_{0,14}$	R-10K$_{0,10}$
I$_{eff}$	0,95	0,86	0,98	0,98	0,98	0,98
HR$_{L}$	0,95	0,86	0,99	0,99	0,99	0,99
PP$_{W}$	1,00	1,00	0,99	0,99	0,99	0,99
TS	0,95	0,86	0,98	0,98	0,98	0,98
OR	18,98	6,07	42,75	42,75	49,43	49,43
MR	0,05	0,14	0,02	0,02	0,02	0,02
R$_{MA}$	0,05	0,14	0,01	0,01	0,01	0,01
R$_{FA}$	0,00	0,00	0,01	0,01	0,01	0,01
ER	0,05	0,14	0,02	0,02	0,02	0,02
MFB	1,00	1,00	0,61	0,61	0,55	0,55

The results show similar performance for the four simulations derived using a relative criterion (R15-C$_{0,14}$ R15-C$_{0,10}$ R10-C$_{0,14}$ R10-C$_{0,10}$) . The values of the success indicators are always high: well above 95%, for I$_{eff}$, HR, TS, PP$_{w}$, while OR ranges between 42 and 49 (**Fig. 9 a**). This is due to the high value of CPs compared to those of MAs and FAs, underlining a good performance of the early warning model for these four simulations. In fact, also the error indicators are very low in terms of percentage, around 1-2% (**Fig. 9 b**). Lower values are observed for the combination obtained considering the absolute criterion, and in particular for A$_{1,18}$, with MR, R$_{MA}$ and ER around 14%. The MFB is generally high for all simulations denoting a bad capability of the model to predict LEs of classes 3 and 4. Anyway, it must be emphasized that, considering these landslide

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density criteria, only the simulations R-15K$_{0,10}$, A$_{0,14}$ and A$_{1,18}$ have LEs of class 4 in the period of the analysis (**Tab. 7**).

In conclusion, the parametric analysis shows significant differences between the absolute and relative criterion simulations. For this case study, absolute criterion simulations have lower success performance indicators, in particular for the values of odds ratio (OR) and, very high values of missed and false alert balance (MFB) compared to the performance indicators obtained for relative criterion simulations. Moreover, the absolute criterion simulations produce a number of purple errors that increase the PSM (**Fig. 9 b**).

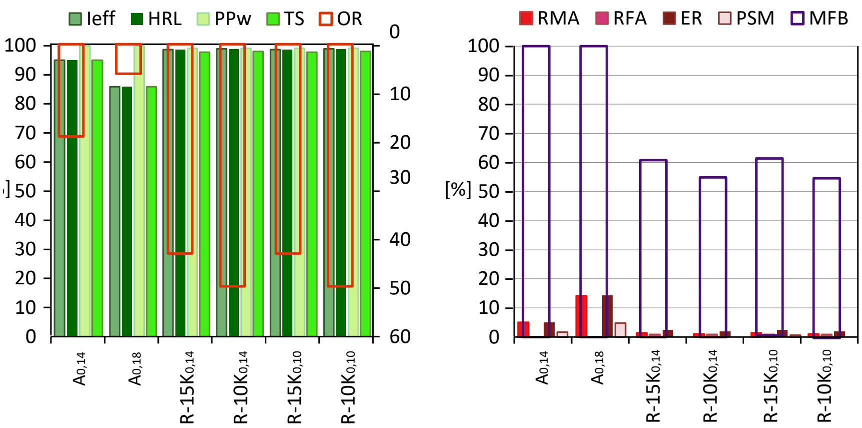

Figure 9. Performance indicators related to the success (a) and to the errors (b) of the warning model, evaluated for the six simulations of landslide density criteria considered in the parametric analysis.

5. Conclusions

The main aim of regional landslide early warning systems is to produce alert advices within a specific warning zone and to inform local authorities and the public of landslide hazard at a given level. To evaluate the performance of the alerts issued by such systems several aspects need to be considered, such as: the possible occurrence of multiple landslides in the warning zone, the duration of warnings in relation to the time of occurrence of landslides, the level of the issued warning in relation to spatial density of landslides in the warning zone and the relative importance system managers attribute to different types of errors. To solve these issues, the EDuMaP method can be seen as a useful tool for testing the performance of regional landslide warning models. Up to now, the method has been applied exclusively to systems that issue alerts on fixed warning zones. By

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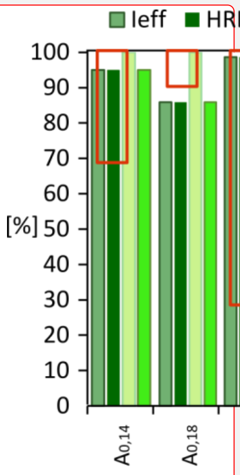

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using data from the Norwegian landslide EWS this study has extended the applicability of the EDuMaP method to warning systems that uses variable size warning zones. In this study, the EDuMaP method has been used to evaluate the performance of the Norwegian landslide early warning system for Vestlandet (Western Norway) for the period 2013-2014. The results show an overall good performance of the system for the area analyzed. Two datasets of landslide occurrences have been used in this study: the first one including all the slope failures registered and gathered in the NVE database within the test area; the second one excluding the phenomena whose typology was either not determined or is not typically associated to rainfall. The results are not too sensitive to the dataset of landslides, although slightly better results are registered with the smallest (i.e. more accurate) dataset. In both cases, the high value of the MFB highlights a high number of MAs compared to the FAs. A recommendation could be to have a MFB lower than 25%, which means that only 1 wrong alert out of 4 is a MA. Following this reasoning, a reduction of the warning level “High” is recommended in order to reduce the MAs and to increase the performance of the Norwegian EWS.

A parametric analysis was also conducted for evaluating the performance sensitivity, to the landslide density criterion, Lden(k), used as an input parameter with EDuMaP. This parameter represents the way landslide events are differentiated in classes. In the analysis the classes were established considering both absolute (2 simulations) and relative (4 simulations) criteria. The parametric analysis shows how the variation of the intervals of the LE classes affects the model performance. The best performance of the alerts issued in Western Norway was obtained applying a relative density criterion for the definition of the LE classes. The parametric analysis shows only minor differences in the performance analysis among the four cases considered with the relative density criteria. In conclusion, this study highlights how the definition of the density criterion to be used in defining the LE classes is a fundamental issue that system managers need to be take into account in order to give an idea on the number of landslides expected for each warning level over a given warning zone.

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