Title

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

Authors

Piciullo Luca(1), Dahl Mads-Peter (2), Devoli Graziella (2,3), Colleuille Hervé(2), Calvello Michele (1)
(1) Department of Civil Engineering, University of Salerno, Italy
(2) Norwegian Water Resources and Energy Directorate, Oslo, Norway
(3) Department of Geosciences, University of Oslo, Oslo, Norway

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.

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 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 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 (LEWS)**

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).

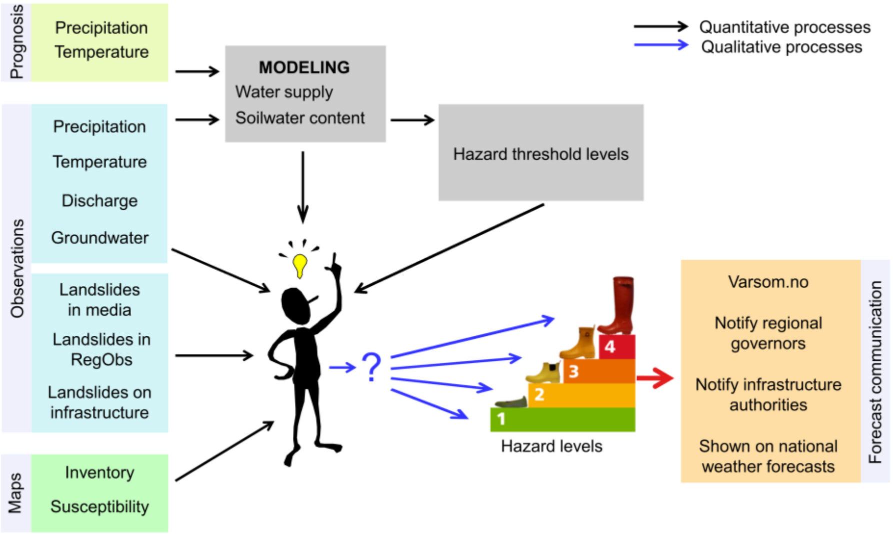


Figure 1. Organization of the landslide early warning system in Norway.

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 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.

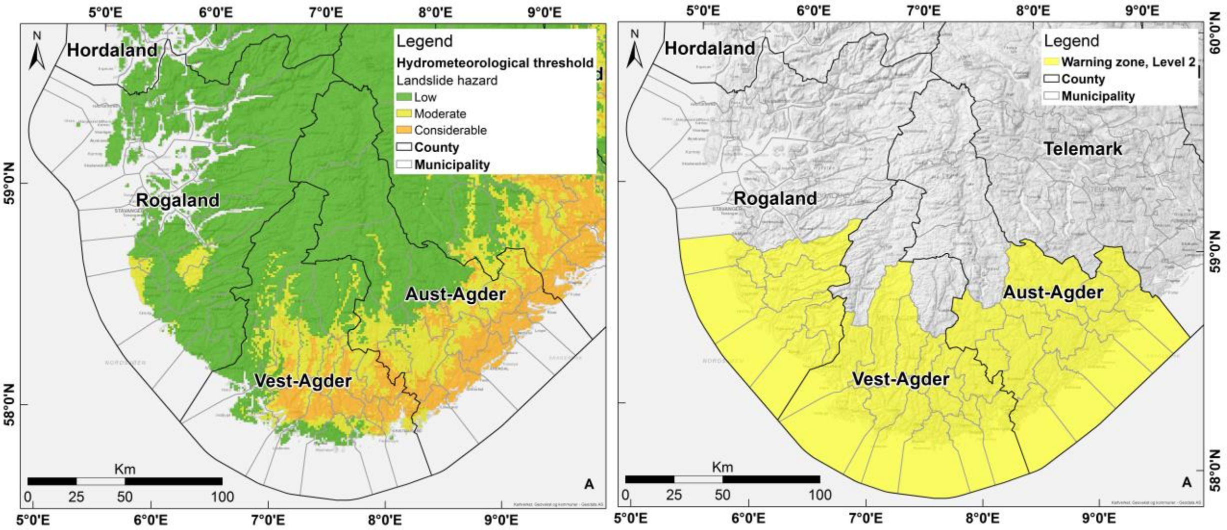


Figure 2. a) Hydrometeorological thresholds indicating potential landslide hazard in the counties of Rogaland, Vest-Agder, Aust-Agder and Telemark in South-Eastern Norway on 15.02.2014. b) The resultant early warning zone, on warning level 2 ("yellow level") issued on 15.02.2014 for the same area and 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.

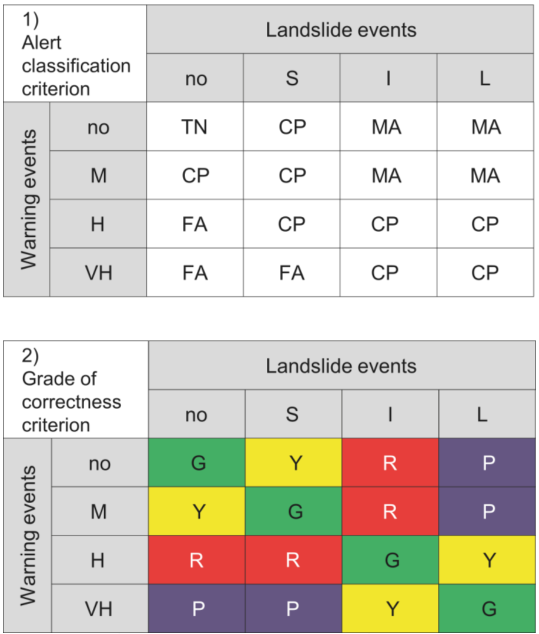
Warning level	Classification criteria
4 (Red)	> 14 landslide (per 10-15.000 km2) Hazard signs: Several road blockings due to landslides or flooding Extreme situation that occurs very rarely, requires immediate action and may cause severe damages within a large extent of the warning area. This level corresponds 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 Man-made events (from e.g. leakage, deposition, construction work or explosion)

2.4 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 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. 3**). 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. 3**), 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 indicators may be derived from the two performance criteria described. **Table 2** 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 3. 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 2. 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)/ Σij dij (excluding d11)
Missed and false alerts balance	MFB	MA/(MA+FA)
Probability of serious mistakes	P_{SM}	Pur/$\Sigma_{ij}d_{ij}$ (excluding d_{11})

2.5 Adaptation of the EDuMaP method

LEWSs may adopt a fixed or a variable spatial discretization for warnings (ΔA(k)). In the first case the warning zones are univocally defined with fixed extents. For each warning zone, the warnings are issued over the whole zone according to site specific rainfall thresholds and decisional algorithms. Thus, only one level of warning can be issued in each warning zone in the minimum temporal discretization adopted for warnings (Δt). The performance analysis with the EDuMaP method is carried out separately for each warning zone. Therefore, in this case, the dij components of the duration matrix represent the time evaluation of the combination of warning levels issued and landslide events occurred in a specific warning zone in a period of analysis.

In the case of a variable spatial discretization for warnings the number and extent of the warning zones vary in time in the period of analysis (ΔT). The number of warning zones is defined by the number of warning levels issued in the minimum temporal discretization (Δt). For instance, if only two levels (e.g. green and orange) are issued in a given Δt, the area of analysis (A) would be divided into two warning zones. The extent of the warning zones is obtained grouping together all the territorial units (TUs) alerted with the same level of warning (see **Fig. 4**). In a given Δt, the Event analysis phase is carried out for all the warning zones simultaneously. The time evaluation of the elements of the duration matrix in a given Δt (timeij) for the area of analysis (A) is carried out by weighting the spatial contribution of each warning zone in relation to the total area. In particular, the values of $time_{ij,}$ for variable size warning zones, are computed as follows:

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

where: Δt is the minimum temporal discretization adopted for warnings (for the Norwegian EWS, equal to 1 day); A is the area of analysis; TU_{ij} is the extent of the territorial units alerted with a warning level *i*, and class of the landslide event, *j*, in a given Δt. Each element of the duration matrix, d_{ij}, 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, as follows:

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

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. 4**). 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 4**: 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. 4**) 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 **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.

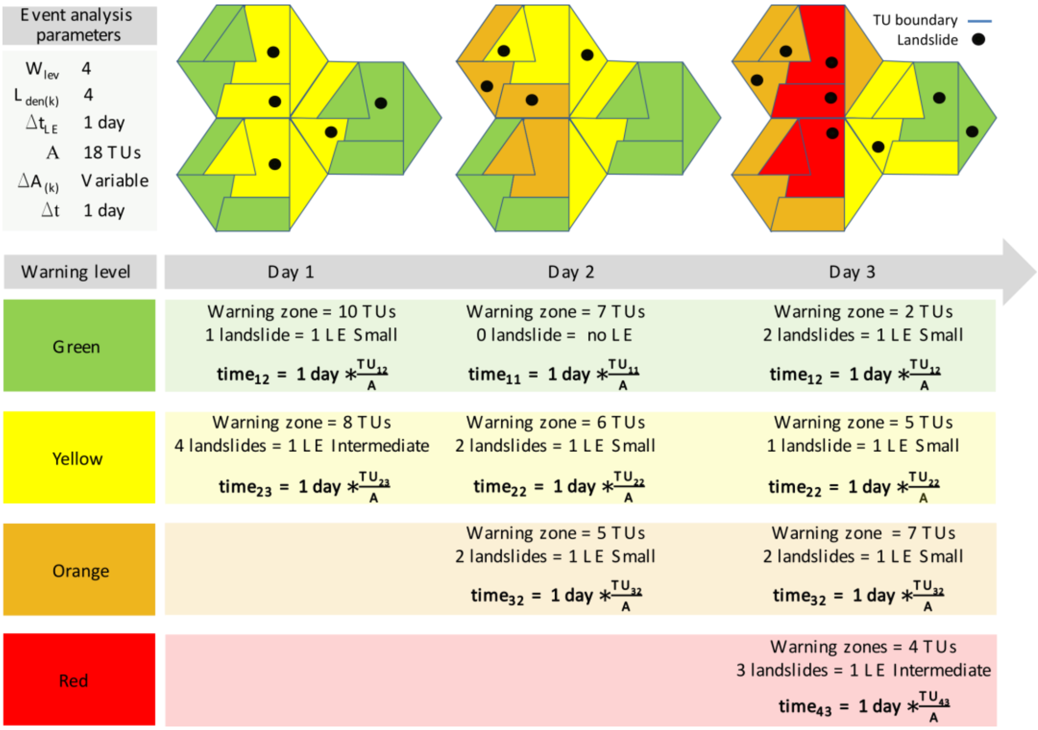


Figure 4: Computation of $time_{ij}$ elements as a function of warning levels and LEs occurred for each warning zone for three hypothetical days of warning.

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 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. 3**). 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 3. 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 5**. Most of the alerted warning zones were completely included in the study area (**Fig. 5 c, d, f**). However, some warnings were mainly issued for neighboring areas to the 4 regions chosen as case study (**Fig. 5 a, b, e**). The examples of **Figure 5** also illustrates the diversity in having variable instead of fixed size warning zones.

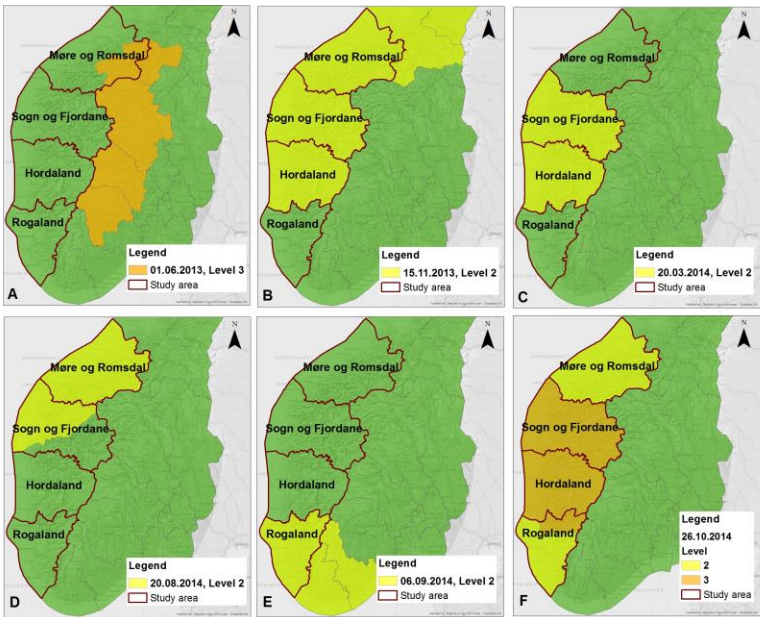


Figure 5. Examples of early warning areas and levels during 2013-2014.

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 datasets 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 Events analysis

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 available databases; definition and computation of a duration matrix.

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. It adopts four warning levels: green (no warning), yellow (WL_1), orange (WL_2), red (WL_3). Daily warnings are issued throughout the country (i.e., Δt, is set to 1 day) considering municipalities as the minimum warning territorial unit (TU). Hence, municipalities alerted with the same warning level define a warning zone of level *i*. 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. 4**). Parameters t_{LEAD} and t_{OVER} are both set to zero. LEs are defined by grouping together landslides occurred within each warning zone 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 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

3.3 Duration matrices and performance indicators

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
	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.

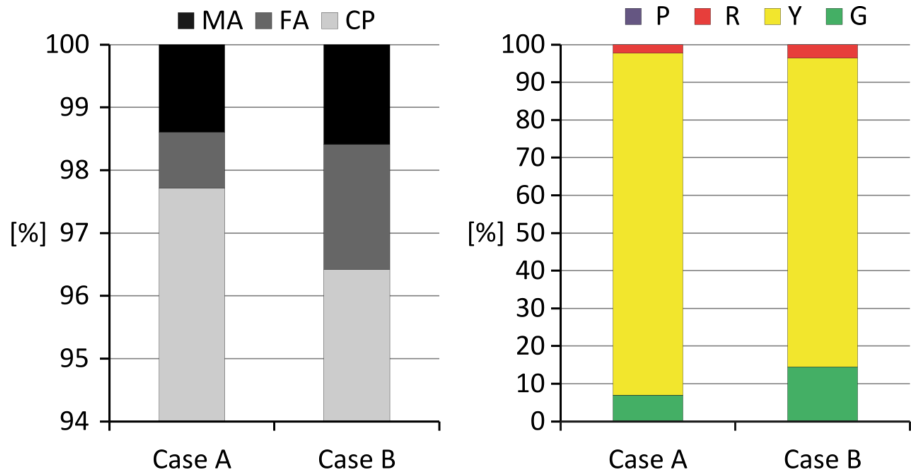


Figure 6: Duration matrix results in terms of: criterion 1 (a) and criterion 2 (b).

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 (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**).

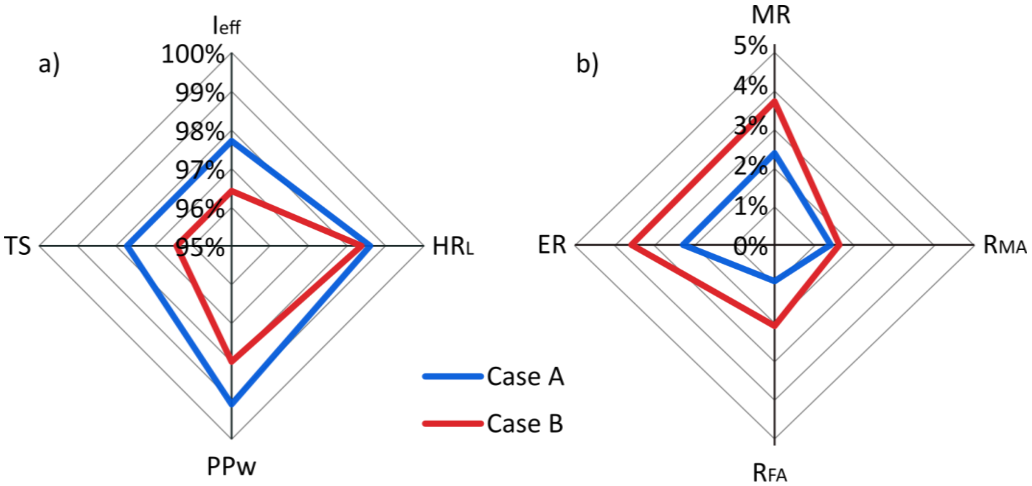


Figure 7: Performance indicators quantifying the landslide early warning performance of Case A (in blu) and Case B (in red) in terms of: success (a) and error (b).

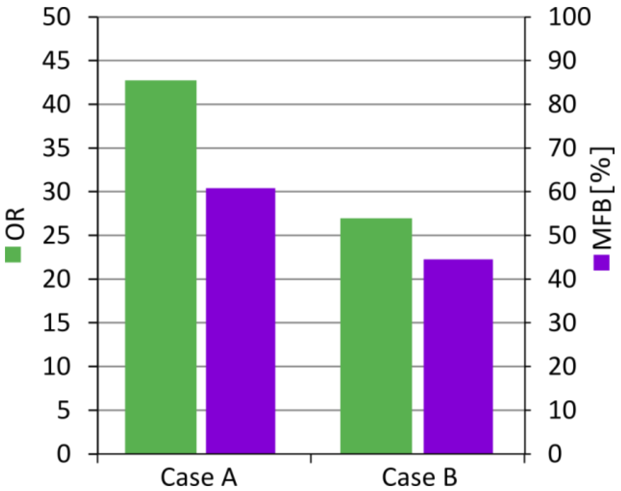


Figure 8: Odds Ratio (OR) and Missed and False alerts Balance (MFB) performance indicators, quantifying the landslide early warning performance of Case A and Case B.

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 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".

3.4 Parametric analysis: the landslide density criterion

A parametric analysis on the landslide density criterion, $L_{den(\mathrm{k})}$, 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, $L_{den(\mathrm{k})}$, 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 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)**			
		1	2	3	4
WE	1	600,48	107,62	0,00	0,00

duration (h)	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.

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

Performance indicator	$A_{0,14}$	$A_{1,18}$	R-15$K_{0,14}$	R-15$K_{0,10}$	R-10$K_{0,14}$	R-10$K_{0,10}$
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 density criteria, only the simulations R-15$K_{0,10,}$ $A_{0,14}$ 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**).

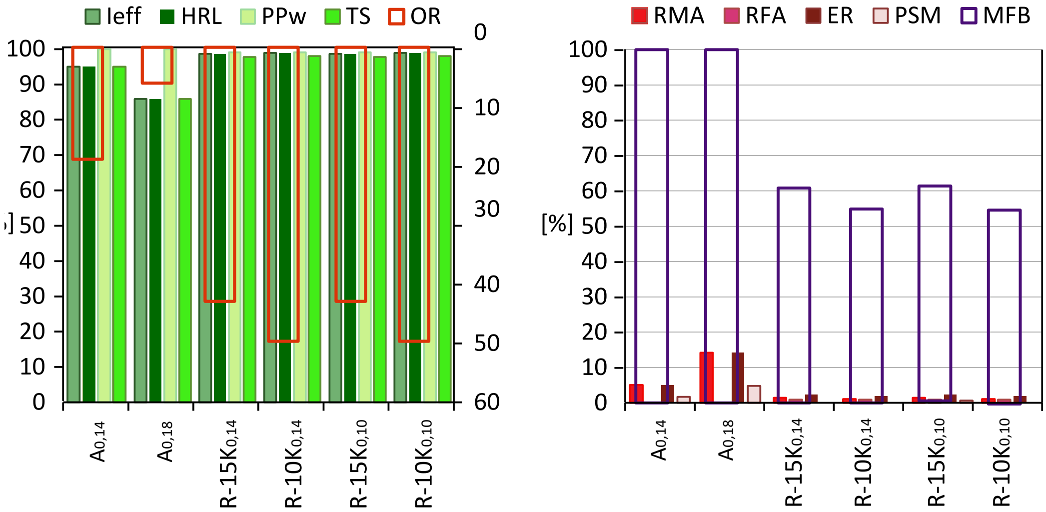


Figure 9. Performance indicators related to the success (a) and to the errors (b) of the warning model, evaluated for the six simulations of landslide density criteria considered in the parametric analysis.

4. 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 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.

Acknowledgement

This work was carried out during a research period of LP as visiting PhD student at NVE, Oslo. The authors are grateful to two NVE employees: Søren Boje for his criticism and comments and, Julio Pereira for GIS data sharing.

References

Alfieri L, Salamon P, Pappenberger F, Wetterhalll F, Thielen J: Operational early warning systems for water-related hazards in Europe. Environ Sci Pol 15(1):35–49. doi:10.1016/j.envsci.2012.01.008, 2012.

Barredo, J I: Normalised flood losses in Europe: 1970–2006. Natural Hazards and Earth System Sciences 9, 97–104, doi:10.5194/nhess-9-97-2009, 2009.

Badoux A, Graf C, Rhyner J, Kuntner R, McArdell B W: A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. Nat Hazards (2009) 49:517–539, doi 10.1007/s11069-008-9303-x, 2009.

Baum R L and Godt J W: Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides, 7: 259–27, doi: 10.1007/s10346-009-0177-0, 2010.

Beldring S, Engeland K, Roald LA, Sælthun NR, Voksø, A: Estimation of parameters in a distributed precipitation-runoff model for Norway. Hydrology and earth system sciences, 7: 304-316, 2003.

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

Boje S, Colleuille H, Cepeda J, Devoli G : Landslide thresholds at regional scale for the early warning system in Norway. Conference Proceedings of the World Landslide Forum. 3, 2-6th June 2014, Beijing, 2014.

Calvello M and Piciullo L: Assessing the performance of regional landslide early warning models: the EDuMaP method. Natural Hazards Earth System Sciences, 16, 103–122, 2016. www.nat-hazards-earth-syst-sci.net/16/103/2016/doi:10.5194/nhess-16-103-2016, 2016.

Calvello M, d'Orsi RN, Piciullo L, Paes N, Magalhaes MA, Lacerda WA: The Rio de Janeiro early warning system for rainfall-induced landslides: analysis of performance for the years 2010–2013. Int J Disast Risk Reduc 12:3–15. doi:10.1016/j.ijdrr.2014.10.005, 2015.

Chen C Y, Lin L Y, Yu F C, Lee C S, Tseng CC, Wang AH, Cheung KW: Improving debris flow monitoring in Taiwan by using high-resolution rainfall products from QPESUMS. Nat Hazards, 40: 447. doi:10.1007/s11069-006-9004-2, 2007.

Cheung, P. Y., Wong, M. C., and Yeung, H. Y.: Application of rainstorm nowcast to real-time warning of landslide hazards in Hong Kong, in: WMO PWS, Workshop on Warnings of Real-Time Hazards by Using Nowcasting Technology, 9–13 October 2006, Sydney, Australia, 2006.

Colleuille H, Haugen LE, Beldring S: A forecast analysis tool for extreme hydrological conditions in Norway. Poster presentation, 6th World FRIEND Conference, Fez, Morocco, 2010.

CRED: EM-DAT. In: The OFDA/CRED International Disaster Database, Universite´ Catholique de Louvain, Brussels, Belgium. www.emdat.be, 2011.

Devoli G, Kleivane I, Sund M, Orthe N-K, Ekker R, Johnsen E, Colleuille H: Landslide early warning system and web tools for real-time scenarios and for distribution of warning messages in Norway, in: Engineering Geology for Society and Territory “Landslide Processes”, Proc. XII International IAEG Congress, Torino, Italy, 625–629, doi:10.1007/978-3-319-09057-3_104, 2014.

Easterling D R, Meehl G A, Parmesan C, Changnon S A, Karl T R, Mearns L O: Climate extremes: observations, modeling, and impacts. Science, Vol. 289, Issue 5487, pp. 2068-2074, doi: 10.1126/science.289.5487.2068, 2000.

Ekker R, Kværne K, Os A, Humstad T, Wartiainen A, Eide V, Hansen RK: regObs – public database for submitting and sharing observations. Proceedings of International Snow Science Workshop, 7-11th October 2013 Grenoble - Chamonix Mont-Blanc, 2013.

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

European Commission: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, 2000.

European Commission: Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, 2007.

European Environment Agency: Mapping the impacts of natural hazards and technological accidents in europe – an overview of the last decade. EEA Technical Report No 13/2010, isbn: 978-92-9213-168-5, 2010.

Fell R, Ho K K S, Lacasse S, and Leroi E: A framework for landslide risk assessment and management, in: Landslide Risk Management, edited by: Hungr, O, Fell, R, Couture, R, and Eberhardt, E, Taylor and Francis, London, 3–26, 2005.

Fischer L, Rubensdotter L, Stalsberg K, Melchiorre C, Horton P, Jaboyedoff M: Debris flow modeling for susceptibility at regional to national scale in Norway. In Eberhardt et al. Landslides and Engineered Slopes: Protecting Society through Improved Understanding, p. 723-729, 2012.

Furseth A: Slide accidents in Norway. Oslo, Tun Forlag, 207 p. (in Norwegian), 2006.

Gariano, S. L., Brunetti, M. T., Iovine, G., Melillo, M., Peruccacci, S., Terranova, O., Vennari, C., and Guzzetti, F.: Calibration and validation of rainfall thresholds for shallow landslide forecasting in Sicily, southern Italy, Geomorphology, 228, 653–665, http://dx.doi.org/10.1016/j.geomorph.2014.10.019, 2015.

Glade T and Nadim F: Early warning systems for natural hazards and risks, Nat. Hazards, 70, 1669–1671, doi:10.1007/s11069-013-1000-8, 2014.

Godt, J. W., Baum, R. L., and Chleborad, A. F.: Rainfall characteristics for shallow landsliding in Seattle,Washington, USA, Earth Surf. Proc. Land., 31, 97–110, doi:10.1002/esp.1237, 2006.

Hyogo Framework for Action: Building the Resilience of Nations and Communities to Disasters, World Conference on Disaster Reduction 18–22 January 2005, Kobe, Hyogo, Japan, 22 pp., 2005.

Huggel C, Khabarov N, Obersteiner M, Ramìrez J M: Implementation and integrated numerical modelling of a landslide early warning system: a pilot study in Colombia. Nat Hazards (2010) 52:501–518. doi:10.1007/s11069-009-9393-0, 2010.

Hungr O, Leroueil S, Picarelli L: The Varnes classification of landslide types, an update. Landslides 11(2):167–194. doi:10.1007/s10346-013-0436-y, 2014.

ICG: Guidelines for landslide monitoring and early warning systems in Europe - Design and required technology. Project Safe Land "Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies”. D4.8, 153p. Available from: http://www.safeland-fp7.eu/results/Documents/D4.8.pdf, 2012.

Jaedicke C, Lied K, Kronholm K: Integrated database for rapid mass movements in Norway. Natural Hazards and Earth System Sciences, 9: 469-479, doi:10.5194/nhess-9-469-2009, 2009.

Lagomarsino, D, Segoni, S, Fanti, R, and Catani, F: Updating and tuning a regional-scale landslide early warning system. Landslides, 10, 91–97. doi:10.1007/s10346-012-0376-y, 2013.

Lagomarsino, D., Segoni, S., Rosi, A., Rossi, G., Battistini, A., Catani, F., and Casagli, N.: Quantitative comparison between two different methodologies to define rainfall thresholds for landslide forecasting, Nat. Hazards Earth Syst. Sci., 15, 2413–2423, doi:10.5194/nhess-15-2413-2015, 2015.

Martelloni, G., Segoni, S., Fanti, R., and Catani, F.: Rainfall thresholds for the forecasting of landslide occurrence at regional scale, Landslides, 9, 485–495, doi:10.1007/s10346-011-0308-2, 2012.

Morss, R, Wilhelmi, O, Meehl, G, Dilling, L: Improving societal outcomes of extreme weather in a changing climate: an integrated perspective. Annual Review of Environment and Resources, 36, 1–25, doi: 10.1146/annurev-environ-060809-100145, 2011.

NOAA-USGS Debris Flow Task Force: NOAA-USGS debris-flow warning system. Final report, US Geological Survey Circular 1283, US Geological Survey, Reston, Virginia, USA: 47. Available at: http://pubs.usgs.gov/circ/2005/1283/pdf/Circular1283.pdf (last access: November 2014), 2005.

Osanai N, Shimizu T, Kuramoto K, Kojima S, Noro T: Japanese early-warning for debris flows and slope failures using rainfall indices with Radial Basis Function Network, Landslides, 7, 325–338, doi:10.1007/s10346-010-0229-5, 2010.

Piciullo L, Siano I, Calvello M: Calibration of rainfall thresholds for landslide early warning purposes: applying the EDuMaP method to the system deployed in Campania region (Italy). In: Proceedings of the International Symposium on Landslides 2016-Landslides and Engineered Slopes. Experience, Theory and Practice. Napoli, Italy, 3:1621–1629. ISBN 978–1–138-02988-0, 2016a.

Piciullo L, Gariano S L, Melillo M, Brunetti M T, Peruccacci S, Guzzetti F., Calvello M: Definition and performance of a threshold-based regional early warning model for rainfall-induced landslides. Landslides. doi:10.1007/s10346-016-0750-2, 2016b.

Ramberg IB, Bryhni I, Nøttvedt A, Rangnes K: The making of a land – geology of Norway. Trondheim. Norsk Geologisk Forening, 624 p., 2008.

Rossi, M, Peruccacci, S, Brunetti, M T, Marchesini, I, Luciani, S, Ardizzone, Balducci, S V, Bianchi, C, Cardinali, M, Fiorucci, F, Mondini, A C, Reichenbach, P, Salvati, P, Santangelo, M, Bartolini, D, Gariano, S L, Palladino, M, Vessia, G, Viero, A, Antronico, L, Borselli, L, Deganutti, A M, Iovine, G, Luino, F, Parise, M, Polemio, M, Guzzetti, F: SANF: National warning system for rainfall-induced landslides in Italy, in: Landslides and Engineered Slopes: Protecting Society through Improved Understanding, edited by: Eberhardt, E., Froese, C., Turner, K., and Leroueil, S., Taylor& Francis, London, 1895–1899, isbn 978-0-415-62123-6, 2012.

Segoni, S., Rossi, G., Rosi, A., and Catani, F.: Landslides triggered by rainfall: a semiautomated procedure to define consistent intensity-duration thresholds, Comput. Geosci., 3063, 123–131, http://dx.doi.org/10.1016/j.cageo.2013.10.009, 2014.

Segoni S, Battistini A, Rossi G, Rosi A, Lagomarsino D, Catani F, Moretti S, Casagli N: Technical note: an operational landslide early warning system at regional scale based on space–time-variable rainfall thresholds. Nat Hazards Earth Syst Sci 15:853–861. doi:10.5194/nhess-15-853-2015, 2015.

Stähli M, Sättele M, Huggel C, McArdell BW, Lehmann P, Van Herwijnen A, Berne A, Schleiss M, Ferrari A, Kos A, Or D, Springman SM: Monitoring and prediction in early warning systems for rapid mass movements. Nat Hazards Earth Syst Sci 15:905–917. doi:10.5194/nhess-15-905-2015, 2015.

Staley D M, Kean J W, Cannon S H, Laber J L, Schmidt K M: Objective definition of rainfall intensity-duration thresholds for the initiation of post-fire debris flows in southern California. Landslides 10: 547-562. doi: 10.1007/s10346-012-0341-9, 2013.

Thiebes B, Glade T, Bell R: Landslide analysis and integrative early warning-local and regional case studies, in: Landslides and Engineered Slopes: Protecting Society through Improved Understanding, edited by: Eberhardt, E., Taylor& Francis Group, London, 1915–1921, isbn 978-0-415-62123-6, 2012.

Tiranti D, and Rabuffetti D: Estimation of rainfall thresholds triggering shallow landslides for an operational warning system implementation. Landslides, 7: 471–481, doi:10.1007/s10346-010-0198-8, 2010.

United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN ISDR): Global Survey of Early Warning Systems: An assessment of capacities, gaps and opportunities towards building a comprehensive global early warning system for all natural hazards, available at:http://www.unisdr.org/2006/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf (last access:November 2014), 2006.