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

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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 was designed for monitoring and forecasting the hydrometeorological conditions potentially triggering slope failures. Decision-making in the LEWS is based upon rainfall thresholds, hydrometeorological 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 models 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.

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 LEWSs 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 LEWS was launched in autumn 2013 by the Norwegian Water Resources and Energy Directorate (NVE). The regional system was developed for monitoring and forecasting the hydrometeorological 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 need to be taken into account by the analyst. Most typically, the performance evaluation is based on two-by-two 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 Event, Duration Matrix, Performance (EDuMaP; Calvello and Piciullo, 2016), allows us 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, and 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., 2015). 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 LEWS in the period of 2013–2014. Western Norway is the area most prone to landslides in Norway and it has been chosen as the 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 $\sim 324\,000\,\text{km}^2$. With its elongated shape of 1800 km, the country reaches from latitude 58 to 71° N. Approximately 30 % of the land area is mountainous, with the highest peaks reaching up to 2500 m a.s.l. and slope angles over 30° 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 experience 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 $3575\,\text{mm}\,\text{yr}^{-1}$. In contrast, the driest areas receiving $< 500\,\text{mm}\,\text{yr}^{-1}$ 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

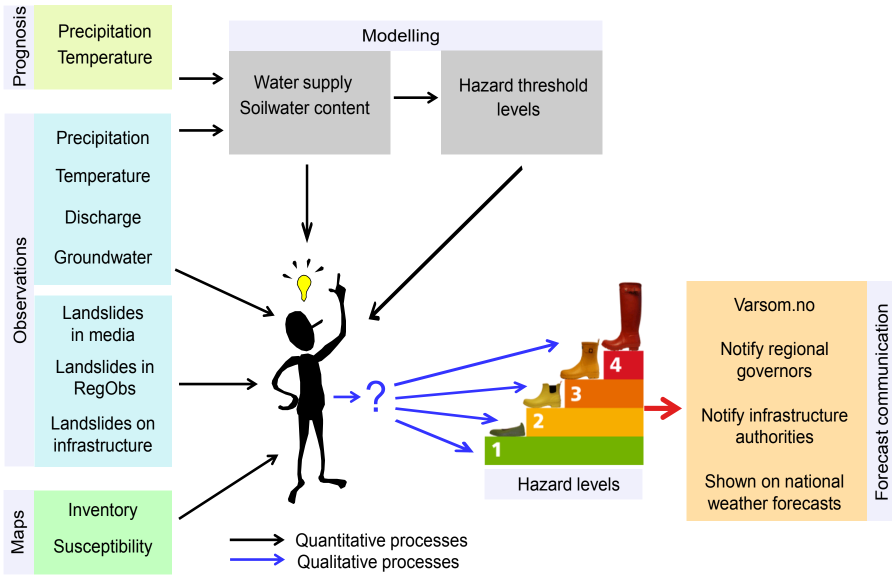

Figure 1. Organization of the landslide early warning system in Norway.

also triggered from or initiated as rockfall or slush flows, developing into, for example, debris flows as they propagate downslope. Shallow landslides constitute a substantial threat to Norwegian society. According to Furseth (2006), at least 230 people have been killed by such slope failures over the last approximately 500 years. In the period 2000–2009, road authorities registered more than 1800 shallow landslides along Norwegian roads.

2.2 The national LEWS

In order to mitigate the risk from shallow landslides, a national EWS has been developed at the 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).

Decision-making in the EWS is based upon hazard threshold levels, hydrometeorological 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 hydrometeorological parameters. Daily hydrometeorological 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 (LEs) 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 normalized 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 model (GAM) statistics (Bell et al., 2014).

Susceptibility maps, hazard threshold levels and other relevant data are displayed in real time on a web page, 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 (Table 1). The warning period follows the time steps of quantitative precipitation and temperature forecasts used to simulate other hydrometeorological parameters and thus lasts from 06:00 to 06:00 UTC

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

Warning level	Classification criteria
4 (red)	> 14 landslide (per 10–15 000 km^2) Hazard signs: several road blocks due to landslides or flooding Extreme situation that occurs very rarely, which requires immediate action and may cause severe damages within a large extent of the warning area. This level corresponds to a > 50-year return period flood warning.
3 (orange)	6–10 landslides (per 10–15 000 km^2) Hazard signs: several road blocks due to landslides or flooding Severe situation that occurs rarely, which requires contingency preparedness and may cause severe damages within some extent of the warning area. This level corresponds to 5–50-year return period flood warning.
2 (yellow)	1–4 landslides (per 10–15 000 km^2) 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 One 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)

each day. Warning levels are updated minimum twice during the 24 h warning period (morning and afternoon) as a function of the weather forecast. Weather forecast updates are received four times per day and warning messages are sent as soon as possible, from 66 h to a few hours ahead. Warning messages are published on a publicly accessible web page (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 hydrometeorological conditions (Fig. 2). Thus, extent and position of warning zones are dynamic and change from day to day.

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 and 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 hydrometeorological conditions are expected to cause more landslides and possibly higher damages (Table 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.

3 The EDuMaP method adapted for variable size warning zones

3.1 The EDuMaP method

The paper proposes the evaluation of the performance of the landslide early warning system operational in Norway by means of the EDuMaP method (Calvello and 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 LEs

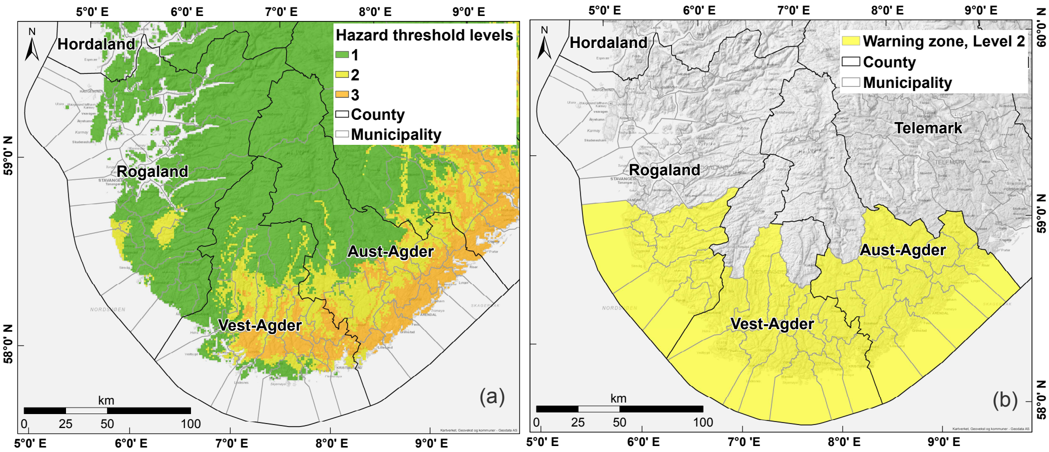

Figure 2. **(a)** Hydrometeorological thresholds indicating potential landslide hazard in the counties of Rogaland, Vest-Agder, Aust-Agder and Telemark in south-eastern Norway on 15 February 2014. **(b)** The resultant early warning zone, on warning level 2 ("yellow level") issued on 15 February 2014 for the same area and including about 32 municipalities.

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 and Piciullo, 2016). Four classes of warning events (key: no means no warning; M is moderate warning; H is high warning; VH is very high warning) and four classes of landslide events (key: no means no landslides; S is a small event, with few landslides; I is an intermediate event, with several landslides; L is a large event with many landslides).

and warning events (WEs). An LE is defined as one or more landslides grouped on the basis of their spatial and temporal characteristics. A WE is defined as a set of warning levels issued within a given warning zone, grouped by their temporal characteristics. There are 10 parameters that need to be defined to carry out the event analysis: (1) warning levels, W_{lev}; (2) landslide density criterion, $L_{\mathrm{den}(k)}$; (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 LEs in relation to the occurrence of WEs, 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), indicated as criterion 1 and criterion 2. The first criterion employs an alert classification scheme derived from a 2×2 contingency table, thus identifying the correct predictions (CPs), false alerts (FAs), missed alerts (MAs) and true negatives (TNs). The second criterion assigns a colour 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} is neglected in order to avoid an over-

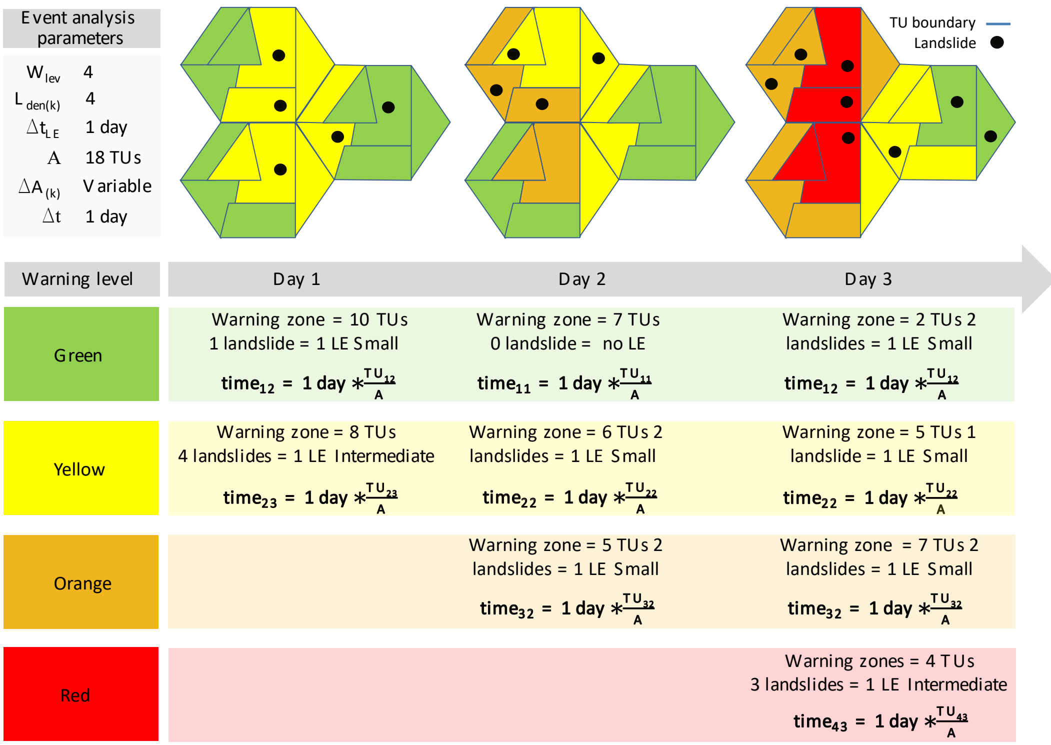

Figure 4. Computation of time_{ij} elements as a function of warning levels and LEs occurred for each warning zone for three hypothetical days of warning.

estimation 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.

3.2 Adaptation of the EDuMaP method

LEWSs may adopt a fixed or a variable spatial discretization for warnings ($\Delta A(k)$). 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 d_{ij} 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 by 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 (time_{ij}) 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:

$$\text{time}_{ij} = \Delta t \frac{(\text{TU}_{ij})}{A}, \tag{1}$$

where Δt is the minimum temporal discretization adopted for warnings (for the Norwegian EWS, equal to 1 day), A is the area of analysis, and 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:

$$d_{ij} = \sum_{\Delta T} (\text{time}_{ij}). \tag{2}$$

Table 2. Performance indicators used for the analysis.

Performance indicator	Symbol	Formula
Efficiency index	I_{eff}	$\mathrm{CP}/\Sigma_{ij}d_{ij}$ (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	$1 - I_{\mathrm{eff}}$
Missed alert rate	R_{MA}	MA / (CP+MA)
False alert rate	R_{FA}	FA / (CP+FA)
Error rate	ER	(Red&Pur) / $\Sigma_{ij}d_{ij}$ (excluding d11)
Missed and false alert balance	MFB	MA / (MA+FA)
Probability of serious mistakes	P_{SM}	Pur / $\Sigma_{ij}d_{ij}$ (excluding d_{11})

The evaluation of LEs and WEs and the definition and computation of the duration matrix is herein exemplified for three hypothetical days (Fig. 4). For instance, on day 1 two distinct LEs appear, containing four and one 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. On day 3 there are four warning zones, each one alerted with a different warning level and four distinct LEs can be identified, one per warning zone. A landslide density criterion, $L_{\mathrm{den}(k)}$, in four classes has been considered for the example of Fig. 4 – 0 (no landslides), small (one to two landslides), intermediate (three to four landslides) and large ($\geq$ five 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, 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 Eq. (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 Eq. (2) over the time frame of the analysis, ΔT.

4 Performance evaluation of the LEWS in Western Norway for the period 2013–2014

4.1 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 Precambrian 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 large 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, but because of the 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;

Table 3. Significant rainfall, number of days with at least one warning, and number of warnings and landslides in the period 2013–2014.

	2013	2014	Total
Precipitation events, i.e. rainfall and/or snow > 30 mm/24 h	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

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 per 24 h, were registered, with some episodes bringing more than 75–150 mm per 24 h of rain and/or 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 2-year period (Table 3). Most of these were at yellow level, but five warnings at orange level were issued in 2014 in 3 consecutive days. In 12 cases, the yellow warnings issued during the morning evaluation were 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 April 2013, 12–13 August 2013, 7 October 2013, 22 October 2013, 15 November 2013, 28 December 2013, 23 February 2014, 20 March 2014, 14 July 2014, 18–19 August 2014 and 27–28 October 2014.

Examples of warnings issued during 2013 and 2014 are shown in Fig. 5. Most of the alerted warning zones were completely included in the study area (Fig. 5c, d, f). However, some warnings were mainly issued for neighbouring areas to the four regions chosen as case study (Fig. 5a, b, e). The examples of Fig. 5 also illustrate the diversity in having variable instead of fixed-size warning zones.

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 rockfalls 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 "rockfall/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 rockfalls inducing debris avalanches was due to uncertainty about whether precipitation can indeed be considered their triggering cause.

4.2 Event analysis

In earlier studies, the EDuMaP method was applied to analyse the performance of regional LEWSs adopting a fixed spatial discretization for warnings. In contrast, the Norwegian LEWS employs variably sized warning zones. This characteristic influences the first two phases of the EDuMaP method: identification and analysis of LEs and WEs from available databases and definition and computation of a duration matrix.

The values of the 100 input parameters (see Sect. 3) for the two analyses carried out, 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) and red (WL_3). Daily warnings are issued throughout the country (i.e. Δt, is set to 1 day) considering municipalities as the minimum warning 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 by employing a relative landslide density criterion, $L_{\text{den}(k)}$, 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 Table 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 were recorded in the period of analyses (Table 4). For Case B, the 131 considered phenomena have been grouped into 57 LEs, 54 "small" and 3 "intermediate" events (Table 4). A total of 60 warnings were

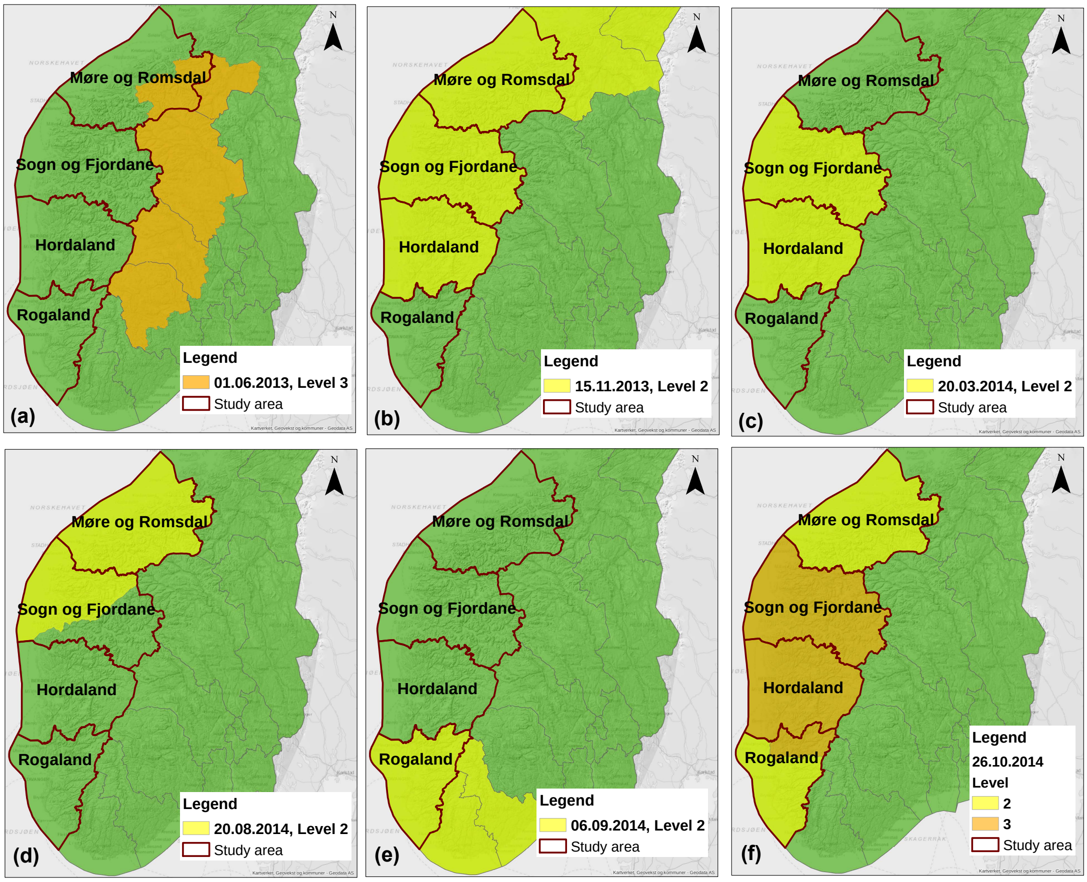

Figure 5. Examples of early warning areas and levels during 2013–2014.

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	137	57
small	132	54
intermediate	5	3
large	0	0
Warning events	60	60
Warning zones alerted	37	37

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 were alerted (Table 4).

4.3 Duration matrices and performance indicators

Two different sets of landslides were 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. Duration matrices for cases A and B; units of time are 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
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

Table 5. Both cases refer to the years 2013–2014; thus, the sum of matrix elements is always equal to 730 days.

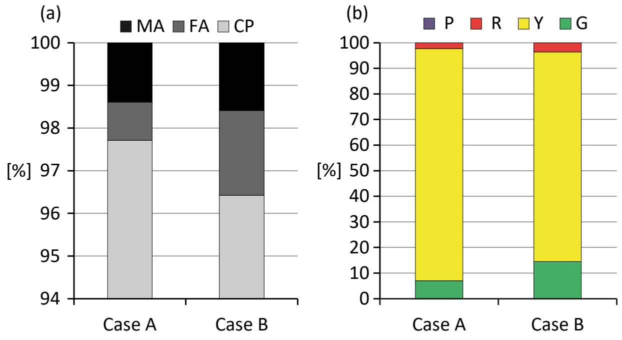

Figure 6. Duration matrix results in terms of criterion 1 **(a)** and criterion 2 **(b)**.

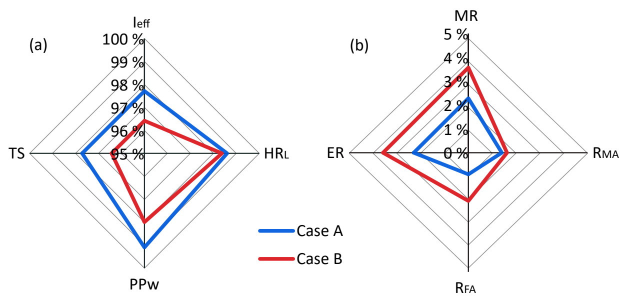

Figure 7. Performance indicators quantifying the landslide early warning performance of Case A (in blue) and Case B (in red) in terms of success **(a)** and error **(b)**.

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), while 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 Case B (Fig. 6a) show a very high percentage of CPs, over 96 %, and around 1.5 % of MAs. The number of FAs is 1 and 2 %, respectively, for cases A and B. Following criterion 2 (Fig. 6b) differences, among cases A and B, can be observed in terms of greens (G), which are respectively equal to 7 and 14.5 %, and yellows (Y), which are respectively equal to 91 and 82 %. No P and just a 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.

The performance indicators used to analyse the duration matrices (Table 3) are grouped into two subsets of indicators, evaluating success and error (Fig. 7). Excluding the odds ratio (OR), the remaining success indicators have a percentage higher than 95 % for both cases due to the high value of CPs

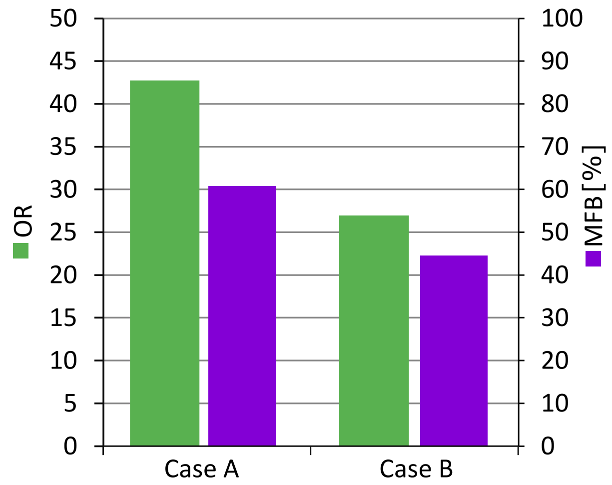

Figure 8. Odds ratio (OR) and missed and false alert balance (MFB) performance indicators, quantifying the landslide early warning performance of Case A and Case B.

that is orders of magnitude higher than MAs and FAs. Therefore the OR, which 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 miss classification rate (MR), error rate (ER), missed alert rate (R_{MA}) and false alert rate (R_{FA}) assume very low values and the differences between the two cases are around 1 % (Fig. 7b). The missed and false alert balance (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).

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, four out of five LEs 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. (2016b), 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 and 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 a 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".

4.4 Parametric analysis: the landslide density criterion

A parametric analysis of the landslide density criterion, $L_{\mathrm{den}(k)}$, 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 LE classes on the performance indicators computed according to the EDuMaP method. The landslide density, $L_{\mathrm{den}(k)}$, 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 (Table 6), referring to the criteria used in the Norwegian EWS (Table 1). Two of them employ an absolute criterion using different numbers of landslides per LE class; the other four simulations, obtained by considering the relative criterion, vary as a function of both number of landslides and territorial extensions (10 000 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 ith warning event is concomitant with a class jth landslide event, may vary the jth index, causing a movement of the element along the ith 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 six combinations of landslide density criteria.

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 (Table 8a, 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 (Table 6), which causes a relocation of time$_{i4}$ along the rows.

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.

The results show similar performance for the four simulations derived using a relative criterion (R15-$C_{0.14}$, R15-$C_{0.10}$, R10-$C_{0.14}$ and R10-$C_{0.10}$). The values of the success indicators are always high: well above 95 % for I_{eff}, hit rate, threat score and PP$_{\mathrm{w}}$, while OR ranges between 42 and 49 (Fig. 9a). 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, the error indicators are also very low in terms of percentage, around 1–2 % (Fig. 9b). 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 (Table 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 OR, and very high values of 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 probability of serious mistakes (PSM) (Fig. 9b).

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 using data from the Norwegian LEWS 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 analysed. Two datasets of landslide occurrences have been used in this study: the first one including all the slope failures registered and gath-

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			
	$A_{0.14}$	$A_{1.18}$	$R\text{-}15K_{0.14}$	$R\text{-}15K_{0.10}$	$R\text{-}10K_{0.14}$	$R\text{-}10K_{0.10}$
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			
	$A_{0.14}$	$A_{1.18}$	$R\text{-}15K_{0.14}$	$R\text{-}15K_{0.10}$	$R\text{-}10K_{0.14}$	$R\text{-}10K_{0.10}$
Small	124	32	132	132	133	133
Intermediate	9	9	5	3	4	4
Large	4	4	0	2	0	0

Table 8. Duration matrix results for simulations R-$15_{0.10}$ and R-$15_{0.14}$.

$R\text{-}15K_{0.10}$		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
$R\text{-}15K_{0.14}$		LE duration (h)			
		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

ered in the NVE database within the test area and the second one excluding the phenomena whose typology either was 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 one wrong alert out of four 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, $L_{\mathrm{den}(k)}$, 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 (two simulations) and relative (four 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 by 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 used in defining the LE classes is a fundamental issue that system managers need to take into account in order to give an idea of the number of landslides expected for each warning level over a given warning zone.

Data availability. Here is the doi with the landslide and warning databases considered for carrying out the analysis: https://doi.org/10.13140/RG.2.2.18642.35520 (Piciullo and Graziella, 2017).

Competing interests. The authors declare that they have no conflict of interest.

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
$\mathrm{HR_L}$	0.95	0.86	0.99	0.99	0.99	0.99
$\mathrm{PP_W}$	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

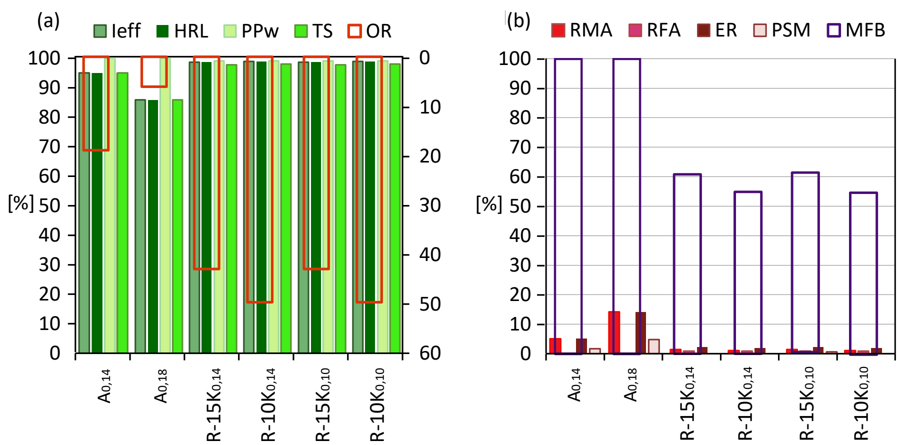

Figure 9. Performance indicators related to the success **(a)** and to the errors **(b)** of the warning model, evaluated for the six simulations of landslide density criteria considered in the parametric analysis.

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