



Assessing the performance of regional landslide early warning models

M. Calvello and L. Piciullo

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Assessing the performance of regional landslide early warning models: the EDuMaP method

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tasks may be executed before a catastrophic event impacts such communities (Villagrán de León et al., 2013). Landslide early warning systems (LEWSs) mitigate the risk to life associated to the occurrence of landslides by temporarily removing people – i.e. the elements at risk – from hazardous areas whenever landslide risk is considered to be not acceptable. According to Glade and Nadim (2014), the installation of an early warning system is often a cost-effective risk mitigation measure and in some instances the only suitable option for sustainable management of disaster risks. Within the landslide risk management framework proposed by Fell et al. (2005), landslide early-warning systems may be considered a non-structural passive mitigation option to be employed in areas where risk, occasionally, rises above previously defined acceptability levels.

In the priority for action 2: established by the Hyogo Framework for Action – i.e. identify, assess and monitor disaster risks and enhance early warning – the following key activity is identified: establish institutional capacities to ensure that early warning systems are subject to regular system testing and performance assessments (HFA, 2005). Despite the fact that the scientific literature reports many studies on landslide early warning systems, either addressing a single landslide at slope scale (Lollino et al., 2002; Blikra, 2008; Intrieri et al., 2012; Michoud et al., 2013; Thiebes et al., 2013a; among others) or concurrent phenomena in areas of relevant extension at municipal/regional/national scale (NOAA-USGS, 2005; Martelloni et al., 2012; Calvello et al., 2015a, b; Stahli et al., 2015; Segoni et al., 2015; among others), no standard requirements exist for assessing their performance. To this aim, many questions need to be addressed, among which: how are data of registered landslides and warnings used to check on the performance of early warning models? How are model errors quantified? How are false and missed alerts defined when the warning model includes more than two warning levels? What are the most relevant model performance indicators? All the previous questions may be summed up in: how should model validation be performed by LEWSs managers? The answer to this question is not trivial, differently to what it may seem at first sight.

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The performance quantification issue is often overlooked, both by system managers and by researchers dealing with warning models for LEWSs. For instance, the main focus of researchers dealing with warning systems for rainfall-induced landslides at regional scale, which are typically based on empirical rainfall thresholds (Guzzetti et al., 2007, and references therein), is on improving the correlation between rainfall indicators and landslides. Rarely, literature studies back analyze the relationship between landslides and warnings which would have been issued adopting those correlations. Especially for LEWSs operating at regional scale (ReLEWSs), empirical evaluations are often carried out by simply analyzing the time frames during which significant high-consequence landslides occurred in the test area (Keefer et al., 1987; Baum and Godt, 2010; Capparelli and Tiranti, 2010; Aleotti, 2004). Alternatively, the performance evaluation is based on 2 by 2 contingency tables computed for the joint frequency distribution of landslides and alerts, both considered as dichotomous variables (Yu et al., 2003; Cheung et al., 2006; Godt et al., 2006; Restrepo et al., 2008; Tiranti and Rabuffetti, 2010; Kirschbaum et al., 2012; Martelloni et al., 2012; Peres and Cancelliere, 2012; Staley et al., 2013; Lagomarsino et al., 2013; Greco et al., 2013; Gariano et al., 2015; Stähli et al., 2015). The four elements of these tables – i.e. correct alerts (CA) or true positives; missed alerts (MA), false negatives or type II errors; false alerts (FA), false positives or type I errors; true negatives (TN) – are then used to assess the weight of the correct predictions, CA and TN, in relation to the model errors, MA and FA, by means of a series of statistical indicators of the model performance. In all these cases, however, model performance is assessed neglecting some important aspects which are peculiar to ReLEWSs, among which: the possible occurrence of multiple landslides in the warning zone; the duration of the warnings in relation to the time of occurrence of the landslides; the level of the issued warning in relation to the landslide spatial density in the warning zone; the relative importance system managers attribute to different types of errors.

The paper proposes a methodology in which the analyst is able to explicitly consider all the above mentioned aspects for the performance assessment of a landslide



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The literature presents many examples of landslide early warning systems operating at local scale (Lollino et al., 2002; Blikra, 2008; Intrieri et al., 2012; Thiebes et al., 2013b; among others) while much rarer are the scientific references to regional warning systems (Wilson, 2004; NOAA-USGS, 2005; Lagomarsino et al., 2013; Calvello et al., 2015b; Stähli et al., 2015, and references therein). The characteristics of landslide warning systems at local scale are strongly affected by numerous constraints and factors, from time to time different, related to the characteristics of the boundary value problem to address. An interesting contribution aiming at providing guidance for the design of such systems is proposed by ICG (2012), wherein the authors deal with the technical and practical issues related to monitoring and early warning for landslides and identify the best technologies available in the context of both hazard assessment and system design. Concerning regional warning systems, a few examples of systems for rainfall-induced landslides currently operating around the world are presented in the following.

In USA, the US Geological Survey has been long working on ReLEWSs in a number of states: California, Colorado, Oregon and Washington (Chleborad, 2000; Baum and Godt, 2010; NOAA-USGS, 2005; Cannon et al., 2011). The state of knowledge and resources available to issue alerts of precipitation-induced shallow, rapidly moving landslides and debris flows vary across the USA; for instance, in the city of Seattle, WA, the alert system includes four levels – Null, Outlook, Watch and Alarm – and warnings are based on the measured or expected exceedance of cumulated rainfall and intensity-duration thresholds combined with criteria using monitored soil moisture. In Hong Kong (Chan and Pun, 2004; Cheung et al., 2006; <http://www.weather.gov.hk/wservice/warning/landslip.htm>), the correlation model between rainfall events and landslides is based on an increasing probability of landslide occurrence depending on the measured rolling 24 h rainfall for four different types of man-made slopes: soil cuts, rock cuts, fills and retaining structures. In Japan, a nationwide early-warning system for landslide disasters was created by the government in 2005 (Osanai et al., 2010); the occurrences of debris flows and slope failures are related to several rainfall indices

(e.g. legal framework, demands from different stakeholders). Intrieri et al. (2013), describe LEWSs as the balanced combination of four main activities: design, monitoring, forecasting and education. Calvello et al. (2015b) state that the objectives of LEWSs should be defined considering the scale of analysis and the type of landslides; they also represent the process of designing and managing landslide early warning systems by a “wheel” with 4 concentric rings identifying: the necessary skills, the activities to be performed, the means to be used, the basic elements of the system.

Figure 1 and Table 1 show an original schematic of the components of regional early warning systems for rainfall-induced landslides. The proposed scheme is based on a clear distinction among correlation laws, warning models and warning systems. Within this framework, a regional correlation law for rainfall-induced landslides, ReCoL, is defined as a functional relationship between rainfall events, RE, and landslide events, LE (see Sect. 3.1 for details on the definition, classification, identification and analysis of landslide events), eventually including other relevant monitored variables. A regional landslide warning model, ReLWaM, includes the regional correlation law as well as: warning events, WE (see Sect. 3.1 for details on the definition, classification, identification and analysis of warning events), and decision making procedures to issue the warnings. A regional early warning system, ReLEWS, includes the regional warning model and the following components: monitoring and warning strategy; communication strategy; emergency plan. Each component of ReLEWS may also be related to a number of actors involved with their deployment, operational activities and management. As reported in Table 1, three classes of such actors are herein identified: people, managers and scientists. All the system components are relevant for more than one class of actor. For instance, it is important to highlight that both the decision making and emergency plan components, within which the evacuation procedures and the procedures used to issue and withdraw the warnings are defined, are significantly influenced by people’s risk perception as well as by operational aspects the managers need to address in cooperation with the scientists.

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istered during the warning phases (Yu et al., 2003; Calvello et al., 2015b). The “Events analysis” step of the EDuMaP method aims at defining the most appropriate landslide events (LE) and warning events (WE) to be used to assess the model performance. To this aim, databases of recorded landslides and warnings must be available (Fig. 3).

The results of the analysis depend on the values assumed by a series of well-identified parameters (Table 2), which are defined to allow the analyst to make choices on how to select and group landslides and warnings.

Figure 3 exemplifies the relationships among rainfall, landslide and warning data for the performance analysis of a warning model employed for rainfall-induced landslides within regional systems. The assessment of the model performance requires the preliminary identification of “landslide events” (LE) and “warning events” (WE) from analyses carried out, respectively, on the landslides and warnings databases. Landslide events are herein defined as a series of landslides grouped on the basis of their characteristics, so as to implicitly evaluate and classify the magnitude of a set of multiple phenomena occurring in a given area within a given time period. Landslide events are retrieved from the landslides database according to data, classification, spatial and temporal characteristics of the landslide records. As reported in the figure, the previous four characteristics may be associated to the following four questions words: how (e.g. how does the database report landslide data?); what (e.g. what types of landslides are relevant for the warning model?); where (e.g. where did landslides occur in relation to the alert zones of the warning system?); when (e.g. when did landslides occur?). Warning events are herein defined a set of warning levels issued within a given warning zone, grouped considering their temporal characteristics. Warning events are retrieved from the warnings database according to decision making and warning levels criteria, respectively addressing: the procedures employed to activate the warnings; the meaning of the warning levels in relation to the warnings issued in the alert zones. Looking at the proposed scheme, it is evident that the identification and computation of the duration matrix (see following section for a detailed explanation of the second step of the EDuMaP method) does not require rainfall data, as it only depends on temporal

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analyses carried out on the landslide and warning events. For completeness, however, the figure also reports the typical relationships employed among rainfall, landslide and warning events. Warning events (i.e. the warning model output) are indeed typically generated by evaluating the characteristics of the monitored rainfall in relation to appropriately defined rainfall thresholds, which are in turn based on a correlation law between rainfall events (i.e. the triggering factor) and landslide events (i.e. the hazard for which warnings are issued).

The identification of landslide events and warning events from the respective databases is influenced by a series of choices the analyst needs to make in selecting and grouping, respectively, landslides and warnings. These choices must be carried out considering the characteristics of the warning model whose performance the analyst wants to assess. Table 2 reports the ten parameters which need to be defined to carry on the events analysis: (1) warning levels, W_{lev} , i.e. number of warning classes used by the model, (2) landslide density criterion, $L_{den(k)}$, i.e. thresholds used to differentiate among k classes of landslide events on the basis of their spatial characteristics, (3) lead time, t_{LEAD} , i.e. value of the time interval between the sending out of the first warning level identified within a warning event and the assumed beginning of the warning event, (4) landslide typology, L_{typ} , i.e. landslides addressed by the warning model, (5) minimum interval between landslide events, Δt_{LE} , i.e. time quantifying the maximum temporal gap among landslides included within a single landslide event, (6) over time, t_{OVER} , i.e. time interval between the last landslide identified within a landslide event and the assumed ending of the landslide event, (7) area of analysis, A , i.e. area for which both landslides and warnings data are available, (8) spatial discretization adopted for warnings, $\Delta A_{(k)}$, i.e. subdivision of the area of analysis in k classes on the basis of the spatial criteria adopted to issue the warnings, (9) time frame of analysis, ΔT , i.e. temporal length of databases for which both landslides and warnings data are available, (10) temporal discretization of analysis, Δt , i.e. minimum unit of time used to identify landslide and warning events.

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The first two parameters, W_{lev} and $L_{den(k)}$, are relevant for the classification of the warning and landslide events, respectively. Concerning the second parameter, Table 3 reports three examples of landslide density criteria which could be used to classify landslide events in four classes: the first criterion is based on the number of landslides, the second one on the number of landslides per unit area, the third one is a combination of the previous two. The following four parameters are relevant for the identification of the warning and landslide events. In particular, L_{typ} is used to select, from the landslides database, only the landslides which are considered relevant for the early warnings. The meaning of t_{LEAD} , Δt_{LE} and t_{OVER} is schematized in Fig. 4. Figure 4a reports one set of landslides and three series of landslide events identified considering three different combination of values for Δt_{LE} and t_{OVER} . Figure 4b reports one set of warning levels (in four classes) and three series of warning events identified considering three different values of t_{LEAD} . It is important to highlight that the latter two variables should be seen as time variables which are relevant for decision making purposes. The lead time is related, for instance, to how evacuation procedures are defined within the warning system; the over time may be related to the procedures issued to withdraw the warnings. The last four parameters, whose meaning is straightforward, are relevant for the temporal analyses of both landslide events and warning events.

3.2 Duration matrix

The key element of the numerical evaluation of the performance of a warning model is the definition and computation of a matrix, herein called “duration matrix” (Fig. 5), whose elements report the time associated with the occurrence of landslide events in relation to the occurrence of warning events, in their respective classes. The classification of landslide events and warning events (see parameters L_{den} and W_{lev} in Table 2) establishes the structure of the duration matrix. Indeed, the number of rows and columns of the matrix is equal to the number of classes defined for the warning and landslide events, respectively. The matrix reported in Fig. 5a is drawn as a 4 by 4 matrix, under the hypothesis of: four classes of warning events, indicated with num-

bers from 1 to 4 and letters representing the descriptors no, Medium, High and Very High; four classes of landslide events, indicated with numbers from 1 to 4 and letters representing the descriptors no, Small, Intermediate and Large. Each element of the duration matrix, d_{ij} , is computed, within the time frame of the analysis, ΔT , as follows:

$$d_{ij} = \sum_{\Delta T} \text{time}_{ij} \quad (1)$$

where: i is the number of classes of the warning events; j is the number of classes of the landslide events; time_{ij} is amount of time for which a class i th warning events is concomitant with a class j th landslide event.

Figure 5b shows a graphical example of temporal analysis needed for the computation, following Eq. (1), of the elements of the duration matrix. It is important to highlight that the dimension of the elements of the duration matrix, d_{ij} , is time and that the sum of all elements, $\sum_{ij} d_{ij}$, is always equal to the time frame of the analysis, ΔT .

To further clarify how the duration matrix is computed, Tables 4 and 5 report a set of synthetic data exemplifying the performance of a fictitious regional landslide warning model, herein created considering a time frame of one year (the year 2000). Table 4 shows the set of warnings issued by the model – together with the information which are supposedly retrieved from the warnings database – and the corresponding warning events. Table 5 shows the set of landslides recorded during the same time frame – together with the information retrieved from the landslides database – and the corresponding landslide events. Both the warning and the landslide events have been derived following the procedure described in the previous section, assuming the following parameters' values: four warning levels, W_{lev} ; landslide density thresholds, L_{den} , equal to 0 (class 1), 1 (class 2), 2 to 10 (class 3), > 10 (Class 4); lead time, t_{LEAD} , equal to zero; L_{typ} equal to all the landslides recorded in the database, independently of the values assumed by typology and accuracy of time record; minimum interval between landslide events, Δt_{LE} , equal to 12 h; over time, t_{OVER} , equal to zero; constant area of analysis, A ; spatial discretization adopted for warnings, $\Delta A_{(k)}$, equal to the area of

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analysis; time frame of the analysis, ΔT , equal to 1 year; temporal discretization of the analysis, Δt , equal to 1 h.

Three landslide events occurred in the year 2000, herein identified as LE_2000_01 (from 13 to 14 January), LE_2000_02 (18 March) and LE_2000_03 (22 November), and classified in the following classes: 4(L), 2(S), 3(I). On the same dates of the landslide events, the following three warning events are recorded: WE_2000_01 (from 13:00 LT on 13 January to 18:00 LT on 14 January), with warning levels varying from 2(M) to 4(VH); WE_2000_02 (from 07:30 to 18:00 LT on 18 March), with warning level equal to 3(M); WE_2000_03, (from 10:00 LT on 22 November to 19:30 LT on 23 November) with warning levels varying from 2(M) to 3(H). The total number of distinct warning levels issued is, in this case, equal to seven. Table 6 and Fig. 6 report the result of the temporal analysis conducted, for the year-long time frame, on these events. The resulting duration matrix is shown in Fig. 6.

3.3 Performance assessment: criteria and indicators

Typically, the evaluation of system performance and accuracy uses statistical indicators derived from 2 by 2 contingency tables. It is straightforward to understand that a good performance of a ReLWaM must be associated to few missed and false alerts. Yet, when landslide events and warning events are not expressed as dichotomous variables, the identification of missed or false alerts is not unambiguous. To properly evaluate performance, another key issue to consider is the relative importance assigned by the system managers to the different types of errors. The latter is, in turn, related to the meaning assigned to the warnings issued in the alert zones in terms of expected number of landslides. To address these issues, the “performance assessment” step of the EDuMaP method is based on the definition of a series of performance criteria and indicators applied to the duration matrix.

A first judgment on the results from the duration matrix may be based on the computation of the distribution of landslide events and warning events in relation to each

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other, in their respective classes. To this purpose, the following matrix normalizations may be employed:

$$d_LE_{ij} = \frac{d_{ij}}{\sum_{k=1}^4 d_{kj}} N_LE_j \quad (\text{for } j = 2 - 4) \quad (2)$$

$$d_WE_{ij} = \frac{d_{ij}}{\sum_{k=1}^4 d_{ik}} N_WL_i \quad (\text{for } i = 2 - 4) \quad (3)$$

where: d_{ij} is the element of the original duration matrix; d_LE_{ij} is the element of the duration matrix normalized in relation to the landslide events; N_LE_j is the number of landslide events classified as class j within the time frame of the analysis; d_WE_{ij} is the element of the duration matrix normalized in relation to the warning events; N_WL_i is the number of warning levels of class i within in the time frame of the analysis.

Figure 7 reports a graphical representation of a more comprehensive analysis of the duration matrix based on a set of two performance criteria, both of them assigning a performance meaning to all but one element of the matrix, d_{11} , which expresses the number of hours when no warnings are issued and no landslides occur. Both criteria purposefully neglect element d_{11} , whose value is typically orders of magnitude higher than the values of the other elements, in order to allow a more useful relative assessment of the information located in the remaining part of the duration matrix. The first criterion (A) fulfills the task employing an alert classification scheme derived from a 2 by 2 contingency table, thus identifying: correct alerts, CA; false alerts, FA; missed alerts, MA; true negatives, TN. The second criterion (B) assigns a color code to the elements of the matrix in relation to their grade of correctness, herein classified in four classes as follows: green, Gre, for the elements which are assumed to be representative of the best model response; yellow, Yel, for elements representative of minor model

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work of 33 rain gauges and rainfall thresholds defined considering the antecedent cumulated rainfall for the following three durations: 1, 24, 96 h. The three cumulated rainfall measures are treated independently by means of a series of either/or rules which define warning levels associated to four landslide probabilities of occurrence: (1) low, if mass movements triggered by rainfall are not expected, (2) medium, if only occasional occurrences of landslides triggered by rainfall are expected, predominantly in artificial slopes, (3) high, for an expected diffuse occurrence of landslides in both natural and artificial slopes, (4) very high, if the expected areal distribution of landslides is significant and the phenomena are expected to be widespread in slopes and roads cuts. Landslide warnings are issued, at any given time, over the whole affected alert zone without explicitly differentiating among areas characterized by different levels of landslide susceptibility, as defined by a municipal susceptibility map available at 1 : 10 000 (D’Orsi, 2012). This landslide susceptibility map is also reported in Fig. 8 because the parametric analysis presented in the following sections to evaluate the performance of the Alerta-Rio warning model according to the EDuMaP method allows to explicitly consider the extent of the area most susceptible to landslides for the classification of the landslide events (i.e. definition of the input parameter $L_{den(k)}$).

4.2 Setup of parametric analysis

The analysis presented herein uses data on recorded landslides and issued warnings of the Alerta-Rio system for the three-year period 2010–2012 in two alert zones: Baia de Guanabara and Zona Sul. Since 2010 the GEO-Rio foundation is publishing information on landslide occurrences by means of yearly landslide reports (<http://www0.rio.rj.gov.br/alertario/>) which comprise the time of occurrence, the main characteristics and the location of the recorded phenomena. The warnings database has been created from information directly gathered at the GEO-Rio Foundation. For the chosen period of analysis Calvello et al. (2015b) show that: 72 % of the recorded landslides occurred in Baia de Guanabara and seven warning events reached a high or

very high warning level; 10 % of the recorded landslides occurred in Zona Sul, where the warning events reaching a high or very high warning level were five.

The parametric analysis conducted herein has a twofold purpose: to compare the performance of the Alerta-Rio early warning model in two different alert zones of the city; to evaluate the effect of the choices the analyst needs to make to define landslide events (LE) and warning events (WE) on the performance indicators computed according to the EDuMaP method within a given alert zone. To investigate the latter, the Baia de Guanabara alert zone was chosen.

Table 9 shows the values used for each simulation of the parametric analysis for the ten input parameters needed to define the landslide and warning events. In the first two simulations, ZS_T1 and G_T1, which respectively refer to the two base cases for the alert zones Zona Sul (area of analysis, A, equal to ZS) and Baia de Guanabara (area of analysis, A, equal to G), the following values of the remaining nine input parameters are used: warning levels, W_{lev} , equal to four; landslide density, $L_{den(k)}$, defined according to the mixed criterion shown in Table 3; lead time, t_{LEAD} , equal to zero; landslide typology, L_{typ} , equal to all recorded landslides; minimum interval between landslide events, Δt_{LE} , equal to 12 h; over time, t_{OVER} , equal to zero; spatial discretization adopted for warnings, $\Delta A_{(k)}$, equal to the area of analysis A; time frame of analysis, ΔT , equal to the three-year period 2010–2012; temporal discretization of analysis, Δt , equal to 1 min.

All the remaining simulations, from G-U01 to G-W05, refer to the alert zone Baia de Guanabara. These simulations are used to explore the sensitivity of the performance evaluation of the Alerta-Rio regional warning model to changes in the input parameters, whose values differ, depending on choices made by the analyst, also under the same set of landslides and warnings data. To this purpose, the input parameters investigated are: landslide density, $L_{den(k)}$, defined according to the mixed criterion shown in Table 3 either in relation to the whole area of analysis (A) or in relation to the extent of the area most susceptible to landslides (A_{susc}); lead time, t_{LEAD} , varying from zero to three hours; landslide typology, L_{typ} , equal to all recorded landslides (ALL), all typologies of landslides excluding rock falls (R-I) and earth slides in artificial slopes (T1); minimum

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interval between landslide events, Δt_{LE} , equal to 12 and 24 h; over time, t_{OVER} , varying from zero to 12 h; time frame of analysis, ΔT , equal to the whole three-year period 2010–2012 or to the single years 2010, 2011 and 2012.

4.3 Results of parametric analysis

The duration matrices of Tables 10 and 11 report the results of the first two simulations of the parametric analysis, ZS_T1 and G_T1, which only differ in relation to the area of analysis, the Zona Sul and the Baia de Guanabara alert zones respectively. Following the description of the third step of the EDuMaP method, at this stage the analyst needs to define some performance criteria and indicators and to apply them to the computed duration matrices. The two performance criteria used herein, respectively called criterion A and criterion B, are the ones shown in Fig. 7. Criterion A is defined in accordance to a standard alert classification criterion derived from a 2 by 2 contingency table, thus identifying correct alerts, false alerts, missed alerts and true negatives. Criterion B is defined assigning to the elements of matrix a colour code of four classes, from green to purple, in relation to their grade of correctness. As already stated, both criteria purposefully neglect the duration matrix element d_{11} , whose value is typically orders of magnitude higher than the values of the other elements. The performance indicators computed on the basis of these criteria (Table 12) are the ones shown in Table 8.

Figures 9 and 10 show a comparison of the results of the first two simulations, ZS_T1 and G_T1. Considering performance criterion A, Zona Sul and Baia de Guanabara both present a high rate of true negatives (TNs) and a low rate of missed alerts (MAs). The low rate of computed MAs also turns into a good predicting capability in relation to intermediate and large landslide events occurring in these zones. Baia de Guanabara shows time values associated to correct alerts (CAs) much higher than the corresponding values in Zona Sul, respectively 18.3% vs. 3.2% of the total considered time. These differences justify the fact that the value of efficiency index (I_{eff}) computed for Baia de Guanabara, 75%, is higher than the one computed for Zona Sul, 66%; R_{MA} is also slightly higher for Zona Sul. The results for Zona Sul also highlight a relatively high rate

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of FAs (32 %), probably due to values of rainfall thresholds inadequately low for this alert zone. This condition, together with a low value of CAs, explains the high value of RMA (91 %) for Zona Sul. Considering performance criterion B, approximately the same time rate of yellow elements (minor model errors) and red elements (significant model errors) are observed for the two alert zones. Significant is, however, the difference in the time rate of purple elements (worst model errors), much higher for Zona Sul than for Baia de Guanabara. It is interesting to notice that Zona Sul has a low rate of MAs, yet I_{MA} is equal to 1 because the only value of MA is a serious model error. Finally, slightly high values are computed for Zona Sul for the probability of serious mistakes (P_{SM}), probability of serious no-warning mistakes (P_{SM-NW}) and probability of serious no-landslides mistakes (P_{SM-NL}).

Simulations G_T1 to G_W5 refer to the alert zone Baia de Guanabara and may thus be used to explore the sensitivity of the performance evaluation to the changes in the values of the other input parameters (Figs. 11 and 12). The simulations addressing the parameters landslide density, $L_{den(k)}$, and landslide typology, L_{typ} , are the following: G_T1, G_U1, G_Z1, G_W1, G_W5. The definition of the landslide density parameter, $L_{den(k)}$, in relation to the whole area of analysis (A) or in relation to the extent of the area most susceptible to landslides (A_{sus}) does not play an important role for some performance indicators (e.g. $EI_{(A)}$, $GC_{(B)}$, PP_W , HR , OR , R_{FA}) while it may be very relevant for others (e.g. P_{SM-NW} , P_{SM-NL} , I_{MA}). The area considered when computing this parameter has, indeed, a strong influence on the number of landslides set as thresholds to differentiate among classes of landslide events. In particular, when the area reduces, the threshold values decrease and, other parameters being equal, the number of very large and large landslide events tend to increase. The latter implies an increasing probability of MAs and of the worst model errors (Pur) in this region of the matrix. For instance, the fact that simulation G_U1 shows high values of P_{SM-NW} and I_{MA} depends on a single missed Landslide Event classified as class 4(L), differently from the classification 3(I) resulting from the base simulation G_T1. As far as landslide typology is concerned, the results from the two combinations associated only to the

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occurrence of earth slides on artificial slopes (G_W1 and G_W5) are similar and show: $I_{\text{eff(A)}}$ less than 70 %, HR around 100 %, very few MAs, around 35 % of FAs, I_{FA} values much higher than the rest of the simulations. Probably the latter is due to two concurrent factors: threshold values which are set too low for this landslide typology; lower average duration of the landslide events due to the reduced number of landslides compared to the other simulations. Concerning the three parameters lead time, t_{LEAD} , over time, t_{OVER} , and minimum interval between landslide events, Δt_{LE} , the simulations relevant to explore their importance are the following: G_T1, G_A1, G_B1, G_C1, G_E1, G_F1. High values of Δt_{LE} considerably increase the values of the performance indicators related to the rate of MAs (R_{MA} , ER, MR, $P_{\text{SM-NW}}$), while the rate of FAs does not change significantly. This is due to the fact that the higher is the value of Δt_{LE} , the lower is the number of landslide events, the higher is the duration of each landslide event, the higher is the chance to have time periods associated to landslide events without warning events. These results seem to indicate that an appropriate performance evaluation needs parameter Δt_{LE} to be set, by the analyst, to a value lower than 24 h. The comparison of results for G_T1 and G_A1 shows that the introduction of a t_{OVER} of six hours increases the performance by reducing the FAs and increasing the CAs. Consequently I_{FA} and R_{MA} slightly decrease compared to the case G_T1, for which t_{OVER} is equal to zero. On the contrary, parameter t_{LEAD} does not play an important role for this analysis. Finally, the simulations which are relevant to explore the importance of the time frame of analysis, ΔT , are the followings: G_T1, G_T2, G_T3, G_T4. The resulting values of the performance indicators from these simulations highlight the importance played by the dataset used for the performance analysis. Indeed, the inconsistency between the results of the two simulations which consider the single years 2011 and 2012 (G_T3 and G_T4) and the rest of the simulations may be ascribed to the very limited amount of data available for those years, for which very few landslides occurred and very few warnings were issued.

5 Conclusions

A regional landslide early warning system may be schematized as a system with the following components: regional warning model; monitoring and warning strategy; communication strategy; emergency plan. The focus of this article was on the performance evaluation of regional warning models for rainfall-induced landslides, that is to say on the effectiveness of the functional relationship between rainfall events and landslide events used within the decision making procedures adopted to issue the warnings. It is important to highlight that the proposed performance assessment method does not address other important issues related to system effectiveness, such as: risk perception, policy adopted to communicate with the people at risk, evacuation procedures, monitoring network, instruments used to issue the warnings.

The proposed approach, which has been called EDuMaP method, evaluates the performance of a regional landslide warning model following three successive steps: (1) identification and analysis of landslide events and warning events derived from available landslides and warnings databases, (2) definition and computation of a duration matrix reporting the time associated with the occurrence of landslide events in relation to the occurrence of warning events, (3) evaluation of the model performance by means of criteria and indicators applied to the duration matrix.

The main innovations introduced by the EDuMaP method, in relation to means more commonly used to assess the performance of such models, are the following:

- recorded landslides and issued warnings are not analyzed as a series of individual occurrences but they are grouped within landslide and warning events, respectively, which consider their spatial and temporal characteristics by means of ten input parameters;
- the evaluation of the correlation between landslide and warning events is not based on counting the pairs on which the two data sets agree or disagree, but on computing the duration of the agreement/disagreement;

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- the correspondence between landslide and warning events is not expressed as a 2 by 2 confusion matrix but as a matrix, herein called duration matrix, whose number of columns and rows depends on the schemes adopted to classify, respectively, landslide events and warning events;
- the assessment of the duration matrix is based on performance indicators derived from a set of performance criteria, which must be defined by the system analyst/manager considering the specific characteristics and aims of the early warning system under evaluation.

The applicability of the EDuMaP method has been tested by conducting a parametric analysis using three years of landslides and warnings data from the municipal landslide early warning system operating in Rio de Janeiro (Brazil). The input parameters most affecting the results of the events analysis and, thus, the value of the elements of duration matrix for the different simulations, are: the landslide density thresholds used to differentiate among the classes of landslide events; the set of landslides considered in the simulations; the time set as the minimum time interval between landslide events; the time interval between the last landslide identified within a landslide event and the assumed ending of the landslide event; the area of analysis; the time frame of the analysis. For instance, the criterion herein employed to define landslide density does not work well, somehow counterintuitively, when the number of landslides per unit area is computed using the area mapped as the most susceptible instead of the whole area of analysis. The latter does not mean that a higher number of landslides occur outside the most susceptible area, it only means that the thresholds used in the criterion more adequately represent a landslide density computed over the whole alert zone. Another parameter to which the results are very sensitive is the time interval used to identify the number of landslides to include within a single landslide event. When this period becomes too long (equal to or higher than 24 h), the duration of some landslide events increases too much, thus some time intervals are misleadingly accounted for as serious missed alerts. Finally, as expected, the performance assessment has proved

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Table 1. Components of regional landslide early warning systems (ReLEWS) for rainfall-induced landslides, relevance for system parts – i.e. regional correlation law (ReCoL), regional landslide warning model (ReLWaM) – and system actors – i.e. people, managers and scientists.

| Components | Relevance for system parts | | | Relevance for system actors | | |
|---------------------------------|----------------------------|--------|--------|-----------------------------|----------|------------|
| | ReCoL | ReLWaM | ReLEWS | People | Managers | Scientists |
| Warning events (WE) | YES | YES | YES | | YES | YES |
| Landslide events (LE) | YES | YES | YES | | YES | YES |
| Other variables | YES | YES | YES | | YES | YES |
| Warning events (WE) | | YES | YES | YES | YES | partly |
| Decision making | | YES | YES | YES | YES | partly |
| Monitoring and warning strategy | | | YES | | YES | YES |
| Communication strategy | | | YES | YES | YES | YES |
| Emergency plan | | | YES | YES | YES | partly |

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Table 2. Input parameters for the classification, identification and temporal analysis of landslide events (LE) and warning events (WE).

| Parameters of the events analysis | Symbol | Relevant for |
|--|------------------|--------------------------------|
| 1. Warning levels | W_{lev} | Classification of WE |
| 2. Landslide density criterion | $L_{den(k)}$ | Classification of LE |
| 3. Lead time | t_{LEAD} | Identification of WE |
| 4. Landslide typology | L_{typ} | Identification of LE |
| 5. Minimum interval between Landslide Events | Δt_{LE} | Identification of LE |
| 6. Over time | t_{OVER} | Identification of LE |
| 7. Area of analysis | A | Temporal analyses of LE and WE |
| 8. Spatial discretization adopted for warnings | $\Delta A_{(k)}$ | Temporal analyses of LE and WE |
| 9. Time frame of analysis | ΔT | Temporal analyses of LE and WE |
| 10. Temporal discretization of analysis | Δt | Temporal analyses of LE and WE |

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Table 3. Examples of landslide density criteria which can be used to classify the landslide events.

| LE class | Absolute criterion [No. of landslides] | Relative criterion [No. of landslides/Area] | Mixed criterion |
|----------|---|---|---|
| 1 | 0 | 0 | 0 |
| 2 | 1 | from 0.001 to 0.02 km ⁻² | 1 |
| 3 | 2 to 10 | from 0.021 km ⁻² to 0.1 km ⁻² | from 2 to MIN (10; 0.1 km ⁻²) |
| 4 | > 10 | > 0.1 km ⁻² | > MIN (10; 0.1 km ⁻²) |

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Table 4. Synthetic data exemplifying the performance of a regional landslide warning model: warnings issued and corresponding warning events.

| Level | Warnings issued | | | Warning event | |
|-----------|----------------------|--------------------|-----------------|---------------|--------|
| | From (date and hour) | To (date and hour) | Duration (h:mm) | ID | class |
| Medium | 13 Jan 2000 13:00 | 13 Jan 2000 16:00 | 3:00 | WE_2000_01 | 2 (M) |
| High | 13 Jan 2000 16:00 | 13 Jan 2000 17.30 | 1:30 | WE_2000_01 | 3 (H) |
| Very High | 13 Jan 2000 17:30 | 14 Jan 2000 06:00 | 12:30 | WE_2000_01 | 4 (VH) |
| Medium | 14 Jan 2000 06:00 | 14 Jan 2000 18:00 | 12:00 | WE_2000_01 | 2 (M) |
| High | 18 Mar 2000 07:30 | 18 Mar 2000 18:00 | 10:30 | WE_2000_02 | 3 (H) |
| Medium | 22 Nov 2000 10:00 | 22 Nov 2000 12:00 | 2:00 | WE_2000_03 | 2 (M) |
| Very High | 22 Nov 2000 12:00 | 23 Nov 2000 07:30 | 19:30 | WE_2000_03 | 3 (H) |

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Table 5. Synthetic data exemplifying the performance of a regional landslide warning model: landslide database and corresponding landslide events.

| Number | Typology | Landslide database | | Landslide event | |
|--------|----------|----------------------------|-------------------------|-----------------|-------|
| | | Date and hour | Accuracy of time record | ID | class |
| 1 | A | 13 Jan 2000 10:20 | exact time | LE_2000_01 | 4 (L) |
| 15 | A | 13 Jan 2000 10:00 to 11:00 | time interval | LE_2000_01 | 4 (L) |
| 3 | B | 13 Jan 2000 10:00 to 11:00 | interval estimated | LE_2000_01 | 4 (L) |
| 2 | A | 13 Jan 2000 12:35 | exact time | LE_2000_01 | 4 (L) |
| 1 | B | 13 Jan 2000 12:40 | exact time | LE_2000_01 | 4 (L) |
| 4 | A | 13 Jan 2000 12:00 to 13:00 | time interval | LE_2000_01 | 4 (L) |
| 2 | C | 13 Jan 2000 12:00 to 13:00 | time interval | LE_2000_01 | 4 (L) |
| 3 | A | 13 Jan 2000 13:00 to 14:00 | interval estimated | LE_2000_01 | 4 (L) |
| 1 | A | 13 Jan 2000 19:15 | exact time | LE_2000_01 | 4 (L) |
| 1 | B | 13 Jan 2000 19:20 | exact time | LE_2000_01 | 4 (L) |
| 2 | A | 13 Jan 2000 20:00 to 21:00 | time interval | LE_2000_01 | 4 (L) |
| 7 | A | 13 Jan 2000 21:00 to 22:00 | time interval | LE_2000_01 | 4 (L) |
| 2 | B | 13 Jan 2000 21:00 to 22:00 | time interval | LE_2000_01 | 4 (L) |
| 1 | A | 14 Jan 2000 01:45 | exact time | LE_2000_01 | 4 (L) |
| 1 | A | 18 Mar 2000 12:30 | exact time | LE_2000_02 | 2 (S) |
| 1 | A | 18 Mar 2000 17:00 to 18:00 | time interval | LE_2000_02 | 2 (S) |
| 2 | A | 22 Nov 2000 11:00 to 12:00 | time interval | LE_2000_03 | 3 (I) |
| 1 | B | 22 Nov 2000 13:20 | exact time | LE_2000_03 | 3 (I) |
| 2 | A | 22 Nov 2000 16:00 to 17:00 | time interval | LE_2000_03 | 3 (I) |
| 1 | C | 22 Nov 2000 16:00 to 17:00 | interval estimated | LE_2000_03 | 3 (I) |

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Table 6. Temporal analysis of warning events (WE) and landslide events (LE) using data from Tables 4 and 5.

| From (date and hour) | Time | | Warning event | | Landslide event | |
|----------------------|--------------------|--------------|---------------|-------|-----------------|-------|
| | To (date and hour) | Duration (h) | ID | class | ID | class |
| 1 Jan 2000 00:00 | 13 Jan 2000 10:00 | 298 | | 1 | | 1 |
| 13 Jan 2000 10:00 | 13 Jan 2000 13:00 | 3 | | 1 | LE_2000_01 | 4 |
| 13 Jan 2000 13:00 | 13 Jan 2000 16:00 | 3 | WE_2000_01 | 2 | LE_2000_01 | 4 |
| 13 Jan 2000 16:00 | 13 Jan 2000 17:30 | 1 | WE_2000_01 | 3 | LE_2000_01 | 4 |
| 13 Jan 2000 17:30 | 14 Jan 2000 01:45 | 8 | WE_2000_01 | 4 | LE_2000_01 | 4 |
| 14 Jan 2000 01:45 | 14 Jan 2000 6:00 | 4 | WE_2000_01 | 4 | | 1 |
| 14 Jan 2000 06:00 | 14 Jan 2000 18:00 | 12 | WE_2000_01 | 2 | | 1 |
| 14 Jan 2000 18:00 | 18 Mar 2000 07:30 | 1525 | | 1 | | 1 |
| 18 Mar 2000 07:30 | 18 Mar 2000 12:30 | 5 | WE_2000_02 | 3 | | 1 |
| 18 Mar 2000 12:30 | 18 Mar 2000 18:00 | 5 | WE_2000_02 | 3 | LE_2000_02 | 2 |
| 18 Mar 2000 18:00 | 22 Nov 2000 10:00 | 5968 | | 1 | | 1 |
| 22 Nov 2000 10:00 | 22 Nov 2000 11:00 | 1 | WE_2000_03 | 2 | | 1 |
| 22 Nov 2000 11:00 | 22 Nov 2000 12:00 | 1 | WE_2000_03 | 2 | LE_2000_03 | 3 |
| 22 Nov 2000 12:00 | 22 Nov 2000 17:00 | 5 | WE_2000_03 | 4 | LE_2000_03 | 3 |
| 22 Nov 2000 17:00 | 23 Nov 2000 07:30 | 14 | WE_2000_03 | 4 | | 1 |
| 23 Nov 2000 07:30 | 31 Dec 2000 23:59 | 928 | | 1 | | 1 |

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Table 7. Duration matrix: results using data from Table 6.

| | | LE duration (h) | | | |
|-----------------------|---|-----------------|---|---|---|
| | | 1 | 2 | 3 | 4 |
| WE duration (h) | 1 | 8719 | 0 | 0 | 3 |
| | 2 | 13 | 0 | 1 | 3 |
| | 3 | 5 | 5 | 0 | 1 |
| | 4 | 18 | 0 | 5 | 8 |

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Table 8. Performance indicators derived from the two performance criteria reported in Fig. 7 using data from duration matrix reported in Table 7.

| Performance indicator | Performance criterion | Symbol | Formula | Value |
|---|-----------------------|------------------|--|-------|
| Efficiency index | Criterion A | I_{eff} | $(CA + TN) / \sum_{ij} d_{ij}$ (excluding d_{11}) | 0.44 |
| Hit rate | Criterion A | HR_L | $CA / (CA + MA)$ | 0.67 |
| Predictive power | Criterion A | PP_W | $CA / (CA + FA)$ | 0.33 |
| Threat score | Criterion A | TS | $CA / (CA + MA + FA)$ | 0.29 |
| Odds ratio | Criterion A | OR | $(CA + TN) / (MA + FA)$ | 0.77 |
| Misclassification rate | Criterion A | MR | $1 - I_{\text{eff}}$ | 0.56 |
| Missed alert rate | Criterion A | R_{MA} | $1 - HR$ | 0.33 |
| False alert rate | Criterion A | R_{FA} | $1 - PP$ | 0.67 |
| Error rate | Criterion B | ER | $(Red + Pur) / \sum_{ij} d_{ij}$ (excluding d_{11}) | 0.56 |
| Probability of serious mistakes | Criterion B | P_{SM} | $Pur / \sum_{ij} d_{ij}$ (excluding d_{11}) | 0.39 |
| Probability of serious no-warning mistakes | Criterion B | P_{SM-NW} | $Pur_{i4} / \sum_{ij} d_{ij}$ (for $i = 1, j = 2-4$) | 1 |
| Probability of serious no-landslides mistakes | Criterion B | P_{SM-NL} | $Pur_{4j} / \sum_{ij} d_{ij}$ (for $i = 2-4, j = 1$) | 0.5 |
| Index of severity of missed alerts | Criteria A and B | I_{MA} | $(Pur + MA) / MA$ | 0.86 |
| Index of severity of false alerts | Criteria A and B | I_{FA} | $(Pur + FA) / FA$ | 0.64 |

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Table 9. Simulations of the parametric analysis: values of the input parameters needed to define the landslide and warning events.

| | ZS-T1 | G-T1 | G-U1 | G-T2 | G-T3 | G-T4 | G-Z1 | G-W1 | G-A1 | G-B1 | G-C1 | G-E1 | G-F1 | G-W5 |
|------------------|---------------|---------------|-------------------------------|--------------|--------------|--------------|-------------------------------|-------------------------------|---------------|---------------|---------------|---------------|---------------|---------------|
| W_{lev} | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| $L_{den(k)}$ | mixed (A) | mixed (A) | mixed (A _{susc}) | mixed (A) | mixed (A) | mixed (A) | mixed (A _{susc}) | mixed (A _{susc}) | mixed (A) | mixed (A) | mixed (A) | mixed (A) | mixed (A) | mixed (A) |
| t_{LEAD} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 h | 3 h | 1 h | 0 | 0 | |
| L_{typ} | ALL | ALL | ALL | ALL | ALL | ALL | R-I | T1 | ALL | ALL | ALL | ALL | ALL | T1 |
| Δt_{LE} | 12 h | 12 h | 12 h | 12 h | 12 h | 12 h | 12 h | 12 h | 12 h | 12 h | 24 h | 12 h | 24 h | 12 h |
| t_{OVER} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 h | 6 h | 12 h | 0 | 0 | 0 |
| A | ZS | G | G | G | G | G | G | G | G | G | G | G | G | G |
| $\Delta A_{(k)}$ | ZS | G | G | G | G | G | G | G | G | G | G | G | G | G |
| ΔT | 2010– 2012 | 2010– 2012 | 2010– 2012 | 2010 | 2011 | 2012 | 2010– 2012 | 2010– 2012 | 2010– 2012 | 2010– 2012 | 2010– 2012 | 2010– 2012 | 2010– 2012 | 2010– 2012 |
| Δt | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' | 1' |

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Table 10. Duration matrix of simulation ZS_T1.

| | | LE duration (h) | | | |
|-----------------------|--------|-----------------|-------|-------|-------|
| | | 1 (no) | 2 (S) | 3 (I) | 4 (L) |
| WE duration (h) | 1 (no) | 8185.1 | 19.1 | 20.4 | 0.0 |
| | 2 (M) | 288.4 | 16.7 | 0.7 | 0.0 |
| | 3 (H) | 90.0 | 6.0 | 3.1 | 32.4 |
| | 4 (VH) | 28.5 | 0.1 | 38.1 | 31.4 |

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Table 11. Duration matrix of simulation G_T1.

| | | LE duration (h) | | | |
|-----------------------|--------|-----------------|-------|-------|-------|
| | | 1 (no) | 2 (S) | 3 (I) | 4 (L) |
| WE duration (h) | 1 (no) | 8281.8 | 0.4 | 0.0 | 0.0 |
| | 2 (M) | 302.0 | 0.0 | 0.0 | 5.4 |
| | 3 (H) | 100.1 | 0.2 | 0.0 | 2.8 |
| | 4 (VH) | 54.8 | 0.0 | 0.0 | 12.6 |

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Table 12. Values of the performance indicators for all the simulations of the parametric analysis.

| Performance indicator | ZS-T1 | G-T1 | G-U1 | G-T2 | G-T3 | G-T4 | G-Z1 | G-W1 | G-A1 | G-B1 | G-C1 | G-E1 | G-F1 | G-W5 |
|-----------------------|-------|------|------|------|-------|------|------|------|------|------|------|------|------|------|
| I_{eff} | 0.66 | 0.75 | 0.73 | 0.71 | 0.92 | 1.00 | 0.71 | 0.64 | 0.78 | 0.78 | 0.68 | 0.75 | 0.65 | 0.60 |
| HR_L | 0.74 | 0.83 | 0.76 | 0.79 | 0.98 | 0.00 | 0.74 | 0.99 | 0.85 | 0.83 | 0.46 | 0.81 | 0.49 | 1.00 |
| PP_W | 0.09 | 0.46 | 0.48 | 0.40 | 0.83 | 0.00 | 0.43 | 0.16 | 0.53 | 0.54 | 0.65 | 0.46 | 0.50 | 0.06 |
| TS | 0.09 | 0.42 | 0.42 | 0.36 | 0.82 | 0.00 | 0.38 | 0.16 | 0.49 | 0.49 | 0.37 | 0.42 | 0.33 | 0.06 |
| OR | 1.98 | 2.95 | 2.74 | 2.50 | 11.51 | 0.00 | 2.42 | 1.78 | 3.58 | 3.64 | 2.17 | 2.99 | 1.87 | 1.47 |
| MR | 0.34 | 0.25 | 0.27 | 0.29 | 0.08 | 0.00 | 0.29 | 0.36 | 0.22 | 0.22 | 0.32 | 0.25 | 0.35 | 0.40 |
| R_{MA} | 0.26 | 0.17 | 0.24 | 0.21 | 0.02 | 0.00 | 0.26 | 0.01 | 0.15 | 0.17 | 0.54 | 0.19 | 0.51 | 0.00 |
| R_{FA} | 0.91 | 0.54 | 0.52 | 0.60 | 0.17 | 0.00 | 0.57 | 0.84 | 0.47 | 0.46 | 0.35 | 0.54 | 0.50 | 0.94 |
| ER | 0.34 | 0.25 | 0.27 | 0.29 | 0.08 | 0.00 | 0.29 | 0.36 | 0.22 | 0.22 | 0.32 | 0.25 | 0.35 | 0.40 |
| P_{SM} | 0.13 | 0.05 | 0.09 | 0.05 | 0.05 | 0.00 | 0.11 | 0.13 | 0.03 | 0.03 | 0.04 | 0.05 | 0.07 | 0.17 |
| P_{SM-NW} | 0.00 | 0.00 | 0.52 | 0.00 | 0.00 | 0.00 | 0.73 | 0.00 | 0.00 | 0.00 | 0.10 | 0.00 | 0.13 | 0.00 |
| P_{SM-NL} | 0.12 | 0.07 | 0.07 | 0.07 | 0.09 | 0.00 | 0.09 | 0.15 | 0.06 | 0.05 | 0.05 | 0.07 | 0.08 | 0.15 |
| I_{MA} | 1.00 | 0.00 | 0.59 | 0.00 | 0.00 | 0.00 | 0.59 | 0.00 | 0.00 | 0.04 | 0.14 | 0.04 | 0.15 | 0.00 |
| I_{FA} | 0.35 | 0.23 | 0.24 | 0.21 | 0.64 | 0.00 | 0.31 | 0.37 | 0.18 | 0.18 | 0.15 | 0.23 | 0.25 | 0.43 |

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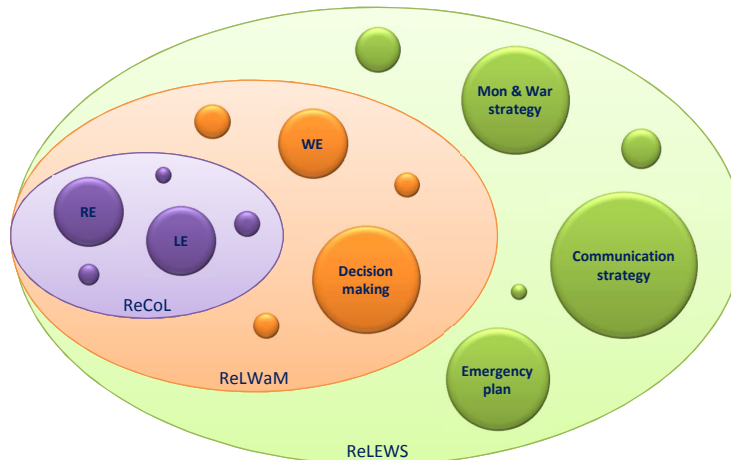


Figure 1. Scheme of the components of regional early warning systems for rainfall-induced landslides. Legend: RE = rainfall events; LE = landslide events; WE = warning events; ReCoL = regional correlation law; ReLWaM = regional landslide warning model; ReLEWS = regional landslide early warning system.

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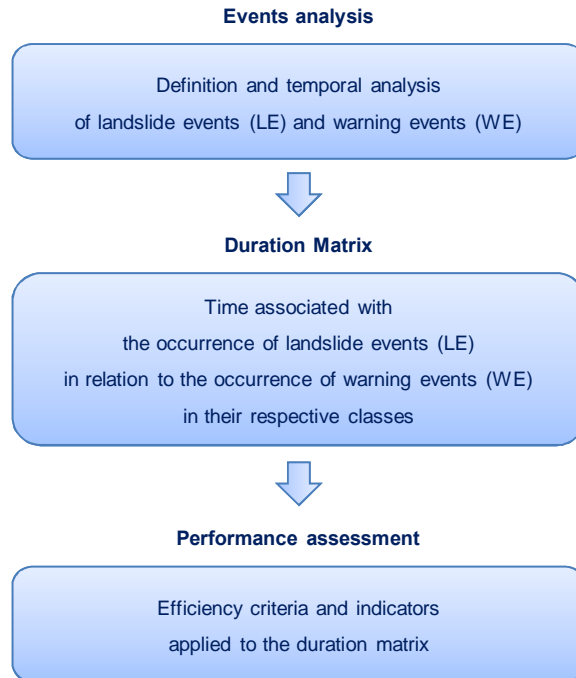


Figure 2. Scheme of the “Events, Duration Matrix, Performance (EDuMaP) method”.

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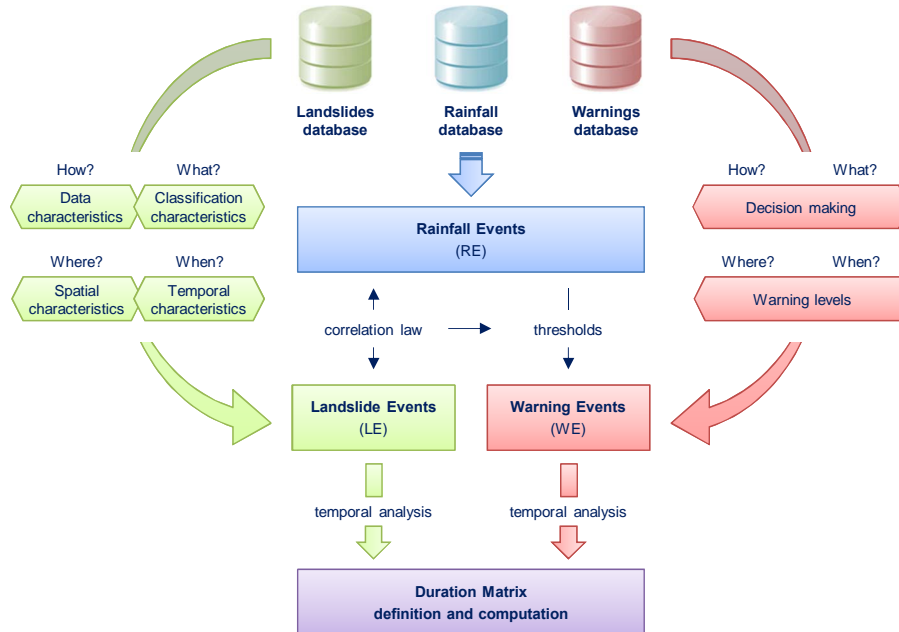


Figure 3. Scheme of the relationships among rainfall events, landslide events and warning events for the definition and computation of the duration matrix.

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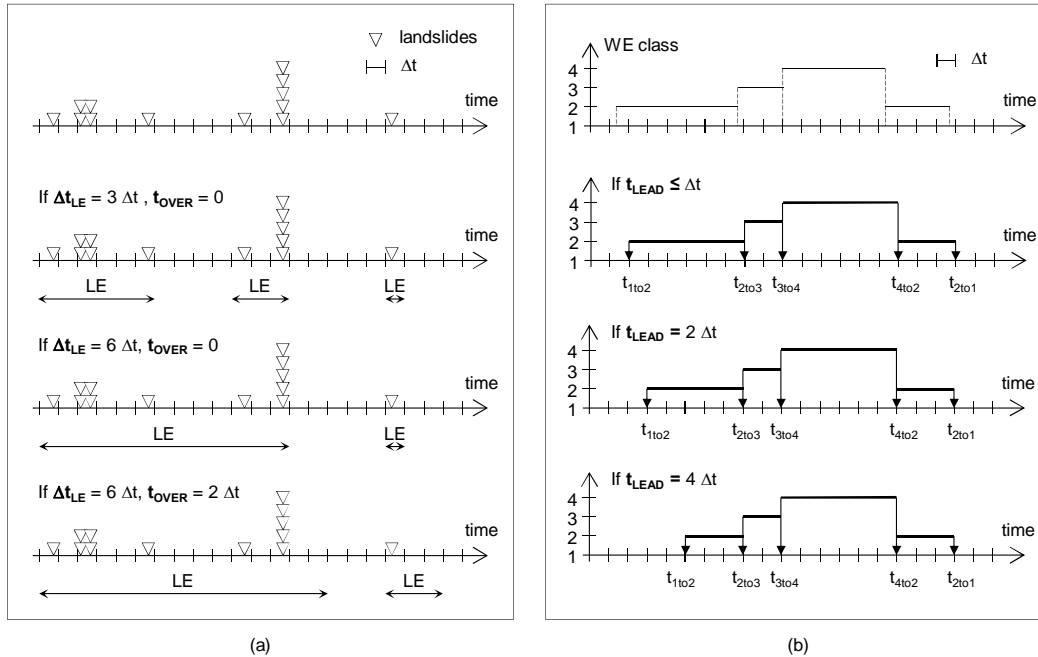


Figure 4. Exemplification of the meaning of parameters: minimum interval between landslide events, Δt_{LE} , and over time, t_{OVER} (a); lead time, t_{LEAD} (b).

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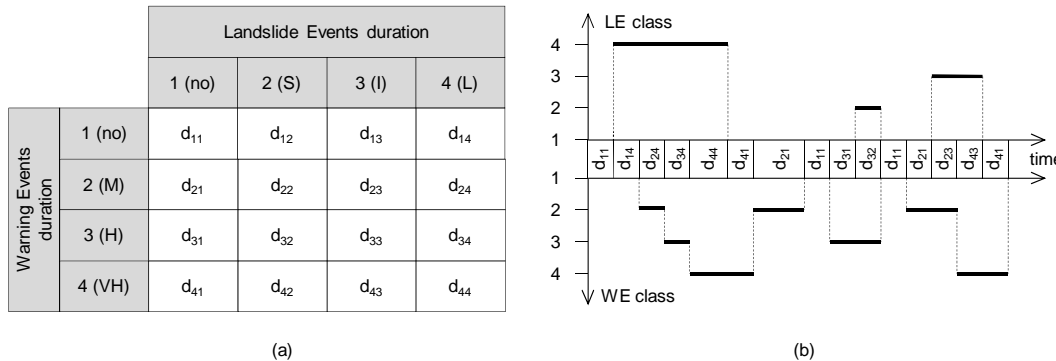


Figure 5. Structure of the duration matrix and graphical exemplification of the temporal analysis needed for its computation.

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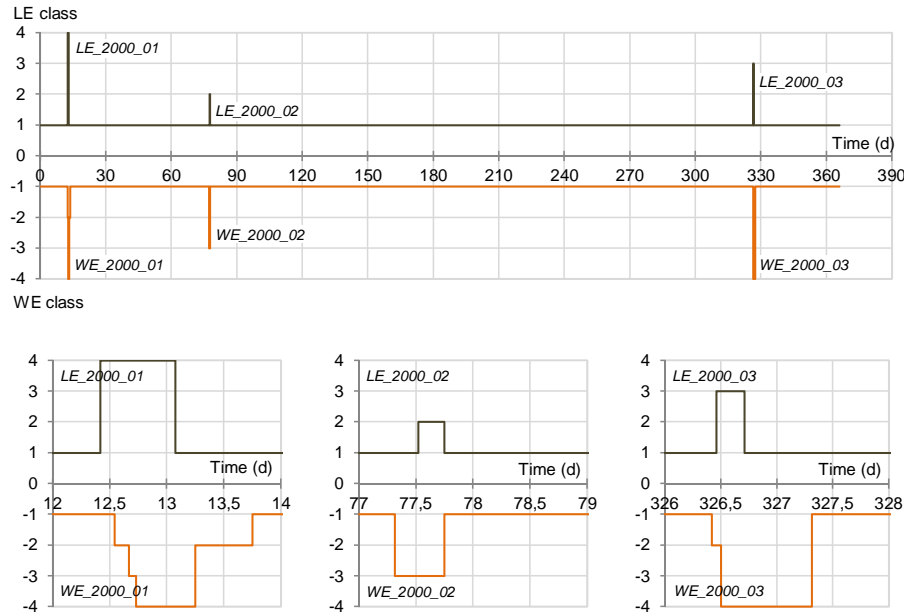


Figure 6. Graphical representation of temporal analysis reported in Table 6.

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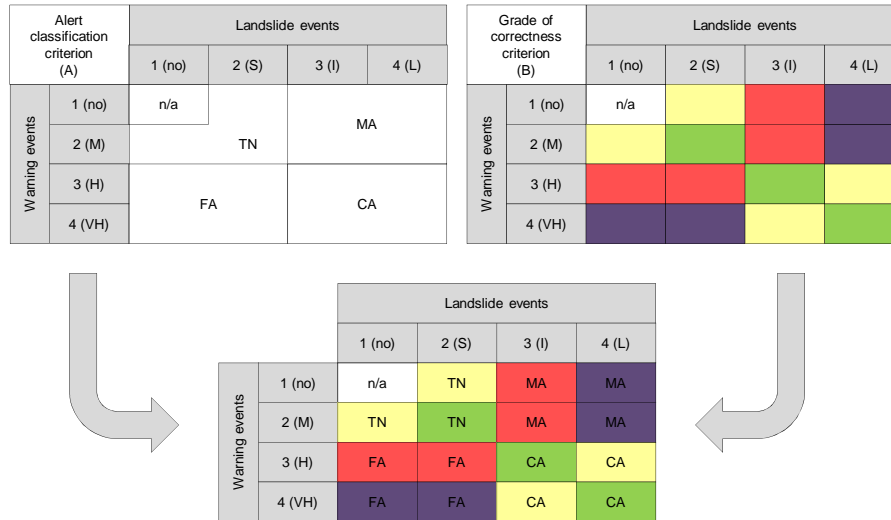


Figure 7. Examples of performance criteria which can be used for the analysis of the duration matrix: alert classification criterion (A) and grade of correctness criterion (B).

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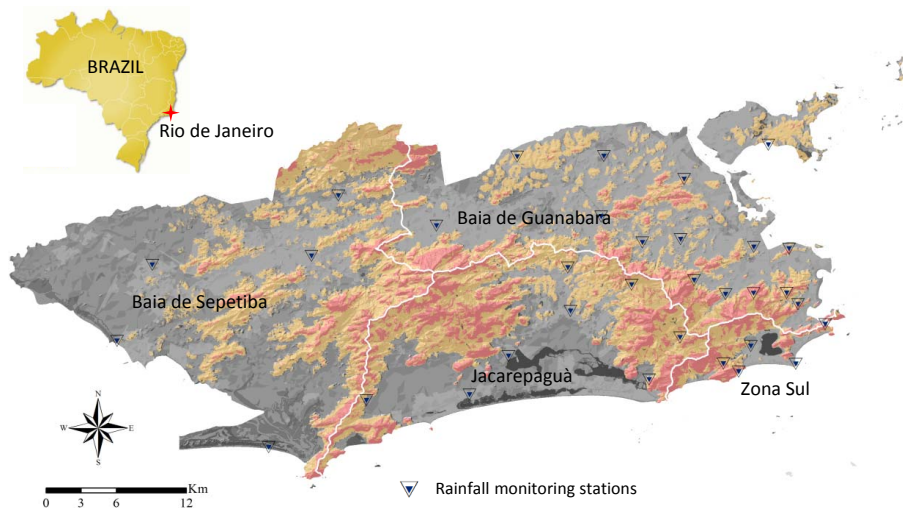


Figure 8. Subdivision of the Rio de Janeiro municipal territory for early warning purposes, susceptibility map and location of the rainfall monitoring stations.

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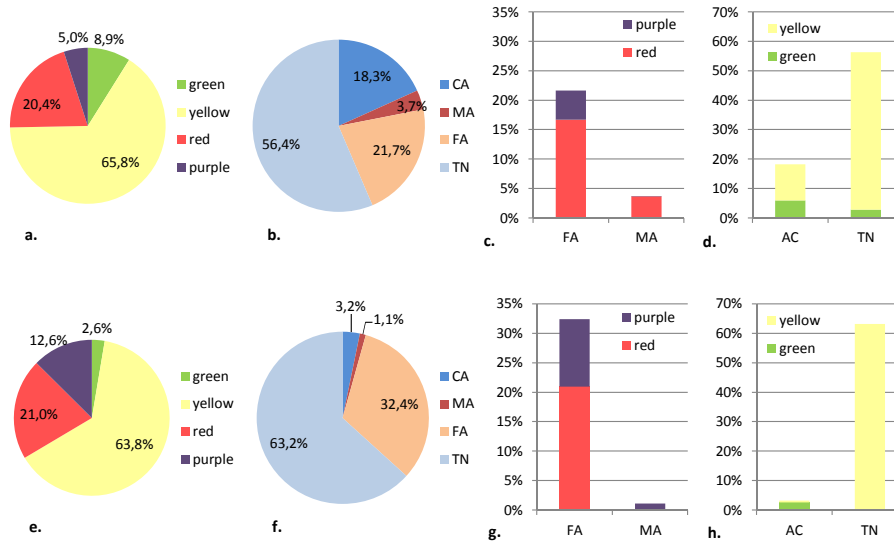


Figure 9. Simulations ZS-T1 and G-T1: distribution of the elements of the duration matrix according to the two performance criteria adopted.

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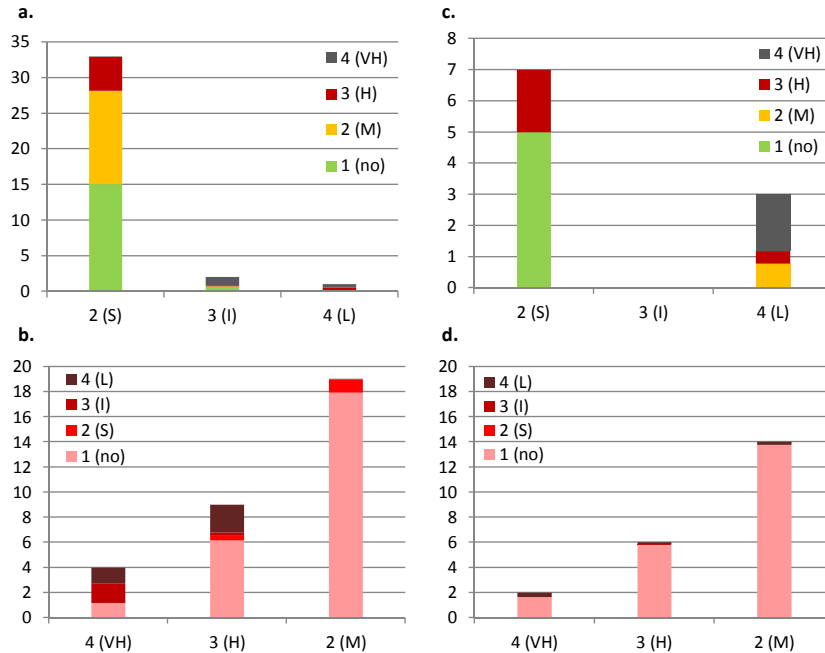


Figure 10. Simulations ZS-T1 and G-T1: values of the elements of the duration matrices normalized in relation to landslide events, $d_{LE_{ij}}$ (Eq. 2), and warning events, $d_{WE_{ij}}$ (Eq. 3).

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Assessing the performance of regional landslide early warning models

M. Calvello and L. Piciullo

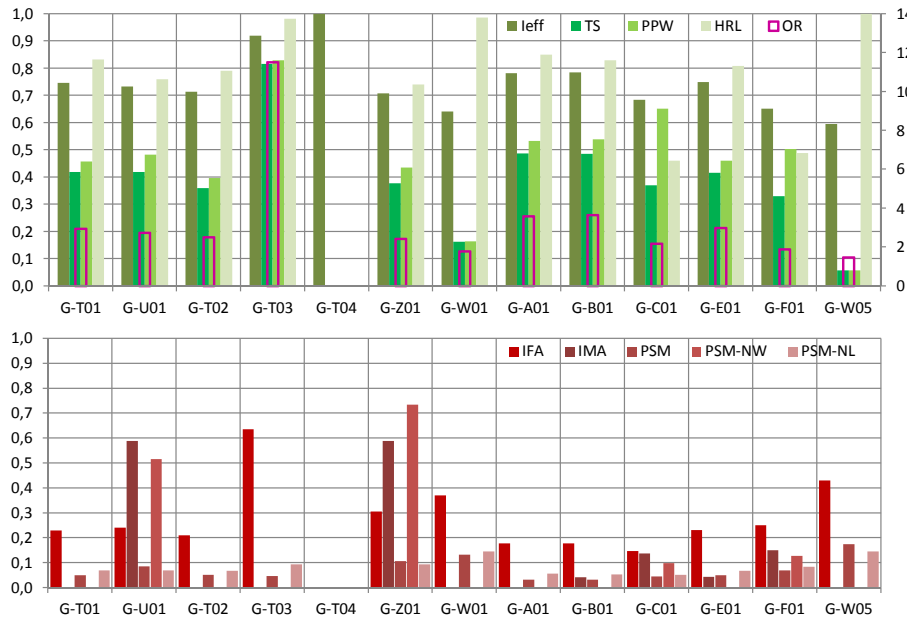


Figure 11. Simulations G_T1 to G_W5: values of performance indicators related to the success **(a)** and to the errors **(b)** of the warning model.

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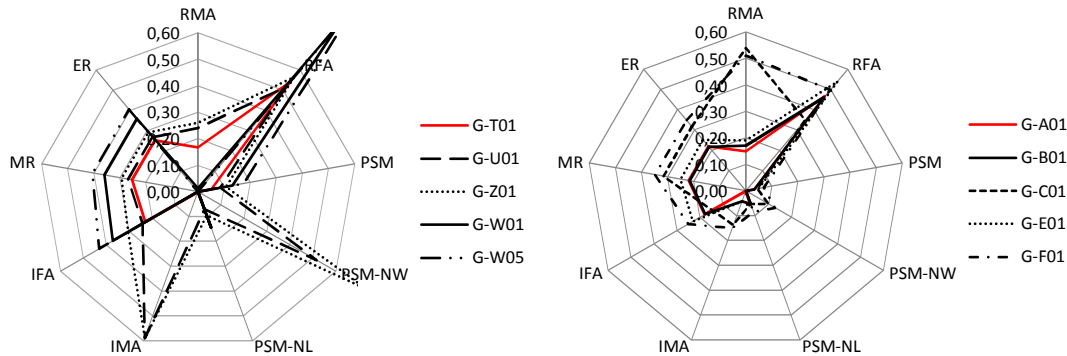


Figure 12. Simulations G_T1 to G_W5: values of all the performance indicators related to errors of the warning model, grouped to highlight the effect of parameters $L_{den(k)}$ and L_{typ} **(a)** and parameters Δt_{LE} , t_{LEAD} and t_{OVER} **(b)**.

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