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PERFORMANCE ANALYSIS OF LANDSLIDE EARLY WARNING SYSTEMS AT REGIONAL SCALE

ANALISI DELLA PRESTAZIONE DEI SISTEMI DI ALLERTA DA FRANA A SCALA REGIONALE

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ABSTRACT

Landslide early warning systems are non-structural risk mitigation strategies aiming at dealing with intolerably high probabilities of landslide occurrence by reducing risk through the reduction of the exposed elements. The majority of landslide early warning systems deal with rainfall-induced landslides. The systems can be classified, as a function of the scale of analysis, into: "local" and "regional" systems. Several differences exists among these two different types of warning systems, such as: the actors involved in the process, the monitoring tools, the variables selected to define triggering thresholds, the way the warnings are issued and spread to the public. This work exclusively deals with regional landslide early warning systems (ReLEWSs). These systems are used to assess the probability of occurrence of landslides over appropriately-defined homogeneous alert zones of relevant extension, typically through the prediction and monitoring of meteorological variables, in order to give generalized warnings to administrators and the population. At first, a detailed review of the structure and the functioning of these systems is presented. The information has been gathered mainly from the literature, with the exception of the regional system operating in Campania region, Italy, the municipal system of Rio de Janeiro, Brazil, and the national Norwegian landslide early warning system. The functioning and the structure of the latter two systems have been analyzed in greater depth thanks to research periods spent, respectively, at the GEO-Rio foundation in Rio de Janeiro and at The Norwegian Water Resources and Energy Directorate (NVE) in Oslo. In literature, several authors provided a general description of the structure of a landslide early warning system. Starting from the analysis of these contributions, an original scheme and the main components of such systems for rainfall-induced landslides forecast is proposed. The scheme is based on a clear distinction among the following components: correlation laws, decisional algorithm and warning management. Subsequently, the functioning of the reviewed ReLEWSs has been described according to these components, with a special attention on how the performance of the various warning models was assessed. It is straightforward that a periodical assessment of the technical performance of a landslide early warning system, in terms of evaluation of the warning issued in relation to the landslides occurred, is a required task in order to continuously keep the system reliable. Nevertheless, no standard requirements exist for assessing the performance of regional warning models (ReWaMs) and, typically, this is evaluated by computing the joint frequency distribution of landslides and warnings, both considered as dichotomous variables. Herein, an original methodology to assess the performance of ReWaMs, called the "Event, Duration Matrix, Performance" (EDuMaP) method, is proposed. The performance is evaluated taking into account: the possible occurrence of multiple landslides in the warning zone; the duration of the warnings in relation to the time of occurrence of the landslides; the warning level issued in relation to the landslide spatial density in the warning zone; the relative importance system managers attribute to different types of errors. The applicability of EDuMaP method is tested considering three different ReLEWSs: the municipal early warning system operating in Rio de Janeiro (Brazil); the Norwegian landslide early warning system; the landslide early warning system for hydro-geological risk management of the Campania region, Italy. The main differences among these systems are discussed in great detail, mainly dealing with the functioning and the databases available for the three case studies. The LEWS operational in Rio de Janeiro is employed to issue a certain level of warning in four warning zones in which the municipality is divided. The warnings can be issued at any time during the day if the monitored rainfall exceeds pre-identified thresholds. The Norwegian landslide early warning system is employed to issue daily warnings adopting variable warning zones. In the LEWS of the Campania region each municipality has a reference rain gauge for which three different rainfall threshold are specified for the activation of 3 warning levels. The EDuMaP method was successfully employed to assess the performance for all these case studies, thus underlying the wide applicability of the method, which can be easily adopted to evaluate the performance of any regional landslide early warning systems for which landslides and warnings data are available. For the three case studies, sensitivity analyses are also conducted by varying some of the input parameters of the EDuMaP method. The results of these analyses indicate that the input parameters most affecting the performance of the warning models are: i) the landslide density criterion used to differentiate among the classes of landslide events; ii) the database on landslides considered in the simulations; iii) the time set

as the minimum time interval between landslide events; iv) the area of analysis; v) the time frame of the analysis. In conclusion, the analyses prove the applicability of the EDuMaP method in evaluating the performance of real case studies related to ReLWaMs characterized by different decisional algorithms, components and input parameters. The method can also be used as an effective tool to calibrate a warning model by back-analysing landslide and warning data in test area with the aim of defining the set of warning criteria which maximises the model performance.

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ABOUT THE AUTHOR

Luca Piciullo graduated with honour at the University of Salerno, Italy, with a thesis on the modelling of debris flow runout and entrainment phenomena through an advanced code based on the Smoothed-particle hydrodynamics (SPH) method. In 2013 he won a PhD scholarship at the same University to deal with the study of landslide early warning systems at a regional scale. As a part of his PhD, he had the opportunity to spend research periods in Rio de Janeiro, Brazil and Oslo, Norway, where he examined in depth the functioning of the landslide early warning systems there employed. In particular he collaborated with the GEO-Rio Foundation, in Rio de Janeiro, and the Norwegian Water Resources and Energy Directorate (NVE), in Oslo, to collect data on landslides and warnings to be employed in the analysis of the landslide early warning systems performance. During his PhD he developed a methodology to analyse the performance of a landslide early warning system at a regional scale, named "Event, Duration Matrix, Performance (EDuMaP) method". He presented the work from his thesis participating as lecturer in many National and International conferences between 2014 and 2016. He also participated as author in several scientific contributions dealing with both debris flow runout and entrainment modelling, and the explanation and application of the EDuMaP method to several case studies.

1 INTRODUCTION

In the last decades an increased number of consequences in terms of economic losses (Barredo, 2009) and fatalities have been caused by natural hazards throughout Europe (European Environment Agency, 2010; CRED, 2011). The reasons can mostly be associated with societal changes rather than human-induced climatic changes (Barredo, 2009), even if most of the natural disasters are related to extreme rainfall events, which are increasing 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) certainly constitute a significant option available to the authorities in charge of risk management and governance. The United Nations define EWSs as "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss" (UNISDR, 2009). In generic terms, early warning constitutes a process whereby information generated from tailored observations of natural phenomena is provided to communities at risk, or to institutions which are involved in emergency response operations, so that certain tasks may be executed before a catastrophic event impacts such communities (Villagrán de León et al., 2013).

Landslide occurrence is one of the natural hazards addressed by early warning systems. Landslide early warning systems (LEWSs) mitigate the risk to life associated to the occurrence of landslides by informing the public—i.e. the elements at risk—whenever landslide risk is considered to be intolerable high. 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. Two categories of landslide early warning systems (LEWSs) can be defined on the basis of their scale of analysis and operation: "local" systems and "regional" systems (ICG 2012; Thiebes et al. 2012; Calvello et al. 2015). Rainfall-induced landslides are, by far, the most diffuse class of landslide warning systems operating around the world.

Chapter 2 of this work provides a review on regional early warning systems for rainfall-induced landslides (ReLEWS) operating worldwide. The majority of information on the systems have been gathered by the literature, except for the systems operating in the Campania region, Italy, in Rio de Janeiro, Brazil, and in Norway, which have been personally collected and analysed. In particular, the last two systems have been investigated during research periods spent, respectively, at the GEO-Rio Foundation in Rio de Janeiro, and at The Norwegian Water Resources and Energy Directorate (NVE) in Oslo. Several schemes proposed in the literature by different authors (UNISDR, 2006; Di Biagio and Kjekstad, 2007; Intrieri, et al., 2013), describing the structure of a EWS, are presented in this chapter. Moreover, an original scheme and the main components composing EWSs for rainfall-induced landslides forecast are proposed. The scheme is based on a clear distinction among the following components: correlation laws, decisional algorithm and warning management. Subsequently the ReLEWSs have been reviewed describing, wherever possible, the main characteristics of the systems component by component. Finally, an analysis on how performance was considered in these systems has been carried out.

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 (Hyogo Framework for Action, 2005). In fact a periodical LEWSs performance analysis, in terms of level of warning issued and landslides occurred, is necessary in order to keep the system reliable. To this aim, in Chapter 3 an original methodology to evaluate the technical performance of a ReLEWS has been proposed. The methodology is called "Event, Duration Matrix, Performance (EDuMaP) method" and it is used to assess the performance of the warning model employed by a LEWS, herein called ReWaM. Thanks to this method the analyst is able to explicitly consider in the performance assessment: 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 applicability of the EDuMaP method is tested and discussed using real landslides and warnings data from three case studies: the municipal early warning system operating in Rio de Janeiro (Brazil); the national Norwegian landslide early warning system and the landslide early warning system for hydro-geological risk management deployed in the Campania region, Italy. The differences among these systems in terms of functioning, characteristics and components are shown in Chapter 4.

In Chapter 5 the EDuMaP method has been applied to the three case studies explaining the procedures for the application of the method for ReWaMs with different structures and functioning. The results of the performance analyses are presented separately for each case study. Moreover some parametric analysis have been carried out to assess the sensitivity of the EDuMaP method to varying input parameters.

Lasciare bianca questa pagina solo se (come in questo caso) il capitolo precedente finisce in una pagina dispari. Questo per garantire che ogni nuovo capitolo inizi su una pagina a destra (ovvero dispari).

2 WORLDWIDE LANDSLIDE EARLY WARNING SYSTEMS AT REGIONAL SCALE

2.1 LANDSLIDE EARLY WARNING SYSTEMS AS RISK MITIGATION STRATEGY

2.1.1 Structure of early warning systems

The continuous urbanization process in areas with a high susceptibility of natural hazards and the occurrence of high intensity atmospheric phenomena have dramatically increased, in many parts of the world, the losses and damage related to such hazards. Several measures can be applied to reduce the risk for human life associated to the occurrence of hazardous events, among them early warning systems (EWS) are an important and often used non-structural mitigation measure. The purpose of an EWS is to reduce the loss-of-life risk level by inviting people present in areas characterized, at specific times, by an intolerable high hazard to act properly. In the Hyogo framework for Action, 2005–2015, which was adopted by the World Conference on Disaster Reduction held in January 2005 at Kobe, Japan (UN ISDR 2005), early warning systems were recognized as important tools for disaster risk reduction and for achieving sustainable development and livelihoods. Generally, early warning systems can be defined as the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss (UNISDR, 2009). This definition is rather concise yet it highlights the importance assumed, within such systems, by the elements at risk, i.e. the people. People-centered early warning systems always comprise, independently from the type of threat they are addressing, few essential components. According to UNISDR (2006), a complete and effective early warning system comprises four interrelated elements, spanning from knowledge of hazards and vulnerabilities to preparedness and capacity to respond: i) knowledge of risks; ii) monitoring, analysis and forecasting of hazards; iii) communication and dissemination of alerts and warnings; iv) local capabilities to respond to warnings (Fig. 2.1). A weakness or failure in any one part could result in failure of the whole system.

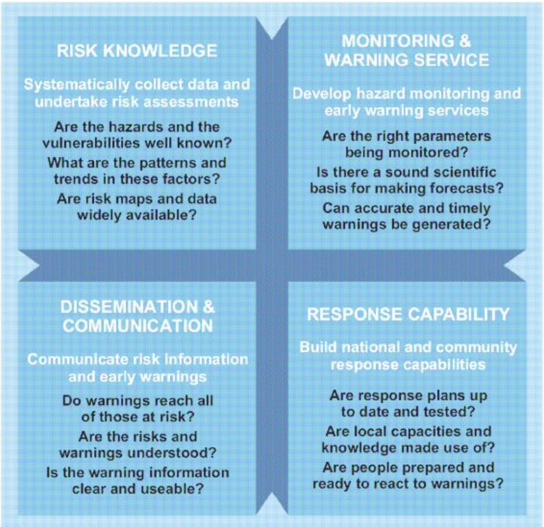

Figure 2.1 The four components of a people-centered early warning system (UNISDR, 2006).

Knowledge of risks indicates the study of hazards and vulnerabilities in a given area aimed at defining a level of risk. Monitoring deals with the collection of data necessary to control, in time, the trend of variables which significantly affect the hazard and risk level. To this end, the equipment used can be very different depending on the purpose, the characteristics and scale of the warning system to be designed. Communication and dissemination of warnings aims at informing people at risk. Finally, response capability may be associated to the education of the population, to the information provided on how to evacuate from areas at risk and to specific procedures adopted for handling emergency situations. These activities must take into account: needs and vulnerability of the population exposed at risk, identification of issues that people can encounter when acting in response to an alert, characterization of geological and meteorological conditions which influence landslide triggering, definition of geo-indicators.

An alternative schematic of the structure of landslide warning systems is the one proposed by Di Biagio and Kjekstad, 2007, who use a block diagram to outline the four main steps of a landslide warning system: monitoring; data analysis and forecasting; warning; response (Fig. 2.2).

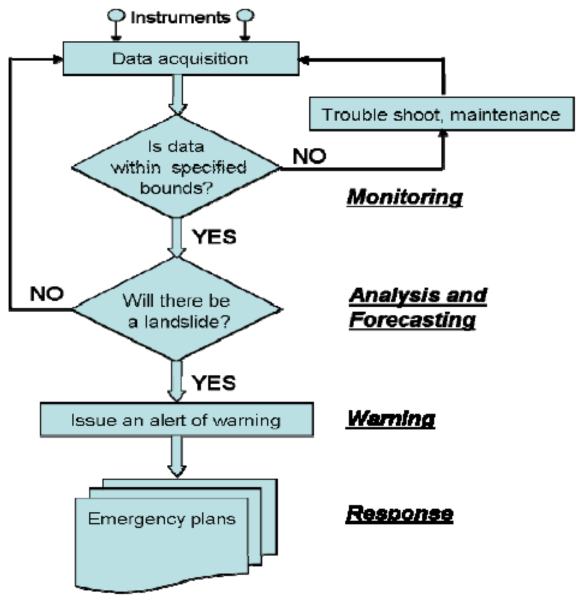

Figure 2.2 Scheme of the main phases of a landslide warning system (Di Biagio and Kjekstad, 2007)

According to them, the key technical issue for the realization of an effective landslide warning system is the identification, monitoring and measurement of precursors that precede the occurrence of landslides. The choice of precursors to be monitored varies with the type of system that is to be realized and with the objective to be pursued. Typical examples of precursors are heavy rains, ground vibrations from earthquakes, accelerations and velocities of existing phenomena, rapid increase of pore water pressures. Depending on the type of precursor, typical instruments used within the monitoring network of a landslide warning system include: rain gauges, geophones, seismographs, piezometers, inclinometers, extensometers and other devices measuring ground or subsurface movements.
By elaborating the definitions provided by UNISDR (2006) and Di Biagio and Kjekstad (2007), Intrieri et al. (2013) highlight the main

elements of landslide early warning systems as a balanced combination of the following four activities: planning, monitoring, forecasting, education (Fig. 2.3). The planning activity is mainly focused on defining: needs and vulnerability of people exposed at risk; identification of constraints that people can encounter acting in response to an alert; the characterization of geological and meteorological conditions that contribute to trigger landslides; the definition of geo-indicators. Monitoring, which includes instruments selection and installation, is a crucial activity to gather data on landslide triggering factors in a landslide early warning system project area. Monitoring typically begins during the design phase to study landslide occurrences and rainfall characteristics for rainfall correlation purposes. Based on the scheme proposed by Intrieri et al. (2013), forecasting is the main element of the landslide warning systems and it includes: definition of thresholds, models, other components necessary to issue a warning. Finally, the education activities aim to educate people about the risk at which they are exposed, clearly explaining the behavior to be assumed during different alert stages.

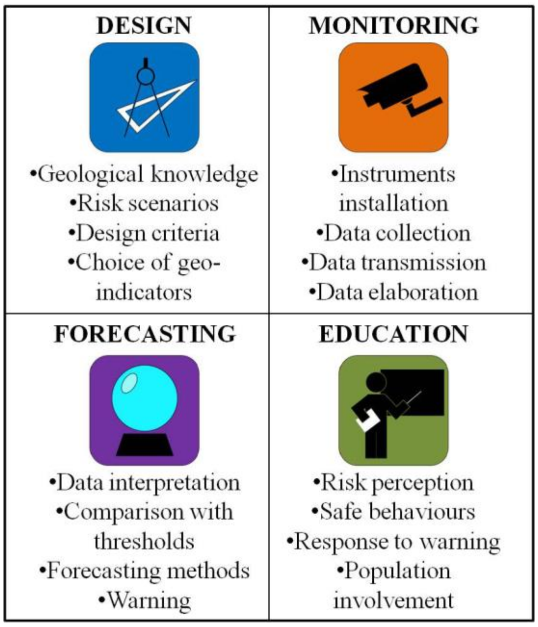

Figure 2.3 Four activities of a landslide early warning system (Intrieri et al., 2013).

Combining the different contributions from the literature with an idea focused on different detail levels, an original schematic representation of designing and managing processes of landslide early warning systems has been defined (Fig. 2.4). Once the objectives of the system are defined depending on the scale of analysis and the type of landslides, it is necessary to detail, as shown by the 4 concentric rings of the proposed "wheel" scheme: the necessary tools, the activities to be performed, the means to be used and the basic elements of the system (Calvello and Piciullo 2014; Calvello et al., 2015). As shown by the outer ring of the "wheel", design of landslide early warning systems implies the synergy between technical and social tools. The firsts are related to everything necessary to technically design a landslide early warning system, such as: choice of variables to be monitored and monitoring instruments, definition of rainfall thresholds and warning levels definition. Social tools refer to people-oriented activities aiming to inform population of a high level of risk and to encourage them to act properly in order to reduce risk to life. The second ring defines the main activities needed to define a landslide early warning system: monitoring, modelling, warning, emergency, education and decision making. The monitoring and modelling activities belong to the technical tools because they deal with data gathering, analysis and comparison of data with rainfall thresholds. Some decision-making activities are also included in technical tools because a performance analysis on a landslide early warning system may induce the decision of varying rainfall thresholds and variables to be monitored. The warning, emergency, education and decision-making activities are linked with people and belong to the social tools. For instance, when a rainfall threshold is exceeded warning statements are broadcasted among population to inform of the possible occurrence of dangerous landslide phenomena. Therefore, if a serious event occurs, emergency actions need to be undertaken for rescuing people. At the same time, population has to be educated about the risk it is exposed and to know how to act in emergency. The third ring highlights the necessary means to accomplish the activities: instruments, correlation laws, warning levels and procedures. Finally the "wheel" scheme highlights that to design a landslide early warning system four fundamental elements are necessary: availability of data on variables to be monitored, definition of rainfall thresholds and alerts, possibility to issue alert statements to inform people. Therefore data, thresholds, alerts and people are located at the core of "wheel" scheme.

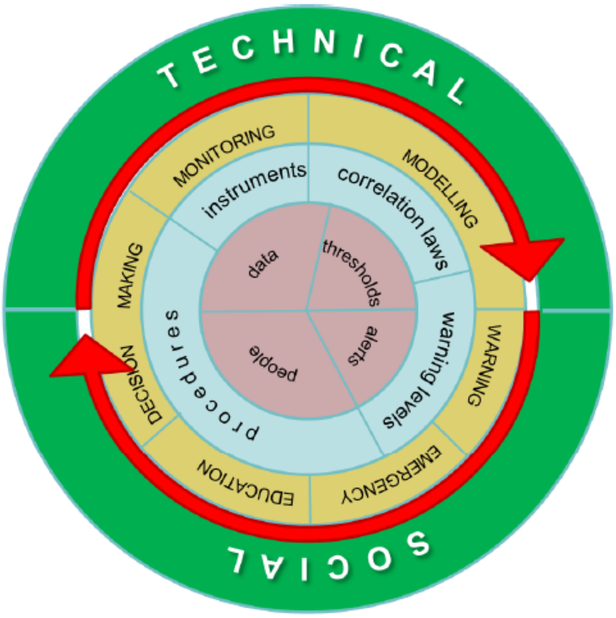

Figure 2.4 Schematic of the design process and operation of a landslide early warning system (from outer to inner ring): skills needed, activities to be undertaken, means to be used, the basic elements of the system (Calvello and Piciullo, 2014; Calvello et al., 2015).

The arrows indicate the direction of the conceptual design and management process, highlighting the temporal continuity of the activities to be undertaken for the continuous updating of the system. Generally, effective design of early warning systems always requires proper synergy between technical and social know-hows (Glade T., et al. 2008, Bell R., et al., 2008), as shown in the ring's outer wheel. The main objective of the designers is the definition of a "reliable" system. To pursue this aim the procedures defined within the technical and the social subsystem need to be "effective".

2.1.2 The scale of analysis: Regional systems for rainfall-induced landslides (ReLEWSs)

Warning systems for landslides can be designed and employed at different scales of analysis. Two categories of landslide early warning systems (LEWSs) can be defined on the basis of their scale of analysis and operation: “local” systems and “regional” systems (ICG 2012; Thiebes et al. 2012; Calvello et al. 2015). Landslide warning systems at regional scale, herein referred to as ReLEWSs, are used to assess the probability of occurrence of landslides over appropriately-defined homogeneous alert zones of relevant extension, typically through the prediction and monitoring of meteorological variables, in order to give generalized warnings to the population. Differently, the main aim of local landslide warning systems is the temporary evacuation of people from areas where, at specific times, the risk level to which they are exposed is considered to be intolerably high. The scale of analysis inevitably also influence the stakeholders involved, the data to be used, the type of forecasting, the emergency phases, the communication strategies and many other activities necessary for designing and operating such systems. 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., 2013; Michoud et al., 2013; 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., 2015; 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 the monitoring phase and identify the best technologies available in the context of both hazard assessment and system design.

Concerning regional warning systems, 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 (Godt, et al., 2006). 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 24h 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., 60' cumulative rainfall, soil-water index), whose thresholds have been mainly computed considering rainfall data recorded as not triggering disasters. In Brazil, the municipal system operating in Rio de Janeiro (d'Orsi et al., 1997; d'Orsi, 2012; Calvello et al., 2015) issues two different co-existing alert sets, rainfall warnings and landslide warnings; the landslide warning levels are four, they are based on the comparison between rainfall measured by the monitoring stations and rainfall thresholds and they are related to an expected spatial density of landslides. In Europe, two national systems for rainfall-induced have been recently implemented, one in Norway, managed by the Norwegian Water Resources and Energy Directorate (Devoli et al., 2014), the other in Italy, designed and operated by the research centre CNR-IRPI on behalf of the national civil protection (Rossi et al. 2012). The Norwegian system is a national early warning system for landslides and floods, with the aim of assisting road and railway authorities, as well as local authorities and policy makers, in taking preventive measures before the occurrence of potentially dangerous events. The Italian system, which is called SANF, is based on sub-hourly rainfall measurements obtained by a national network of 1950 rain gauges, quantitative rainfall forecasts and cumulated rainfall-duration rainfall thresholds. Besides the national system, following a recent national law written on this subject (DPCM, 2004), other relevant experiences are also present in many Italian regions, such as in Emilia Romagna (Berti et al., 2012; Lagomarsino et al., 2013), Piemonte (Tiranti and Rabuffetti, 2010), Campania (DPGR n. 299/2005), Toscana (DGR n. 895/2013, DGR n. 395/2015), Umbria (DGR n. 2312/2007) and Sicily (DPRS n. 626/2014). A more comprehensive review of systems for rainfall-induced landslides currently operating around the world is presented in the following sections.

2.2 ReLEWS COMPONENTS AND PERFORMANCE ANALYSIS

2.2.1 ReLEWS components: a proposal

As previously discussed, a landslide early warning system can be designed at different scales of analysis, local or regional, and numerous could be the differences in the two cases, such as in relation to: monitoring instrumentation, modeling phase, actors, types of alerts emitted. Referring to ReLEWSs, Figure 2.5 and Table 2.1 show an original schematic and the main components of such 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, REs, and landslide events, LEs, eventually including other relevant monitored variables. In this work, RE is generally refers to the amount of rainfall, of a certain duration, capable of triggering one or more landslides. In literature there are several studies dealing with the assessment of rainfall conditions responsible for landslide phenomena. The majority of them are based on subjective analyses and only few contributions present objective criteria for the definition of rainfall events or for the quantitative measurement of rainfall conditions that characterize a rainfall event (Melillo et al., 2014; Segoni et al., 2014). The landslide event, LE, is herein considered as the number of landslides grouped together on the basis of temporal and spatial characteristics. Only few authors considered LEs in rainfall thresholds analyses (Lumb 1975, Giannecchini et al., 2012) but without defining any objective criteria for grouping landslide phenomena. An objective methodology to define LE has been herein proposed and it will be presented in the next section.

A regional landslide warning model, ReLWaM, includes the regional correlation law, ReCoL, as well as the decisional algorithm, which defines: the number of warning levels, WLs, to be considered in the model; decision making procedures to issue the warnings; everything else necessary to define WEs for the system functioning period. A WE is herein defined as a set of warning levels issued within a given warning zone, grouped considering their temporal characteristics. A warning zone

is the portion of territory alerted with the same warning level and it can be seen as the spatial discretization adopted for warnings.
A regional landslide early warning system, ReLEWS, includes the regional warning model, ReLWaM and the warning management, which includes the following components: monitoring and warning strategy; communication strategy; emergency plan (Fig. 2.5). 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 2.1, 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.

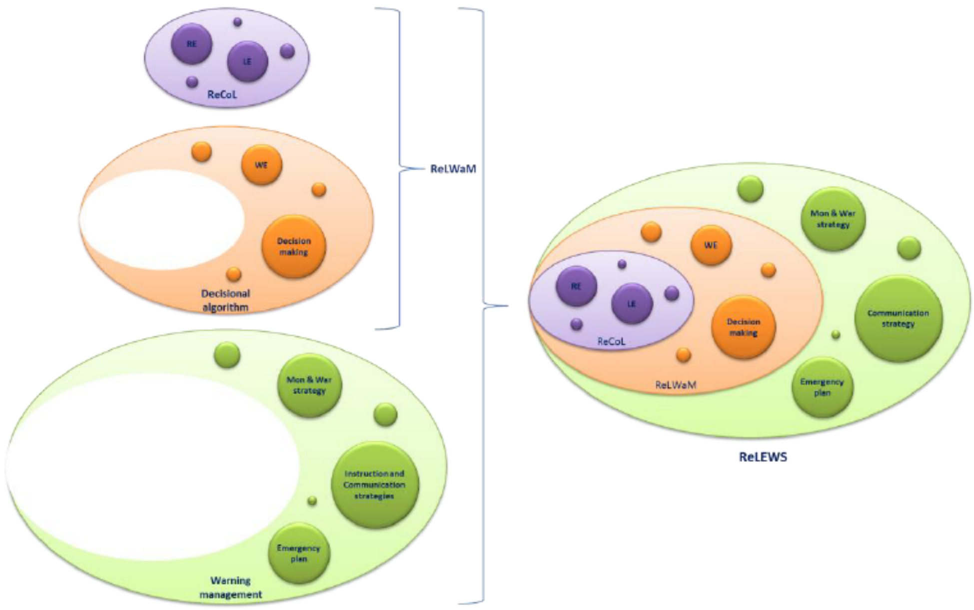

Figure 2.5 Scheme of the components of regional early warning systems for rainfall-induced landslides. Legend: RE = rainfall events; LE = landslide events; WE = warning events; ReCoL = regional correlation laws; ReLWaM = regional landslide warning models; ReLEWS = regional landslide early warning systems (Calvello and Piciullo, 2016).

Table 2.1 Components of regional landslide early warning systems for rainfall-induced landslides, relevance for system parts (ReCoL, ReLWaM, ReLEWS) and system actors: people, managers, scientist; (Calvello and Piciullo, 2016).

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 levels (WL)		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

2.2.2 The importance of the performance analysis

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 (Hyogo Framework for Action, 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., 2013; 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., 2015; Stahili et al., 2015; Segoni et al., 2015; among

others), no standard requirements exist for assessing their performance. 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).
As highlighted by Calvello and Piciullo, 2016, 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, Lagomarsino et al., 2015). The four elements of these tables—i.e. correct alerts or true positives; missed alerts, false negatives or type II errors; false alerts, false positives or type I errors; true negatives —are then used to assess the weight of the correct predictions in relation to the model errors 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.
Maskrey (1997) states that the effectiveness of an early warning system should be judged less on whether warnings are issued per se but rather on the basis of whether the warnings facilitate appropriate and timely decision-making by those most at risk. As previously discussed and

stated in Calvello et al. (2015) the design of landslide warning systems require synergy between technical and social tools.
In particular the procedures defined within the technical and social subsystems are important in making landslide early warning systems an "effective" tool to reduce, respectively, both the number of false and missed alerts and the risk to life. Because false alarms create nuisances and erode credibility but on the other hand, the absence of an advisory when debris-flows do cause death or destruction becomes a dereliction of duty (Wilson, 2004).

2.3 RELEWSS: A REVIEW

2.3.1 Setup

ReLEWSs for fast slope movements have become a sustainable risk management approach worldwide operating over areas of relevant extension. In fact during the last decades, several systems have been designed (Fig. 2.6), not only in developing countries (UNISDR 2006) but also in developed countries, to reduce damage by small-magnitude and high-frequency landslides. In the literature there are few contributions dealing with operative ReLEWS and a complete review is not available differentiating among regional and local scales. The United Nations Environment Programme (UNEP, 2012) provided a worldwide compilation of LEWSs for different natural hazard processes; Baum and Godt (2010) summarized EWSs of shallow landslides and debris flows in the USA; Thiebes (2012) briefly described landslide early warning system both at regional and local scale; Stähli et al. (2015) listed numerous LEWSs worldwide reported in the scientific literature without distinction between different scales of analysis. Within this section all available information on ReLEWSs, gathered from literature and personal experience, are presented (Fig. 2.6 and Tab. 2.1) and the main components of each system are analysed, following the scheme previously proposed (Fig. 2.5), in terms of: ReCoL, decisional algorithm, warning management.

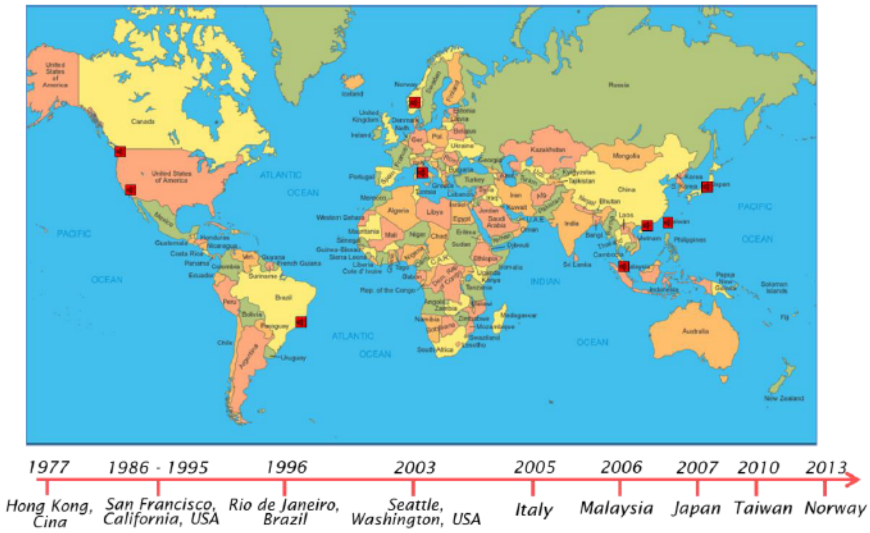

Figure 2.6 Worldwide regional landslide early warning systems: location and year of setup.

A summary on ReLEWSs location and year of employment is shown in figure 2.6, whereas table 2.2 resumes the main characteristics of such systems. All systems are operative nowadays except the landslide early warning system in San Francisco Bay, which terminated in 1995 because of National Weather Service (NWS) forecast office relocation and a net staff reduction. The warning system for debris flow and shallow landslide in Southern California burned areas is a prototype and it operates under formal agreement since 2005 whereas the one in Seattle is employed under informal agreement since 2002. Landslide is the main natural hazard for which warning statements are issued but many of the listed systems also handle different natural hazards, issuing warning statements for: heavy rainfalls, floods, typhoons and snow avalanches.

Table 2.2 ReLEWS reported in the literature: general information.

Location	Institution	Name	Status	Period of activity	Type of hazard
Hong Kong, China	GEO Hong Kong	Landslip Warning system	Active	1977 to date	Landslides
Rio de Janeiro, Brazil	GEO-Rio	Alerta-Rio	Active	1996 to date	Landslides, rainfalls
Rio de Janeiro, Brazil	GEO-Rio	A2C2	Active	2011 to date	Landslides
San Francisco, California, USA	USGS and NWS	-	Not active	1986 - 1995	Landslides
Seattle, Washington, USA	USGS, NWS, City of Seattle	-	Prototype	2002 to date	Landslides
Several Italian regions	Civil defence	-	Active	2004 to date	Rainfall, floods and landslides
Taiwan	DGH	-	Active	2010 to date	Landslides
Taiwan	NCDR	SATIS	Active	2005 to date	Typhoons-induced landslides
Malaysia	PLUS	RTMS	Active	2006 to date	Landslides
Japan	MLIT and JMA	-	Active	1984 to date, upgrade in 2007	Landslides
Southern California	NOAA and USGS	-	Prototype	2005 to date	Landslides and floods
Italy	CNR-IRPI	SANF	Active	2010 to date	Landslides
Oslo, Norway	NVE	-	Active	2013	Landslides, floods, snow avalanches

Hong Kong, China

The oldest system was conceived in Hong Kong, China, in the early 1970s, when the city experienced a number of disastrous landslides, including the notable events in 1972 at Po Shan Road and Sau Mau Ping where 67 and 71 people died respectively. These catastrophes led to the establishment, in 1977, of the Geotechnical Control Office (now the

Geotechnical Engineering Office - GEO) under the Civil Engineering and Development Department of Hong Kong, whose main aims were to mitigate landslide risks and to enforce slope safety (Cheung et al., 2006). The system is still active and it operates issuing warnings for the whole municipality of Hong Kong considered as a unique warning zone (Tab. 2.1). The hazard detected refers to landslides on artificial slopes and the monitoring system is based on a radar and a network of 110 automatic rain-gauge units over the territory, 86 of them operated by GEO and 24 by Hong Kong Observatory-HKO (Fig. 2.7).

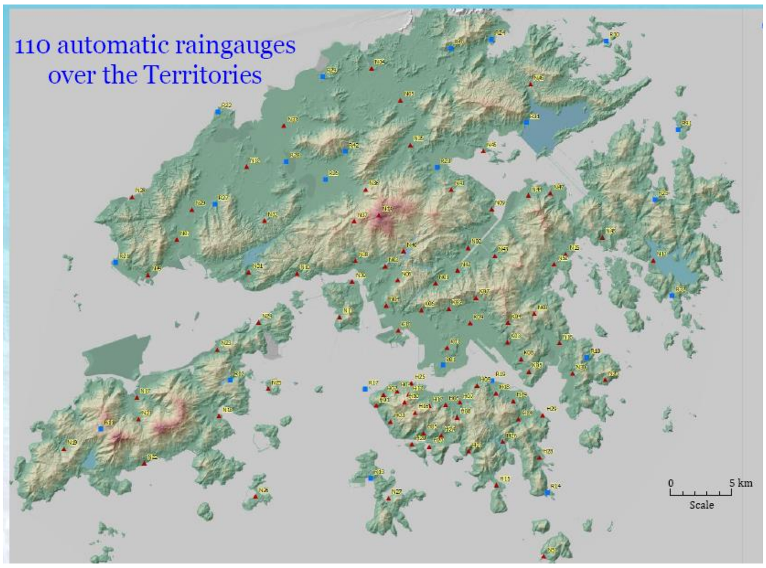

Figure 2.7 Rain-gauges location (Cheung et al., 2006).

San Francisco Bay, California, USA

In the early January of 1982, a disastrous rainstorm struck the San Francisco Bay region, in California, USA, triggering thousands of debris flows and other shallow landslides across the region, causing many millions of dollars in property damage and 25 deaths (Wilson, 2004). Consequently to this event the Landslide Working Group at the USGS (U.S. Geological Survey) decided to define the concept of 'rainfall threshold' – as a critical amount of rainfall required to trigger debris flows on susceptible slopes (Wilson, 2004). The system stayed active in the period 1986-1995 and during its period of operation, the debris-flow warning system issued advisory statements in response to several unusual events approaching the San Francisco Bay region. The principal tool for monitoring rainfall intensity concentrations across the San Francisco Bay region was the ALERT system of 60 radio-telemetered automatic rain gauges.

Rio de Janeiro, Brazil

In Rio de Janeiro, Brazil, the first pilot program to automatically monitor rainfall for early warning purposes—the SIGRA project, Sistema de Instrumentação Geotécnica Via Rádio—was initiated by GEO-Rio in the late 1980s (d'Orsi 2012). At that time, two landslide prone areas were chosen among about 400 risk areas reported in the landslide susceptibility map of the city (Barros at al. 1992). From that pioneering attempt, the Alerta-Rio system was conceived and developed. The Alerta-Rio system, which is still operational, started at the end of 1996 with a telemetric network of 30 rain gauges. These stations contain gauges and other meteorological sensors (wind, humidity, temperature, and air pressure) that collect relevant data automatically and uninterruptedly at regular intervals of 15 minutes. On April 6–7, 2010, Rio de Janeiro and several neighbouring municipalities were again the victims of extreme weather conditions and hundreds of landslides occurred throughout the city. After that event the GEO-Rio Foundation undertook "The Risk Reduction Action Program" focused, among other issues, on the: improvement of the Alerta Rio system by expanding the number of technicians, updating technical equipment and programs, and purchasing, installing, and operating a weather surveillance radar system to be installed within the city limits; installation of an audible early warning (siren) system linked to automatic rain meters in the poorer communities on the slopes where high-risk areas have been identified in the risk maps of the occupied parts of the Tijuca Massif and surrounding areas. These latest actions effectively constitute a two-tier (i.e. alert and alarm) citywide landslide early warning system (Calvello et al., 2014).
The community-based alert and alarm system, i.e. the second tier of the landslide early warning strategy in Rio de Janeiro, was initiated in 2011 following an updated large scale zonation of the landslide risk within all the informal communities of the Tijuca Massif and surrounding areas (Fig. 2.8a). The main purpose of this system, locally known as A2C2 "Sistema de Alerta e Alarme Comunitário para Chuvas Fortes," is the

temporary evacuation of the population from areas mapped at high risk whenever the probability of rainfall-induced landslides in those areas, and thus the related risk for the human life, increases to intolerable levels. The evacuation order is issued, on the basis of local rainfall monitoring data and purposefully defined rainfall thresholds, by means of sirens used as audible early warning devices. The audible early warning alarm system is not designed to be permanent because the sirens are supposed to be uninstalled from communities when, as it is planned, the risk will be lowered to acceptable levels either through stabilization works or by the removal of dwellings (depending on results from cost-benefit analyses). The system includes more than 150 gathering points and 166 sirens stations, 86 of which are equipped with automatic rain gauges transmitting rainfall data to the municipal operations centre (CO-Rio) at 15’ intervals. The majority of the communities have at least one siren in their territory—only six of them share the sirens (Calvello et al., 2014).

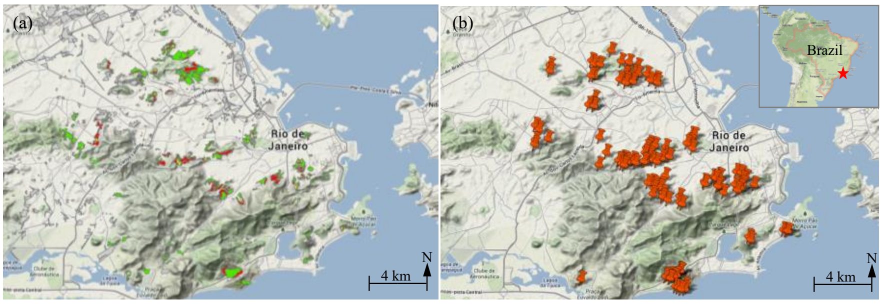

Figure 2.8 (a) Landslide risk zoning maps of the informal communities of the Tijuca Massif and (b) location of the sirens within the communities where the A2C2 system is currently being deployed.

Seattle, Washington, USA

In Seattle, Washington, USA, winter storms in 1934, 1972, 1986, 1990, 1996, 1997, and 2001 have triggered tens to hundreds of landslides (Tubbs 1974; Laprade et al. 2000; Chleborad 2000, 2003). In 1999, the USGS began a project to identify precipitation thresholds that might be used to forecast the occurrence of landslides in Seattle. Four years of soil moisture and pore pressure observations at sites near Seattle indicated spatial, seasonal and short-term variations in soil wetness and pore pressure and the association of shallow landslide occurrence with times of high soil wetness (degree of saturation in excess of 60–80%; Baum et al. 2005; Godt et al. 2009). Landslide alerts or advisories for Seattle began in 2003 and evolved into an informal, experimental warning system. The USGS issued informal landslide advisories to city officials in connection with two storms in 2003, one storm in 2004, and one storm in 2005. Since 2006, the National Weather Service (NWS) has issued landslide alerts based on USGS tracking of rainfall conditions relative to the thresholds.

Regional early warning systems in Italy

Following a national law written on this subject (DPCM, 2004), ReLEWS experiences are present in all the Italian regions. The regional Functional Centers, as required by DPCM 2004, make assessments in real time, both for the events prediction of the next 24 hours and for the monitoring and surveillance of current events. Among others, the most interesting contributions are employed in: Emilia Romagna (Arpa Emilia-Romagna P70519/ER, Berti et al., 2012; Lagomarsino et al., 2013), Piemonte (Tiranti and Rabuffetti, 2010), Campania (DGR n. 299/2005), Calabria (Sirangelo & Versace, 1992, Sirangelo 2003). The Civil Protection Agency of the Emilia Romagna Region implemented the SIGMA model in their ReLEWS, using a network of rain-gauges for the analysis of the amount of rainfall able to trigger landslides. The model is based on a set of statistical rainfall thresholds defined on the basis of a single parameter: the cumulate rainfall (Martelloni et al. 2012). The Piemonte regional warning system service, managed by the Environmental Protection Agency of Piemonte ("ARPA Piemonte" as official Italian acronym), is based on an advanced meteo-hydrological automatic monitoring system and it is integrated with forecasting activities of severe weather-related natural hazards. In 2010 the Shallow landslides Movements Announced through Rainfall Thresholds (SMART) was developed (Tiranti and Rabuffetti, 2010). The warning system for rainfall-induced landslides in the Campania region is managed by the regional civil protection agency as part of the regional warning system developed to deal with the so-called "hydraulic and hydrogeological risks", i.e. floods and landslides (DPGR 299, 2005). The system is based on two different activities: weather forecast and rainfall monitoring. For weather forecast purposes, 8 different Alert Zones are defined in the Campania Region as a function of: hydrography and morphology; rainfall; geology and land use; hydraulic and hydrogeological risk; administrative limit. The Alert Zones are defined as homogeneous areas for the expected occurrence of rainfall events. The rainfall monitoring phase is carried out in real-time acquiring data from rain-gauges and comparing the amount of rainfall with cumulative thresholds. In the Calabria region the model used for landslide risk assessment is FLAIR - Forecasting Landslides Induced by Rainfall model (Sirangelo & Versace, 1992), which has been implemented in the regional early warning system (Sirangelo et al., 2003).

National early warning system for rainfall-induced landslides (SANF), Italy

In Italy also exists a nationwide early-warning system aimed at forecasting, over the entire national territory, the possible occurrence of rainfall-induced landslides. The system is named SANF (an acronym for national early warning system for rainfall-induced landslides), it has been designed by researchers at CNR-IRPI (Rossi et al., 2012) and it has been operational since October 2009. The system is based on: (i) rainfall thresholds for possible landslide occurrences, (ii) sub-hourly rainfall measurements obtained by a national network of 1950 rain gauges, and (iii) quantitative rainfall forecasts. Twice a day, the system compares the measured and the forecasted rainfall amounts against pre-defined ID thresholds, and assigns to each rain gauge a probability of landslide occurrence. This information is used to prepare synoptic-scale maps showing where rainfall-induced landslides are expected in the next 24 hours.

North-South motorway, Malaysia

In Malaysia, a North-South Express motorway called PLUS, which opened in 1994 has been frequently afflicted by landslides. The majority of landslides along the motorway are caused by prolonged and intense rainfall, high ground water table and unfavourable geological discontinuities. To alert the motorists as well as enhancing the maintenance regime, the owner of the motorway initiated, in 2006, a web based real time monitoring system (RTMS) employing rain gauges along many stretches of the Expressway.

Japan

The Japanese Ministry of Land, Infrastructure, Transport and Tourism has developed a landslide early-warning system in 1984 to protect people from injury, loss of life, and loss of livelihood. In 2005, the Japanese government initiated a new nationwide early-warning system for landslides disasters. The main characteristic of the system is the existence of a criterion for occurrences of debris flows and slope failures based on several rainfall indices (60-min cumulative rainfall and soil–water index) in each 5-km grid mesh covering all of Japan.

Norway

In autumn 2013 The Norwegian Water Resources and Energy Directorate (NVE) launched their ReLEWS. The purpose of the system is to analyse, forecast and follow the hydro-meteorological conditions that possess the potential of triggering landslides over the whole territory of Norway. The hydro-meteorological conditions are derived from real-time measurements, model simulations and forecasts. The system is developed to inform the public and the authorities in advance about the occurrence of possible catastrophic events connected to: debris flows, debris slides, debris avalanches, and slush flows at regional scale. In order to achieve this purpose many activities have been undertaken in the last 3 years: (a) landslide characterization and susceptibility analysis to support threshold development, probability analysis, and verification; (b) installation and maintenance of meteorological and hydrological monitoring networks for accurate warnings, particularly in localities with high or frequent landslide incidence; (c) development and reinforcement of meteorological and hydro-geological modelling components; (d) improvement of existing warning thresholds through statistical methods; (e) design and development of computer and communication tools/networks to support the operations and (f) organization of the operational infrastructure and professional staff (Devoli et al., 2014).

2.3.2 Regional correlation law

Early warning systems for rainfall-induced landslides are the most diffuse class of landslide warning systems. The modelling phase of such systems consists in defining a correlation law between landslide occurrences and rainfall events in an area of interest. The rainfall thresholds established through correlation models can be either based on a conceptual schematization of the causal relationship between rainfall and landslides or on empirical laws derived from a statistical analysis of historical data. Concerning the latter, a comprehensive investigation on rainfall thresholds for the initiation of landslides is presented by Guzzetti et. al (2007). They identify three main categories of rainfall thresholds: i) thresholds that combine precipitation measurements obtained from specific rainfall events; ii) thresholds that consider the antecedent conditions; iii) other thresholds. For the first category four sub-categories of thresholds are also defined depending on the rainfall variables used to characterize a rainfall event: intensity-duration (ID); total event rainfall (E); rainfall event-duration (ED); rainfall event-intensity (EI). The majority of rainfall thresholds employed in ReLEWSs analyzed herein (Tab. 1.3) are defined as event-duration (ED) thresholds, evaluated considering a combinations of precipitation measurements obtained from individual or multiple rainfall events that resulted (or did not result) in landslides. For these systems the monitored variables to be compared with thresholds are cumulative rainfalls with different time intervals.

Table 2.3 ReLEWS reported in the literature: ReCoL.

Location	Institution	Name	Correlation model	Rainfall thresholds	Monitored variable	Other variables considered	Reference of the CM
Hong Kong, Cina	GEO Hong Kong	Landslip Warning sytem	Failure frequency and rolling 24 hour rainfall in semi-log plot	event-duration (ED)	mm/24h	-	Lump (1975), Brand et al. (1984), Pun et al. (2003), Yu et al. (2004)
Rio de Janeiro, Brasile	GEO-Rio	Alerta-Rio	Cumulative rainfalls with different durations	event-duration (ED)	mm/1h, mm/24h, mm/24 and mm/96h	-	Tatizana et al. (1987), d'Orsi et al. (1997)
Rio de Janeiro, Brasile	GEO-Rio	A2C2	Cumulative rainfalls with different durations	event-duration (ED)	mm/1h, mm/12h, mm/96h	-	-
San Francisco, California, USA	USGS and NWS	-	Adaptation of Wieczorek's (1987) and Cannon and Ellen's (1988) thresholds	event-duration (ED)		MAP	Wilson et al. (1993)
Seattle, Washington, USA	USGS, NWS, City of Seattle	-	Cumulative rainfalls comparisons, power law	event-duration (ED), intensity-duration (ID)	Chleborad (2008), Godt (2006)	AWI, Soil moisture, pore pressure, snow	Chleborad (2003), Godt et al. (2006)
Emilia Romagna, Italy	CFR	SIGMA	Statistical distribution of the rainfall Series (cumulative – durations)	Multiples of the standard deviation (σ) used as thresholds	mm/1,2,3d; mm/4 to 63-245 d	-	Martelloni et al., (2012); Lagomarsino et al., (2013)
Campania, Italy	CFR	-	Statistical approach considering different return periods (2,5,10 years)	event-duration (ED)	mm/24h, mm/48h, mm/72h	-	-
Calabria, Italy	CFR	FLaIR	Mobility function depending on antecedent rainfall and a filter function	critical value of mobility function depending on past landslides	mm/d	-	B. Sirangelo, & P. Versace (1992); B. Sirangelo, & P. Versace (1996); Sirangelo et al., (2003)
Piemonte, Italy	CFR	SMART	Intensity-duration (ID)	regional, local and pragmatic approaches	mm/h	-	Tiranti, Rabuffetti. (2010)
Taiwan	DGH	-	Cumulative, intensity-duration	event-duration (ED), intensity-duration (ID)	mm/26h, cumulated rainfall (mm)	-	-
Taiwan	NCDR	SATIS	Averaged rainfall intensity	Averaged rainfall intensity	mm/h	Rivers and reservoirs status	-
Malaysia	PLUS	RTMS	Cumulative	event-duration (ED)	mm/3d and mm/6d, mm/0,5h or mm/1h or mm/2h	Ground water	Lloyd et al. (2001)
Japan	MLIT and JMA	-	Radial Basis Function Network (RBFN) to draw the area of low probability	event-duration (ED)	short-term rainfall index (60-min cumulative rainfall), and long-term rainfall index is (soil–water index)	-	Kuramoto et al. (2001), Kuramoto et al. (2005)
Southern California	NOAA and USGS	-	Intensity- duration rainfall	Peak storm- duration rainfall	mm/duration	Overland flow, soil moisture, sediment transport, channel changes, and numerous meteorological parameters, including rainfall in the Intensive Research Area (IRA)	Cannon et al. (2008); Staley et al., (2012)
Italy	CNR-IRPI	SANF	Mean intensity-duration		mm/duration	Antecedent rainfall	Brunetti et al. (2010)
Oslo, Norway	NVE	-	Water supply-soil water content		rain and snowmelt, soil saturation/groundwater	temperature	Boje et al. (2014)

Hong Kong, China

In the ReLEWS employed in Hong Kong different correlation models were used to define thresholds for issuing warnings. Preliminary studies were pursued by Lump in 1975, who related the occurrence of serious landslide events to 24-hour rainfall and antecedent rainfall in the previous 15-day. In Brand et al. (1984), thresholds were based on the amounts of rainfall in 24 hours or the rainfall in one hour, using landslides and rainfall records over a 20-year period. The thresholds defined were largely adopted as the basis for the issuance of landslide alerts between mid-80s and late-90s. A substantial review of the alert criteria was carried out considering the study of Pun et al., 2003, which established a linear relationship between the landslide density and the rolling 24-hour rainfall and proposed a new criterion based on the total number of predicted landslides over the territory. This refined correlation model was subsequently adopted from 2000 to 2003. In 2003, Yu et al., introduced major changes: correlating maximum rolling 24-hour rainfall, R24*, with landslides frequency (i.e. failure probability), f, instead of landslide density (Pun et al., 2003); using analyzed rainfall values on grid cells; considering different slope types and hence different failure probabilities. In this model, the territory was divided up into 40×40 grid cells (Fig. 2.9), each having a planar area of 1.5 km by 1.2 km. About 700 of these grid cells contain land area. The spatial distribution of different type of man-made slopes in each cell was determined from the GEO Catalogue of Slopes which registered all sizeable man-made slopes in Hong Kong (Fig. 2.9). A new set of bi-linear correlations between f and R24* in semi-log plot was determined for 4 common types of slopes in Hong Kong: soil cut slopes, rock cut slopes, fill slopes and retaining walls (Fig. 2.10), considering about 118 rainstorms in 1984-2001 with a maximum rolling 24-hour rainfall exceeding 50 mm.

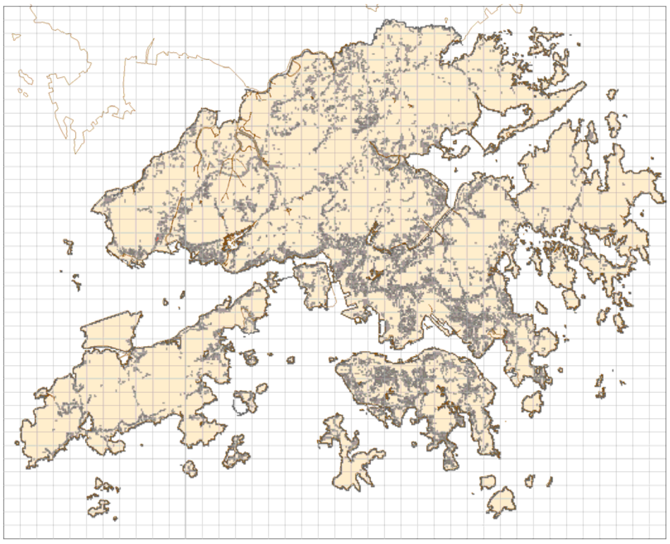

Figure 2.9 Spatial distribution of man-made slopes (grayed areas) in Hong Kong. The grid lines indicate the discretization of the territory into 1,600 cells (Cheung, LARAM 2013).

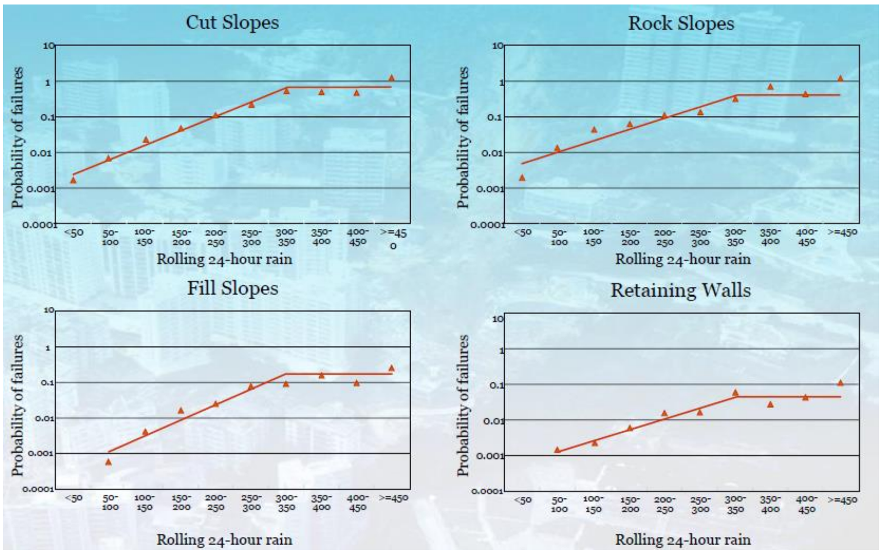

Figure 2.10 Failure frequency for the 4 different types of slopes (Cheung, LARAM 2013).

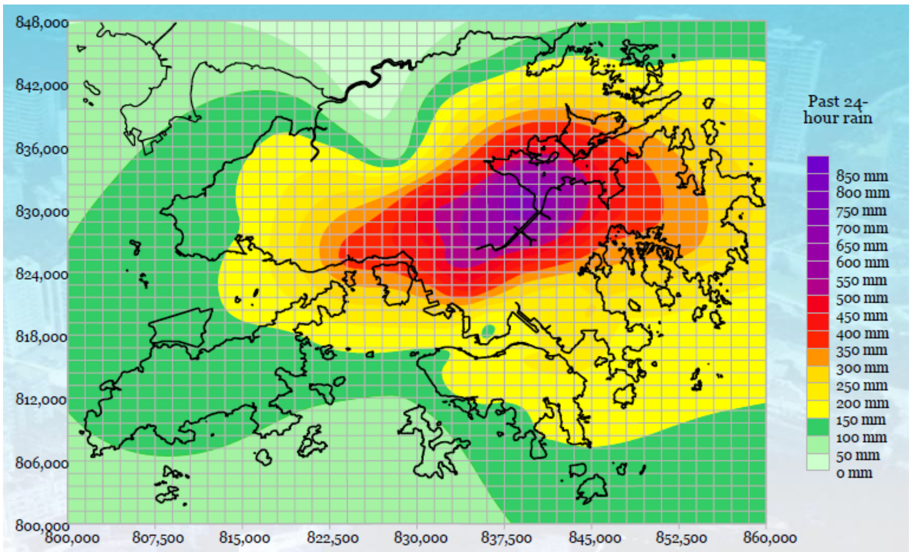

Figure 2.11 Rolling 24-hours rainfall distribution (Cheung, LARAM 2013).

San Francisco Bay, California, USA

Cannon and Ellen (1985) developed thresholds for the San Francisco Bay region, using data from the January 1982 storm and several other major storms. Initially, Cannon and Ellen (1985) separated the historical rainfall data into two groups on the basis of whether the mean annual precipitation (MAP) in the area of the rain gauge was above or below 660mm. They found that abundant debris-flow activity in the more humid upland areas required storm rainfall with a minimum duration and average intensity of 4 hours at 15 mm/hr, 12 hours at 10 mm/hr, or 20 hours at 8 mm/hr. The Cannon and Ellen (1985) threshold formed the basis for the debris-flow warning system in the San Francisco Bay region when it was initiated formally in February 1986. By 1989, the USGS developed a pair of cumulative rainfall/duration relationships for a spectrum of size and frequency of debris flows (Wilson et al., 1993). The pair of relationships between the duration and cumulative amount of peak rainfall outlined a spectrum of debris-flow activity (Fig. 2.12). The lower 'safety' threshold was adapted from Wieczorek's (1987) threshold for the initiation of individual debris flows in the La Honda study area to represent a rainfall level below which significant debris flow hazards were considered unlikely. The upper 'danger' threshold was adapted from the threshold of Cannon and Ellen (1988) and was intended to represent a rainfall level above which abundant debris flows are likely to occur across broad areas in the San Francisco Bay region. The relationship between rainfall, soil moisture and slope failure in climates with a strongly asymmetric distribution of rainfall through the year, such as the Pacific coast of California, creates an additional complication, the so-called 'antecedent condition', that has important implications for the operation of a landslide warning system. In the San Francisco Bay region, the rainfall and evapotranspiration cycles are about six months out of phase, leading to significant seasonal variations in soil moisture (Fig. 2.13). There is a period in which positive pore pressures may be formed and intense rainfall can trigger debris flows and this period, in a typical year, begins in late December and extends through late March.

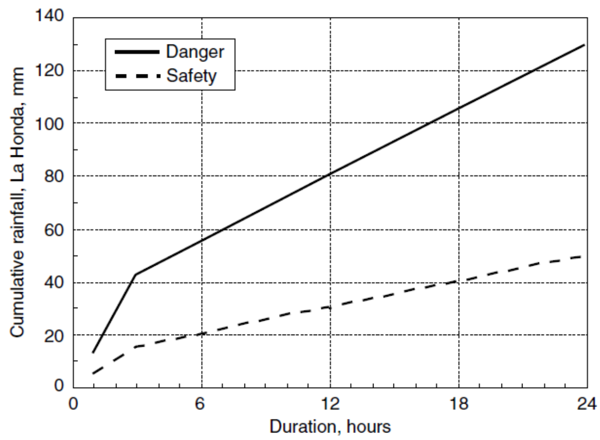

Figure 2.12 Rainfall/debris-flow thresholds determined for La Honda, California: slight chance of significant debris-flow activity below the Safety threshold, a likelihood of damaging debris flows above the Danger threshold (Wilson, 2004).

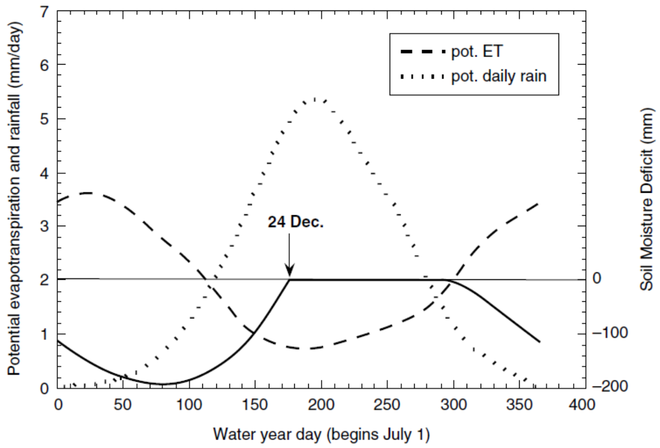

Figure 2.13 Variations in rainfall, evapotranspiration and soil-moisture content in a typical year on a hillslope in the Santa Cruz Mountains (Wilson, 2004).

Rio de Janeiro, Brazil

The oldest published studies dealing with rainfall thresholds for defining the landslide probability in Rio de Janeiro date back to 1997, when a relationship between rainfall and landslides was established based on 65 past events and rainfall data from a set of five rain gauges (d'Orsi et al., 1997). This preliminary study led to the first criteria for landslide warning adopted by GEO-RIO which considered the following two rainfall variables: 24-hour and 96-hour antecedent cumulated rainfall (Ortigao et al., 2002). The criteria assumed a 24-hour antecedent cumulated rainfall threshold dependent on the 96-hour antecedent cumulated rainfall by means of a function linearly increasing up to a maximum value and then asymptotically decreasing to zero. The next development occurred in 2004, when a third rainfall variable, i.e. the monitored hourly cumulated rainfall, was added to the previous two, following a detailed analysis of data from about 800 landslides of different typologies (d'Orsi et al., 2004). The rainfall variables were, since then, treated independently and different thresholds and a series of either/or rules were established to define warning levels associated to landslide probability of occurrence. These thresholds have been recently refined following new correlation analyses between monitored rainfall and landslide events. Table 2.4 show the current rainfall thresholds and the associated landslide probability warning levels adopted by GEO-RIO.

Table 2.4 Rainfall thresholds currently adopted by GEO-RIO to define landslide warning levels during heavy rainstorms (Calvello et al., 2014).

Rainfall thresholds					
R1 [mm/h]		**R2** [mm/24h]		**R2 & R3** [mm/24h & mm/96h]	**Warning level** *(Alerta Para Escorregamento)*
25-50	or	85-140	or	25-50 & 140-220	Medium (*Média*)
50-80	or	140-220	or	50-100 & 220-300	High (*Alta*)
>80	or	>220	or	>100 & >300	Very High (*Muito Alta*)

Seattle, Washington, USA

The prototype early warning system in Seattle uses different thresholds: a cumulative rainfall threshold (CT), a rainfall intensity–duration threshold (ID) and antecedent water index (AWI). Chleborad's (2000, 2003) CT compares the amount of rainfall in the last 3 days (72 h) to the rainfall in the previous 15 days. The 3to15-day cumulative rainfall threshold is based on an analysis of historical precipitation data associated with wet-season landslides that occurred during the period 1933–1997 in Seattle (187 + 108 additional landslides occurred in 1950-1990; Tubbs, 1974; Laprade 2000 and others). To make a prediction of landslides induced by rainfall, a level of landslide activity was defined for which it is reasonable to assume that rainfall is causally involved. The level selected was three or more landslides in a 3-day (72-hour) period. To incorporate the two ideas of antecedent wetness and unusual recent rainfall, two variables were defined: P3, the 3-day precipitation immediately prior to the landslide event and P15, the antecedent precipitation that occurred prior to the 3 days of P3 (Chleborad, 2006). The rainfall threshold thus defined is interpreted as an approximate lower-bound threshold, below which the specified level of rainfall-induced landslide activity (3-day events with three or more landslides) does not occur or occurs only rarely and above which it may occur under certain conditions. In practice, the CT is an indicator of antecedent rainfall that is a precursor to landslide activity. Moreover an intensity–duration threshold (ID) and antecedent water index (AWI) were developed for forecasting major landslide events in the Seattle area (Godt 2004, Godt et al. 2006). The ID is defined as I=82.73D–1.13 (in inches: I=3.257D–1.13), in which I is the average rainfall intensity, in millimeters per hour, for the entire storm, and D is the duration, in hours (Fig. 2.14). On the basis of observed hourly rainfall, rainstorms were bounded by periods of no rainfall at least 3 hours in duration at individual rain gages.

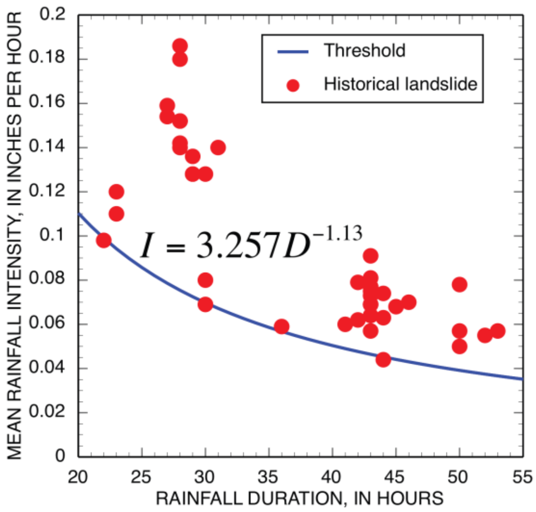

Figure 2.14 Rainfall intensity and duration threshold (ID) in inches for Seattle, Washington (Godt, 2004).

The observation that landslides occur primarily during the rainy season at times when the soil is relatively wet led to the definition of an AWI (Godt et al. 2006). The AWI has dimensions of length and represents the depth of water above or below the amount required to bring a 2-m-deep column of soil to "field capacity" (estimated to be 0.18 m for Seattle area soils; Godt et al. 2006). The estimated field capacity is the basis for the seasonal antecedent rainfall amount threshold (180 mm for Seattle).

$$AWI_t = AWI_{t-1} + \frac{I_i}{k_d}\ , AWI < 0 \qquad \text{(Eq. 2.1)}$$

$$AWI_t = AWI_{t-1}\exp(-k_d \Delta t) + \frac{I_i}{k_d}\ (1 - \exp(-k_d \Delta t)), AWI \geq 0 \qquad \text{(Eq. 2.2)}$$

In Equations 2.1 and 2.2, kd is an empirical drainage constant (0.01 for Seattle; Godt et al. 2006), Δt is the time increment (1h), Ii is the current rainfall intensity minus the evapotranspiration rate (obtained from published measurements, where available), and the subscripts t and t−1 refer to the present and previous time steps.

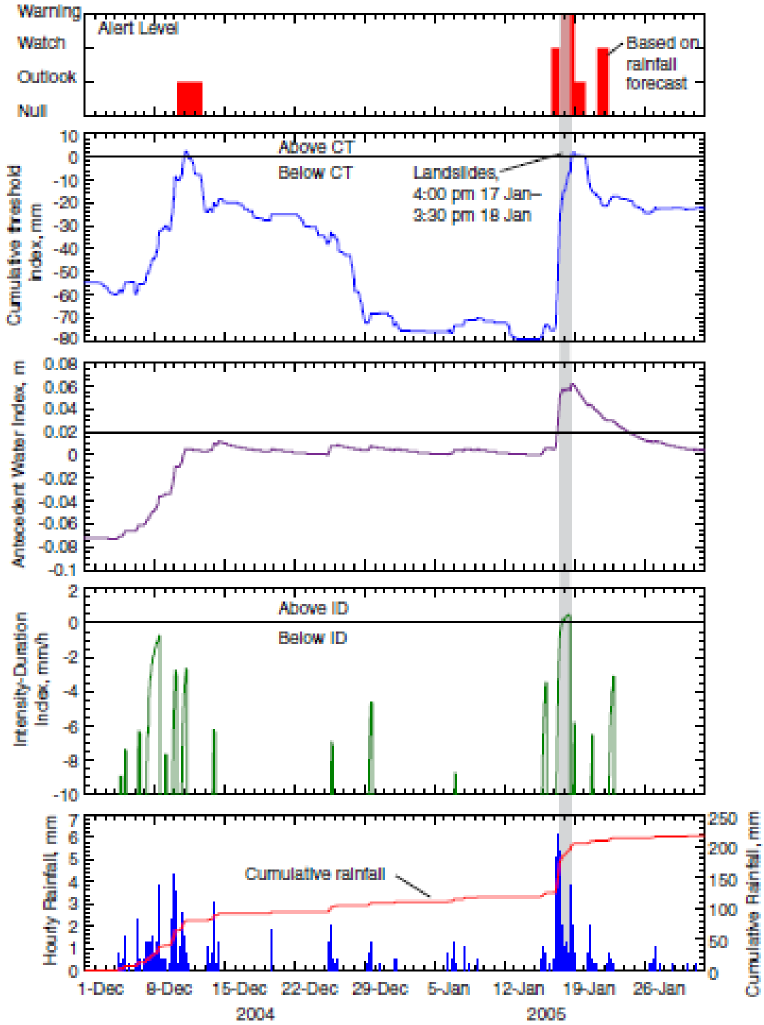

Figure 2.15 Rainfall threshold indices, antecedent water index, alert levels, and rainfall at the Seattle-Tacoma International Airport, December 2004–January 2005. The indices indicate how far rainfall conditions at any given time are above (positive values) or below (negative) the thresholds (Baum and Godt, 2010).

At the end of the summer dry season, the initial value of the AWI is set to −0.18 m to represent dry soil (Fig. 2.15), and the rainfall increments (minus evapotranspiration) are added to the AWI until it becomes positive (Eq. 1). The exponential drainage terms in Eq. 2 are applied only after the AWI reaches zero (Godt et al. 2006). The AWI was defined in such a way as to mimic instrumentally observed variations in soil wetness (Baum et al. 2005). However, the index does not account for the time lag that results from downward movement of rainwater through the soil and thus usually leads the actual soil moisture response by several hours. Soil is considered too dry to produce large numbers of landslides when $AWI<-0.1$; soil is considered wet enough to produce abundant landslides if rainfall also exceeds the intensity–duration threshold when $AWI>0.02$. To clarify the meaning of these thresholds during a rainfall event, figure 2.15 shows the CT, the AWI, the ID and the alerts over a period of fewa days between 2014 and 2015. Automated tracking of the AWI has been substituted for soil moisture and pore pressure monitoring since landslides destroyed the sensors in 2006 (Godt et al. 2009).

Emilia Romagna region, Italy

In the Emilia Romagna region, Italy, the model SIGMA is constructed around the computation of standard deviations of measured rainfall. The SIGMA model originates by the a.s.c.a.v method (Galliani et al., 2001), based on a statistical analysis of the cumulative rainfalls with an n-day wide moving window shifting at 1-day time steps along the whole rainfall record. Starting from the original series of daily precipitation (typically 1951–2009), the time series of cumulated data from 1 to 365 days was built for each TU reference rain gauge. The cumulative rainfall series are approximated to the standard Gaussian distribution through a target function ($y = \alpha \cdot \sigma$), where α is a constant and σ is the standard deviation. From a particular value of σ or its multiples, the corresponding cumulative frequency sample is calculated and from this a cumulative precipitation value (in millimetres) is computed. Proceeding in the same way for the number of cumulative rainfalls between 1 and 365 days, it is possible to build the precipitation curves (σ curves) associated with various probabilities of not being overcome. Increasing values of the standard deviation (σ) are used as thresholds for issuing an alert level.

Campania region, Italy

In Campania region, Italy, six hydrogeological and hydraulic risk scenarios are identified in the system at municipal level, each one associated to critical rainfall events (cumulative rainfall on different durations). Among these, only one risk scenario refers to landslide risk and in particular to the possible occurrence of shallow landslides and debris flows. The pluviometric precursors associated to the landslide risk scenario are three, they refer to the cumulated rainfall recorded over 24, 48 and 72 hours and they are evaluated for three return periods (2, 5 and 10 years).
The rainfall intensity thresholds of the warning model are estimated on the basis of statistical analyses of historical records of rainfall considering different return periods. Given the maximum annual rainfall aggregate at an assigned duration, X, its value XT, related to the return period T, is defined by the following relationship:

$$XT = KT\mu(X) \quad \text{(Eq. 2.3)}$$

where: KT is a probabilistic growth factor, function of the return period T; $\mu(X)$ is the average value of the distribution of the variable X. The thresholds, if exceeded, activate one of the three warning levels defined for the early warning system: attention, pre-alarm, alarm. Each municipality has a set of rainfall thresholds depending on the rain gauge used for the statistical analysis carried out for defining thresholds.

Calabria region, Italy

In the province of Cosenza in the Calabria region the Forecasting of Landslides Induced by Rainfalls (FLaIR) hydrological model has been implemented to correlate rainfalls to landslide or mudflow occurrences. The FLaIR model is composed of two modules (Sirangelo & Versace 1996; Sirangelo et al., 2003; Sirangelo & Braca, 2004). The first one, indicated as "Rainfall–Landslide" module, correlates precipitation and landslide occurrence. It suggests a simple conceptual modelling of the hydrological processes that, beginning from the rainfall, produce variation in the hill-slope pressure field and then may trigger a landslide. The second one, called "Stochastic Rainfall" module, provides a tool for real-time forecasting. It allows probabilistic evaluation of rainfalls by reproducing the behaviour of the observed data. This module, in conjunction with the "Rainfall–Landslide" module, enables a probabilistic evaluation of future landslide occurrences. In the "Rainfall–Landslide" module, a mobility function Y(t), depending on antecedent rainfall, is related to a probability P[E(t)] of landslide occurrence at time t:

$$P[E(t)] = F[Y(t)] \qquad \text{(Eq. 2.4)}$$

Among the various admissible relationships between mobility function Y(t) and probability P[E(t)], the simplest one is given by the threshold scheme:

$$P[E(t)] = \begin{cases} 0 \ if \ Y(t) \leq Y_{lim} \\ 1 \ if \ Y(t) > Y_{lim} \end{cases} \qquad \text{(Eq. 2.5)}$$

in which Y_{lim} is the critical value of Y(t). The mobility function Y(t) is defined as:

$$Y(t) = f[I(s)],\ -\infty < s \leq t \qquad \text{(Eq. 2.6)}$$

in which I(s) is the infiltration rate. Under the assumption of linear behavior of the model, the mobility function can be expressed in the form:

$$Y(t) = \ k_0 \int_{-\infty}^{t} \varphi\,(t-s) I(s) ds \qquad \text{(Eq. 2.7)}$$

in which Y(*) is a filter function and k0 is a constant depending on the characteristics of the groundwater system. In the FLaIR model, moreover, the following simple relationship between rainfall (P) and infiltration (I) is adopted:

$$I(s) = \ cP'(s) \quad P'(s) = \begin{cases} P(s) if \ P(s) \leq P_0 \\ P_0(s) if \ P(s) > P_0 \end{cases} \qquad \text{(Eq. 2.8)}$$

where P0 depends on soil characteristic with c being a factor of proportionality. Because the mobility function is defined up to an arbitrary multiplicative factor, it is possible to choose: cKo = 1
so that:

$$Y(t) = \int_{-\infty}^{t} \varphi\,(t-s)P'(s)ds \qquad \text{(Eq. 2.9)}$$

The parameter estimation is made by the so called ranking criterion. It finds the parameter vector q such that the mobility function reaches the maximum value at time of landslide movement t*1. When only one mobilization is known, the estimated parameter vector qˆ is given by:

$$\hat{\theta}\!:\; Y(t *_1; \theta) = \max_{t \in T}[Y(t;\theta)] \qquad \text{(Eq. 2.10)}$$

Use of FLaIR model for real-time forecasting in order to identify hazard conditions for mudflow or landslide occurrence consists in evaluating, with a suitable lead time, the probability that at time t, the function Y(t) exceeds the critical value Ylim, estimated on the basis of historical information on previous movements. Computation of the value of mobility function reaching at time t—carried out at time s with s < t, indicated as Ys(t)—can be developed by dividing the convolution integral into two terms:

$$Y_\tau(t) = \int_{-\infty}^{t} \varphi\,(t-u)P(u)du + \int_{\tau}^{t} \varphi\,(t-u)P(u)du \qquad \text{(Eq. 2.11)}$$

The first term on the right-hand side, after model identification and parameter estimation, is evaluated on the basis of observed rainfall depth until time s; this one can be considered as the deterministic component of Ys(t). The second term is evaluated on the basis of statistical prediction of rainfall depth. Equation 2.11 can be usefully rewritten as follows:

$$Y_\tau(t) = Y_\tau(t)_{det} + Y_\tau(t)_{sto} \qquad \text{(Eq. 2.12)}$$

Piemonte region, Italy

Tiranti and Rabuffetti (2010) developed thresholds for the Piemonte region, Italy, correlating rainfall and landslides (429) which occurred from 1990 to 2002. For the definition of rainfall thresholds an empirical approach was used. Each rainfall event was separated from the next by a time interval equal to 6 h, in which it is observed the absence of rain. From the total of 429 shallow landslides were discarded: i) those related to anthropogenic factor; ii) those for which the time of the occurrence was ignored. The number of landslides used for the analysis was equal to 160. The dataset obtained was used to achieve different thresholds: regional, local and "pragmatic". The regional threshold was derived using the complete dataset of shallow landslides considering the data of critical intensity of rainfall of the closest rain-gauges, for the whole territory.

$$I = 2.5 * d^{-0.13} \quad \text{(Eq. 2.13)}$$

The critical rainfall dataset is plotted in the log–log space using mean intensity, I [mm/h] vs. duration, D [h] (Fig. 2.16).

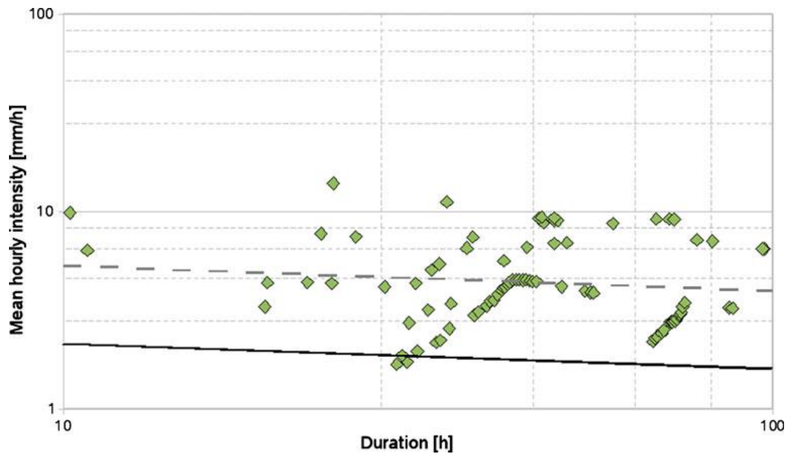

Figure 2.16 The Piemonte regional threshold. Unbroken line is the best fit, the dashed line is the lower envelope obtained by offsetting the best fit. (Tiranti and Rabuffetti, 2010).

To realize the local threshold two different areas on the basis of geological, topographical and distribution of rainfall in the Piedmont region were distinguished (Fig. 2.17): mountain environment, i.e. zones principally characterized by metamorphic rocks, igneous rocks, dolostones or limestones and flysh formations in Alpine and Apennine environments that require high values of critical rainfall; hills environment, i.e. zones principally characterized by sedimentary bedrock in hilly and Apennine environments that require low values of critical rainfall (Tiranti e Rabuffetti 2010).

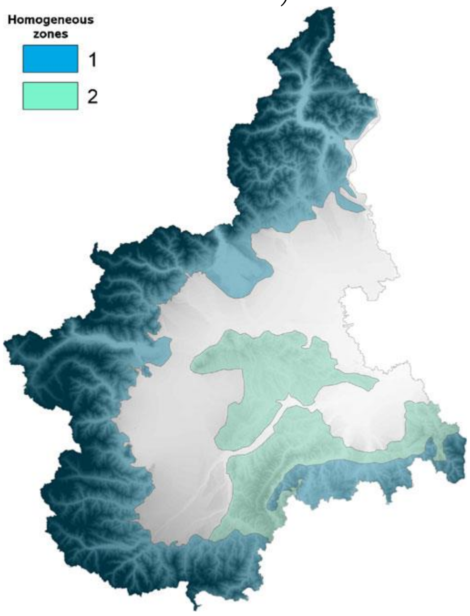

Figure 2.17 The two homogeneous zones in Piemonte (1 mountain environment; 2 hills environment) superimposed with hillshade map (Tiranti and Rabuffetti, 2010).

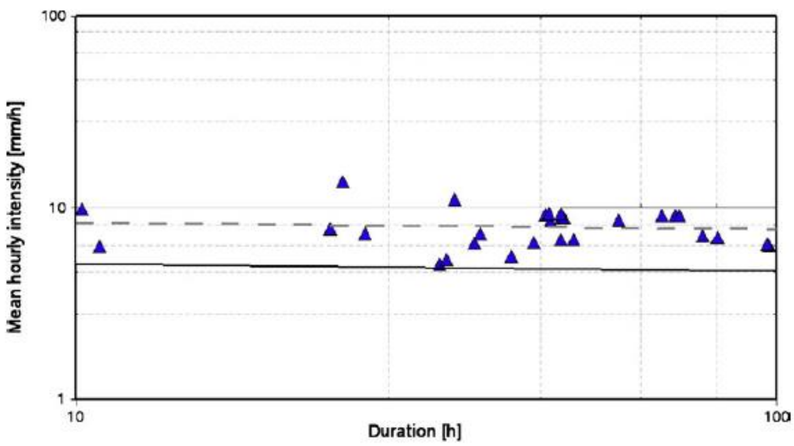

Figure 2.18 The Piemonte local thresholds for Zone 1, mountain environment, Unbroken lines are the best fits, the dashed lines are the lower envelopes obtained by offsetting the best fits (Tiranti and Rabuffetti, 2010).

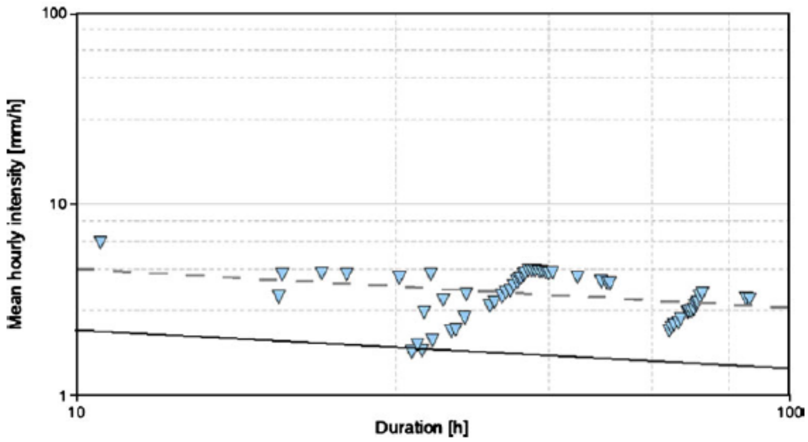

Figure 2.19 The Piemonte local thresholds, Zone 2: hills environment. Unbroken lines are the best fits, the dashed lines are the lower envelopes obtained by offsetting the best fits (Tiranti and Rabuffetti, 2010).

This classification contributes to a better understanding of the process but still gives sparse I–D plots (Fig. 2.18-2.19):

$$I = 5.5 * d^{-0.04} \quad \text{(Eq. 2.14)}$$

$$I = 2.9 * d^{-0.16} \quad \text{(Eq. 2.15)}$$

In the "pragmatic" threshold, for each single rainfall event, all the recorded landslides and related critical rainfall, are lumped into a single value of critical rainfall, calculated as the mean duration and mean rainfall cumulative, used to represent the whole event. Following this simple procedure, each marker in the I–D plot is representative of all the landslides triggered during the single rainfall event. The number of points is reduced from 160 shallow landslide records to 10 rainfall events triggering a large number of shallow landslides. Using the two zones defined previously, this general expression of the rainfall threshold was considered:

$$I = a * d^{n-1} \quad \text{(Eq. 2.16)}$$

where "n" is the Montana coefficient (Estorge et al. 1980) characteristic of the intense rainfall in the studied area (Boni and Parodi 2001) (Fig. 2.20) so that in the calibration process, the variability ranges of "n" in each area is fixed while "a" remains the only free parameter.

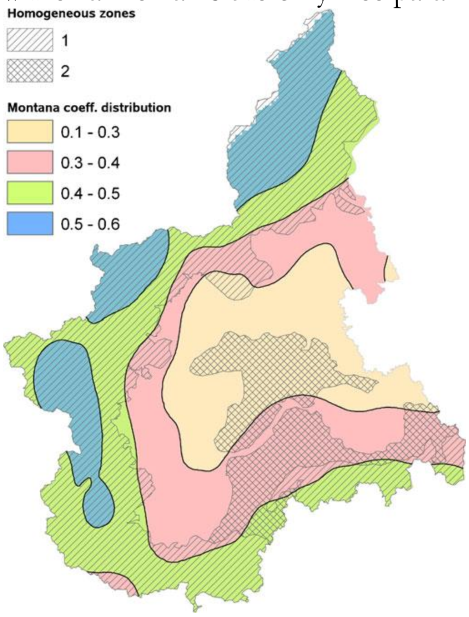

Figure 2.20 Distribution of the Montana coefficient in Piemonte (Boni and Parodi 2001) and intersection with homogeneous zones (Tiranti and Rabuffetti, 2010).

The thresholds defined from a minimum duration of 12 h to a maximum of 60 h, respectively, for the zones 1 and 2, have the following formulation:

$$I = 40 * d^{-0.65} \quad \text{(Eq. 2.17)}$$

$$I = 25 * d^{-0.45} \quad \text{(Eq. 2.18)}$$

As seen in Fig. 2.21, the thresholds are again drawn, once fixed the slope, as the lower envelope curve of the data points.

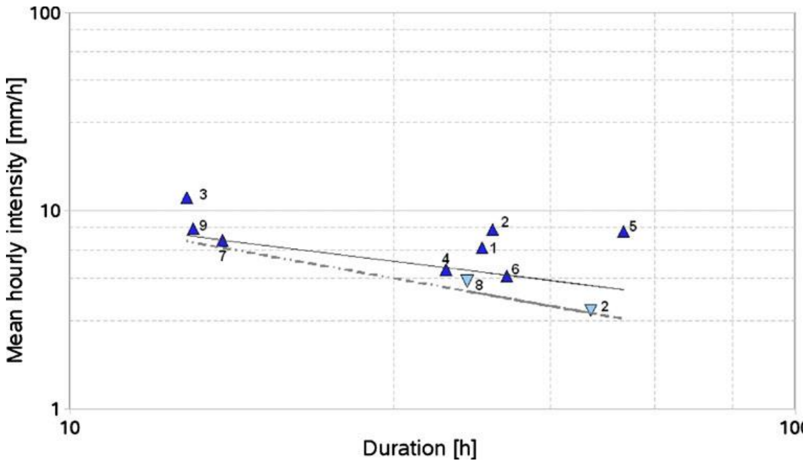

Figure 2.21 I–d plots and thresholds for the two zones (darkblue dots for the mountain and light-blue dots for the hills). Each dot represents the whole rainfall-landslide event: 1 September 1993; 2 November 1994 (for mountain and hill environments); 3 September 1998; 4 April 2000; 5 October 2000; 6 May 2002; 7 June 2002; 8 July 2002; 9 August 2002 (see for details the reports provided in www.arpa.piemonte.it in the section "servizi on-line – Rapporti d'Evento") (Tiranti and Rabuffetti, 2010).

National early warning system for rainfall-induced landslides (SANF), Italy

In the SANF early warning system the empirical thresholds are obtained statistically from studying past rainfall events that have resulted in slope failures (Rossi et al., 2012). For each landslide event in the database, the rainfall duration (D) and the rainfall mean intensity (I) that have resulted in the slope instability are established analyzing the rainfall record of the most representative rain gauge. For most of the landslides, the representative rain gauge was the closest to the landslide. To define reproducible, objective and reliable thresholds for possible landslide occurrence, the researchers have devised a specific method. The method assumes that the threshold curve is a power law, $I = \alpha \cdot D{-}\beta$, where, I, is the mean rainfall intensity (in mm/h), D is the rainfall duration (in h), and α and β are positive coefficients. Currently, the system uses a single threshold with 1% exceedance probability defined for the entire Italian territory (Fig. 2.22).

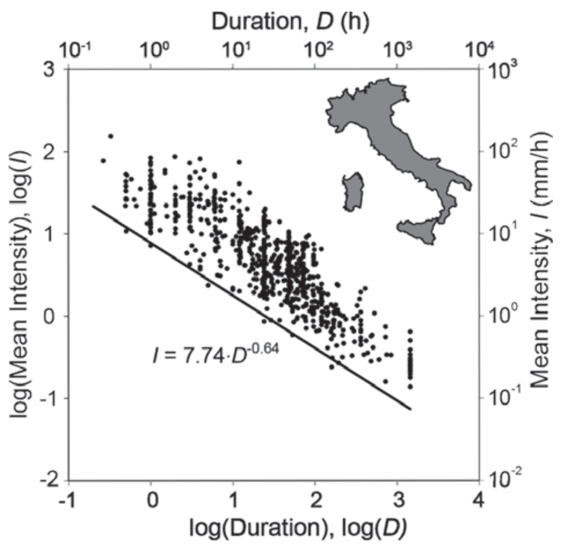

Figure 2.22 Intensity-duration conditions (dots) that resulted landslides in Italy. Black line is the rainfall threshold at 1% exceedance probability implemented in the SANF early warning system (Rossi et al., 2012).

Japan

Since 1984, the basic concept for issuing early-warning information in Japan has been based on two hypotheses which have not changed. The first hypothesis is that mass-movement occurrence can be predicted using both a short-term rainfall index and a long-term rainfall index, because mass movements are driven by both surface water and ground water. The second hypothesis is that, in a chart with short- and long-term rainfall index axes, the area of mass-movement occurrence and non-occurrence can be identified plotting points representative of rainfall with disasters (occurrence rainfall) and without disasters (non-occurrence rainfall). Based on these hypotheses, the underpinning issues to address are: (1) selection of appropriate rainfall indices; (2) improving the method to discriminate between occurrence and non-occurrence rainfall; and (3) collecting locations and timing of many rainfall-related mass-movement occurrences. Figure 2 presents a sketch of the basic concept, showing that it is possible to draw various lines as the criterion of disaster occurrence line (Critical Line, CL) depending on the method. A linear CL is the easiest to set, but an arbitrary shaped CL seems to be the most precise discrimination line based on the data of occurrence and non-occurrence rainfall. The methods before 2005 used a researcher or senior engineer to draw the Critical Line as a straight line fitted by eye, because adequate records of disasters for statistical analysis do not exist in many regions.

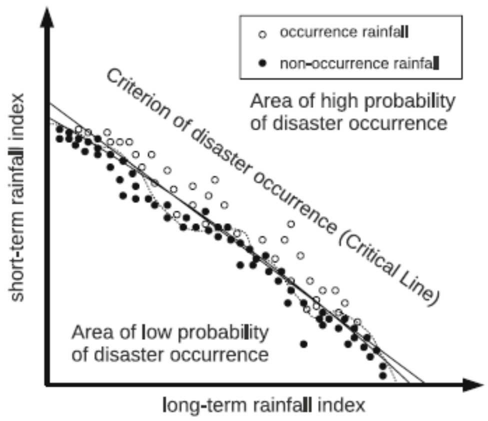

Figure 2.23 The basic concept used for setting the criterion for issuing early-warning information in Japan. The criterion of disaster occurrence is defined as the line discriminating between the area of high and low probability of disaster occurrence (Osanai et al., 2010).

The currently adopted short-term rainfall index is the 60-min cumulative rainfall, and the long-term rainfall index is the soil–water index.
The method adopted since 2005 solves the following problems, which were present in previous methods:
1. the previous methods needed a large set of data related to mass-movement-occurrence rainfall;
2. no records of mass-movement occurrences existed for many regions;
3. a subjective fitting technique to set the criterion generated an accuracy bias from one region to another;
4. the spatial density of rainfall gauges was insufficient to predict CLs precisely for every region in Japan, especially in the mountains.
The range of potentially useful rainfall information has been continuously developing. JMA has produced 2.5-km grid mesh rainfall data since 2001 (5-km grid mesh from 1988) known as Radar Automated Meteorological Data Acquisition System analytical rainfall (Radar

AMeDAS analytical rainfall) and short-time forecasts of rainfall (from 1 to 6 h; actual rainfall and forecast rainfall, respectively). These "actual" rainfall data are provided by estimating rainfall intensity with radar checked against gauged AMeDAS data. Forecast rainfall is more accurate in the nearest future. That is, forecast rainfall in the next hour is more reliable than that forecast in 6 h. These rainfall data are available to solve the 4th problem mentioned above.

Kuramoto et al. (2001) researched a method to solve the 1st to 3rd problems mentioned above. The method is based on the following fundamental concepts:

1. the target mass movements are debris flows, and slope failures with high spatial density, except landslides;
2. the criterion is calculated based on two rainfall indices: a short-term rainfall index and a long-term rainfall index;
3. an arbitrary shaped CL can be drawn objectively using only non-occurrence rainfall with Radial Basis Function Network (RBFN);
4. the shape of CL is easily revised as new data come to hand.

Using the method of Kuramoto et al. (2001), the concept of setting CL can be changed from perceiving CL as the boundary between areas of low and high probability of disaster occurrences that depend on occurrence and non-occurrence rainfall plot, to specifying the area of low probability using only the non-occurrence rainfall.

The output value of RBFN uses the "non-occurrence" rainfall to create the response surface of the grid. Non-occurrence rainfall data has been collected for each 5-km grid mesh at 1-h time resolution for more than 10 years created by JMA. 60-minute cumulative rainfall and soil–water index are calculated for each hour using the collected data. The response surface represents a probability density function of non-occurrence rainfall. The value of the response surface is the RBFN output value as z-axis (Fig. 2.24). The maximum value is 1.0 because all of the 0 mm rainfalls with 0 mm of soil water are "non-occurrence" rainfalls.

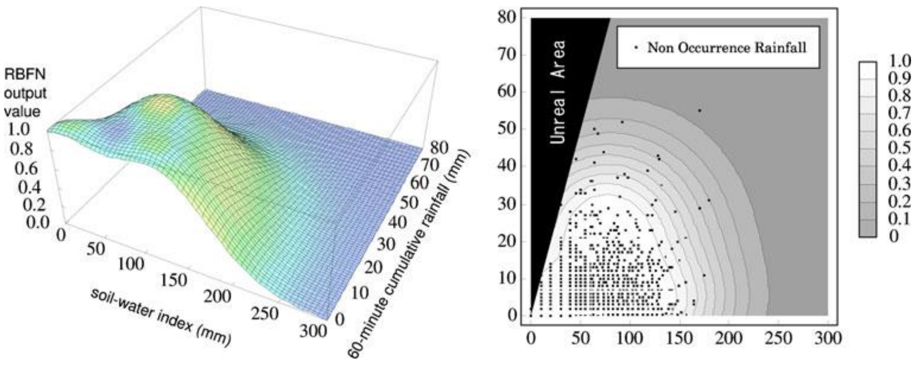

Figure 2.24 Output of RBFN using a test dataset of rainfall indices. Left Three dimensional view of the output response surface. Right Contoured two-dimensional plot (contour lines at 0.1 intervals a potential candidates for the critical line) of response surface on 60-min cumulative rainfall and soil water index as x and y axes, respectively (Osanai et al., 2010).

Norway

The LEWS operative in Norway is based on weather forecasts and information about hydrometeorological conditions that are derived from real-time measurements, model simulations and forecasts. The threshold values, investigated by Colleuille et al. (2010), are visualized through an index that simulate relative water supply of rain or snowmelt and relative soil saturation/groundwater conditions. Used together with a comprehensive expert judgment and data from other models, the index provides the basis for a daily evaluation of the probability of landslide occurrences (Devoli et al., 2014). The thresholds have been derived, empirically, employing a tree-classification scheme using 206 landslide events from different parts of the country (Colleuille et al., 2010). One landslide susceptibility map indicate initiation and runout areas for debris flows at slope scale (Fischer et al., (2012), while another model indicate susceptibility at catchment level, based upon Generalized Additive Models (GAM) statistics (Bell et al., 2014).

2.3.3 Decisional algorithm

The definition of a correlation model is a fundamental step to determine the thresholds to be used in a landslide early warning model. A threshold can be defined as the value of a monitored variable with a given probability of landslide occurrence. Once the threshold values for one or more monitored variables are defined, it is important to associate them to different warning levels. Through a decisional algorithm it is possible to define the main variables to take into account and the thresholds responsible for the activation of different warning levels in a certain warning zone. Each warning level may activate one or more procedures that agencies, authorities and people need to undertake with the aim of reducing the level of risk to life. The majority of ReLEWSs analyzed herein employ four warning levels, with the exception of the National system operative in Italy (SANF), which has five warning levels, and of the systems operative in Hong Kong, Taiwan and Rio de Janeiro (A2C2), which are based on two warning levels. More than two warning levels mean that there are levels with increasing probability of landslide occurrence corresponding to different emergency procedures to undertake. In all cases, the first level refers to a very low probability of landslide occurrence, i.e. good weather conditions or light rainfall. The number of warning levels to be considered in an early warning model (ReLWaM) is defined by the managers of the system for each warning zone. A warning zone can be fixed or variable, when it is composed by grouping together territorial units alerted with the same warning level. In the latter case the extension of a warning zone changes each time an alert is issued. A territorial unit of a ReLWAS can be defined as the minimum portion of territory alerted with a warning level. In the majority of cases the adopted territorial units coincide with administrative units (Tab. 2.5), for practical reasons of emergency plans application and responsibility assignments. In other cases, the territorial units coincide with areas pre-identified with a particularly high level of risk (Tab. 2.5), such as: along roads and highways in Taiwan, the North-South Highway in Malaysia, the informal communities (i.e. favelas) present in the steepest slopes of Rio de Janeiro (A2C2 system).

Table 2.5 ReLEWS reported in the literature: decisional algorithm.

Location	Institution	Name	Area of analysis	Warning zone	Territorial unit	Alert levels
Hong Kong, China	GEO Hong Kong	Landslip Warning system	Municipality of Hong Kong	1	Municipality	2
Rio de Janeiro, Brazil	GEO-Rio	Alerta-Rio	Municipality of Rio de Janeiro	4	Guanabara, Zona Sul, Sepetiba, Jacarepaguà	4
Rio de Janeiro, Brazil	GEO-Rio	A2C2	113 Communities (i.e. Favelas) of Rio de Janeiro	103	Community (i.e. favela)	2
San Francisco, California, USA	USGS and NWS	-	San Francisco Bay Region, CA	1	San Francisco Bay Region	4
Seattle, Washington, USA	USGS, NWS, City of Seattle	-	Municipality of Seattle	1	Municipality	4
Campania, Italia	CFR	-	Campania region	550	Municipality	4
Emilia Romagna, Italy	CFR	-	Emilia Romagna, region	25	Territorial unit	4
Taiwan	DGH	-	Areas at risk along roads, highway in Taiwan	1	Areas at risk along roads, highway in Taiwan	4
Taiwan	NCDR	SATIS	Taiwan	-	Potential areas at risk of landslides	2
Malaysia	PLUS	RTMS	Malaysia	1	North-South Highway	3
Japan	MLIT and JMA	-	Japan	1	5 km cell	2 (warning with 4 levels depending on lead time)
Southern California	NOAA and USGS	-	Southern California	-	Intensive Research Area (IRA), recently burned locations	4
Italy	CNR-IRPI	SANF	Italy	129	-	5
Norway	NVE	-	Norway	Variable	Municipality	4

Hong Kong, China

For the system operative in Hong Kong, given a grid analysis of R24* (Fig. 2.9), the landslide frequencies for all slope types in a grid cell can be readily found according to the correlations (Fig. 2.10). The predicted number of landslides in a grid cell (N24,i) is calculated as the sum of all the landslide frequencies multiplied by the number of slopes, n, in a cell (Eq. 2.19). The total number of predicted landslides for Hong Kong (N24) is obtained by summing over the number of landslides over all grid cells, i.e. N24 is the summation of f • n over all slope types (k) and all grid cells (Eq. 2.19).

$$N_{24} = \sum_{i}^{k} N_{24,i} = \sum_{i=1}^{k} f_i \; x \; n° \; slopes_i \qquad \text{(Eq. 2.19)}$$

The alert is emitted when the predicted number of landslides (N24), in the Municipality of Hong Kong exceeds the threshold value (currently 15).

San Francisco Bay, California, USA

In the San Francisco Bay region system observed rainfall amounts, combined with rainfall forecast, were compared to the warning thresholds to determine the level of hazard and the type of public statement to be issued. Both the NWS and the USGS participated in this phase of operation. Storms with peak rainfall periods that fell below the lower threshold ('safety') were considered unlikely to trigger hazardous debris flows and generally required no statements. For storms with rainfall levels just above the lower threshold, brief statements were sometimes added to an NWS 'Urban and Small Streams Flood Advisory', warning motorists that roadways may be obstructed by rockfalls or debris flows. If the rainfall was forecast to approach the upper threshold, a Flash-Flood/Debris-Flow Watch was issued, advising people living on or below steep hillsides, or near creeks, to stay alert and be prepared to evacuate, as debris flows were a strong possibility during the watch period. Storms that exceeded the upper threshold could trigger numerous, massive debris flows leading to loss of life and substantial property damage. Therefore, when rainfall was observed to exceed the upper threshold, or if reports of significant debris-flow activity were received, the strongest statement – a Flash-Flood/Debris-Flow Warning – was issued. Sample texts for these debris-flow statements were prepared, with wording agreed upon by both the USGS and the NWS, so that timely, informative advisories with complete, relevant information could be issued with a minimum of preparation time.

Rio de Janeiro, Brazil: Alerta-Rio

Two different alert sets co-exist with the Alerta-Rio early warning system: rainfall alerts (Alerta Para Chuva) and landslide occurrence alerts (Alerta Para Escorregamento). Concerning the probability of landslide occurrence, a different set of warnings exist in reference to rainfall alerts, which is based on the comparison between rainfall measured by the meteorological monitoring stations and defined rainfall thresholds (see Tab. 2.5). Also in this case, four warning levels are used to define the probability of landslide occurrence: Baixa (mass movements not directly triggered by rainfall - code color green), Média (occasional occurrences of landslides, mass movements triggered by rainfall, predominantly in artificial slopes, areal distribution not significant), Alta (diffuse occurrence of landslides, mass movements triggered by heavy rains in natural and artificial slopes, moderate to high areal distribution), Muito Alta (widespread occurrence of landslides, mass movements triggered by heavy rains in natural and artificial slopes and especially on roads cuts, very high areal distribution).

Seattle, Washington, USA

For the prototype system in Seattle, 4 warning levels were defined: Null, Outlook,Watch, and Warning (Chleborad et al. 2008). Exceedance of the CT by observed or predicted rainfall (or exceedance of the ID by predicted rainfall) constitutes an Outlook. An Outlook activates more intense monitoring of weather conditions, soil moisture, and pore pressure (if available, otherwise the AWI). Observed or forecast heavy rainfall during an Outlook, or when AWI>−0.1, elevates the alert level to Watch (Fig. 2.25). Wet soil conditions (AWI> 0.02 or degree of saturation >60–80%) combined with rainfall exceeding the ID constitutes the highest level, Warning (Fig. 2.25). In practice, the Outlook and Watch levels may be as useful as Warning because they allow government agencies adequate time for emergency preparedness planning and response. The NWS notifies government officials and the public when the Watch level has been reached through the use of a special weather statement.

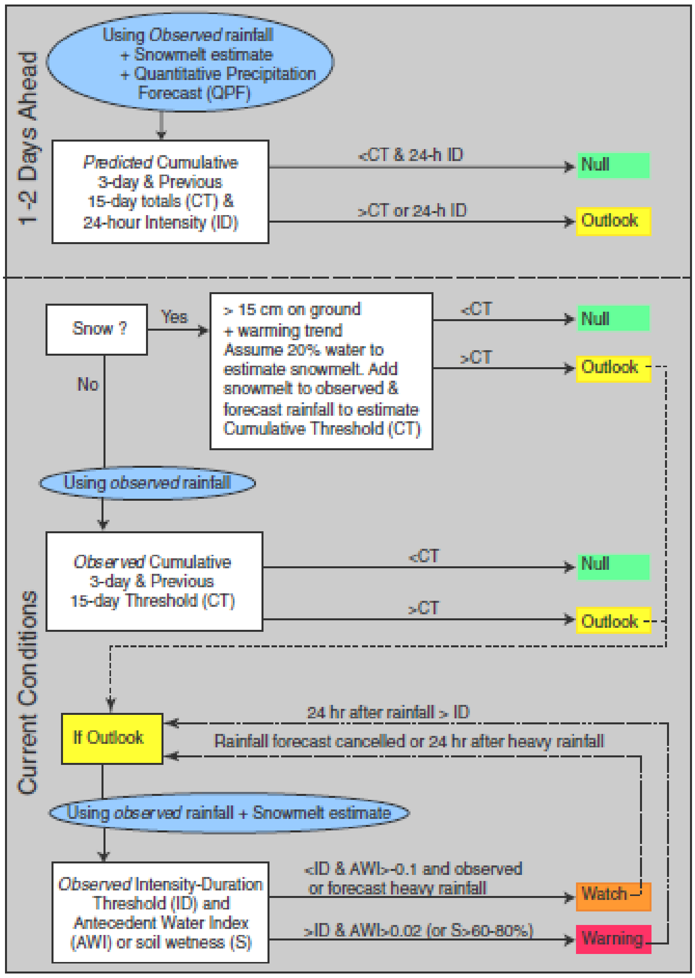

Figure 2.25 Decisional algorithm for the LEWS of Seattle (Baum and Godt, 2010).

Emilia Romagna region, Italy

For the SIGMA model applied in the Emilia Romagna region, Italy, the aforementioned σ curves are implemented in a decisional algorithm that constitutes the core of the SIGMA model. The latter operates separately for each territorial unit (TU), and in real-time applications the model works at daily time steps providing a level of criticality that depends on weather forecasts and rainfall recordings. For each TU, these rainfall amounts are cumulated at increasing time intervals ranging from 1 to 245 days. Such cumulates are compared with the σ curves, which are actually used as thresholds (Fig. X). The decisional algorithm of the SIGMA model was developed to take into account both shallow and deep-seated landslides.

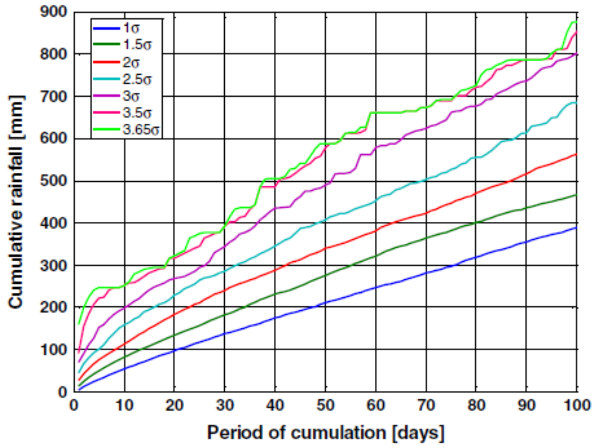

Figure 2.26 Example of rainfall probability curves (σ curves) in a cumulative period up to 100 days (Martelloni et al., 2012).

In the decisional algorithm two different intervals of cumulative rainfall are considered: 1-3 days cumulates takes into account the critical rainfall influencing shallow movements, whilst a variable time interval (up to 240 days) is used to consider the triggering of deep-seated landslides in low permeability terrains (Martelloni et al., 2012). For shallow landslides the equation 2.20 considers the cumulative daily rainfall precipitation up to two days prior to the day of the analysis.

$$C_{1-3} = \left[\sum_{i=1}^{n} P(t+1-i)\right]_{n=1,2,3} \geq [S_n(\Delta)]_{n=1,2,3} \quad \Delta = 1.5\sigma, 2\sigma, 2.5\sigma, 3\sigma$$

(Eq. 2.20)

For deep-seated landslides the algorithm takes into account the cumulative daily rainfall for a time interval varying with the season. During the dry season (May to October), the cumulative daily rainfall over a period of time ranging from 4 to 63 days is considered, while for the wet season, from the 1st November, the cumulative is increased by one per each day until a maximum (the 31st April) of 245 days (Eq. 2.21).

$$C_{4-63} = \left[\sum_{i=1}^{n+3} P(t-2-i)\right]_{n=1,2,\ldots,60} \geq [S_n(\Delta)]_{n=1,2\ldots,60} \quad \Delta = 1.5\sigma, 2\sigma$$

$$C_{4-64} = \left[\sum_{i=1}^{n+3} P(t-2-i)\right]_{n=1,2,\ldots,61} \geq [S_n(\Delta)]_{n=1,2,\ldots,61} \quad \Delta = 1.5\sigma, 2\sigma$$

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$$C_{4-245} = \left[\sum_{i=1}^{n+3} P(t-2-i)\right]_{n=1,2,\ldots,242} \geq [S_n(\Delta)]_{n=1,2,\ldots242} \quad \Delta = 1.5\sigma, 2\sigma$$

(Eq. 2.21)

The algorithm provides a level of criticality on the basis of which σ curves are exceeded (if any), using the four alert levels adopted in the civil protection procedures: “absent”, “ordinary”, “moderate” and “high” (Fig. 32). The standard sigma curves considered by the algorithm (1.5, 2, 2.5, 3σ) delineate exceptional rainfalls with respect to the characteristics of each TU. The decisional algorithm is organized to provide increasing criticality levels with increasing rainfall amounts.

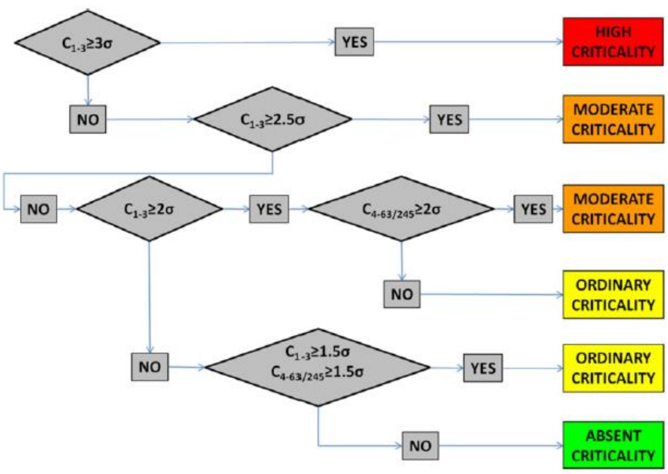


Figure 2.27 Decision algorithm of the SIGMA model. C1–3 indicates the rainfall cumulated from 1 to 3 days; C4–63/245 shows the rainfall cumulated from 4 to 63/245 days; 1.5σ, 2σ, 2.5σ and 3σ indicate the thresholds expressed in standard deviations. (Martelloni et al., 2012).

Campania region, Italy

The response of the regional civil protection on the territory of the Campania region is implemented through the following four alert levels for the hydrogeological and/or hydraulic risk: no warning, attention, warning, alarm. Alerts are issued by Settore di Programmazione Interventi of the Civil Protection Agency. The attention level is activated when the level of criticality is "moderate" or "high" in at least one of the 8 zones of alert and, also, when the local or areal pluviometric precursors exceed the threshold values of attention (return period of 2 years). The department may provide that the Centro Funzionale and the Operational Structure become operative 24/7. The warning level for hydrogeological risk is activated when the local or areal pluviometric precursors exceed the threshold values of warning (return period of 5 years). Moreover, the warning level for hydraulic risk is also activated when hydrometric indicators exceed the "ordinary" level. The alarm level for hydrogeological risk is issued when the local or areal pluviometric precursors exceed the threshold value of alarm (return period of 10 years), taking into account the information from Engineers, Presidi Territoriali and Mayors. Moreover, the alarm level for hydraulic risk is also activated when hydrometric indicators exceed the "extraordinary" level.

National early warning system for rainfall-induced landslides (SANF), Italy

In the SANF system for each rainfall event, the difference between the event intensity and the intensity of the fitted power law is calculated. The probability density of the distribution of the differences is determined through Kernel Density Estimation, and the result fitted with a Gaussian function. Finally, thresholds corresponding to different exceedance probabilities are defined (Brunetti et al., 2010). The scheme (Fig. 2.28) is based on four Frequentist thresholds, namely: T0.005 - T0.5- T1.5 -T5, corresponding to an exceedance probability of 0.005%, 0.5%, 1.5% and 5% of the area under the Gaussian fit (Fig. 18). In the scheme, the four thresholds separate five ID fields (shown by different colors in Fig. 18).

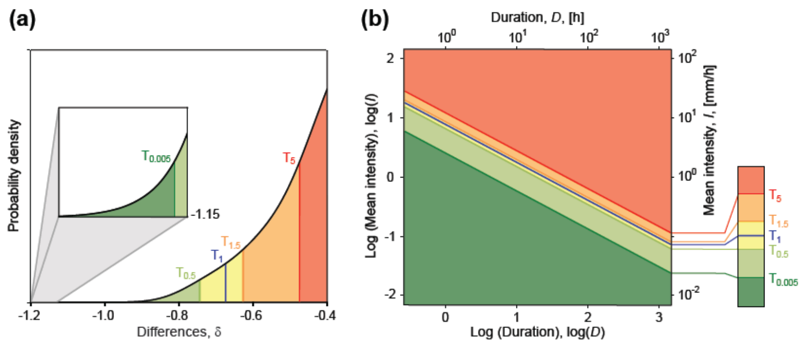


Figure 2.28 Critical rainfall conditions defined by thresholds having different exceedance probability shown (a) in the Gaussian curve (see Fig. 2), and (b) in the D-I plane. Legend: dark green, rainfall condition "well below the threshold"; light green, "below the threshold"; yellow, "on the threshold"; orange, "above the threshold"; red, "well above the threshold" (Brunetti et al., 2010).

For any given rainfall duration, D, when the (measured or predicted) rainfall mean intensity, I, is lower than the 0.005% threshold, the rainfall condition is considered "well below the threshold" (level 1). Similarly, when the rainfall mean-intensity, I, is between the 0.005% and the 0.5% thresholds, the rainfall condition is considered "below the threshold" (level 2). When the rainfall mean intensity, I, is in the range between the 0.5% and the 1.5% thresholds or in the range between the 1.5% and the

5% thresholds, the rainfall condition is considered "on the threshold" (level 3) or "above the threshold" (level 4), respectively. Lastly, when the rainfall mean intensity, I, is equal to, or larger than, the upper 5% threshold, the rainfall condition is considered "well above the threshold" (level 5). In this area, landslides are typically expected, with a chance of false negatives of 5.0%, or more.

2.3.4 **Warning management**

The phase of warning management follows a warning issuing. The actors involved and the activities undertaken are different for each ReLEWS. The warning management phase usually includes peace&war strategies, information and communication strategies as well as the application of emergency plans. Also the type and communications media employed to issue a warning level, as well as the public informed, substantially vary among the ReLEWSs, mainly in relation to the aims for which the system is designed. (Tab. 3). Generally, in ReLEWSs high-level warnings are oriented to people or inhabitant exposed at risk and they are issued by means of public statements, spreading the information via media, such as: television, radio, internet, sms, etc.. . Things are different for systems such as SATIS, in Taiwan and SANF, in Italy, where information is not directly spread to the public but it is managed through internal statements for decision makers, analysts, public authorities and political figures.

Table 2.6 ReLEWS reported in the literature: warning management.

Location	Institution	Name	Warning methods	Information through....	People informed	Decision about issuing or cancelling an alert
Hong Kong, China	GEO Hong Kong	Landslip Warning system	Public statements	Television and radio	People leaving close to steep slopes	Director of the HKO and the Head of the GEO
Rio de Janeiro, Brazil	GEO-Rio	Alerta-Rio	Public statements	Television and radio, internet	To everyone in the zone alerted	Co-Rio
Rio de Janeiro, Brazil	GEO-Rio	A2C2	Public and internal statements	Sirens	Inhabitants	Co-Rio Coordinator and Sub-secretary of civil defence
San Francisco, California, USA	USGS and NWS	-	Public statements	Radio broadcast system, SMS	Motorists, people leaving close to steep slopes	USGS and NWS
Seattle, Washington, USA	USGS, NWS, City of Seattle	-	NWS weather statements	Internet, radio, television	City officials and public	USGS
Campania, Italia	CFR	-	Public statements	FAX	Majors and public institutions	Functional centre of the regional civil defence
Taiwan	DGH	-	Public statements	Local Broadcasting System and text messages	Drivers and residents within or near the high risk potential highway sections.	Directorate General of Highways (DGH)
Taiwan	NCDR	SATIS	Internal statements	Warning message, Broadcasting	Decision makers/analysts	Central Emergency Operations Center (CEOC)
Malaysia	PLUS	RTMS	Public and internal statements	-	Drivers and users	PLUS Headquarters
Japan	MLIT and JMA	-	Public and internal statements	TV, radio, and the Internet	Residents and decision-makers	JMA and local government
Southern California	NOAA and USGS	-	Public and internal statements	Internet, NOAA weather, radio, television	Emergency managers and the public	NWS
Italy	CNR-IRPI	SANF	Internal statements	Synoptic-scale maps of critical levels	National Department for Civil Protection (DPC)	National Department for Civil Protection (DPC)
Oslo, Norway	NVE	-	Public and internal statements	Internet, email, radio and television	Administrative region, Road and railway authorities, public institutions	Section for forecast of flood and landslides hazards (HF/NVE)

Hong Kong, China

In the Hong Kong ReLEWS decisions as to whether and when to issue or cancel an alert are made jointly by the Director of the HKO (Hong Kong Observatory) and the Head of the GEO. When the alert is emitted, a warning bulletin is issued to the public immediately via media and the internet. The television and radio will regularly advise the public to take appropriate precautionary measures and, in case of serious situations, the public is advised to stay in a safe shelter or at home.

Rio de Janeiro, Brazil: Alerta-Rio

For the Alerta Rio system when weather forecasts indicate a high probability of significant rainfall events an alert level depending on the intensity expected is issued. Simultaneously, if the pluviometric network measures rainfall values exceeding the thresholds, the system Alerta-Rio emits warnings concerning the probability of landslide. These types of advertisements can be broadcasted for the entire metropolitan area of Rio de Janeiro or with reference to an individual area of alert. To promote timely communication of alerts to the population, radio and television operators have the possibility to access the main operations room of the coordination center of Rio de Janeiro (Rio-CO) from which, during emergency situations, journalists promptly update listeners on the basis of information provided them in real-time. Additional communication channels used by the GEO-Rio for the dissemination of alerts are: e-mail, texts and twitter to registered users and update in real time of a website in which there are both alert both rainfall and meteorological data acquired. Figure 2.29 shows a schematic operation of the Alerta-rio system.

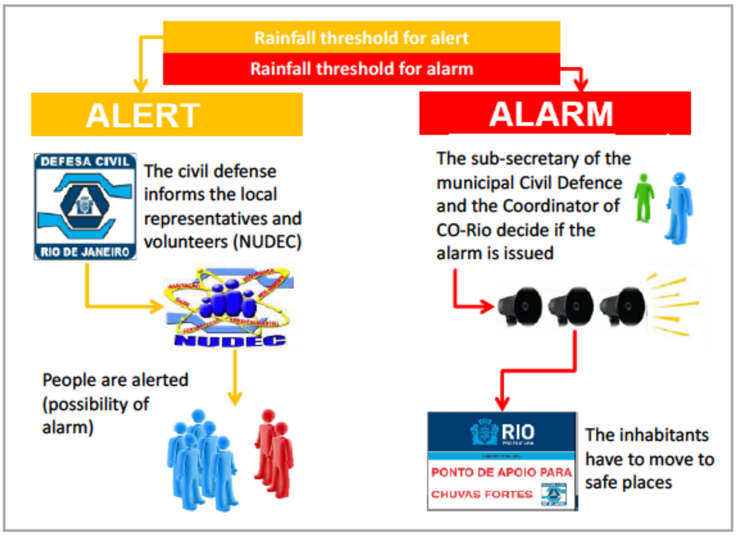


Figure 2.29 Flow chart of the procedure for issuing the alerts and the alarms (Calvello et al., 2014).

Seattle, Washington, USA

For the prototype system in Seattle, the Outlook and Watch levels may be more useful than Warning because they allow government agencies adequate time for emergency preparedness planning and response. The NWS notifies government officials and the public when the Watch level has been reached through the use of a special weather statement (Baum and Godt, 2010).

For each reference rain gauge, software combines rainfall recordings from the regional automated network with rainfall forecasts and compares the resulting cumulative rainfalls with the thresholds. In the territorial units where the latter are exceeded, the software provides the corresponding alert level, according to the decisional algorithm (Fig. 2.25), and then the Regional Civil Protection Headquarters weigh up these SIGMA outputs. Normally, at the ordinary criticality level no particular countermeasure is undertaken except for a more frequent monitoring activity, while moderate and high criticalities can be converted in real alerts addressed to municipalities and to other environmental agencies.

Campania region, Italy

In the Campania Region, Italy an information system has been developed for the management in real time of the alert issued based on pluviometric precursors. The information system is connected to the storage system of rainfall data. The system is able to process and display real-time values of the precursors and alerts about the possibility of exceeding the threshold values. When a threshold value is exceeded, the list of municipalities associated with the precursor and its alert level is automatically generated. This allows to quickly and effectively identifying the competent authorities of the territory, to which the state of alert is communicated via fax. The information system is also incorporated into the geographic information system operating at the Sala Operativa Regionale Unificata. Through the activity of "presidio territoriale", the Sala Operativa Regionale Unificata of the regional Civil Protection monitors the evolution of critical phenomena in the area and notify back to the Centro Funzionale, in relation to the single event in progress.

Japan

In Japan the system is aimed at facilitating the evacuation of residents in advance of the occurrence of disasters, and at assisting the decision-makers, such as mayors, in judging the timing of the evacuation instructions. The main players who send out early-warning information to the residential population are the Japan Meteorological Agency (JMA) and local governments (Fig. 2.30). When torrential rain is expected or falling, the timing of the issuing of early-warning information is determined by the expected values of the 60-min cumulative rainfall and soil water index calculated using the forecast rainfall for 1–3 h into the future. The progress of the actual values of the two indices is logged graphically as a snake line in the graphical space of Fig. 2.31 so that the likelihood of exceeding the CL in the near future can be anticipated to provide enough lead time to evacuate residents before the actual rainfall causes the CL to be exceeded. This allows JMA to initiate the early-warning of debris flows and slope failures. The weather news on a TV, radio, and the Internet then deliver the early-warning information.

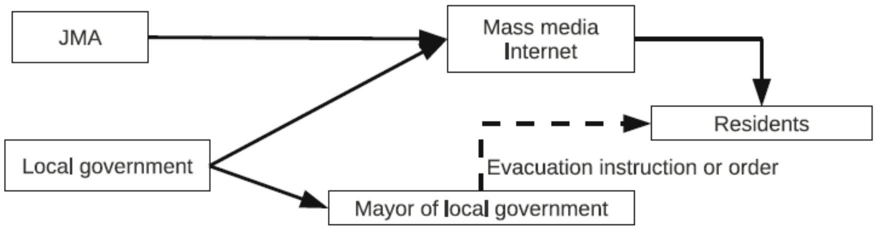


Figure 2.30 The role of major players in transmission of early-warning information (Osanai et al., 2010).

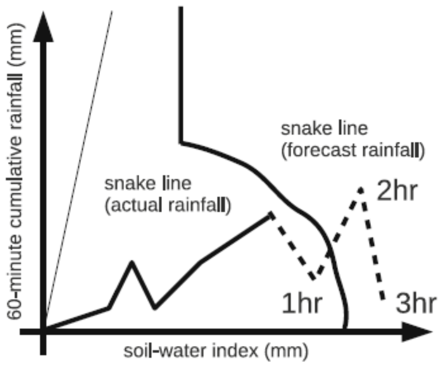


Figure 2.31 The evolution of the "snake line" under actual operational conditions, with projection using forecast rainfall over the next 1–3 h (Osanai et al., 2010).

Norway

The landslide early warning system operative is Norway was designed in 2013 extending the flood and snow forecasting service operative since 1989. Some operative computer tools are developed in collaboration with the meteorological institute, road and railway authorities and private consultants. One of this tool is the "varsom.no" web portal ("varsom" is the Norwegian word for awareness) and it is used to issue and distribute alert messages to both decision makers and the public. The main goal of the web portal is to present and distribute daily warning messages (bulletins) for snow avalanches, floods, landslides and ice conditions in rivers. The portal was developed using a responsive design, html-code allowing the website to adjust to individual screen sizes, emphasizing "mobile first", giving preference/priority to small screen displays (Johnsen 2013). Native apps have been developed later and only an android version is currently available. All of the data that is used is available to the public via (api.nve.no). To make the bulletin as user friendly and educational as possible, the bulletin page contains relevant information such as: warning levels, landslide types, real-time weather radar images, maps that show hazard-related information, user feedback regarding the precision of the bulletin and educational information. The web portal "varsom.no" provides 3 days warning levels for each administrative region. The page displays a map showing the warning level for each region (Fig. 2.32) and more in detail these information are displaying for municipalities too.

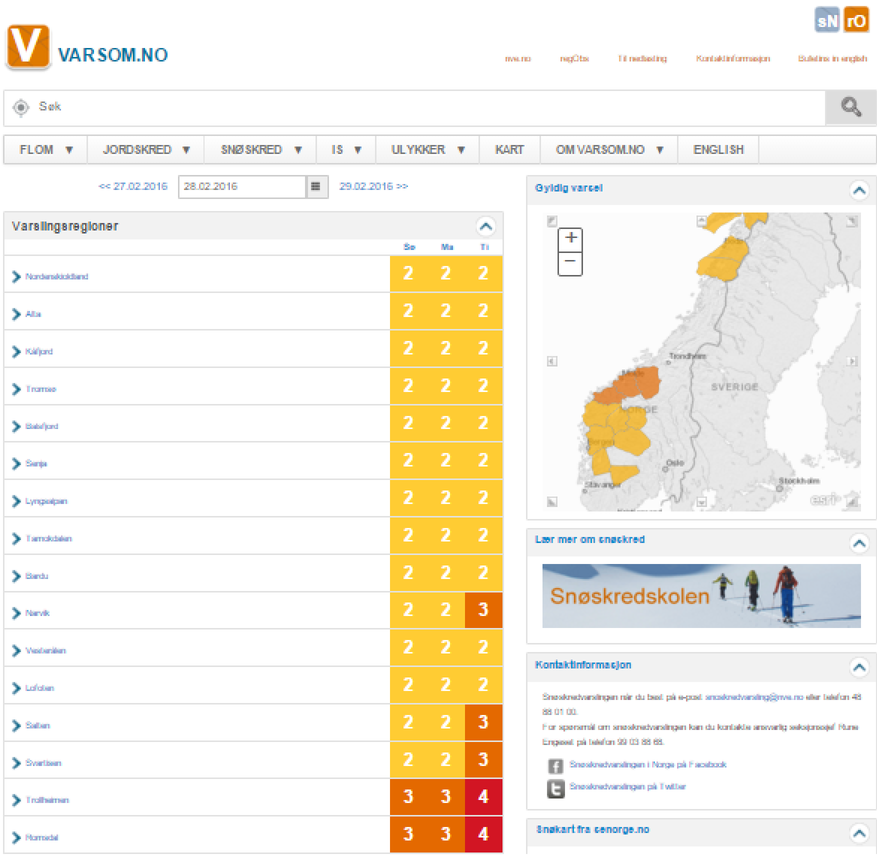


Figure 2.32 Landslide warning messages presented at county scale (www.varsom.no) (Devoli et al., 2014).

2.3.5 Qualitative and quantitative performance analysis

As previously exposed the structure of a landslide early warning system can be depicted as a wheel (Fig. 2.4) where the arrows indicate the direction of the conceptual design and management process, highlighting the continuity of the procedures and the need for a continuous system update. A continuous landslide and rainfall data collection is an important aspect for assessing and reviewing the adopted thresholds and, therefore, to improve the system reliability. It is important to periodically analyze the performance of LEWSs, in terms of level of warning issued and landslides occurred, in order to reduce the number of false alerts and avoid missed alerts. As stated by Wilson (2004), false alarms create nuisances and erode credibility but on the other hand, the absence of an advisory when debris-flows do cause death or destruction becomes a dereliction of duty. Among the ReLEWSs reviewed herein only in few cases the performance of the system is evaluated (Tab. 2.7) and principally by computing the joint frequency distribution of landslides and alerts. In Hong Kong, for the same period of analysis, the alerts issued through the forecasting SWIRLS Landslip Alert module (SLA) have been compared with that resulting by the rolling 24-hour rainfalls monitoring (GEO) and a statistical analysis was carried out. For the prototype system operative in Seattle some statistical analyses on thresholds exceedance and landslides have been evaluated by Chleborad et al. (2006). In Italy the performance of the SIGMA model employed in the ReLEWS of the Emilia Romagna region has been analyzed considering a 2x2 contingency table and several performance indicators. In the ReLEWSs of Southern-California and Norway, a quantitative analysis is informally carried out through the evaluation of occurrence or non-occurrence of landslides during a warning. 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.

Table 2.7 ReLEWS reported in the literature: performance analysis.

Location	Institution	Name	Analysis of the performance
Hong Kong, China	GEO Hong Kong	Landslip Warning system	Yes
Rio de Janeiro, Brazil	GEO-Rio	Alerta-Rio	No
Rio de Janeiro, Brazil	GEO-Rio	A2C2	No
San Francisco, California, USA	USGS and NWS	-	No
Seattle, Washington, USA	USGS, NWS, City of Seattle	-	Yes
Campania, Italy	CFR	-	No
Emilia Romagna, Italy	CFR	SIGMA	Yes
Taiwan	DGH	-	No
Taiwan	NCDR	SATIS	No
Malaysia	PLUS	RTMS	No
Japan	MLIT and JMA	-	No
Southern California	NOAA and USGS	-	Yes
Italy	CNR-IRPI	SANF	No
Oslo, Norway	NVE	-	Yes

Hong Kong, China

Performance analysis have been carried out for the Hong Kong early warning system (Cheung et al., 2006) to both evaluate the landslip warning (GEO) and the capability of forecasting of the SWIRLS Landslip Alert module (SLA). The SWIRLS Landslip Alert (SLA) module takes full account of the rainfall-landslide frequency correlation but uses the rolling 21-hour actual rainfall plus a 3-hour SWIRLS rainfall forecast to make up the rolling 24-hour rainfall, thus providing a lead time of up to 3 hours. In this case a direct correlation between landslide occurrences and warnings issued is investigated and some statistical indicators were evaluated. Table 2.8 summarized all the verification statistics for the SLA and the GEO landslide-rainfall correlation model, including: H (number of "hit"), F (number of "false alarm"), M (number of "miss"), N (total number of predictions = H+F), POD (probability of detection = H/(H+M)), FAR (false alarm ratio = F/(F+H)), CSI (critical success index = H/(H+M+F)), PIL (percentage of ideal lead time = actual lead time / ideal lead time) and the frequency distribution of different SLA lead times. For the SLA, a "false alarm" refers to an alert that the landslip warning criteria is expected to reach in the next 3 hours, i.e. N21+3 >15, but the landslip warning criteria is not reached in reality.

Table 2.8 Verification statistics of SWIRLS Landslip Alert and GEO Landslide-rainfall correlation model over the period 2001-05 (Cheung et al., 2006).

Statistical measures	SWIRLS landslip alert	Landslide-rainfall Model
H	14	7
F	6	2
M	3	0
N	20	9
POD	82 %	100 %
FAR	30 %	22 %
CSI	61 %	78 %
PIL	53 %	-
<0 lead	3	-
0-1 hr lead	6	-
1-2 hr lead	3	-
2-3 hr lead	3	-
>3 hr lead	2	-

Moreover a comparison between the alerts issued with SLA and the rolling 24-hour rainfalls monitoring (GEO) is carried out. Figure 2.33a shows the performance of the Landslide-rainfall correlations over the period 2001-05. The red lines mark the landslides threshold number used to set the alert criteria in the Landslip Warning System (15 landslides). The comparison of the landslide predictions by SWIRLS Landslip Alerts (i.e. N21+3) and the landslide-rainfall correlation model of GEO (i.e. N24) for cases in 2004-2006 (up to June) is presented in figure 2.33b where the red line indicates the perfect match between SWIRL alert and GEO. The obtained results showed that the EWM was generally effective and the SLA provides useful and timely guidance to forecasters.

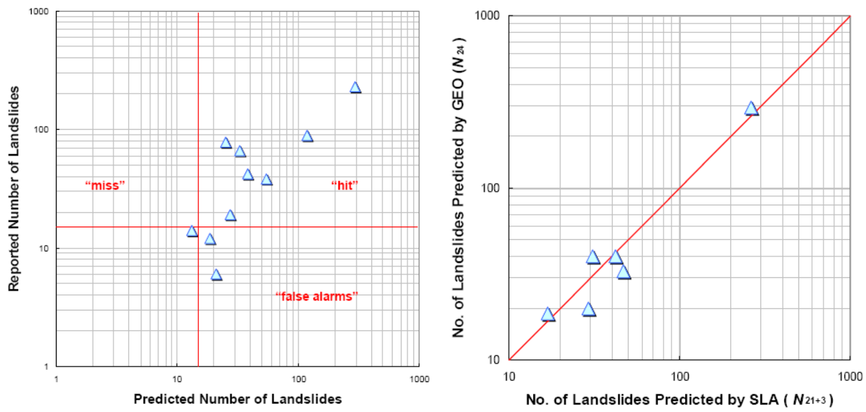


Figure 2.33 a)Performance of the Landslide-rainfall correlations over the period 2001-05. b) Comparison of the landslide predictions by SWIRLS Landslip Alerts and GEO. (Cheung et al., 2006).

Seattle, Washington, USA

Landslide alerts or advisories for Seattle, WA began in 2003 during research to develop landslide-warning thresholds for the Seattle area and evolved into an informal, experimental warning system. The USGS issued informal landslide advisories to city officials in connection with two storms in 2003, one storm in 2004, and one storm in 2005. Since 2006, NWS has issued landslide alerts based on USGS tracking of rainfall conditions relative to the thresholds. Figure 2.34 reports a qualitative performance analysis on the landslide early warning in Seattle, showing the level of warning reached, if the alert was issued and the number of landslide reported. In 2006 a statistical analysis on rainfall threshold exceedance at rain gauges and on landslide occurrences in the Seattle Rain Gage Network was carried out, for the period 1978–2003 (Chleborad et al., 2006).

Date	Thresholds exceeded	Antecedent wetness index, m	Number of landslides reported[a]	Highest warning level reached	Advisory issued?
October 20–21, 2003	CT, ID	−0.121 to −0.033	4	Watch	Yes
November 18–19, 2003	CT, ID	−0.027–0.034	1	Watch	Yes
December 4–14, 2004	CT	−0.073–0.012	0	Watch, based on rainfall forecast	Yes
January 17–18, 2005	ID	0.006–0.062	2	Warning	No
January 22–23, 2005	none	0.032–0.022	0	Watch, based on rainfall forecast	Yes, cancelled after QPF revised downward
January 6–10, 2006	CT, reduced ID	−0.087 to −0.020	11	Watch	Yes
January 29–30, 2006	CT, reduced ID	0.025–0.056	11	Warning	Yes
November 2–6, 2006	CT, ID	−0.158–0.029	3	Watch	No, due to initial dry conditions
November 7–30, 2006	CT	0.022–0.060	0	Outlook	No
December 2–3, 2007	CT, ID	−0.008–0.102	12	Warning	Yes
January 6–7, 2009	CT, ID	0.024–0.091	Many[b]	Warning	Yes

CT cumulative rainfall threshold, *ID* rainfall intensity–duration threshold, reduced ID, 40 mm in 24 h, *QPF* quantitative precipitation forecast

[a] Sources of data include Seattle Department of Public Utilities and local newspapers, the Seattle Times and the Seattle Post-Intelligencer for the dates listed and directly thereafter

[b] At least two within the Seattle city limits and many more in nearby communities

Figure 2.34 Seattle landslide forecasts 2003–2009 (Baum and Godt, 2010).

Emilia Romagna, Italy

For the SIGMA model, applied in the Emilia Romagna region, correct predictions (true positives and true negatives) and errors (missed alarms or false negatives and false alarms or false positives) were defined (Tab. 2.9) and summarized. Landslides are considered predicted if occurred during a day in which the SIGMA model pointed out any level of warning. True positives are days with landslides correctly detected by the model, false positives are days in which an alarm was forecasted but no landslides occurred (false alarms), false negatives are days in which landslides occurred but the model did not forecast them (missed alarms) and true negatives are correct predictions of days without landslides. Taking into account the daily alert level instead of the number of landslides, several statistical attributes were computed to quantitatively define the effectiveness of the SIGMA model; this analysis is reported in the second column of Figure 2.35.

Table 2.9 Confusion matrix definition (Martelloni et al., 2012).

		Landslides occurred	
		Yes	No
Landslide predicted	Yes	True positives	False positives (false alarms)
	No	False negatives (missed alarms)	True negatives

Statistical attributes	SIGMA model
a = True positives	185
b = False positives	913
c = False negatives	68
d = True negatives	19,658
Efficiency $= (a + d)/(a + b + c + d)$	0.95
Misclassification rate $= (b + c)/(a + b + c + d)$	0.047
Odds ratio $= (a + d)/(b + c)$	20.23
Positive predictive power $= a/(a + b)$	0.17
Negative predictive power $= d/(c + d)$	0.997
Sensitivity $= a/(a + c)$	0.73
Specificity $= d/(b + d)$	0.96
False positive rate $= b/(b + d)$	0.04
False negative rate $= c/(a + c)$	0.27
Likelihood ratio = *sensitivity*/(1 − *specificity*)	16.48

Figure 2.35 Statistical indicators considered to evaluate the performance (Martelloni et al., 2012).

Norway

In the ReLEWS employed in Norway documentation on warning levels issued, registered landslides and hazard signs are stored in an Excel database and in the webpage www.xgeo.no together with spatial position of landslides and warning levels issued. Furthermore the landslide expert on duty must provide documentation regarding difficulties and scientific considerations in choosing one warning level instead of another. All these information together with differences in predicted vs. subsequently observed values of the hydrometeorological parameters, provide an important database to be considered for future performance analysis. Actually a quantitative analysis is informally carried out through the evaluation of occurrence or non-occurrence of landslide during a warning. Criteria used by NVE for subsequently evaluating each daily warning level issued are shown in Table 2.10. Besides from specifying an expected number of landslides per area, a specific warning level can also be evaluated as "correct" if hazard signs are observed. This is done to consider the possibility that landslide events may have occurred but have not been registered though media and other sources.

Table 2.10 Verification statistics of SWIRLS Landslip Alert and GEO Landslide-rainfall correlation model over the period 2001-05 (Cheung et al., 2006).

Hazard Level	Classification criteria
4	> 14 landslide (per 10-15.000 km^2) Hazard signs: Several road blockings due to landslides or flooding
3	6-10 landslides (per 10-15.000 km^2) Hazard signs: Several road blockings due to landslides or flooding
2	1-4 landslides (per 10-15.000 km^2) Hazard signs: flooding/erosion in streams
1	No landslide 1-2 landslide caused by local rain showers 1 small debris slide if in area with no signs of elevated hazard level Man-made events (from e.g. leakage, deposition, construction work or explosion)

3 ASSESSING THE PERFORMANCE OF REGIONAL LANDSLIDE EARLY WARNING MODELS: THE EDUMAP METHOD

(extract from Calvello and Piciullo, 2016)

3.1 FRAMEWORK FOR THE PERFORMANCE ANALYSIS OF REGIONAL LANDSLIDE WARNING MODELS

Maskrey (1997) states that the effectiveness of an early warning system should be judged less on whether warnings are issued per se but rather on the basis of whether the warnings facilitate appropriate and timely decision-making by those most at risk. Calvello et al. (2015) state that the design of landslide warning systems require synergy between technical and social skills. According to them, the main objective of the designers of the technical subsystem is the definition of efficient processes, while the procedures defined within the social subsystem are important in making landslide early warning systems an effective tool to reduce risk to life.

Following the previous statements and the scheme proposed in Figure 1, the technical performance of a regional landslide early warning system, ReLEWS, is herein evaluated by means of a method, called "Event, Duration Matrix, Performance (EDuMaP) method" (Figure 3.1), assessing the performance of the warning model, ReLWaM, employed by that system. The EDuMaP method comprises the following three successive steps: 1) Events analysis, i.e. landslide events, LE, and warning events, WE, derived from available landslides and warnings databases; 2) definition and computation of a Duration Matrix, whose elements report the time associated with the occurrence of landslide events in relation to the occurrence of warning events, in their respective classes; 3) evaluation of the early warning model Performance by means of performance criteria and indicators applied to the duration matrix computed in the previous step.

3.1.1 Events analysis: landslide and warning events

Despite the fact that regional warning models typically associate to their warning levels descriptors which consider the potential number of landslides affecting the warning zone, only few examples exist, in the literature, evaluating the system performance differentiating among warning levels and among the number of concurrent landslides registered during the warning phases (Yu et al., 2003; Calvello et al., 2015). 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 (Figure 3.1). The results of the analysis depend on the values assumed by a series of well-identified parameters (Table 3.1), which are defined to allow the analyst to make choices on how to select and group landslides and warnings.
Figure 3.1 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 database and warnings database. 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 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).

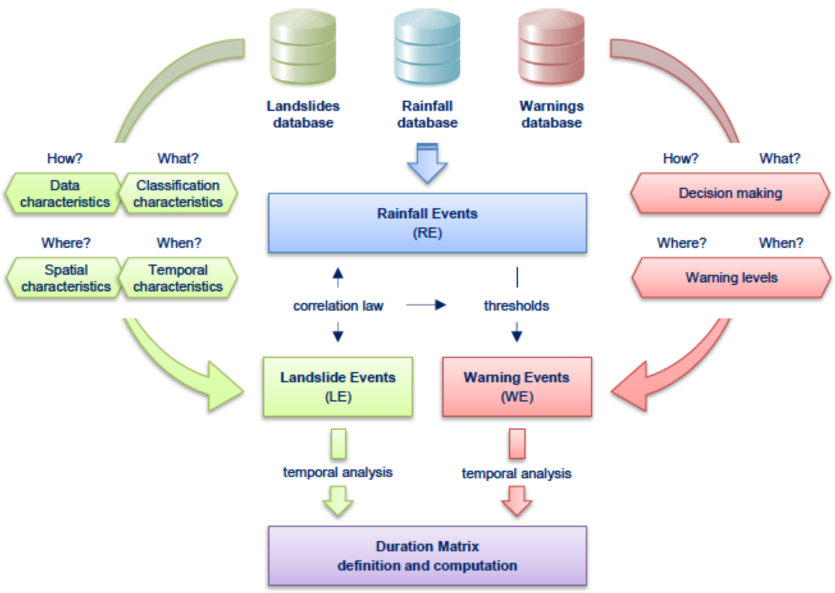


Figure 3.1 Scheme of the relationships among rainfall events, landslide events and warning events for the performance analysis of the warning model employed within regional early warning systems for rainfall-induced landslides. (Calvello and Piciullo, 2016).

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 3.1 reports the ten parameters which need to be defined to carry on the events analysis:

1) warning levels, WL, 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.

The first two parameters, WL and $L_{den(k)}$, are relevant for the classification of the warning and landslide events, respectively. Concerning the second parameter, Table 3.2 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 Figure 3.2. Figure 3.2a reports one set of landslides and three series of landslide events identified considering three different combination of values for Δt_{LE}, the minimum interval between landslide events, and t_{OVER}, the over time. Figure 3.2b 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.

Table 3.1 Input parameters for the classification, identification and temporal analysis of landslide events (LE) and warning events (WE) (Calvello and Piciullo, 2016)

Parameters of the events analysis	Symbol	Relevant for
1. Warning levels	WL	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

Table 3.2 Examples of landslide density criteria which can be used to classify the landslide events (Calvello and Piciullo, 2016).

LE class	Absolute criterion [No. of landslides]	Relative criterion [No. of landslides / WZ 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)

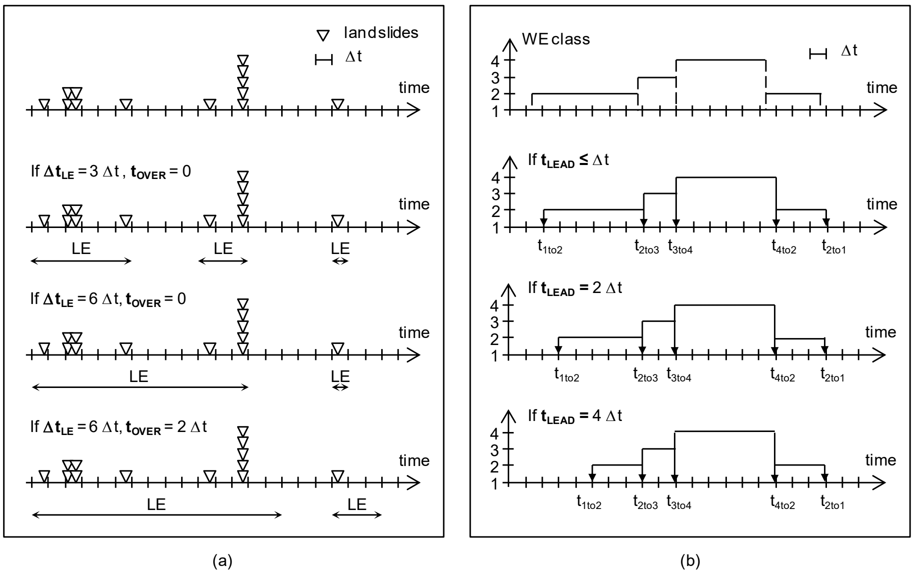


Figure 3.2 Exemplification of the meaning of parameters: a) minimum interval between landslide events, Δt_{LE}, and over time, t_{OVER}; b) lead time, t_{LEAD} (Calvello and Piciullo, 2016).

3.1.2 Duration matrix

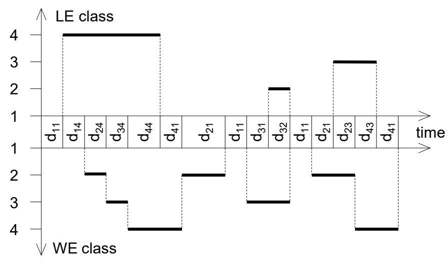
The key element of the numerical evaluation of the performance of a warning model is the definition and computation of a matrix, herein called "duration matrix" (Figure 3.3), whose elements report the time associated with the occurrence of landslide events in relation to the occurrence of warning events, in their respective classes. The classification of landslide events and warning events (see parameters L_{den} and WL in Table 3.1) 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 Figure 3.3a is drawn as a 4x4 matrix, under the hypothesis of: four classes of warning events, indicated with numbers 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, dij, is computed, within the time frame of the analysis, ΔT, as follows:

$$d_{ij} = \sum_{\Delta T} time_{ij} \qquad \text{(Eq. 3.1)}$$

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 3.3b shows a graphical example of temporal analysis needed for the computation, following Eq. 3.1, of the elements of the duration matrix. It is important to highlight that the dimension of the elements of the duration matrix, dij, is time and that the sum of all elements, $\sum_{ij} d_{ij}$, is always equal to the time frame of the analysis, ΔT.

		Landslide Events duration			
		1 (no)	2 (S)	3 (I)	4 (L)
Warning Events duration	1 (no)	d_{11}	d_{12}	d_{13}	d_{14}
	2 (M)	d_{21}	d_{22}	d_{23}	d_{24}
	3 (H)	d_{31}	d_{32}	d_{33}	d_{34}
	4 (VH)	d_{41}	d_{42}	d_{43}	d_{44}

(a)



(b)

Figure 3.3 Structure of the duration matrix and graphical exemplification of the temporal analysis needed for its computation (Calvello and Piciullo, 2016).

To further clarify how the duration matrix is computed, Tables 3.3 and 3.4 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 3.3 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 3.4 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: landslide density thresholds, L_{den}, equal to 0 (class 1), 1 (class 2), 2 to 10 (class 3), >10 (Class 4); four warning levels, WL; time frame of the analysis, ΔT, equal to 1 year; constant area of analysis, A; temporal discretization of the analysis, Δt, equal to 1 hour; 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 hours; lead time, t_{LEAD}, equal to zero; over time, t_{OVER}, equal to zero.

Table 3.3 Synthetic data exemplifying the performance of a regional landslide warning model: warnings issued and corresponding warning events (Calvello and Piciullo, 2016).

Warnings issued				Warning Event	
Level	**From (date and hour)**	**To (date and hour)**	**Duration (h:mm)**	**ID**	**class**
Medium	13/01/2000 13.00	13/01/2000 16.00	3.00	WE_2000_01	2 (M)
High	13/01/2000 16.00	13/01/2000 17.30	1.30	WE_2000_01	3 (H)
Very High	13/01/2000 17.30	14/01/2000 6.00	12.30	WE_2000_01	4 (VH)
Medium	14/01/2000 6.00	14/01/2000 18.00	12.00	WE_2000_01	2 (M)
High	18/03/2000 7.30	18/03/2000 18.00	10.30	WE_2000_02	3 (H)
Medium	22/11/2000 10.00	22/11/2000 12.00	2.00	WE_2000_03	2 (M)
Very High	22/11/2000 12.00	23/11/2000 7.30	19.30	WE_2000_03	3 (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 1:00pm on 13 January to 6:00pm on 14 January), with warning levels varying from 2(M) to 4(VH); WE_2000_02 (from 7:30am to 6:00pm on 18 March), with warning level equal to 3(M); WE_2000_03, (from 10:00am on 22 November to 7:30pm 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 3.5 and Figure 3.4 report the result of the temporal analysis conducted, for the year-long time frame, on these events. The resulting duration matrix is shown in Table 3.6.

Table 3.4 Synthetic data exemplifying the performance of a regional landslide warning model: landslide database and corresponding landslide events (Calvello and Piciullo, 2016).

Landslide database				Landslide Event	
Number	**Typology**	**Date and hour**	**Accuracy of time record**	**ID**	**clas s**
1	A	13/01/2000 10.20	exact time	LE_2000_01	4 (L)
15	A	13/01/2000 10:00 to 11:00	time interval	LE_2000_01	4 (L)
3	B	13/01/2000 10:00 to 11:00	interval estimated	LE_2000_01	4 (L)
2	A	13/01/2000 12.35	exact time	LE_2000_01	4 (L)
1	B	13/01/2000 12.40	exact time	LE_2000_01	4 (L)
4	A	13/01/2000 12:00 to 13:00	time interval	LE_2000_01	4 (L)
2	C	13/01/2000 12:00 to 13:00	time interval	LE_2000_01	4 (L)
3	A	13/01/2000 13:00 to 14:00	interval estimated	LE_2000_01	4 (L)
1	A	13/01/2000 19.15	exact time	LE_2000_01	4 (L)
1	B	13/01/2000 19.20	exact time	LE_2000_01	4 (L)
2	A	13/01/2000 20:00 to 21:00	time interval	LE_2000_01	4 (L)
7	A	13/01/2000 21:00 to 22:00	time interval	LE_2000_01	4 (L)
2	B	13/01/2000 21:00 to 22:00	time interval	LE_2000_01	4 (L)
1	A	14/01/2000 1.45	exact time	LE_2000_01	4 (L)
1	A	18/03/2000 12.30	exact time	LE_2000_02	2 (S)
1	A	18/03/2000 17:00 to 18:00	time interval	LE_2000_02	2 (S)
2	A	22/11/2000 11:00 to 12:00	time interval	LE_2000_03	3 (I)
1	B	22/11/2000 13.20	exact time	LE_2000_03	3 (I)
2	A	22/11/2000 16:00 to 17:00	time interval	LE_2000_03	3 (I)
1	C	22/11/2000 16:00 to 17:00	interval estimated	LE_2000_03	3 (I)

Table 3.5 Temporal analysis of WE and LE using data from Tables 3.3 and 3.4 (Calvello and Piciullo, 2016).

Time			Warning Event		Landslide Event	
From (date and hour)	To (date and hour)	Duration (h)	ID	class	ID	class
01/01/2000 0.00	13/01/2000 10.00	298		1		1
13/01/2000 10.00	13/01/2000 13.00	3		1	LE_2000_01	4
13/01/2000 13.00	13/01/2000 16.00	3	WE_2000_01	2	LE_2000_01	4
13/01/2000 16.00	13/01/2000 17.30	1	WE_2000_01	3	LE_2000_01	4
13/01/2000 17.30	14/01/2000 1.45	8	WE_2000_01	4	LE_2000_01	4
14/01/2000 1.45	14/01/2000 6.00	4	WE_2000_01	4		1
14/01/2000 6.00	14/01/2000 18.00	12	WE_2000_01	2		1
14/01/2000 18.00	18/03/2000 7.30	1525		1		1
18/03/2000 7.30	18/03/2000 12.30	5	WE_2000_02	3		1
18/03/2000 12.30	18/03/2000 18.00	5	WE_2000_02	3	LE_2000_02	2
18/03/2000 18.00	22/11/2000 10.00	5968		1		1
22/11/2000 10.00	22/11/2000 11.00	1	WE_2000_03	2		1
22/11/2000 11.00	22/11/2000 12.00	1	WE_2000_03	2	LE_2000_03	3
22/11/2000 12.00	22/11/2000 17.00	5	WE_2000_03	4	LE_2000_03	3
22/11/2000 17.00	23/11/2000 7.30	14	WE_2000_03	4		1
23/11/2000 7.30	31/12/2000 23.59	928		1		1

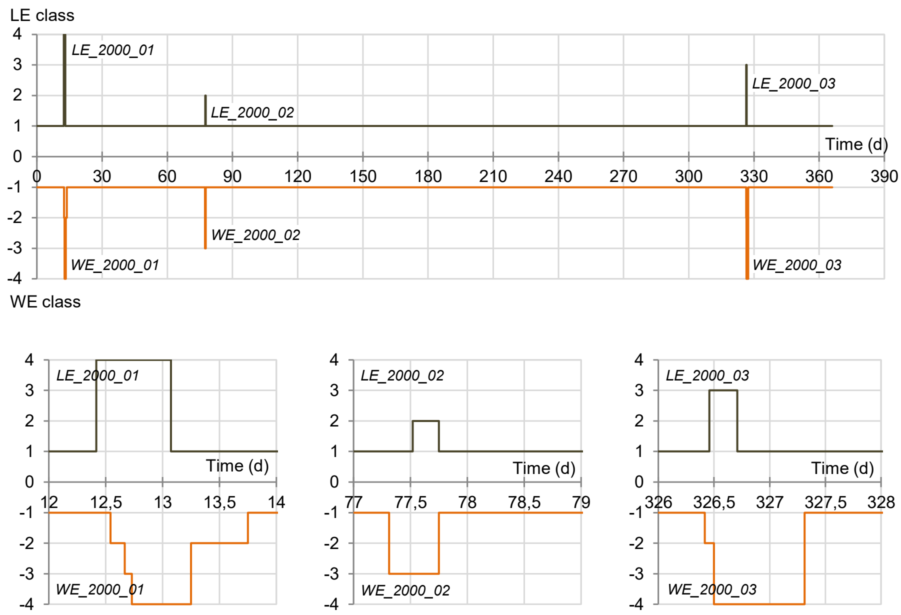


Figure 3.4 Graphical representations of temporal analysis reported in Table 3.5. (Calvello and Piciullo, 2016).

Table 3.6 Duration matrix: results using data from Table 3.5(Calvello and Piciullo, 2016).

		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

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

$$d\_LE_{ij} = \frac{d_{ij}}{\sum_{k=1}^{4} d_{kj}} N\_LE_j \quad \text{for j=2-4} \qquad \text{(Eq. 3.2)}$$

$$d\_WE_{ij} = \frac{d_{ij}}{\sum_{k=1}^{4} d_{ik}} N\_WL_i \quad \text{for i=2-4} \qquad \text{(Eq. 3.3)}$$

where: dij is the element of the original duration matrix; d_LEij is the element of the duration matrix normalized in relation to the landslide events; N_LEj is the number of landslide events classified as class j within the time frame of the analysis; d_WEij is the element of the duration matrix normalized in relation to the warning events; N_WLi is the number of warning levels of class i within in the time frame of the analysis.
Figure 3.5 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 d11, 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 2x2 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 errors; red, Red, for elements representative of a significant model errors; purple, Pur, for elements representative of the worst model errors.

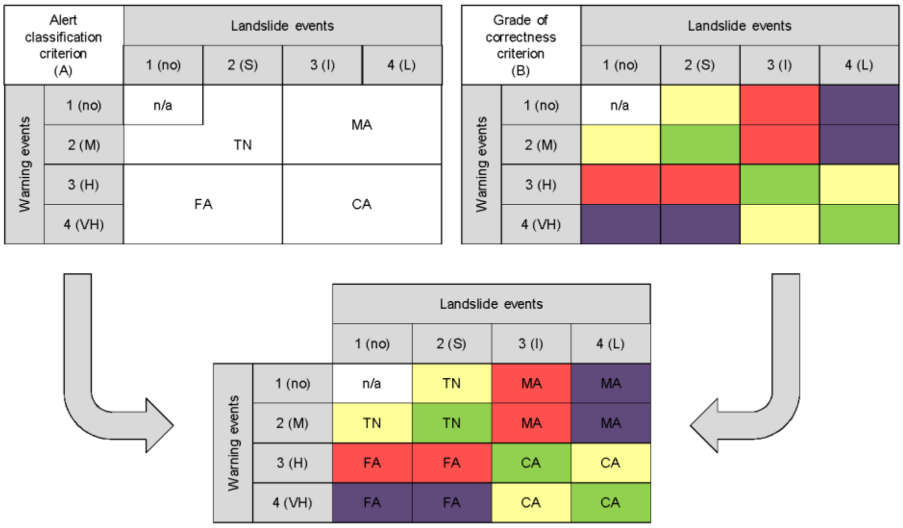


Figure 3.5 Examples of performance criteria which can be used for the analysis of the duration matrix: alert classification criterion (A) and grade of correctness criterion (B) (Calvello and Piciullo, 2016).

A number of performance indicators may be derived from the two performance criteria previously described. Table 3.7 reports their name, symbol, formula and value (computed using the duration matrix data from Table 3.6). The performance indicators related to the alert classification criterion (A) are a series of statistical indicators which are commonly derived from contingency tables: efficiency index, also called efficiency (Martelloni et al., 2012; Lagomarsino et al., 2013) or accuracy (Kirschbaum et al., 2012); hit rate (Tiranti and Rabuffetti, 2010; Cheung et al., 2006), also called sensitivity (Martelloni et al., 2012; Lagomarsino et al., 2013) or probability of detection (Kirschbaum et al., 2012; Restrepo et al., 2008; Gariano et al., 2015) or true positive rate (Staley et al., 2013); predictive power, also called positive predictive power (Martelloni et al., 2012); threat score (Staley et al., 2013; Tiranti and

Rabuffetti, 2010), also called critical success index (Cheung et al., 2006); odds ratio (Martelloni et al., 2012); misclassification rate (Martelloni et al., 2012); missed alert rate, also called false negative rate (Martelloni et al., 2012; Lagomarsino et al., 2013); false alert rate, also called probability of false alarms (Gariano et al., 2015). The other performance indicators, either related to the grade of correctness criterion (B) or to both criteria at once, have been named and defined following a similar reasoning.

Table 3.7 Performance indicators derived from the two performance criteria reported in Figure 3.3.1 using data from duration matrix reported in Table 3.6 (Calvello and Piciullo, 2016).

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

4 REGIONAL LANDSLIDE EARLY WARNING SYSTEMS CASE STUDIES

4.1 STRATEGY FOR LANDSLIDE EARLY WARNING IN RIO DE JANEIRO (BRAZIL)

(based on Calvello et al., 2015)

4.1.1 Landslide identification and zoning

The territory of the city of Rio de Janeiro (Brazil) has long been affected by landslides which often caused, in the last decades, widespread destruction and a significant number of casualties in different areas of the city. The high frequency of these phenomena is to be ascribed both to the geologic, geomorphologic and climatic characteristics of the city (i.e. weathered soils, extensive mountainous areas and a tropical climate) and to the presence of areas characterized by high density of population and by unplanned and spontaneous land occupation (Coelho Netto et al., 2007). The government agency dealing with the problems associated with landslides in Rio de Janeiro is, since 1966, the Geotechnics Foundation of the municipality of Rio de Janeiro (GEO-Rio). Of the various statutory duties assigned to GEO-Rio since its establishment in 1966, the preparation of long-term emergency plans for protecting the city's inhabitants against landslides is certainly among the most important ones.

For landslide risk-mitigation purposes GEO-Rio has produced, over the years, a series of landslide zoning maps covering various areas of the city. The first landslide susceptibility map covering the entire city of Rio de Janeiro was issued—on a scale of 1 to 25,000—in 1989, following a public outcry related to a major landslide disaster which occurred in February 1988 with a death toll of 58 (d'Orsi et al., 2012). Currently, the landslide susceptibility map covers the entire municipal area at 1:10,000 scale (Fig. 4.1). Regarding risk mapping, the first attempt at identifying areas at high risk for landslides was conducted during the 1990s on a scale of 1 to 10,000. The latest fieldwork was carried on a scale of 1 to

5000—also using topographic maps at 1:2000 scale—in a significant number of informal urban settlements (locally known as favelas) located on the slopes of the Tijuca Massif. A total of 196 informal urban settlements are currently mapped with qualitative criteria producing landslide risk zoning maps with the following three risk descriptors: high, moderate and low (d'Orsi et al., 2012).

4.1.2 Landslides triggered by heavy rainfall

Severe weather conditions in Rio de Janeiro are synonymous with heavy rainstorms. Depending on their characteristics, heavy rainstorms may cause flash floods, fast-moving landslides or, in some cases, both emergencies at the same time. Landslides are generally triggered by rainfall events combining consistent prolonged rainfall over multiple days and repeated strong rainfall gusts. The oldest published studies dealing with rainfall thresholds for defining the landslide probability of occurrence in Rio de Janeiro date back to 1997, when a relationship between rainfall and landslides was established based on 65 past events and rainfall data from a set of five rain gauges (d'Orsi et al., 1997). This preliminary study led to the first criteria for landslide warning adopted by GEO-Rio which considered the following two rainfall variables: 24-hour and 96-hour antecedent cumulated rainfall (Ortigao et al., 2002). The criteria assumed a 24-hour antecedent cumulated rainfall threshold dependent on the 96-hour antecedent cumulated rainfall by means of a function linearly increasing up to a maximum value and then asymptotically decreasing to zero. The next development occurred in 2004, when a third rainfall variable, i.e. the monitored hourly cumulated rainfall, was added to the previous two, following a detailed analysis of data from about 800 landslides of different typologies (d'Orsi et al., 2005). The rainfall variables were, since then, treated independently and different thresholds and a series of either/or rules were established to define warning levels associated to landslide probability of occurrence. These thresholds have been recently refined following new correlation analyses between monitored rainfall and landslide events. Table 4.1 shows the current rainfall thresholds and the associated landslide warning levels adopted.

Table 4.1 Rainfall thresholds currently adopted by GEO-Rio to define landslide warning levels during heavy rainstorms (Calvello et al., 2015).

Rainfall thresholds					Warning level
R1 [mm/h]		**R2** [mm/24h]		**R2 & R3** [mm/24h & mm/96h]	*(Alerta Para Escorregamento)*
25-50	or	85-140	or	25-50 & 140-220	Medium (*Média*)
50-80	or	140-220	or	50-100 & 220-300	High (*Alta*)
>80		>220		>100 & >300	Very High (*Muito Alta*)

4.1.3 The "Alerta-Rio" system

The first pilot program to automatically monitor rainfall for early warning purposes, the SIGRA project, was initiated in the late 1980s (d'Orsi et al., 2012). From that pioneering attempt, the Alerta-Rio project, which started at the end on 1996, was conceived and developed. Details on the equipment, the software, the criteria for site selection and the alarm instruments used at that time are reported in (d'Orsi et al., 1997). The Alerta-Rio early warning system underwent a major improvement in 2010, when the team of meteorologists expanded, a municipally-owned weather radar become operational, a number of internal pro¬tocols (e.g., communication strategies, dissemination of weather reports) were significantly revised and the management of the system moved to a multipurpose municipal operations center, CO-Rio. The move to CO-Rio significantly eased: internal communication among the different actors participating to the Alerta-Rio operations; handling and analyses of the data; the speed at which alert bulletins and other information are disseminated to the population. For instance, access to the main operational room is granted to radio and television broadcasting stations, many of which have, during emergency situations, permanent staff working at CO-Rio so as to provide timely and updated information to their audience. In 2010, GEO-Rio also started the publication of yearly landslide reports, which comprise the time of occurrence, the main characteristics and the location of all the landslides recorded within the city (http://www0.rio.rj.gov.br/alertario/).

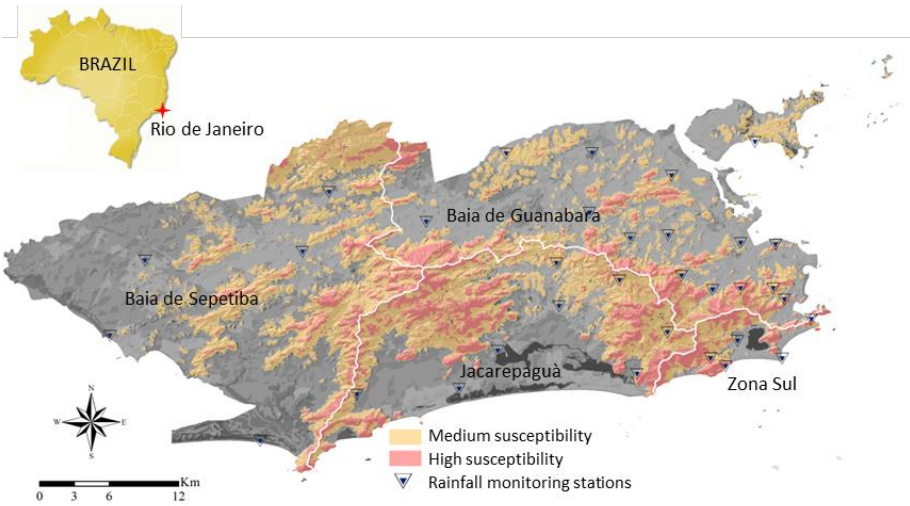


Figure 4.1 Subdivision of the Rio de Janeiro municipal territory for early warning purposes, susceptibility map and location of the rainfall monitoring stations (Calvello and Piciullo, 2016).

The "Alerta-Rio" system (d'Orsi et al., 2004; Calvello et al., 2015) is a ReLEWS operated by the GEO-Rio Foundation in the municipality of Rio de Janeiro, Brazil, designed to inform stakeholders of the possible occurrence of rainfall induced landslides. The municipality of Rio de Janeiro covers around 1'200 km^2 and is divided, for warning purposes, into four alert zones (Fig. 4.1): Baia de Guanabara (390 km^2), Zona Sul (40 km^2), Baia de Sepetiba (492 km^2), Jacarepaguà (302 km^2). Two different alert sets co-exist with the Alerta-Rio early warning system: rainfall warnings (Alerta Para Chuva), which are issued according to short term rainfall forecasts, and landslide warnings (Alerta Para Escorregamento), which are based on the comparison between rainfall measured by the monitoring stations and rainfall thresholds. Concerning landslide warnings, they are currently based on the comparison between rainfall measured by a network of 33 rain gauges and rainfall thresholds defined considering the antecedent cumulated rainfall for the following three durations: 1 hour, 24 hours, 96 hours. 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 (Table 4.2): 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 Figure 4.1because 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 $L_{den(k)}$).

Table 4.2 Landslide warnings: levels, descriptors and main operative procedures (Calvello et al., 2015).

Level and [warning level]	Short-term weather forecast and [landslide probability indicators]	Procedures
Vigilância [Low]	Light or no rain in the next 6 hours [Low: landslides not related to rainfall]	Website update (every 6 hours)
Atenção [Medium]	Moderate rain, occasionally heavy rain, in the next few hours [Medium: occasional landslides may occur]	Website update
		Communication to municipal departments (e.g., civil defence, traffic control, health)
Alerta [High]	Heavy rain in the next few hours [High: diffuse landslides may occur]	Website update
		Communication to Municipal Departments
		Warning Bulletin to TV and radio stations
Alerta Máximo [Very High]	Very heavy rain in the next few hours [Very High: widespread landsliding may occur]	Website update
		Communication to Municipal Departments
		Maximum Warning Bulletin to TV and radio stations

4.2 THE NATIONAL LANDSLIDE EARLY WARNING SYSTEM OPERATIVE IN NORWAY

4.2.1 Physical settings and landslides characteristics

Norway is divided into 19 counties and 428 municipalities with an area of 232'800 km^2. With its elongated shape of 1'800 km, the country reaches from latitude 58°N to 71°N. Approximately 30% of the land area are mountainous, with the highest peaks reaching up to 2'500 m. a.s.l and slope angles over 30 degrees covering 6,7% of the country (Jaedicke et al., 2009). In geological terms, Norway is located along the western margin of the Baltic shield with a cover of Caledonian nappes in the western parts of the country (Etzelmüller et al., 2007; Ramberg et al., 2008). The Caledonian nappes are dominated by Precambrian rocks and metamorphic Cambro-Silurian sediments, while the bedrock in the Baltic shield is dominated by Precambrian basement rocks. Cambro-Silurian sediments and Permian volcanic rocks are found in the Oslo Graben (Ramberg et al., 2008).

Recurrent glaciations, variations in sea level and land subsidence/uplift, as well as weathering, transport and deposition processes have created the modern Norwegian landscape (Gjessing, 1978; Ramberg et al., 2008). Thus, dominating quaternary deposits include various shallow (in places colluvial) soils, as well as moraine and marine deposits (Fig. 4.2).

Because of the latitudinal elongation and the varied topography, the Norwegian climate displays large variations. Along the Atlantic coast, the North Atlantic Current influences the climate whereas the inland areas experiences a more continental climate. Based on the Köppen classification scheme, the Norwegian climate can be classified in three main types: warm temperate humid climate, cold temperate humid climate and polar climate (Gjessing, 1977). 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 with up to 3'575 mm/year. In contrary, the driest areas receiving <500 mm/year are found in parts of Østlandet and Finnmark (Førland, 1993).

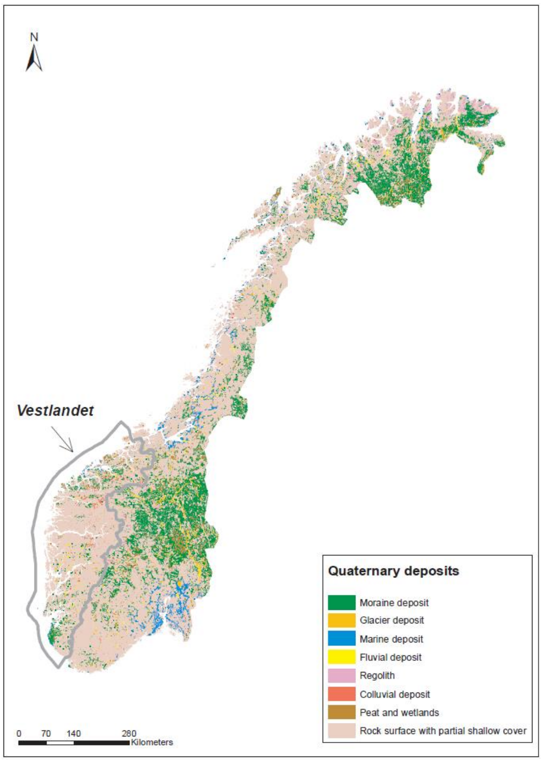


Figure 4.2 Overview of quaternary deposits in Norway. Modified from NGU, (2012).

Steep landforms in combination with various soil and climatic properties provides 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 related slush flows. Landslides are mostly triggered by rainfall, sometimes in combination with snowmelt. Some events are also triggered from/initiated as rockfall or slush flows, developing into foe example debris flows as they propagate downslope. Shallow landslides constitute a substantial threat to the Norwegian society. According to Furseth (2006), at least 230 people have been killed by such slope failures during the latest approximately 500 years. In the period 2000-2009, road authorities registered more than 1’800 shallow landslides along Norwegian roads (Bjordal & Helle, 2011).

4.2.2 The operative functioning of the early warning in Norway

In order to mitigate the risk of shallow landslides, a national landslide early warning system, operational from 2013, has been developed at The Norwegian Water Resources and Energy Directorate (NVE). The system was employed at regional scale to inform the public on the possible occurrence of the following type of landslides: debris flows, debris slides, debris avalanches, and slush flows. The service is nationwide and operational 24/7 and is supervised by 10 hydrologists/geologists that following a weekly rotating duty scheme. Through the system, daily warning levels are issued for all municipalities in the country. The warning period lasts from 06:00 UTC to 06:00 UTC each day. Decision making is based upon threshold levels with different probability of landslides occurrence, hydro-meteorological and real-time landslide observations, as well as landslide inventory and susceptibility maps (Fig. 4.3).

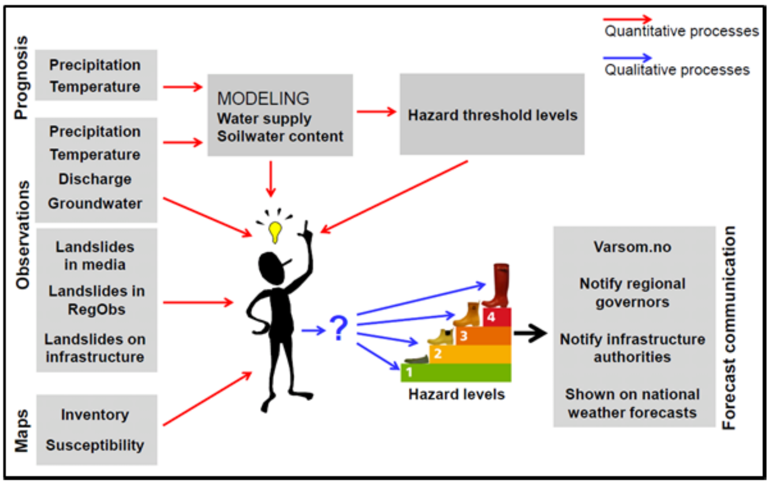


Figure 4.3 Depiction of the organization of the landslide early warning system in Norway.

The thresholds used in the system have been derived from empirical tree-classification using 206 landslide events from different parts of the country (Colleuille et al., 2010), as a function of two variables: relative water supply of rain or snowmelt during 24h and relative soil saturation/groundwater conditions (Fig. 4.4). The correlation model allows to identify 4 warning levels corresponding to different probabilities of landslide occurrence: green, very low probability; yellow, low probability; orange, high probability; red, very high probability. In case of yellow, orange or red warning levels, regional governors and infrastructure authorities are notified and orange and red warning levels are shown on national weather forecasts (Fig. 4.3). Most importantly, the margins for number of expected landslides and size of interested area for each warning level are very wide (Table 4.3).

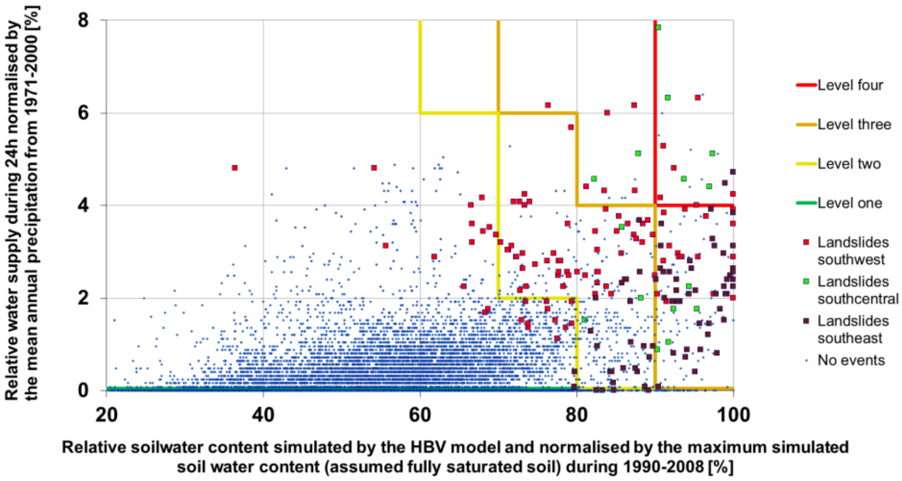


Figure 4.4 Hydrometeorological hazard thresholds used in the Norwegian national LEWS (Colleuille et al., 2010).

Table 4.3 Criteria for evaluating daily hazard levels in the Norwegian national LEWS (Calvello et al., 2015).

Hazard Level	Classification criteria
4	> 14 landslide (per 10-15.000 km^2) Hazard signs: Several road blockings due to landslides or flooding
3	6-10 landslides (per 10-15.000 km^2) Hazard signs: Several road blockings due to landslides or flooding
2	1-4 landslides (per 10-15.000 km^2) Hazard signs: flooding/erosion in streams
1	No landslide 1-2 landslide caused by local rain showers 1 small debris slide if in area with no signs of elevated hazard level Man-made events (from e.g. leakage, deposition, construction work or explosion)

In the last 2 years NVE has been conducting a revision and an update of the adopted thresholds, in collaboration with the Norwegian Geotechnical Institute (NGI), using statistical analysis of various hydro-meteorological data for registered and dated landslide events (Cepeda et al. 2012, NGI 2013a, NGI 2013b, Boje et al., 2014). In a first phase data from the entire country have been analyzed, but later two separate analyses were performed for Northern Norway and South-Eastern Norway respectively (Boje et al., 2014). A hydrological HBV-model (Beldring et al., 2003) has been used to combine, on a daily basis, relative water supply (rain & snowmelt) and relative soil saturation/groundwater conditions for the definition of an hydro-meteorological index (Fig. 4.5). In the LEWS this index is used in combination with a comprehensive expert judgment, data from other models and susceptibility maps in order to provide the basis for a daily evaluation of the warning level in each municipality of Norway. Instead of dealing with fixed geographical warning regions, daily warning levels are set for each municipality, depending on the current hydrometeorological situation, (Fig. 4.5). Thus, extent and position of the warning zones with different hazard levels are dynamic and may change from day to day.

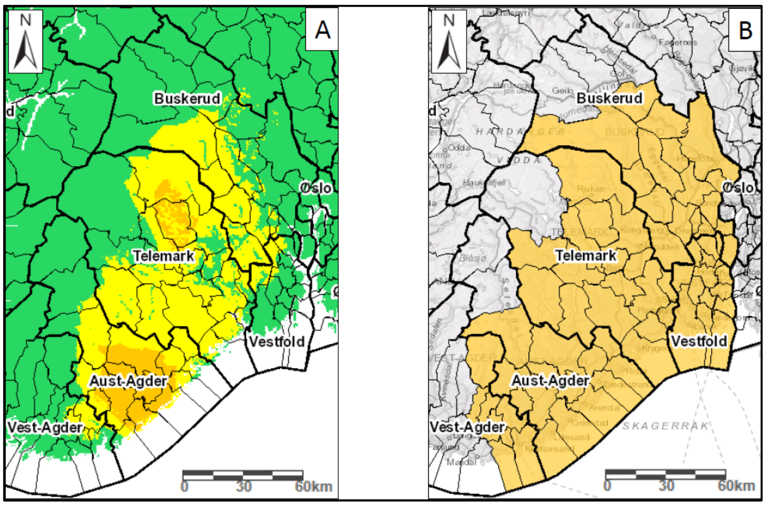


Figure 4.5 Hydrometeorological thresholds indicate landslide hazard in the regions Vest-Agder, Aust-Agder, Telemark, Buskerud, Vestfold SE Norway on 14.09.2015. B: Resultant early warning on level 2 "yellow level" issued for 70 municipalities on 14.09.2015.

Landslide susceptibility maps give an information on the spatial probability of landslides given a set of geoenvironmental factors (Varnes 1984, Guzzetti et al. 1999) and for this reasons they are combined, in the Norvegian LEWS, with an hydro-meteorological index to issue more precise forecasts. Two landslide susceptibility maps are available for Norway: one indicating initiation and runout areas for debris flows at slope scale (Fischer et al., (2012), a second one indicating susceptibility at catchment level, based upon Generalized Additive Models (GAM) statistics (Bell et al., 2014). To combine the landslide susceptibility map with the hydro-meteorological index a pixel-based approach was chosen. Therefore, the landslide susceptibility map at catchment level was converted into a 1km x 1km grid. Subsequently, both data sets were combined via a query using a combination matrix (Bell et al., 2014).

4.2.3 Tools used in landslide early warning

For the management of the LEWS employed in Norway three web tools have been implemented in collaboration with the meteorological institute, road and railway authorities and private consultants, to assist system managers and provide information to the public. The three web tools—xgeo.no, regObs.no and varsom.no—are employed to collect hydrometeorological data and quantitative prognoses used for the forecast and monitoring phases, to get real-time landslide events from field observations and to inform authorities and public about the warning levels issued.

The “xgeo.no” portal shows daily observations and forecast as well as hydrometeorological parameters and several quantitative information, such as thematic maps and time-series data in a web-GIS, within an open access webpage (http://www.xgeo.no). The maps, updated twice a day, show the conditions for the current day, as well as for a few days ahead. Some of thematic maps and time-series available date back to 1957 (Devoli et al., 2014). A landslide expert on duty (as member of a rotation team) uses the information provided by the hydro-meteorological model, the weather forecast, observations and available maps to define the warning zones and decide the warning levels to be issued for each zone (Fig. 4.5). Even if the use of this web tool is reserved to experts, data is made available to the public, thanks to open data policy, through a web portal (Engeset et al. 2004). The portal (http://www.senorge.no), developed and maintained since 2008, is a map centric tool for visualization of temporal and spatial data (Barfod et al. 2013) and includes four main profiles: snow, water, weather and climate (Fig. 4.6).

Figure 4.6 Main profile at web interface portal www.senorge.no.

The second web-tool is a real-time database called "regObs.no" which means "register observations" (Ekker et al. 2013). Initially in 2010 the database was a tool for submitting and sharing snow avalanche observations (Devoli et al., 2014). Later, the database was extended to register observations related to other natural hazards such as landslides, floods and snow conditions. It was designed as a public tool supporting crowd sourcing and is currently available to the public as a website (http://www.regobs.no) and an app, also accessible through a web-service (api.nve.no). The technologies involved in the app are available in smartphones (i.e. camera, GPS, internet, data storage) in order to do large parts of hazard registration immediately "in field" within the app. The users can later access the records via the website to add more information, if needed. The database is used daily by landslide forecasters to register events reported in newspapers or from direct telephone calls from privates. Landslide experts working in the different regional offices of NVE and road authorities complete the database with field observations, which are recorded and visualized after 15 min in xgeo.no. There are two types of records: records pertaining to landslides that have already occurred (Fig. 4.7), records associated with landslide warning signs, like ground cracks or increased turbidity in a stream-water. The data collected are transferred into the national landslide database (http://www.skrednett.no) after a validation process.

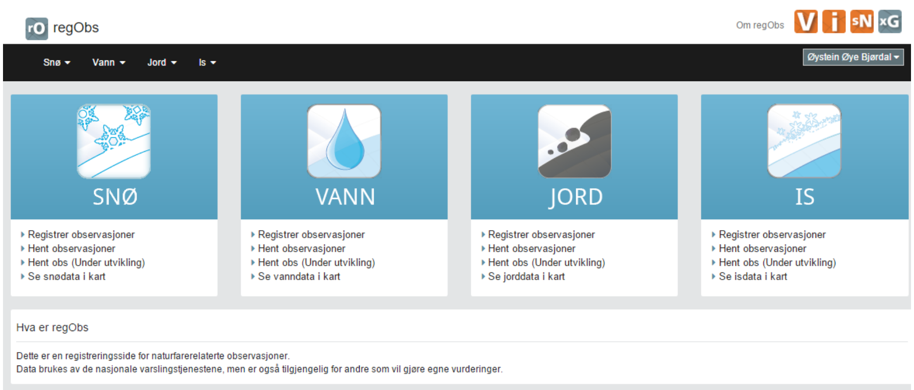


Figure 4.7 Records at web interface portal www.regobs.no.

The LEWS is complemented by the web portal "varsom.no" (http://www.varsom.no). The word "varsom" in Norwegian means awareness. This tool is used to issue and distribute alert messages to both decision makers and the public when thresholds are exceeded in a certain area, thus the warning level exceeds level 1. The main goal of the web portal is to present and distribute daily warning messages (bulletins) for snow avalanches, floods, landslides and ice conditions in rivers. The portal was developed using a responsive html-code allowing the website to adjust to individual screen sizes, emphasizing "mobile first", giving preference/priority to small screen displays (Johnsen 2013). Native apps have been developed at a later stage, and currently only an android version is available. To make the bulletin as user friendly and educational as possible, the bulletin page contains, in addition to the bulletin itself, relevant information such as: definitions of warning levels and landslide types, real-time weather radar images, maps that show hazard-related information, user feedback regarding the precision of the bulletin, educational information. This web tool provides 3 days warning levels for the different administrative regions. These warning details can be found by clicking on the link that opens the page of the region and then of the municipality. The page always features a list and a map of regions with the warning level issued (Fig. 4.8).

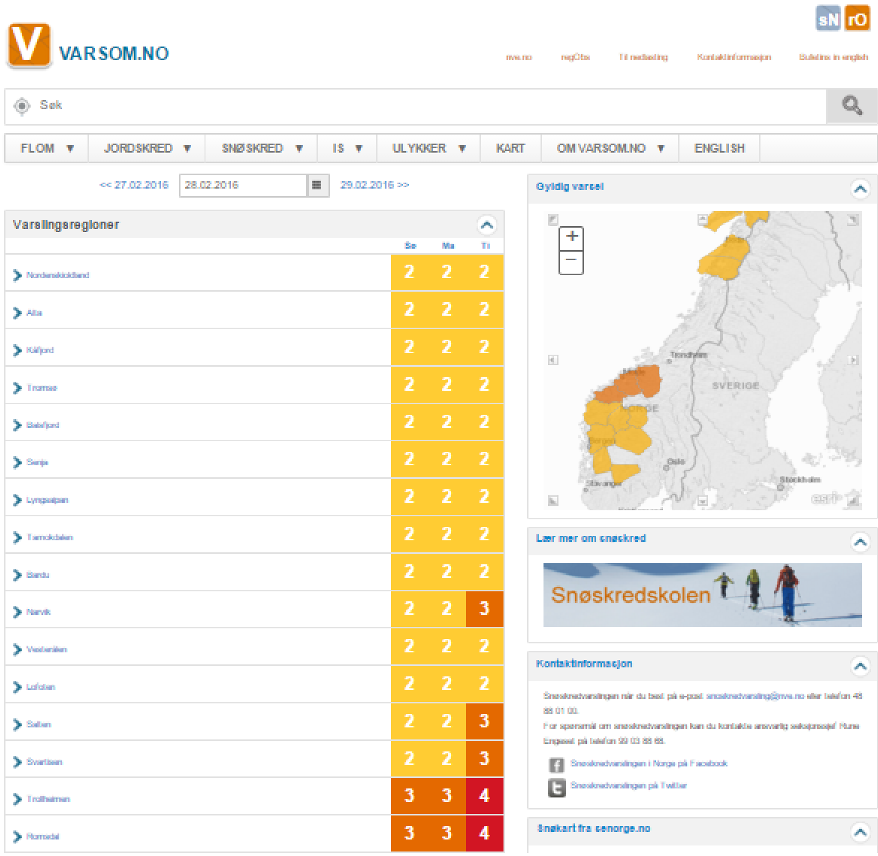


Figure 4.8 Warning levels at web interface portal www.varsom.no.

4.3 A LANDSLIDE EARLY WARNING SYSTEM FOR HYDRO-GEOLOGICAL RISK MANAGEMENT IN THE CAMPANIA REGION, ITALY

4.3.1 Structure of the system

Hydro-geological risk management in the Campania region follows the rules set by the Decree of the President of the Regional Council of Campania (D.P.G.R.) No 299 of June 30, 2005, which is titled: "Il Sistema di Allertamento Regionale per il rischio idrogeologico e idraulico ai fini di protezione civile. Ruoli e compiti delle strutture regionali di protezione civile nell'ambito delle procedure di previsione e prevenzione del rischio idrogeologico per il territorio regionale".
In Campania, the Regional Functional Centre for weather forecasts and monitoring of meteorological and hydrogeological issues is included in the "Settore Programmazione Interventi" of the Campania Region, located in Naples. The Functional Centre undertook research and study activities aiming at designing an early warning system to employ in the Campania region as part of a regional hydrogeological risk mitigation strategy. The duty of this Centre is therefore to concentrate and handle a series of data with the purpose of providing a continuous service throughout the year, working 24/7 when appropriate, in order to assist authorities responsible for warnings issuing and emergency management. To pursue its tasks, the Functional Centre gathers information from several offices, such as: Ufficio Generale dell'Aeronautica Militare (UGM), Servizio Meteoidrologico Regionale (SMR), Agenzia Regionale per la Protezione Ambientale (ARPA) Emilia Romagna, a Regional Competence Centre for Analysis and Monitoring of Environmental Risks (AMRA). It is organized into three main areas, physically and logistically integrated.
The first area is dedicated to the collection, validation, processing and storage of the data collected in the Campania region by networks of detection and monitoring of weather-hydropluviometric parameters. Data and information gathered by the Functional Centre can be classified into two main categories: meteorological data, used and processed for weather forecast, report and warning issuing; weather-hydropluviometric data detected by the monitoring networks in real time, used and processed for the possible occurrence of dangerous

hydrogeological and hydraulic events. The second area of the Centre is dedicated to the interpretation and integrated use of the data and information produced by the forecast model and, for providing full support to Civil Defence authorities for the issuing of warnings. Moreover, this area deals with the forecasting, monitoring and surveillance of meteorological and hydrological events and their effects on the ground. Another duty is the establishment of tools and the definition of how information on the occurrence and evolution of hydrogeological and hydraulic risk must be collected, analyzed and made available to the Unified Regional Operations room (SORU) of the Regional Civil defence area. The activities carried out within this area aim at operating and upgrading the landslide early warning system through the definition of: alert zones and related rainfall thresholds; rainfall precursors and relative threshold values; hydraulic indicators and threshold values. The third area of the Functional Centre deals with the information management in terms of systems ensuring the effectiveness of the communication strategies. In particular, the activities of this area are aimed at optimizing the flow of data and the information available for the prediction of hazardous events and their effects. Summarizing, the Functional Centre provides the following functions:

- weather forecast:
- warning levels issuing for civil defence purposes;
- meteorological, hydrological and landslide monitoring;
- weather, rainfall and hydraulic modelling;
- rainfall and hydrometric thresholds definition;
- programming, design, maintenance and management of monitoring networks.

The service provided by the Functional Centre in real time is carried out through a two-phase wheater forecast and monitoring strategy, implemented in a coordinated and integrated way. The first phase is composed by the meteorological analysis, through numerical modelling, and by the evaluation of the effects of hazardous hydrogeological phenomena in terms of risk to the population, buildings, infrastructures and the environment. The second phase includes: i) the qualitative and quantitative evaluation of meteorological and hydrological events based on monitoring data, ii) hydrological and weather short-term forecasting based on nowcasting technics and rainfall-runoff modelling.

Qualitative and quantitative data are collected from: weather and hydro-pluviometric networks; a national meteorological radar network; various satellite platforms available for earth observation; geological geomorphological and meteorological modelling. The monitored area is approximately 19’200 km2 and includes much of the Campania Region and parts of the neighbouring regions (3’750 Km^2 in Lazio, 800 Km^2 in Basilicata, 1’200 Km2 in Abruzzo and 950 Km^2 in Molise). The existing network of hydro-pluviometric monitoring in real time of the Functional Centre consists of 154 stations with electronic sensors and data transmission, either via tropospheric radio or satellite links. The 154 stations, operating since 2005, are instrumented with the following instruments:

- 128 rain gauges;
- 54 hydrometers;
- 56 thermometers;
- 13 hygrometers (relative atmospheric humidity);
- 5 barometers (atmospheric pressure);
- 4 anemometers (wind speed and direction);
- 4 radiometers (global solar radiation);
- 2 thermometers soil (soil surface temperature);
- 2 hygrometers soil (soil surface moisture);
- 1 wave measurement station.

The data transmission system in real time is constituted by:

- 129 local transceivers in tropospheric radio relay (UHF);
- 25 local transceivers for satellite radio bridge (polar constellation);
- 5 type duplex repeater (including 3 with hot spare);
- 4 repeaters simplex (including 4 with hot spare);
- 9 repeaters half-simplex (including 4 with hot spare);
- 4 Radio frameworks for the control panel (2 main and 2 reserve).

The monitoring stations falling outside the boundaries of the Campania region are 14 (8 in Lazio, 4 in Molise and Basilicata 2) and are instrumented with 10 rainfall sensors (4 in Lazio, 4 in Molise and 2 in Basilicata), 6 temperature sensors (2 in Lazio, 3 in Molise and 1 in Basilicata), and 8 hydrometric sensors (7 in Lazio and 1 in Molise). Pending the establishment of inter-regional agreements, the Campania Region is providing the management of the stations which fall within the

Liri-Garigliano Volturno and Sele catchment areas. One of the future objectives of the regional Civil defense is the upgrading and enhancement of the monitoring network, up to a planned network of 350 stations which would include: 320 rainfall sensors, 150 thermometers, 70 hydrometers, 60 hygrometers and 130 more sensors among anemometric, radiometric, barometric, and snow stations.

4.3.2 **Weather forecast phase**

As defined in the D.P.C.M. 59/2004, an Alert Zone can be seen as a significantly homogeneous area for the expected meteorological and hydrogeological events that may occur within it. The Alert Zones have been introduced specifically and exclusively for the weather forecast phase. The scale of analysis adopted for the Alert Zones is called "mesoscale beta" (40-100 km) because a more detailed scale is not significant for weather forecast purposes, due to the uncertainty of the numerical weather models to forecast the spatial location of heavy rainfalls. The Campania region is divided into 8 Alert Zones (Fig. 4.9) according to homogeneity criteria which consider the following factors: hydrography, morphology, rainfall, geology, land-use, hydraulic and hydrogeological events, administrative boundaries. The main characteristics of each Alert Zone are reported in terms of: morphology, main river basins, altimetry, rainfall characteristics and main risk scenarios.

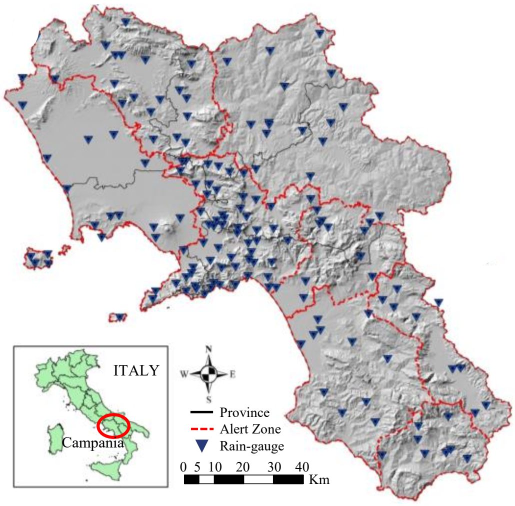


Figure 4.9 Alert zones and rain gauges of the Campania region.

During the weather forecast, the amount of rainfall (in mm) provided by LAMI model (http://www.cineca.it/it/content/il-modello-numerico-cosmo) are adopted as precursors of the possible occurrence of hydraulic and hydro-geological critical events. In the D.P.G.R 299/2005 the precursors are defined as "alarm bells" used to issue a certain warning level once they exceed predetermined threshold values. Furthermore, for each Alert Zone two different type of precursors can be defined: precursors of local criticality, adopted for rainfall events with spatial characteristics able to affect only a portion of the Alert Zone; precursors of areal criticality, adopted for rainfall events with spatial characteristics able to affect the whole Alert Zone. The precursors of local criticality are assumed equal to the maximum value of the average height of rainfall forecasted over an area of about 450 km^2 (corresponding to 9 points of the model LAMI grid) within each Alert Zone. They are evaluated considering time intervals of 6, 12 and 24 hours. The precursors of areal criticality are assumed equal to the maximum value of the height of rainfall expected over the whole Alert Zone, calculated with mobile windows of 24 hours.
Three threshold values have been defined for each group of precursors, per each Alert Zone, identifying three critical conditions: ordinary, moderate and high. In table 4.4 and 4.5 are shown the threshold values per each type of precursor, as a function of the Alert Zone.

Table 4.4 Threshold values for precursors of local criticality, per each Alert Zone, identifying three critical conditions (modified from D.P.G.R 299, 2005).

Alert	ordinary			moderate			high		
Zone	6 h	12 h	24 h	6 h	12 h	24 h	6 h	12 h	24 h
1	46	57	70	61	76	93	73	90	111
2	50	63	79	66	84	106	79	100	126
3	59	75	97	78	101	129	93	120	154
4	38	47	58	51	63	78	60	75	93
5	59	77	99	79	102	132	94	121	157
6	52	66	83	69	88	111	82	105	132
7	42	53	65	56	70	87	67	83	104
8	62	81	105	83	108	140	99	128	166

Table 4.5 Threshold values for precursors of areal criticality, per each Alert Zone, identifying three critical conditions (modified from D.P.G.R 299, 2005).

Alert Zone	ordinary	moderate	high
	24 h	24 h	24 h
1	48	65	77
2	55	74	88
3	68	90	108
4	40	54	64
5	72	96	114
6	58	77	92
7	46	61	72
8	78	104	124

The weather forecast and the evaluation of the rainfall amount, in terms of height, is provided to the Functional Centre by different agencies, by means of the following tools and models: ECMWF 12, ECMWF ENSEMBLE, LAMI, LAMI 00 and 12, METEOSAT, NEFODINA, NEFOMEDI, IXEUR, Grazzanise RADAR, LIGHTNING DETECTOR, AIR FORCE CARDS, CARDS MetOffice, radiosonde SEA PRACTICE, Prometheus.

All these tools and models provide meteorological data and information which are needed to: the Regional Meteorological Bulletin, notifications of Adverse Weather Conditions, forecasting of short-term events to evaluate conditions of criticality. The Functional Centre transmits the Regional Meteorological Bulletin, for civil defence purposes, to the Unified Regional Operations Room of the Civil defence (SORU), which forwards it to local and regional authorities. The Functional Centre, considers the Meteorological Daily Bulletin issued by the Department of

Civil defence, its Regional Meteorological Bulletin and, eventually, other additional information to issue a Regional Notice of Adverse Weather Conditions whenever there is the possibility of occurrence of critical conditions due to heavy meteorological events (rainfalls, wind, temperature variations, rough sea). If the meteorological events refer to rainfall, a Regional Notice of Adverse Weather Conditions for hydrogeological and hydraulic risks is issued. With the issuance of the Notice of Adverse Weather Conditions, the Functional Centre states the possible level of criticality, the type of events, the risk scenarios expected. The Notice of Adverse Weather Conditions is issued normally by 14:00 and has minimum validity of 24 hours.
In general, the level of criticality for each Alert Zone is established taking into account the results of the meteorological analysis and the thresholds exceedance of precursors of criticality. The level of criticality ORDINARY is issued, in an Alert Zone, if the following conditions exist: the Notice of Adverse Weather Conditions predicts significant rainfall events for the following 24 hours; based on the results of LAMI model, one of the precursors of criticality exceed the threshold value corresponding to the ordinary condition criticality. The level of MODERATE is issued, in an Alert Zone, if the following conditions exist: the Notice of Adverse Weather Conditions predicts heavy rainfall events; based on the results of LAMI model, one of the precursors of criticality exceed the threshold value corresponding to the moderate condition criticality. The level of HIGH is issued, in an Alert Zone, if the following conditions exist: the Notice of Adverse Weather Conditions predicts heavy rainfall events; based on the results of LAMI model, one of the precursors of criticality exceed the threshold value corresponding to the high condition of criticality..

4.3.3 **Monitoring phase**

In Campania hydraulic and hydrogeological events induced by heavy rainfall typically refer to debris flows, earth flows in pyroclastic soils (Varnes 1978), shallow landslides, hyper-concentrated flows (Coussot and Meunier 1996), floods, localized floods for embankment failures, erosion by overland flow.
The D.P.G.R. n. 299/05 differentiates among six classes of critical rainfall events, by considering the characteristics of the hydrographical basins as follows:

- heavy rainfall events in time intervals of 0-6 hours that can generate an hydraulic crisis in basins having areas smaller than 100 km2 (including urban drainage areas);
- II. heavy rainfall events in time intervals lasting 3-12 hours, which can generate an hydraulic crisis in basins having areas between 100 km2 and 500 km2;
- III. heavy rainfall events in time intervals lasting 6-24 hours, which can generate an hydraulic crisis in basins having areas from 500 km2 to 2000 km2
- IV. heavy rainfall events in time intervals lasting 12-48 hours, which can generate an hydraulic crisis in basins having areas between 2'000 km2 and 5'000 km2;
- V. heavy rainfall events in time intervals of 24-48 hours, which can generate an hydraulical crisis in proximity of the mouth of the Volturno river (catchment larger than 5'000 km2);
- VI. heavy rainfall events in time intervals lasting 24-72 hours, considered as critical for the occurrence of shallow landslides and debris flows.

Taking into account the previous classification, for each Municipality one or more classes of risk in relation to the type of rainfall event can be defined:

- Class I. municipalities with hydraulic risk territories included in catchments whose size is smaller than 100 km2;
- Class II. municipalities with hydraulic risk territories included in catchments whose size is between 100 and 500 km2;
- Class III. municipalities with hydraulic risk territories included in catchments whose size is between 500 and 2,000 km2;
- Class IV. municipalities with hydraulic risk territories included in catchments whose size is between 2000 and 5000 km2;
- Class V. municipalities with hydraulic risk territories included in catchments whose size is larger than 5000 km2;
- Class VI. municipalities with territories at risk for the occurrence of fast slope movements.

All municipalities belong to class I, which means that they can potentially experience a crisis situation for a flood in a small basin (including urban catchment). The classes II, III, IV and V have been assigned to municipalities with areas at risk included in catchments bigger than 100

km2. The class VI, the only class of interest for this research, includes 212 municipalities of the Campania region deemed susceptible to fast slope movements after the disastrous landslides which occurred in Sarno in 1998 (Cascini 2004) plus municipalities in hilly and mountainous areas for which at least one landslide has been recorded in the AVI database CNR-GNDCI. An Annex to D.P.G.R. 299/2005 reports a table assigning the class of risk per each Municipality of the Campania region as shown in figure 4.9.
Rainfall precursors are, also in this phase, distinguished in local and areal precursors. Local precursors are defined as the heights of rainfall measured individually by each pluviometer. While the areal precursors are defined as the average heights of rainfall calculated in the catchment, as measured by several rain gauges of the monitoring network. For each risk class the following rainfall precursors have been considered:

- Class I: local precursors at time intervals of 1, 3, 6 hours;
- Class II: areal precursors at time intervals of 3, 6, 12 hours;
- Class III: areal precursors at time intervals of 6, 12, 24 hours;
- Class IV: areal precursors at time intervals of 12, 24, 48 hours;
- Class V: areal precursors at time intervals of 24, 48 hours;
- Class VI: local precursors at time intervals of 24, 48, 72 hours;

For each type of rainfall precursor and time interval, threshold values have been obtained from statistical analysis on available historical rainfall series. For each Municipality, belonging to risk class I and VI, a single pluviometer has been chosen as reference and its height of rainfall used as local precursor. On the contrary for each Municipality of classes II, III, IV, V a reference catchment has been assigned and the mean height of rainfall over the carchment is used as areal precursor. Independently of the type and time interval of the rainfall precursor, three different threshold values have been determined based on the following return periods of rainfall: 2, 5, 10 years. The three different values obtained for each type of precursor correspond to three levels of warning for hydrogeological and/or hydraulic risk assigned, for each municipality of the Campania Region, as follows: attention, pre-alarm, alarm. In particular, the attention level is activated when the rainfall precursors exceed the threshold value corresponding to a return period of 2 years. The attention level is also issued by regional Civil defence on the basis of Notice of Criticalities emitted by the Functional Centre with if "moderate" or "high" critical conditions exist in at least one of the 8 alert zones. Pre-alarm status for hydrogeological risk is activated only as a function of rainfall precursors and in particular, if they exceed the pre-alarm threshold values (return period of 5 years). Finally, the Alarm level for hydrogeological risk is activated if rainfall precursors exceed the alarm threshold values corresponding to a return period of 10 years.

Rainfall precursors are, also in this phase, distinguished in local and areal precursors. Local precursors are defined as the heights of rainfall measured individually by each pluviometer. While the areal precursors are defined as the average heights of rainfall calculated in the catchment, as measured by several rain gauges of the monitoring network. For each risk class the following rainfall precursors have been considered:

- Class I: local precursors at time intervals of 1, 3, 6 hours;
- Class II: areal precursors at time intervals of 3, 6, 12 hours;
- Class III: areal precursors at time intervals of 6, 12, 24 hours;
- Class IV: areal precursors at time intervals of 12, 24, 48 hours;
- Class V: areal precursors at time intervals of 24, 48 hours;
- Class VI: local precursors at time intervals of 24, 48, 72 hours;

For each type of rainfall precursor and time interval, threshold values have been obtained from statistical analysis on available historical rainfall series. For each Municipality, belonging to risk class I and VI, a single pluviometer has been chosen as reference and its height of rainfall used as local precursor. On the contrary for each Municipality of classes II, III, IV, V a reference catchment has been assigned and the mean height of rainfall over the catchment is used as areal precursor. Independently of the type and time interval of the rainfall precursor, three different threshold values have been determined based on the following return periods of rainfall: 2, 5, 10 years. The three different values obtained for each type of precursor correspond to three levels of warning for hydrogeological and/or hydraulic risk assigned, for each municipality of the Campania Region, as follows: attention, pre-alarm, alarm. In particular, the attention level is activated when the rainfall precursors exceed the threshold value corresponding to a return period of 2 years. The attention level is also issued by regional Civil defence on the basis of Notice of Criticalities emitted by the Functional Centre with if "moderate" or "high" critical conditions exist in at least one of the 8 alert zones. Pre-alarm status for hydrogeological risk is activated only as a function of rainfall precursors and in particular, if they exceed the pre-alarm threshold values (return period of 5 years). Finally, the Alarm level for hydrogeological risk is activated if rainfall precursors exceed the alarm threshold values corresponding to a return period of 10 years.

4.3.4 Rainfall thresholds definition

Six hydrogeological and hydraulic classes of risk are identified in the system at municipal level, each one associated to critical rainfall events of different duration. Among these classes, only the risk class named VI refers to landslide risk, in particular to the possible occurrence of fast slope movements; the other classes deal with hydraulic risks. To risk class VI are associated local precursors evaluated considering the cumulated rainfall at intervals of 24, 48 and 72 hours. The threshold values selected for the activation of the warning states of attention, pre-alarm and alarm, have been estimated considering reference return periods equal to 2, 5 and 10 years, respectively. The rainfall thresholds of the warning model have been estimated for each pluviometer on the basis of statistical analyses on historical records of rainfall. Given the maximum annual rainfall aggregate at an assigned duration, X, its value XT related to the return period T, is defined by the following relationship:

$$XT = KT\mu(X) \qquad \text{(Eq. 4.1)}$$

where: KT is a probabilistic growth factor, function of the return period T; $\mu(X)$ is the average value of the distribution of the variable X.

The decisional algorithm therefore includes three rainfall thresholds (cumulated rainfall at 24, 48 and 72 hours) evaluated for three return periods (2, 5, 10 years) for each pluviometer. The thresholds, if exceeded, activate one of the three warning levels defined for the early warning system: attention, pre-alarm, alarm. Each municipality has a set of rainfall thresholds, which depend on the pluviometer to which they are associated.

5 EDuMaP METHOD APPLICATIONS

5.1 RIO DE JANEIRO, BRAZIL

(based on Calvello and Piciullo, 2016)

5.1.1 Setup of parametric analysis for the years 2010-2013

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. (2015) 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 (Fig. 5.1).

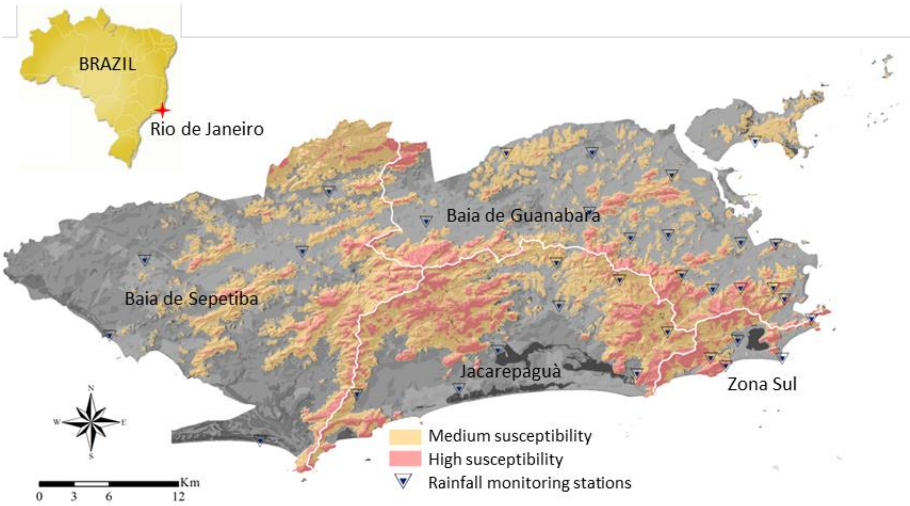


Figure 5.1 Subdivision of the Rio de Janeiro municipal territory for early warning purposes, susceptibility map and location of the rainfall monitoring stations (Calvello and Piciullo, 2016).

Table 5.1 shows the values used for each simulation of the parametric analysis for the ten input parameters needed to define the landslide and warning events. The values of the input parameters chosen for simulations ZS_T1 and G_T1, which respectively refer to the two base cases for the alert zones Zona Sul and Baia de Guanabara, adequately represent the structure and the operative procedures of the warning model employed within Alerta-Rio. For these two simulations, the following values of the ten input parameters are used: area of analysis, A, equal to ZS and G respectively; warning levels, W_{lev}, equal to four; landslide density, $L_{den(k)}$, defined according to the mixed criterion shown in Table 5.1; 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 hours; 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 minute. 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 5.2 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 interval between landslide events, Δt_{LE}, equal to 12 and 24 hours; over time, t_{OVER}, varying from zero to 12 hours; time frame of analysis, ΔT, equal to the whole three-year period 2010-2012 or to the single years 2010, 2011 and 2012.

Table 5.1 Simulations of the parametric analysis: values of the input parameters needed to define the landslide and warning events. (Calvello and Piciullo, 2016).

	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	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	2010-12	2010-12	2010-12	2010	2011	2012	2010-12	2010-12	2010-12	2010-12	2010-12	2010-12	2010-12	2010-12
Δt	1’	1’	1’	1‘	1’	1‘	1’	1’	1’	1’	1’	1’	1’	1’

Table 5.2 Examples of landslide density criteria which can be used to classify the landslide events (Calvello and Piciullo, 2016).

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)

5.1.2 Results of parametric analysis

The duration matrices of Tables 5.3 and 5.4 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. Figures 5.2 and 5.3 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% versus 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 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}).

Table 5.3 Duration matrix of simulation ZS_T1 (Calvello and Piciullo, 2016).

		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

Table 5.4 Duration matrix of simulation G_T1 (Calvello and Piciullo, 2016).

		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

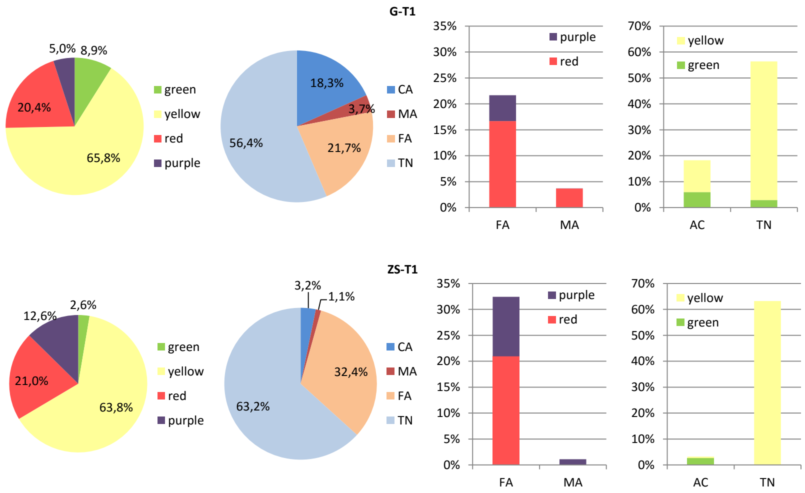


Figure 5.2 Simulations for the base cases of alert zones Guanabara (G-T1) and Zona Sul (ZS-T1): distribution of the elements of the duration matrix in terms of Criterion A (Correct Alerts, CA, Missed Alerts, MA, False Alerts, FA, True Negatives, TN) and Criterion B (color code following a grade of correctness from green to purple) (Calvello and Piciullo, 2016).

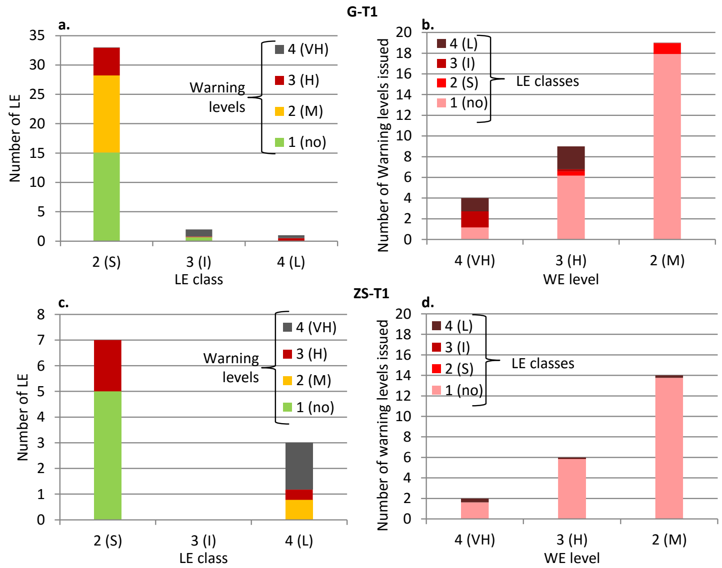


Figure 5.3 Simulations for the base cases of alert zones Guanabara (G-T1) and Zona Sul (ZS-T1).Number of landslide event (LE) and warning levels issued, normalized respectively in relation to: a.,c.) landslide events, d_LEij (Eq. 3.2); b.,d.) warning events, d_WEij (Eq. 3.3) (Calvello and Piciullo, 2016).

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 (Tab. 5.5 and Fig.s 5.4 and 5.5). 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_{susc}) 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. $P_{SM\text{-}NW}$, $P_{SM\text{-}NL}$, I_{MA})(Tab. 5.5). 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 $P_{SM\text{-}NW}$ and I_{MA} (Tab. 5.5) 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 occurrence of earth slides on artificial slopes (G_W1 and G_W5) are similar and show: $I_{eff(A)}$ less than 70%, *HR* around 100%, very few MAs, around 35% of FAs, I_{FA} values much higher than the rest of the simulations (Tab. 5.5). 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*, $P_{SM\text{-}NW}$), 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 hours. 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 (Tab. 5.5), 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.

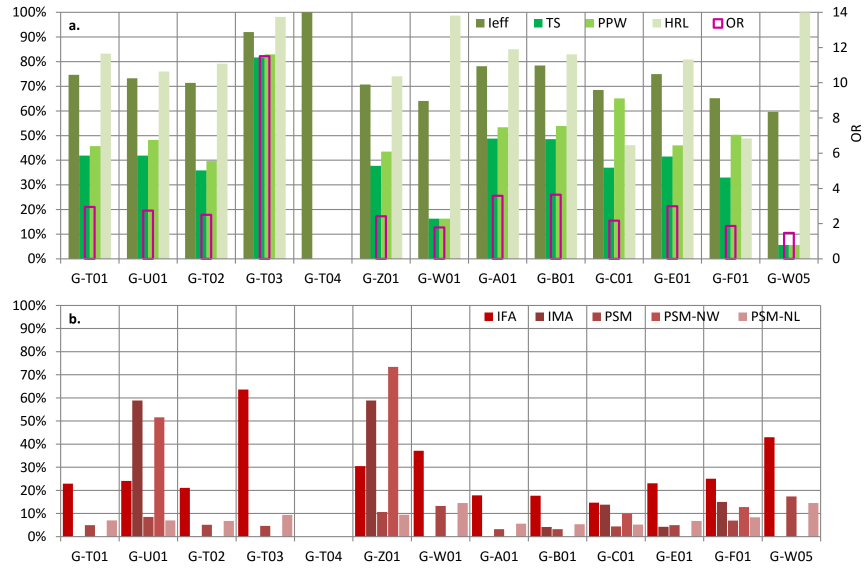


Figure 5.4 Simulations for different cases of alert zone Guanabara, G_T1 to G_W5 (see Table 9 for the input parameters used for the Events analysis): values of performance indicators related to the success (a) and to the errors (b) of the warning model (Calvello and Piciullo, 2016).

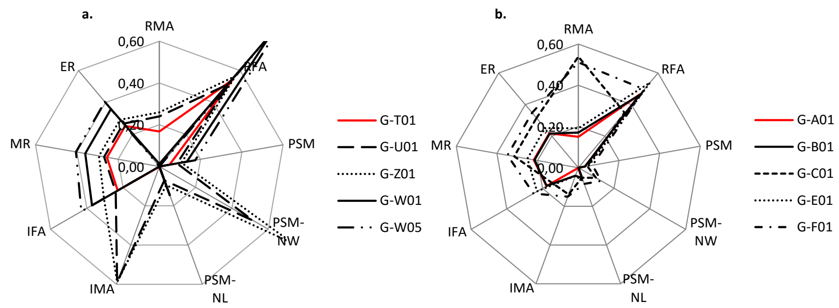


Figure 5.5 Simulations for different cases of alert zone Guanabara, G_T1 to G_W5 (see Table 9 for the input parameters used for the Events analysis): values of all the performance indicators related to errors of the warning model, grouped to highlight the effect of parameters $L_{den(k)}$, and L_{typ} (a) and parameters Δt_{LE}, t_{LEAD} and t_{OVER} (b) (Calvello and Piciullo, 2016).

Table 5.5 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

5.2 NORWAY

5.2.1 The events analysis phase for variable warning zones

In Calvello & Piciullo 2015 and Piciullo et al. 2016, the EDuMaP method has been applied to analyse the performance of regional landslide early warning systems adopting a fixed spatial discretization for warnings, $\Delta A_{(k)}$. Differently, the Norwegian landslide early warning system works by issuing daily alerts for variable warning zones. This characteristic influences the event analysis phase of the EDuMaP method. The following approach explains how to define landslide events (LEs) and warning events (WEs) and how to evaluate model performance in case of variable warning zones.
The area of analysis is composed by four regions located in the Norwegian west-coast: Rogaland, Hordaland, Sogn og Fjordane and Møre og Romsdal. In the period of analysis 2013-2014 a total number of 385 rainfall-and snowmelt-induced landslides occurred (Fig. 5.6). The 64% of the occurrences (254 out of 385) have been classified as landslide in soil, not well specified, they can be debris avalanche, debris flow or earth slide (Varnes 1978), but not enough information were available for an adequate categorization. The 19% (74 out of 385) of all the landslide occurred in the period of analysis (Tab. 5.6) were debris slide/debris avalanche which are difficult to categorize if the slide has developed from slide to avalanche. The remain landslides were debris flow (7%), soil slide/debris slide (5%) and slush flow (5%).

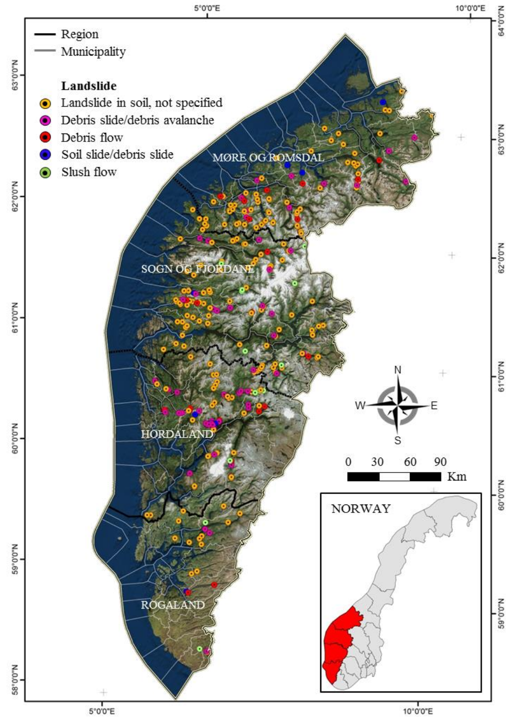


Figure 5.6 Location and classification of rainfall-and snowmelt-induced landslides occurred in Rogaland, Hordaland, Sogn og Fjordane and Møre og Romsdal in the period of analysis 2013-2014.

Table 5.6 Classification of rainfall-and snowmelt-induced landslides occurred in Rogaland, Hordaland, Sogn og Fjordane and Møre og Romsdal in the period of analysis 2013-2014.

Type	n°	%
Landslide in soil, not specified	245	64
Slush flow	19	5
Soil slide/debris slide	20	5
Debris slide/debris avalanche	74	19
Debris flow	27	7
Tot.	385	

The Norwegian landslide early warning system uses municipal administrative area as minimum territorial units (TU) for warning purpose. For alert purposes the Municipalities with the same warning level are grouped together, thus defining a larger warning zone of warning level i^{th}. The Norwegian landslide early warning system is based on four warning levels. Therefore, in a given day of alert, up to 4 warning zones can be alerted (Fig. 5.6), each one with a different warning level i^{th}. In this circumstances LEs and WEs need to be defined per warning zone and day of alert. As figure 5.6 clarifies using a syntetic example, LEs are defined grouping together landslides occurred within a territory alerted with the same warning level i^{th}, i.e. warning zone. For instance, in "day 1" two distinct landslide events have been identified, composed respectively by 4 and 1 landslides. The first belongs to the warning zone alerted with level 2 and the latter to the warning zone alerted with level 1. In "day 3" there are 4 warning zones, each one alerted with a different level of warning. In this case 4 distinct LEs can be defined, one per warning zone. The class LEs belong to, as defined in section 3.2, depends by the landslide density criterion, $L_{den(k)}$, chosen for the analyses.

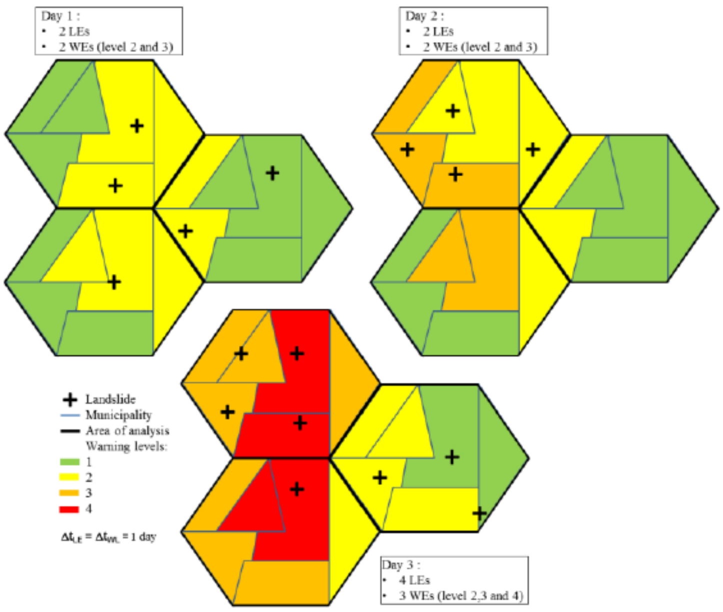


Figure 5.7 Identification of warning zones and classification of WEs and LEs for three hypothetical days of warnings: a. Day 1, b. Day 2, c. Day 3.

As previously discussed, the events analysis phase of the EDuMaP method depends on the values assumed by a series of well-identified parameters, which are defined to allow the analyst to make choices on how to select and group landslides and warnings.
Table 5.7 shows, in relation to the base case of the analyses performed for this case study (A-$C_{0,14}$), the ten input parameters needed to define landslide and warning events. It adequately represents the structure and the operative procedures of the warning model employed in the Norwegian national landslide early warning system. The period of analysis, ΔT, is 2013-2014, the temporal discretization of analysis, Δt, is equal to 1 day. Parameters t_{LEAD} and t_{OVER} are both set equal to zero. The four warning levels, W_{lev}, are: green (no warning), yellow (level Medium), orange (level High), red (level Very High). All rainfall- and snowmelt-induced landslides present in the database are used for the analyses and grouped into landslide events considering a Δt_{LE} of 1 day. The four classes LEs are defined with a fixed landslide density criterion, $L_{den(k)}$, which, in accordance with table 1, considers the occurrence of 1 to 3 landslides as a small LE (class S), 4 to 13 landslides as an intermediate LE (class I) and more than 13 landslides as a large LE (class L).

Table 5.7 Event analysis parameters for case A-$C_{0,14}$, that adequately represents the structure and the operative procedures of the warning model employed in the landslide early warning operative in Norway

	A-$C_{0,14}$
W_{lev}	4
$L_{den(k)}$	4 – Absolute criterion
t_{LEAD}	0
L_{typ}	Rainfall-and snowmelt-induced
Δt_{LE}	12
t_{OVER}	0
A	4 Regions on the Norwegian west coast
$\Delta A_{(k)}$	variable
ΔT	2013-2014
Δt	1 day

In 2013-214, in the 4 regions of the Norwegian west-coast considered as case study, 385 landslide phenomena occurred (see section 3.1) and 137 landslide events have been defined. The majority belong to a LE class

"Small" (124 out of 137), 9 to class "Intermediate" and 4 to class "Large". The alerts were 60, but no warnings "Very high" have been issued, just 5 warning zones received the warning level "High" and 45 zones have been alerted with the warning level "Medium". In the period of analysis 37 different warning zones have been alerted (Tab. 5.8).

Table 5.8 Number of landslide, LEs, warnings issued and warning zones alerted in 2013-2014 in the area of analysis.

	Number
Landslide	385
Landslide events	137
Alerts issued	60
Warning zones alerted	37

5.2.2 The Duration matrix phase for variable warning zones

The class definition for landslide events (LEs) and warning events (WEs) establishes the duration matrix structure. 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 evaluation of time associated with the occurrence of landslide events (LE) in relation to the occurrence of warning events (WE) in their respective classes is a fundamental step to determine the duration matrix elements, $time_{ij}$. The $time_{ij}$ is the amount of time of a warning events of class i^{th} is concomitant with a landslide event of class j^{th} in a certain period of analysis, ΔT (see Eq. 5.1). In Calvello & Piciullo, 2016 and Piciullo et al., 2016, the d_{ij} components of the duration matrix are computed for a fixed warning zone. Conversely, for the landslides early warning operative in Norway, performance is evaluated for the whole area of analysis, A, in a period of analysis, ΔT, summing the $time_{ij}$ for different warning zones in the same duration matrix.
The landslide early warning system operative in Norway produces daily alerts for up to 4 variable warning zones alerted with different warning levels. Therefore the day is the minimum temporal discretization adopted to analyse this early warning system. The $time_{ij}$ are computed for each warning zone as ratio among the sum of areas of territorial units alerted with the same i^{th} warning level on the total area of analysis (Eq.

5.2). Each element of the duration matrix, d_{ij}, is then computed, within the time frame of the analysis, ΔT, as follows:

$$time_{k,ij} = \Delta t * \frac{(TUA_{k,ij})}{A} \quad \forall k \in A \qquad \forall \Delta t \in \Delta T \qquad \text{(Eq. 5.1)}$$

$$d_{ij} = \sum_{\Delta T} \sum_{k} (time_{k,ij}) \qquad \text{(Eq. 5.2)}$$

where: $time_{ij}$ is amount of time for which a level i^{th} warning events is concomitant with a class j^{th} landslide event in a certain warning zone *k*; Δt is the minimum temporal discretization, in this case equal to 1 day; A is the area of analysis; TUA_{ij} is the territorial unit area for which the level of the warning event is equal to *i* and the class of the landslide event is equal to *j*.

To further clarify how the duration matrix elements have been computed, Figure 5.8 reports a synthetic analysis, exemplifying the $time_{ij}$ evaluation for each warning zone for hypothetical three days of alert and landslide phenomena. Landslide events have been identified for each warning zone hypothesizing a fixed landslide density criterion, $L_{den(k)}$, with 4 classes: no landslide (1), "small" (2), "Intermediate"(3), "Large"(4) respectively for LEs composed by 1 to 2, 3 to 4 and 5 or more landslides. Four are the warning levels considered. In "day 1"(Fig. 5.8a) two different warning zones are alerted with two warning levels, the first is composed by 8 territorial units and the second by 1. In the first and second zones, respectively, a WEs of class 1 and 2 are issued and LEs "small" (2) and "intermediate" (3) occurred. Once defined the warning and landslide events per warning zone, $time_{12}$ and $time_{23}$ are evaluated as a function of the territorial units areas alerted respectively with warning level 1 and 2. The previous consideration can be applied for "day 2" and "day 3" of alert in figure 5.8, to evaluate the $time_{ij}$. The methodology, structured to evaluate the elements d_{ij}, follows the duration matrix main characteristic, i.e. the sum of all elements, $\sum_{ij} d_{ij}$, is equal to the time frame of the analysis, *ΔT*.

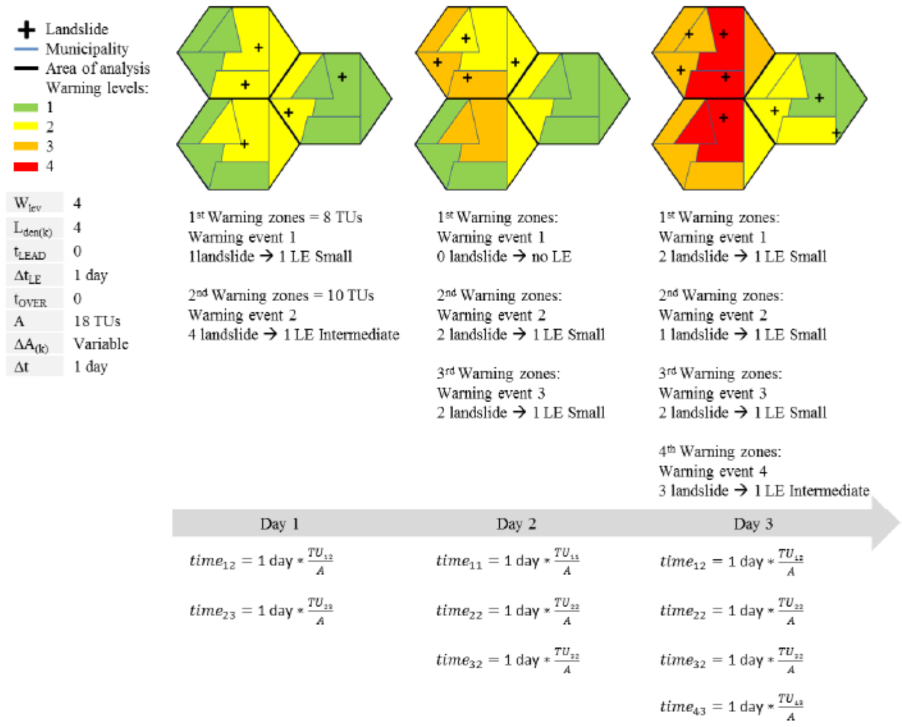


Figure 5.8 Computation of $time_{ij}$ elements as a function of WE and LE occurred per each warning zone for three hypothetical days of warning as defined in figure 5.7.

5.2.3 Performance evaluation for the years 2013-2014: criteria and indicators

The EDuMaP method has been applied to analyse the performance of the landslide early warning system of 4 regions located on the Norwegian west-coast for the period of analysis 2013-2014 (Fig. 5.6). Once defined the warning zones which have been alerted, landslide (LEs) and warning events (WEs) and, consequently, the duration matrix elements d_{ij} have been evaluated. The evaluation of the duration matrix is based on the same set of performance criteria and parameters used in the previous case study (see Tab. 5.7). In particular, two sets of performance indicators have been derived from two performance criteria to quantify successes and errors of the early warning models.

The duration matrix obtained for the case A-$C_{0,14}$ is shown in figure 4 in terms of criterion A and B, respectively derived from a 2x2 contingency table and a color-code structure. The sum of matrix elements is equal to 730 days, which represents the amount of time, expressed in days, of the period of analysis, i.e. years 2013-2014.

	no	*S*	*I*	*L*
no	*600,48*	*105,62*	*2,00*	*0,00*
M	*10,24*	*5,57*	*2,17*	*2,18*
H	*0,00*	*0,58*	*0,58*	*0,58*
VH	*0*	*0*	*0*	*0*

Figure 5.9 Duration matrix for case A-$C_{0,14}$.

The results obtained for criterion A (Fig. 5.10a) show a high percentage of true negatives (TNs), 94%, and around 5% of missed alerts (MAs). Following criterion B (Fig. 5.10b) a low percentage of red (3,7%) and purple errors (1,7%) and 90% of yellows are observed. Figure 5.10c depicts the duration matrix results as percentage of CAs, FAs, MAs and TNs expressed in terms of colour code criterion. The 94% of TNs is mainly composed by yellows and around 34% of MAs are composed by purple errors. The percentage of CAs and FAs are low compared to TNs, respectively 0,9% and 0,4% and for the latter, purple errors are not observed.

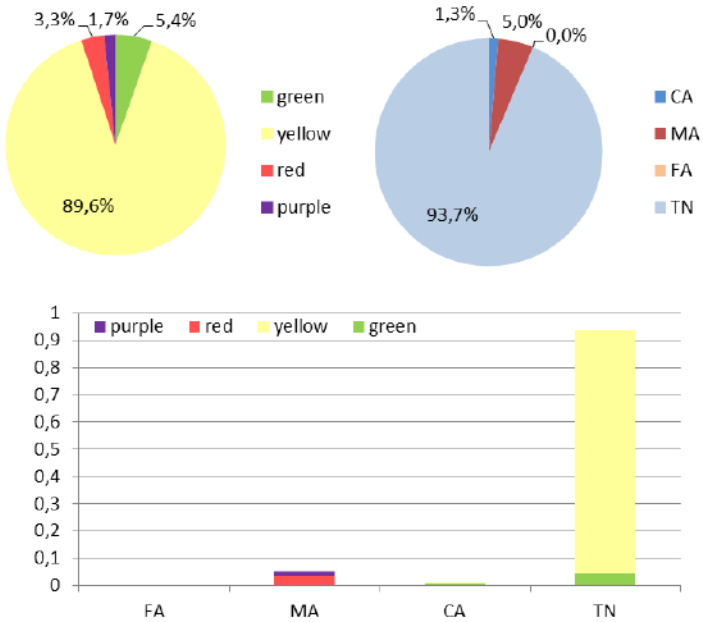


Figure 5.10 Duration matrix results in terms of: a. color code criterion; b. contingency table identifying CAs, FAs, MAs and TNs; c. percentage of CAs, FAs, MAs and TNs expressed in terms of colour code criterion.

The performance indicators used to analyse the duration matrix and to evaluate the early warning model performance are shown in terms of name, symbol, formulas and values in table 5.9. The performance indicators are grouped into 2 sub-sets evaluating successes and errors (Fig. 6. a, b). Success indicators show a high percentage of I_{eff}, around 95%, mainly due to the high value of TNs mainly composed by yellows (90%). The PPw is evaluated as the rate between CA durations and the amount of time of emitted alerts and it reaches the 67%. The HR has a quite low percentage (15%) compared to I_{eff} and PPw. It represents the warning model capability of detecting LE of class Intermediate (I) and Large (L), avoiding MAs. The low values of HR and TS (14%) together with the high percentage of R_{MA} (85%) underline that the MAs negatively influence the performance analysis, stressing a low capability of the warning model in detecting LEs of class I and L. Moreover the I_{MA} specifies that 34% of MAs are characterized by purple errors.

Table 5.9 Performance indicators used for the analysis.

Performance indicator	Symbol	Formula	Value
Efficiency index	I_{eff}	$(CA+TN)/\Sigma_{ij}d_{ij}$ (excluding d_{11})	95%
Threat score	TS	CA/(CA+MA+FA)	14%
Predictive power	PPW	CA/(CA+FA)	67%
Hit rate	HR_L	CA/(CA+MA)	15%
Odds ratio	OR	(CA+TN)/(MA+FA)	18
False alert rate	R_{FA}	FA/(CA+FA)	33%
Missed alert rate	R_{MA}	MA/(CA+MA)	85%
Probability of serious mistakes	P_{SM}	Pur/Σijdij (excluding d11)	2%
Probability of serious no-warning mistakes	$P_{SM\text{-}NW}$	Pur_{i4}/Σijdij (for i=1, j=2-4)	0%
Probability of serious no-landslides mistakes	$P_{SM\text{-}NL}$	$Pur/\Sigma_{ij}d_{ij}$ (for i=2-4, j=1)	0%
Index of severity of missed alerts	I_{MA}	(Pur&MA)/MA	34%
Index of severity of false alerts	I_{FA}	(Pur&FA)/FA	0%

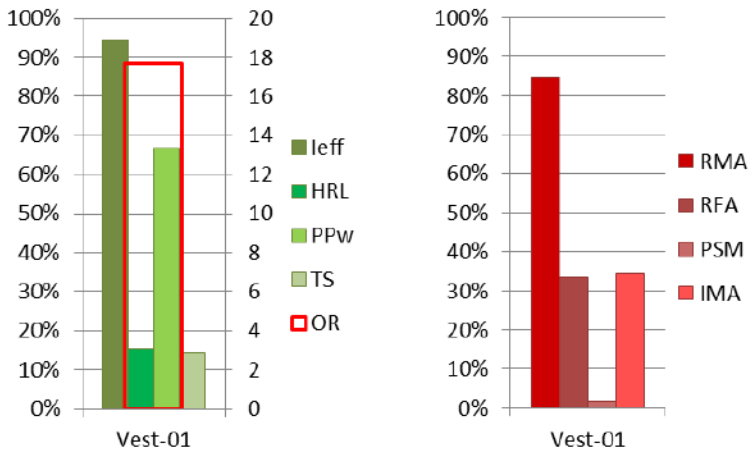


Figure 5.11 Distinct performance indicators subsets quantifying the landslide early warning performance in terms of: a., successes and b., errors.

In this performance analysis the high value of I_{eff}, (95%), could be interpreted as an excellent result but, in contrast, the high values of R_{MA} and I_{MA} point out the presence of some issues related to the missed alert quadrant of the duration matrix and to the purple errors. In conclusion the performance analysis suggests to decrease the thresholds employed to activate the warning level "High" with the aim of reducing MAs and purple errors and simultaneously increase CAs and the greens, which contribute to obtain a better warning model performance. It is relevant to underline the importance of assessing both success and error performance indicators. Indeed, as in this case, dealing with some indicators neglecting others could cause a wrong evaluation of the early warning model performance.

5.2.4 Parametric analysis: landslide density

The parametric analysis conducted herein has a twofold purpose: to compare the performance of the early warning model varying the landslide density criterion, $L_{den(k)}$; to evaluate the effect of the choices the analyst needs to make to define landslide events (LE) classes on the performance indicators computed according to the EDuMaP method. The landslide density, $L_{den(k)}$, represents the criterion used to differentiate among *n* classes of landslide events. The classes may be established with an absolute (A) or a relative (R) criterion, i.e. respectively defining the number of landslide for each class or a spatial density in terms of number of landslides per area. Six combinations of landslide density criterion have been considered, 2 of which refer to an absolute criterion and 4 to a relative one (Tab. 5.10). The combinations for the absolute criterion have a different interval of landslides per LE class (A-$C_{0,14}$ and A-$C_{1,18}$). Moreover the spatial density, of the four combinations considered for the relative criterion, vary as a function of both number of landslides and territorial extensions (10'000 and 15'000 km^2). For all 6 combinations the other event analysis parameters are kept unchanged and assumed equal to those considered for the base case simulation A-$C_{0,14}$ (Tab. 5.9), because they adequately represent the structure and the operative procedures of the warning model employed within the Norwegian landslide early warning system.

Table 5.10 Six combinations of the landslide density criterion considered to classify the landslide events.

LE class	Absolute criterion [No. of landslides]		Relative criterion [No. of landslides / Area]			
	A-$C_{0,14}$	A-$C_{1,18}$	R15-$C_{0,14}$	R15-$C_{0,10}$	R10-$C_{0,14}$	R10-$C_{0,10}$
0	0	1	0	0	0	0
SMALL	1 to 4	2 to 4	(1 to 4)/15'000 km²	(1 to 4)/15'000 km²	(1 to 4)/10'000 km²	(1 to 4)/10'000 km²
INTERMEDIATE	5 to 14	5 to 18	(5 to 14)/15'000 km²	(5 to 10)/15'000 km²	(5 to 14)/10'000 km²	(5 to 10)/10'000 km²
LARGE	> 14	> 18	> 14/15'000 km²	> 10/15'000 km²	> 14/10'000 km²	> 10/10'000 km²

Keeping unchanged the parameters of the events analysis phase, but changing the definition of LE classes, the duration matrix and the performance indicators also vary because a redefinition of the d_{ij} components occur. In particular the $time_{ij}$ element, which is the amount of time for which a level i^{th} warning events is concomitant with a class j^{th} landslide event, may vary the j^{th} index causing a movement of the element along the i^{th} row.
As an example, the combinations R15-$C_{0,10}$ and R15-$C_{0,14}$ differ only for the spatial density threshold used to differentiate between "Intermediate" and "Large", LEs. Comparing the results of the duration matrices (Tab. 5.11a,b) a shift 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 the spatial density for LE class "Large", from 0,67 landslides per 1000 km^2 to 0,93 landslides per 1000 km^2 (Tab. 5.11a,b), which causes a relocation of $time_{i4}$ along the rows. For the combinations R15-$C_{0,14}$ and A-$C_{0,14}$ a change of all the values defining the LE classes is observed. In this case a change in each cell of the matrix can indeed be expected.

Table 5.11 Duration matrix results for the landslide density criterion combinations: a. R15-$C_{0,10}$; b. R15-$C_{0,14}$; c. A-$C_{0,14}$.

R15-$C_{0,10}$		**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

R15-$C_{0,14}$		**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

A-$C_{0,14}$		**LE duration (h)**			
		1	2	3	4
WE duration (h)	1	600,48	105,62	2,00	0,00
	2	9,88	5,79	2,30	2,18
	3	0,00	0,00	1,16	0,58
	4	0,00	0,00	0,00	0,00

These results clarify how duration matrix may change according to the landslide density criterion variation. Consequently also the values of the performance indicators are subject to change. Table 5.12 presents a summary of all the 6 combinations of landslide density criterion analysed in terms of performance indicators.

The values of performance indicators (Tab. 5.12) substantially highlight a similar performance for all the relative criteria adopted (R15-$C_{0,14}$ R15-$C_{0,10}$ R10-$C_{0,14}$ R10-$C_{0,10}$). The values for efficiency index (I_{eff}) and predictive power (PP_W) do not change and they are respectively 98% and 33%. The hit rate (HR) and threat score (TS) slightly change, varying respectively from 24% and 16% for R15-$C_{0,14}$ and R15-$C_{0,10}$ to 29% and 18% for R10-$C_{0,14}$ and R10-$C_{0,10}$. Ultimately, the results of the six analysed landslide density criteria are almost equal in pairs, when the success performance indicators are considered (Fig. 5.12). The results for R15-$C_{0,14}$ are equal to R15-$C_{0,10}$ as for R10-$C_{0,14}$ and R10-$C_{0,10}$. Similar comments can be made when looking at the error performance indicators, except for R15-$C_{0,10}$ which shows 46% of severity of false alerts. It means that half of the false alerts are composed by purple errors. This is due to the density criterion considered for R15-$C_{0,10,}$ which defines the lowest density for LEs of class "large" of all 6 combinations (Tab. 5.10). For this reason, some LEs change their class from "intermediate" to "large" and the time durations, related to these LEs, fill the matrix cell of component $d_{2,4}$ which correspond to purple error in the false alert quadrant.

Table 5.12 Performance indicators for the 6 combination considered for the parametric analysis on the landslide density criterion.

Performance indicator	A-$C_{0,14}$	A-$C_{1,18}$	R15-$C_{0,14}$	R15-$C_{0,10}$	R10-$C_{0,14}$	R10-$C_{0,10}$
I_{eff}	0,95	0,86	0,98	0,98	0,98	0,98
HR_L	0,21	0,21	0,24	0,24	029	0,29
PP_W	1,00	1,00	0,33	0,33	0,33	0,33
TS	0,21	0,21	0,16	0,16	0,18	0,18
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}	0,79	0,79	0,76	0,76	0,71	0,71
R_{FA}	0,00	0,00	0,67	0,67	0,67	0,67
ER	0,05	0,14	0,01	0,01	0,01	0,01
P_{SM}	0,02	0,05	0,00	0,01	0,00	0,00
P_{SM-NW}	0,00	0,00	0,00	0,00	0,00	0,00
P_{SM-NL}	0,00	0,00	0,00	0,00	0,00	0,00
I_{MA}	0,34	0,34	0,00	0,46	0,00	0,00
I_{FA}	0,00	0,00	0,00	0,00	0,00	0,00

Significant differences can be found between the absolute and relative combinations. For this case study, the first ones show higher values of the predictive power (PP_W), lower values of odd ratio (OR) and missed alert rates (R_{MA}) slightly higher than those evaluated with a relative criterion. The false alert rate (R_{FA}) is equal to zero for the combinations employing the absolute criterion and is around 65% for the relative ones. The efficiency index (I_{eff}) is around 96% and it is lower for the combination A-$C_{1,18}$ (86%), because in this case the number of true negatives are lower than in other criteria.

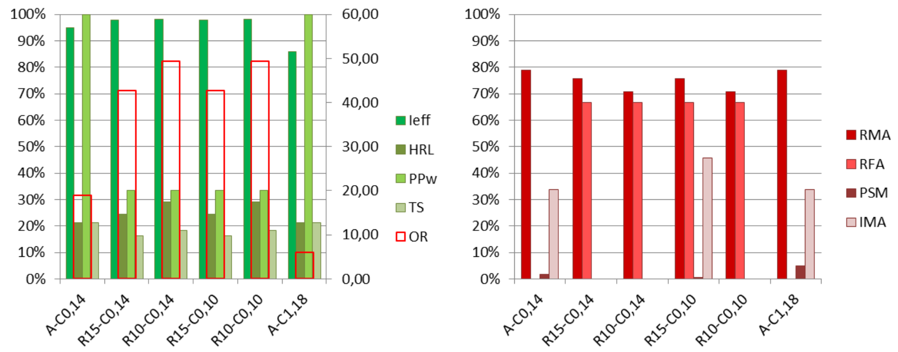


Figure 5.12 Performance indicators related to the a., success and to the b., errors of the warning model, evaluated for the 6 combinations considered for the parametric analysis conducted on the landslide density criterion.

5.3 CAMPANIA REGION, ITALY

5.3.1 Area of analysis and database for the years 2010-2013

The area of the case study, one of the eight warning zones defined by the system, includes the following hilly-mountainous areas: Lattari mountains, Avella-Pizzo d'Alvano massif, Picentini mountains (Fig. 5.13). The area covers 1619 km^2, it includes 110 municipalities, 60 rain-gauges and it is very susceptible to rainfall-induced shallow landslides and debris flows, mainly because of the presence of pyroclastic soil deposits on carbonate bedrock (Cascini et al., 2008).

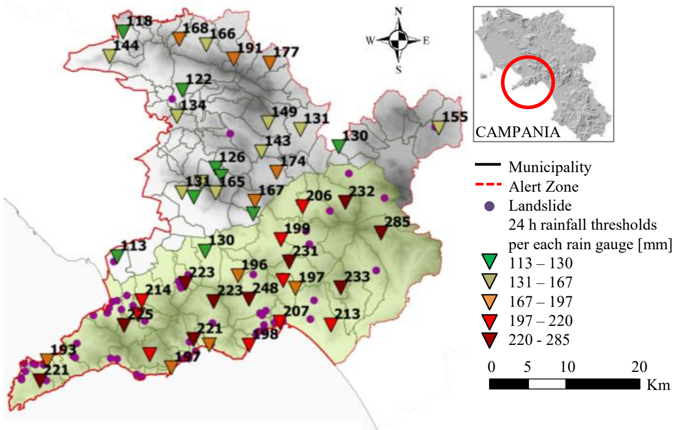


Figure 5.13 Area of analysis with indication of: sub-zones "north" and "south", rainfall-induced landslides recorded in 2010-2013, location and 24h thresholds of rain gauges.

The dataset used to analyze the case study includes rainfall measurements and information on landslide occurrences for the years 2010-2013. The rainfall measurements were derived from the regional civil protection agency database which reports the rainfall recorded at each rain-gauge every 10 minutes. The data on landslide occurrences were derived from the project "Franeitalia" (Calvello et al., 2013), an inventory of landslides in Italy retrieved from on-line journalistic sources. The information reported for each record of the landslide database always includes the number of landslides per rainfall event, the source of the news, the site of occurrence and the date of occurrence. Multiple landslides occurring in the same date, within the same province or region, are inventoried together in one single record of the database. For each record the database may also report, if the related information is available: hour of occurrence; landslide characteristics; activity phase; effects on people, structures, infrastructures, cars or other elements; links to related photos or videos. The database reports 2622 landslides in Italy for the years 2010-2013, 213 of which occurred in Campania region. The landslides reported within the zone chosen for the case study are 89, yet only 64 of them may be considered, on the basis of an evaluation taking into account the cumulative rainfall of the previous 72 hours, rainfall-induced phenomena (see Fig. 5.13).

As discussed in the previous chapter, warning levels are defined by comparing local pluviometric precursors (cumulated rainfall at 24, 48 and

72 hours) with rainfall thresholds defined considering three different return periods (2, 5 and 10 years). Based on an analysis of the rainfall thresholds defined for each warning level for the rain gauges installed in the study area, two relatively homogenous sub-zones are defined, herein called "north" and "south" (Figure 5.13). The north sub-zone covers 789 km^2, it includes 59 municipalities, 28 rain gauges and it shows the highest values of rainfall thresholds for all three return periods. The south sub-zone covers 830 km^2, it includes 51 municipalities and 32 rain gauges. In the period of analysis, 59 and 5 landslides occurred, respectively, within the south and north sub-zone. Three rain-gauges have been considered for the performance analysis conducted herein, two of them belonging to south sub-zone and one to north sub-zone. Table 5.13 reports the rainfall thresholds of the three rain gauges.

Table 5.13 Rainfall thresholds of the three rain gauges selected for the performance analysis.

	Cumulated rainfall (mm)		
	Attention	**Pre-alarm**	**Alarm**
Cava dé Tirreni (CdT)	105/24h, 135/48h, 156/72h	139/24h, 180/48h, 208/72h	166/24h, 214/48h, 248/72h
Agerola (A)	91/24h, 116 /48h, 133/72h	121/24h, 154/48h, 177/72h	144/24h, 183/48h, 211/72h
Mercogliano (M)	70/24h, 84/48h, 94/72h	94/24h, 113/48h, 125/72h	112/24h, 134/48h, 149/72h

As already mentioned, the vast majority of landslides occurred in the south sub-zone, yet the highest number of threshold exceedances is observed for the north sub-zone. The two rain gauges chosen for the south sub-zone are, respectively, the ones showing the highest (Agerola) and lowest (Cava dé Tirreni) value of hours of exceedances within this sub-zone; the third rain gauge (Mercogliano) is characterized by the overall highest value of exceedance time (Tab. 5.14) and it belongs to the north sub-zone.

Table 5.14 Rainfall thresholds of the three rain gauges selected for the performance analysis.

	Exceedance time (h)		
	Attention	**Pre-alarm**	**Alarm**
Cava dé Tirreni (CdT)	98	0	0
Agerola (A)	180	37	0
Mercogliano (M)	762	206	151

5.3.2 Performance evaluation

The EDuMaP method was applied to evaluate the performance of the rainfall thresholds of three rain gauges, two of them located in the south sub-zone, Agerola and Cava dé Tirreni, and one in the north sub-zone, Mercogliano (see also previous section). The values of the input parameters of the events analysis are shown in Table 5.15. The period of analysis, ΔT, is 2010-2013. The temporal discretization of analysis, Δt, is equal to 1 hour. Parameters t_{LEAD} and t_{OVER} are both set equal to zero. The four warning levels, W_{lev}, are: no warning (no), attention (level M), pre-alarm (level H), alarm (level VH). All landslides belonging to the database were used for the analyses and grouped into landslide events considering a Δt_{LE} of 12 hours. The four classes of landslide events (LEs) are defined with a fixed landslide density criterion, $L_{den(k)}$, which considers the occurrence of 1 to 2 landslides as a small LE (class S), 3 to 9 landslides as an intermediate LE (class I) and more than 10 landslides as a large LE (class L). Landslide phenomena have been grouped in LEs considering the two sub-zones (north and south) as different areas of analysis, A. Table 5.16 reports the number of the landslide events which occurred in the two sub-zones between 2010 and 2013. Most of the LEs can be classified as small LE and none of them can be classified as a large LE.

Table 5.17 shows the duration matrices computed for the three analyses, respectively conducted using the rainfall data and the thresholds related to the Agerola, Cava dé Tirreni and Mercogliano rain gauges. The LEs which occurred in the south sub-zone (i.e. associated to both Agerola and Cava dé Tirreni) have a total duration of 76 hours, with the following class distribution: 53 hours related to the occurrence of small LEs; 23 hours for intermediate LEs; none for large LEs. Whereas, the time computed for the five LEs recorded in the north sub-zone (i.e.

associated to Mercogliano) falls in one single element of the matrix, the one associated to a small LE with no warning issued. Cava dé Tirreni and Agerola also show, as expected, a relatively low number of hours associated to all the warning levels (i.e. WE class higher than 1). On the contrary Mercogliano shows a total of 357 hours associated to the highest two warning levels (i.e. WE levels 3 and 4) even if no intermediate or large LEs occurred in the north sub-zone during the period of analysis.

Table 5.15 Rainfall thresholds of the three rain gauges selected for the performance analysis.

	CdT	A	M
W_{lev}	4	4	4
$L_{den(k)}$	4	4	4
t_{LEAD}	0	0	0
L_{typ}	ALL	ALL	ALL
Δt_{LE}	12	12	12
t_{OVER}	0	0	0
A	south	south	north
$\Delta A_{(k)}$	fixed	fixed	fixed
ΔT	2010-2013	2010-2013	2010-2013
Δt	1 hour	1 hour	1 hour

Table 5.16 Number of landslide events, per LE class, recorded for the two sub-zones in the period 2010-2013.

Sub-zone	Small	Intermediate	Large
South	29	6	0
North	5	0	0

Figure 5.14 shows the results of the three analyses, considering the two classification criteria of the duration matrix previously proposed (see Section 3.1.3). For both criteria, the best results are obtained in the analysis carried out using the rain gauges belonging to south sub-zone. In particular, the use of the Cava dé Tirreni rain gauge allows the major errors–i.e. FA and MA for criterion A; Red and Pur for criterion B–never to exceed 15%. Differently, the analysis carried out on the north sub-zone using the Mercogliano rain gauge shows a higher rate of

false alerts (31%), half of which belonging to the worst model errors, i.e. purple errors for criterion B. This is due to the significant number of hours of alert issued for the highest warning levels when no landslide events occurred (see also Tab. 5.17). Finally, it's worth noting that none of the analyses reports a significant rate of correct alerts (criterion A) or best model response (criterion B). This was, however, to be expected given the absence of large landslide events and the relatively low number of intermediate landslide events, none of which occurred in the north sub-zone (see Table 5.16). The lack of correct alerts in the analyses also turns into a lack of significance for some of the performance indicators derived from the duration matrices, such as the hit rate.

Table 5.17 Duration Matrices for the three analyses: Cava dé Tirreni (CdT), Agerola (A), Mercogliano (M).

CdT		**LE duration (h)**			
		no	small	intermediate	large
WE duration (h)	no	34891	53	22	0
	M	97	0	1	0
	H	0	0	0	0
	VH	0	0	0	0

A		**LE duration (h)**			
		no	small	intermediate	large
WE duration (h)	no	34774	52	21	0
	M	177	1	2	0
	H	37	0	0	0
	VH	0	0	0	0

M		**LE duration (h)**			
		no	small	intermediate	large
WE duration (h)	no	33920	5	0	0
	M	782	0	0	0
	H	206	0	0	0
	VH	151	0	0	0

The performance indicators computed for the three analyses are shown in Figure 5.15 and Table 5.18. Both the positive and the negative indicators coherently point at the analysis conducted on the south sub-zone using the Cava dé Tirreni rain gauge as the best one. For instance, the high value of odds ratio reported for Cava dé Tirreni is due to both the higher true negatives and to the lower ER values obtained in this analysis in relation to the analyses referring to the other two rain gauges. On the contrary, the results of the analysis conducted on the Mercogliano rain gauge produce a high value of the index of severity of false alerts, IFA, which is equal to zero for the other two analyses. Finally, it is worth noting that the efficiency index, Ieff, a function of both true negatives and correct alerts, practically coincides, in all the analyses, with the percentage of true negatives (reported in Figure 5.14).

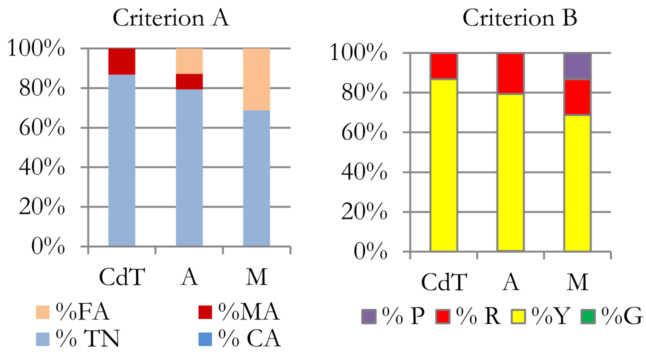


Figure 5.14 Relative distribution of the terms of the duration matrices from Table 5.17 considering the two classification criteria proposed.

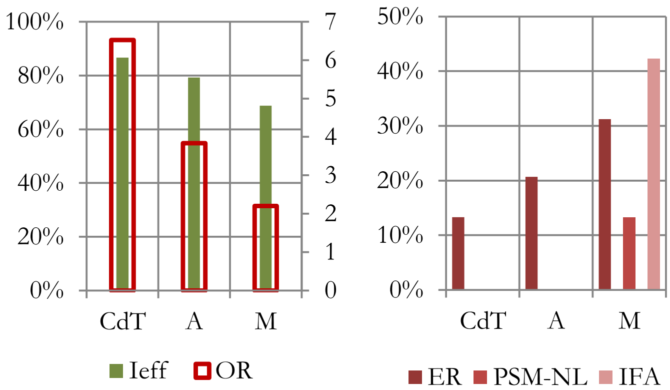


Figure 5.15 Relative distribution of the terms of the duration matrices from Table 5.17 considering the two classification criteria proposed.

Table 5.18 Performance indicators values for the three analyses: Cava dé Tirreni (CdT), Agerola (A), Mercogliano (M).

Performance indicator	CdT	A	M
I_{eff}	0,87	0,79	0,69
HR_L	0,00	0,00	0,00
OR	6,52	3,83	2,20
MR	0,13	0,21	0,31
R_{MA}	1,00	1,00	1,00
ER	0,13	0,21	0,31
P_{SM-NL}	0,00	0,00	0,13
I_{FA}	0,00	0,00	0,42

2.1.1 A proposal of rainfall thresholds calibration

The calibration herein proposed employs the EDuMaP method to maximize the performance of a warning model created using one of three rain gauges previously reported, Agerola, by varying the thresholds of the local pluviometric precursors (see Tab. 5.13). To this aim, two parametric analyses have been conducted, respectively varying by a fixed percentage: all three thresholds at once; only the second threshold of the warning events, i.e. from attention (class M) to pre-alarm (class H). For each simulation, a duration matrix has been evaluated and the related performance indicators calculated, employing both criteria A and B.
For the first parametric analysis, the rainfall intensity thresholds of the three warning levels have been increased and decreased using a percentage step of 10%. Figure 5.16 reports the results of the analysis for both performance criteria. The best performance in the considered period of analysis is obtained by increasing the model threshold values by 10%, simulation for which the highest value of I_{eff} (90%) and the lowest value of ER (11%) are observed. It is also important to underline that no correct alerts are detected by this simulation, given that all the 6 LEs of class I are missed (missed alert ratio equal to 10%). When the rainfall thresholds are increased by more than 10%, the FAs are equal to 0 and the hours of MAs remain constant, yet their value increases percentagewise because the hours of TNs decrease. This is due to the transition of some hours in the d_{11} cell of the duration matrix, which is neglected in both adopted performance criteria. When the thresholds are decreased, some of time associated to class I LEs moves along the third column of the duration matrix increasing the CAs while the MAs

decrease. Consequently the HR, which is the rate of CAs over the sum of CAs and MAs, increases (up to 65%); yet, also the FA rate increases substantially (up 41%), which thus explains the computed lower efficiency of these simulations.

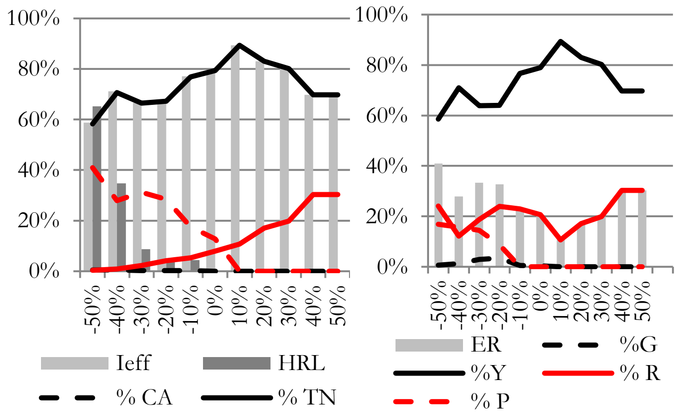


Figure 5.16 Results of the parametric analysis on the Agerola rain gauge conducted varying all three thresholds at once: performance indicators for criteria A and B.

For the second parametric analysis, whose results are reported in Figure 5.17, only the second threshold (from attention to pre-alarm) is varied, using a percentage step of 5%. In this case, when the warning threshold is decreased, some of the time in the duration matrix associated to LEs, belonging to all the four LE classes, moves from WE level M to level H, potentially increasing both the FA and the CA ratios. By reducing the thresholds, the following can be observed: many hours of TNs move into the WE level H, increasing the hours of FAs; not a significant increase of CAs is recorded, mainly because a very low number of hours is associated to intermediate LEs classified and none to large LEs. When the thresholds are increased, the matrix rows for WE levels H and VH assume null values, thus the performance indicators of both criteria, A and B, remain constant. The threshold boundaries of the analysis, corresponding to ±20% of the original thresholds, coincide with the warning level thresholds M (from no warning to attention) and VH (from pre-alarm to alarm).

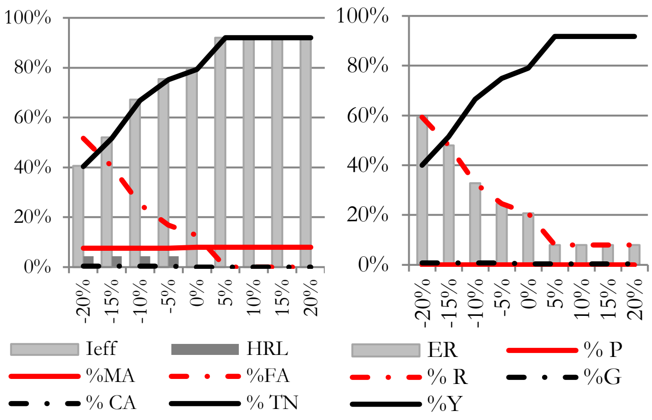


Figure 5.17 Results of the parametric analysis on the Agerola rain gauge conducted varying the attention to pre-alarm threshold: performance indicators for criteria A and B.

6 CONCLUSIONS

The continuous urbanization process in areas with a high susceptibility of natural hazards and the occurrence of high intensity atmospheric phenomena have dramatically increased, in many parts of the world, the losses and damage related to such hazards. Several measures can be applied to reduce the risk for human life associated to the occurrence of hazardous events; among them, early warning systems (EWSs) are an important and often used non-structural risk mitigation measure. Among the various natural hazards EWSs deal with, the attention has been herein focused on landslide early warning systems (LEWSs) and in particular on landslide warning systems operating at regional scale, herein referred to as ReLEWSs. An important distinction among LEWSs can be done on the basis of the scale of analysis in "local" and "regional" systems. The differences among the two systems mainly consist in: monitoring instrumentation, modeling phase, actors, types of alerts emitted. ReLEWSs are used to assess the probability of occurrence of landslides over appropriately-defined homogeneous alert zones of relevant extension, typically through the prediction and monitoring of meteorological variables, in order to give generalized warnings to the population. The review on the structure and functioning of ReLEWSs lead to the definition of a scheme describing the main components necessary to practically deploy the systems. 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 (REs) and landslide events (LEs) eventually including other relevant monitored variables. A regional landslide warning model (ReLWaM) includes the regional correlation law as well as the decisional algorithm, which defines: the number of warning levels to be considered in the model; decision making procedures to issue the warnings; everything else necessary to define warning events (WEs) for the period the system is operational. A ReLEWS includes the regional warning model and the warning management, which is composed by the following components: monitoring and warning strategy; communication strategy; emergency plan. Among the ReLEWSs reviewed herein only in few cases the performance of the system is evaluated; however, also in those case, the performance analysis is based on a rather subjective interpretation of the joint frequency distribution of landslides and warnings, principally considered as dichotomous variables. Moreover, in all cases, 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. To overcame these issues, the technical performance of the model employed in ReLEWS, was herein assessed through the introduction of the "Event, Duration Matrix, Performance" (EDuMaP) method. The EDuMaP method comprises the following three successive steps: 1) Events analysis, i.e. identification of landslide events and warning events derived from available landslides and warnings databases; 2) definition and computation of a Duration Matrix, whose elements report the time associated with the occurrence of landslide events in relation to the occurrence of warning events, in their respective classes; 3) evaluation of the early warning model Performance by means of performance criteria and indicators applied to the duration matrix computed in the previous step. The main innovations introduced by the EDuMaP method, in relation to procedures 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 10 input parameters;
- the evaluation of the correlation between landslide and warning events is based not on counting the pairs on which the two data sets agree or disagree but rather on computing the temporal duration of the agreement/disagreement;
- the correspondence between landslide and warning events is expressed not as a 2 by 2 contingency table 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 performance is assessed considering not only false and missed alerts but a series of success and error indicators.

The EDuMaP method can be easily adopted to evaluate the performance of any regional landslide early warning systems for which landslides and warnings data are available. The EDuMaP method was herein applied to three real case studies, related to ReLEWSs operating in different areas of the world, to prove its technical applicability and adaptability to ReLWaMs characterized by different decisional algorithms, components and input parameters. The considered test areas are: the municipality of Rio de Janeiro in Brazil; the Vestlandsel area of Norway; the Campania region in Italy.

Main issues investigated through the EDuMaP method

The main issues investigated in this work differ in the three case studies considered herein. The LEWS operational in Rio de Janeiro (Brazil) is employed to issue a certain level of warning in four warning zones in which the municipality is divided. The warnings can be issued at any time during the day if the monitored rainfall exceed pre-identified thresholds. Four years from 2010 to 2014 of landslides and warnings data, gathered by the managers of the systems at the GEO-Rio foundation, have been considered to evaluate the performance of the system and to conduct a parametric analysis on the 10 input parameters used in the first phase of the EDuMaP method. Differently from the ReLEWS operational in Rio de Janeiro, the Norwegian landslide early warning system is employed to issue daily warnings adopting a variable spatial discretization for warnings. This feature influences the event analysis phase of the EDuMaP method. The approach applied in this work, clarifies how landslide events (LEs), warning events (WEs) and the model performance need to be evaluated when variable warning zones are adopted. Two years of data, 2013 and 2014, have been used for the performance analysis of this system. Furthermore, a parametric analysis was carried out to compare the performance of the early warning model as a function of the landslide density criterion adopted to define the LEs. In the LEWS of the Campania region (Italy) each municipality has a reference rain gauge with different rainfall thresholds for the activation

of 3 warning levels. In this case, the event analysis phase was carried out considering landslide and warning databases from 2011 to 2013, within a case study area coincident with one of the eight Alert Zones in which the Campania Region is divided. Three rain gauges have been selected in the area of analysis and the effect, in terms of performance, that rainfall thresholds variations have on a landslide early warning model on the whole Alert Zone has been investigated.
In all the case studies analyzed two performance criteria have been considered for the analyses. The first criterion is defined in accordance to a standard alert classification scheme derived from a 2 by 2 contingency table, thus identifying correct alerts, false alerts, missed alerts and true negatives. The second criterion is defined by assigning a color code to the elements of matrix, from green to purple, in relation to their grade of correctness. Both criteria purposefully neglect the duration matrix element d11, whose value is typically orders of magnitude higher than the values of the other elements. Other criteria could be usefully adopted to assess the results of a duration matrix. It is important to highlight, however, that a reasonable performance criterion should always keep the latter assumption adopted herein. Indeed, if a criterion does consider the value of the element d11, the resulting performance indicators would be positively "biased" for obvious reasons (i.e., rainfall-induced landslides do not occur when it does not rain).

Test area No.1: Rio de Janeiro, Brazil

A sensitivity analysis, varying the 10 input parameters considered for the first phase of the EDuMaP method, was conducted using four years of landslides and warnings data. Several simulation have been carried out varying more than one parameter at a time. The input parameters most affecting the results of the events analysis and, thus, the value of the duration matrix elements for the different simulations, are: i) the landslide density criterion, $L_{den(k)}$, used to differentiate among the classes of landslide events; ii) the database on landslides considered in the simulations; iii) the time set as the minimum time interval between landslide events, Δt_{LE}; iv) the area of analysis, A; v) the time frame of the analysis, ΔT. In particular the relative landslide density criterion, $L_{den(k)}$ considered, did not lead to a good model performance when the number of landslides per unit area was 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 occurs outside the most susceptible area; but it is mainly due to the thresholds adopted for warnings, which more adequately represent a landslide density computed over the whole alert zone. Another sensitive parameter substantially influencing the model performance is the time interval, Δt_{LE}, used to identify the number of landslides to be included 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, and thus some time intervals are misleadingly accounted for as serious missed alerts. Finally, as expected, the performance assessment has proved to be very sensitive to the number of data used, mainly function of the two parameters defining the type of landslides, L_{typ}, and the time frame of the analysis, ΔT. Of course, the results of the performed analysis cannot be easily generalized. This is true for a number of reasons: they have to be considered specific of the warning model adopted by the Rio de Janeiro early warning system; ; the time for which both landslides and warnings data are available is relatively short; not all the input parameters were tested in the parametric analysis.

Test area No.2: Vestlandet, Norway

The EDuMaP method has been applied to analyse the performance of the landslide early warning system for 4 regions located on the Norwegian west-coast for the period of analysis 2013-2014. This LEWS is characterized by daily alerts issued for variable warning zones. The applicability of the EDuMaP method to early warning systems considering a variable spatial discretization for warnings has been assured by the definition of a specific algorithm for the evaluation of the timeij elements of the duration matrix in each day of alert. A parametric analysis was also conducted with the aim of evaluating the model performance sensitivity, varying the landslide density criterion, $L_{den(k)}$. The latter represents the way landslide events are differentiated in n classes, which define the number of columns of the duration matrix. The classes were established considering an absolute and a relative criteria, i.e. respectively defining the number of landslide for each class or a spatial density in terms of number of landslides per area. As in the previous case study, also in this case the best performance results are associated, both for absolute and relative criteria, to smaller numbers of landslides defining the LE classes. More generally, the parametric analysis highlighted how varying the numerical interval of LE classes affects the performance by means of a transition of the timeij elements along the rows of the duration matrix. Finally, a comparison in terms of success and error indicators highlighted: a substantial variation of the positive predictive power (P_{Pw}), which reaches the maximum value for the absolute criteria; high values of both missed alert rate (R_{MA}) and false alert rate (R_{FA}) reached for the relative criteria.

Test area No.3: Campania region, Italy

For the Campania region case study the analyses were conducted using landslide and warning data from 2011 to 2013, within a test area coincident with one of the eight Alert Zones of the Campania Region. Three rain gauges with different thresholds for the activation of 3 warning levels have been considered. The results seem to indicate that rainfall measurements alone are not sufficient, in this case, for a reliable prediction of landslide occurrence. It is also important to underline, however, that the database plays an important role in the performance evaluation, as not many hours of LEs occurred in this case in the period of analysis. Two different parametric analyses were also conducted for one of the three considered rain gauges, varying the threshold adopted for the activation of the warning levels. The first time by changing the rainfall thresholds of all warning levels, the second time by varying only one warning level threshold. These analyses highlight some of the possibilities that managers of warning systems have to calibrate the thresholds adopted for warning levels, i.e. to choose the solution which maximizes the positive performance indicators (e.g., I_{eff}, H_{RI}) and minimize the negative ones (e.g., ER, I_{FA}), through the application of the EDuMaP method.

On the applicability of EDuMaP method

In conclusion, the analyses proved the applicability of the EDuMaP method in evaluating the performance of real case studies related to ReLWaMs characterized by different decisional algorithms, components and input parameters. Indications on the importance of the input parameters and the landslide density criterion in influencing the performance analysis have been also provided. The EDuMaP method has also proved effective as a tool to calibrate a warning model by back-analysing landslide and warning data in test area with the aim of defining the optimal combination of rainfall thresholds to be assigned as warning levels or, to state it in more general terms, to define the set of warning criteria which maximises the model performance.

Some final important remarks, which must be read as an invitation to exercise engineering judgment and caution whenever the performance of a ReLEWS must be assessed, are the following:

- a performance evaluation is strictly connected to the availability of rainfall and landslide catalogues and to the accuracy of the information therein contained;
- the definition of the most adequate performance criteria considered to evaluate a ReLWaM must be related to management policies of the early warning system;
- the proposed performance assessment method does not address important issues related to the social effectiveness of a ReLEWS, such as: risk perception, policy adopted to communicate with the people at risk, evacuation procedures, efficiency and reliability of the monitoring network, instruments used to issue the warnings.

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APPENDIX

1 PRELIMINARY ANALYSIS OF ALERTA-RIO FOR THE YEARS 2010-2013

(extract from Calvello et al., 2015)

1.1 RAINFALL EVENT

The GEO-Rio Foundation defines "rainfall event" (*Evento Pluviométrico Significativo*) a rainfall characterized by a minimum amount of rain recorded by a given number of rain gauges according to specified criteria (Tab. 1). In such cases, the beginning of the rainfall event is set to the time when the recorded rainfall reached a level of 1mm/h in each one of the considered rain gauges. A rainfall event ends when the cumulative rainfall recorded by any rain gauge is less than 1mm/h and this condition persists for at least 6 consecutive hours.

In the period of analysis, from 2010 to 2013, the rainfall events registered in the municipality of Rio de Janeiro were 110 (29 in 2010, 23 in 2011, 21 in 2012, 37 in 2013). A first analysis was carried out considering both the duration of the rainfall events and the maximum cumulated rainfall recorded during the events for each one of the four alert zone (i.e. Guanabara, Zona Sul, Sepetiba and Jacarepagua). Figure 1 clearly shows, as it may have been expected, relevant differences both in the maximum cumulated rainfall recorded in the four zones during an event and in the duration of the rainfall events. The two longest and most intense rainfall events were both recorded in 2010. A second analysis considered the minimum and maximum rainfall registered, during a rainfall event, by the rain gauges installed in each one of the four alert zones. Figure 2 shows the extreme values of registered rainfall for each rainfall event for each alert zone. The rainfall event series (110 series for each graph) are reported as a function of rainfall duration. The data indicate that the minimum recorded rainfall values are almost always both very low and very different from the corresponding maximum recorded values during the same rainfall event, independently from the duration of the rainfall event. Some slight differences in "rainfall heterogeneity" seem to exist among the four zones, with Guanabara appearing the most heterogeneous of the four zones.

Table 1 Criteria for the identification of a rainfall event.

<table>
<tr><th rowspan="2">Zone</th><th colspan="3">Measured rainfall intensity</th></tr>
<tr><th>≥ 10 mm/h</th><th>≥ 20 mm/h</th><th>≥ 40 mm/h</th></tr>
<tr><td>Guanabara</td><td>in at least 5 rain gauges</td><td rowspan="4">in at least 2 rain gauges</td><td rowspan="4">in at least 1 rain gauges</td></tr>
<tr><td>Zona Sul</td><td rowspan="3">in at least 3 rain gauges</td></tr>
<tr><td>Jacarepaguà</td></tr>
<tr><td>Sepetiba</td></tr>
</table>

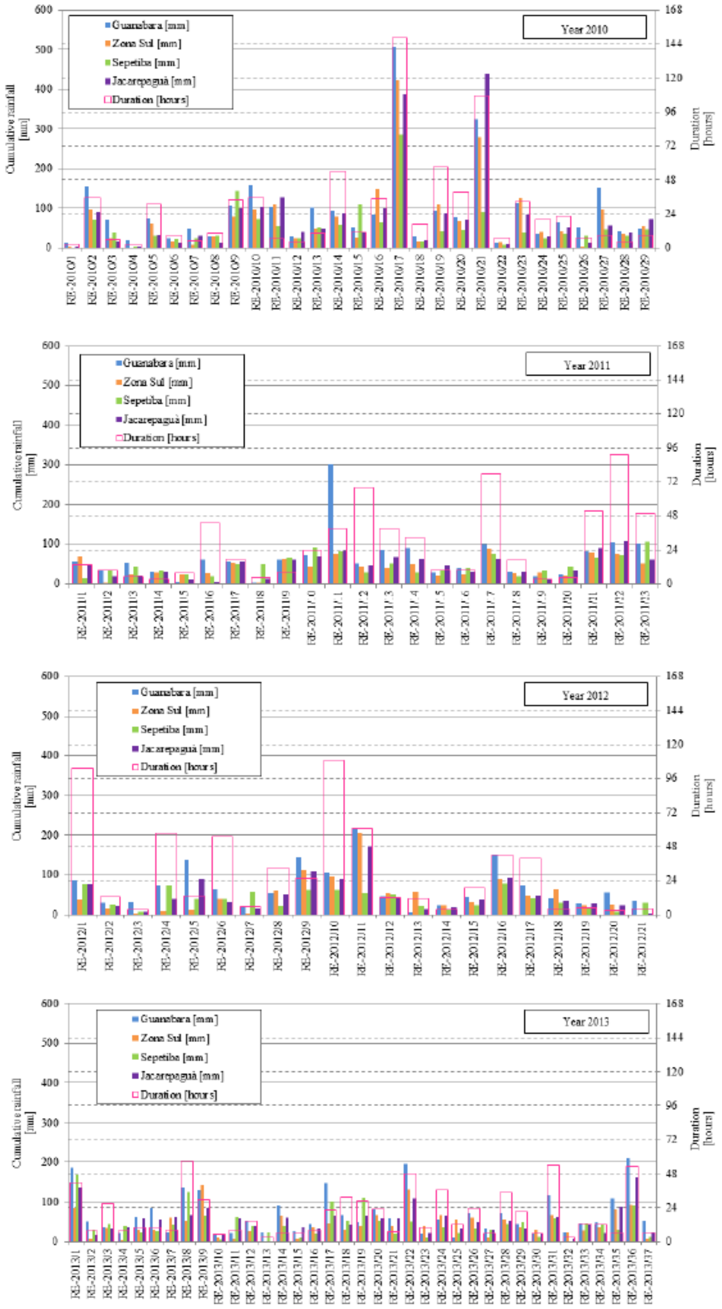

Figure 1 Rainfall events recorded in 2010–2013 : cumulated rainfall in the four alert zones (various colours) and duration of the events (pink).

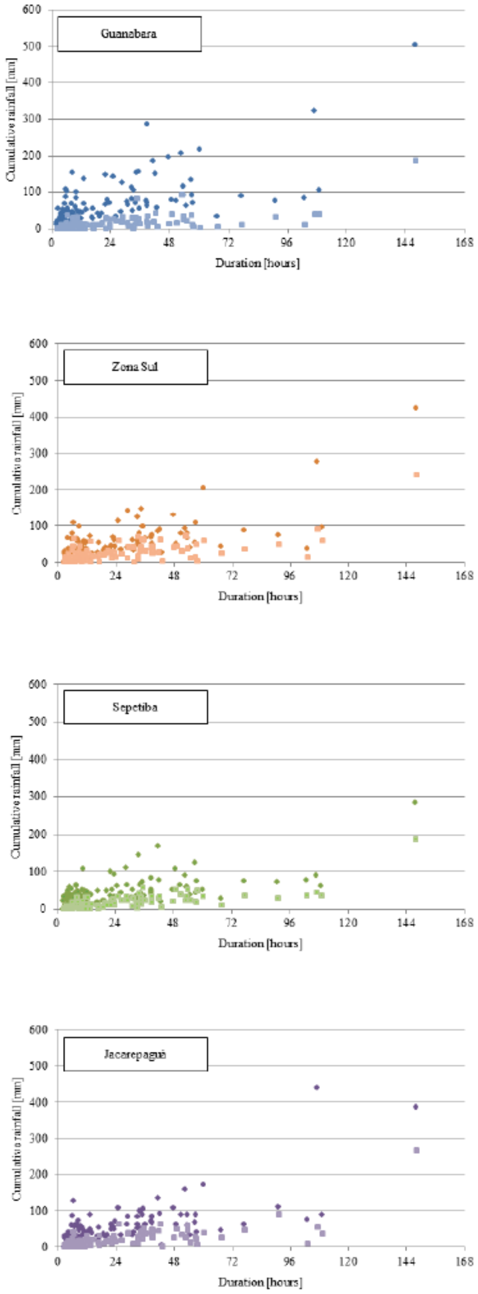

Figure 2 Minimum (light colors) and maximum (dark colors) rainfall registered by the rain gauges installed in each one of the four alert zones during the 110 rainfall events recorded in 2010-2013, reported as a function of rainfall duration.

1.2 LANDSLIDE OCCURRENCES AND EVENTS

The GEO-Rio Foundation manages and continuously updates a detailed inventory database of landslide occurrences in the city of Rio de Janeiro, which is used as a source of valuable geo-referenced data both in relation to the Alerta-Rio early warning system as well as for other landslide hazard and risk analyses. Table 2 presents the number of landslide occurrences recorded in 2010-2013, divided by typology and alert zone. In the period of analysis the majority of single typology landslides were rock slide on artificial slope (28%), earth slide on natural slope (18%) and failure of slope stabilization work (11%). Multiple typology landslides amount to about 33% of the total occurrences. The majority of landslides were recorded in 2010 and within the Guanabara alert zone (534/714).

Table 2 Landslides recorded in 2010-2013, by typology and alert zone. Typology legend: ES/tc: Earth slide on artificial slope (excavation); ES/R/tc: Earth and rock slide on artificial slope (excavation); ER/tc: Rock slide on artificial slope (excavation); RA: Earthwork failure; ES/en: Earth slide on natural slope; ES/R/en: Earth and rock slide on natural slope; ER/en: Rock slide on natural slope; Q/R: Rock fall (blocks and slabs); ET: Talus movements; REC: Failure of slope stabilization work; EL/E: Waste slide; C: Flow; PE/A: Erosion and landfill; Comp.: two or more typologies in the same occurrence.

Typology	Alert zones (Guanabara - Zona Sul – Sepetiba - Jacarepaguà)				Tot
	2010	2011	2012	2013	
1. ES/tc	81-14-0-30	10-0-0-1	0-0-0-1	59-2-8-10	216
2. ES/R/tc	5-0-0-1	1-0-0-0	0-0-0-0	2-0-0-0	9
3. ER/tc	1-0-0-0	2-0-0-0	0-0-0-0	0-1-0-0	4
4. RA	5-1-0-3	0-0-0-0	0-0-0-0	3-0-1-0	13
5. ES/en	70-9-1-5	2-0-0-0	0-0-0-0	8-0-1-0	96
6. ES/R/en	3-0-0-2	0-0-0-0	0-0-0-0	1-0-0-0	6
7. ER/en	0-0-0-0	0-0-0-0	0-0-0-0	1-0-0-0	1
8. Q/R	2-0-0-1	6-0-0-0	0-0-0-0	10-3-0-1	23
9. ET	2-0-0-0	0-0-0-0	0-0-0-0	2-0-0-0	4
10. REC	38-1-2-55	4-0-0-2	1-0-1-0	27-0-6-6	93
11. EL/E	2-0-0-0	0-0-0-0	1-0-0-0	1-0-0-1	4
12. C	3-0-0-1	0-0-0-0	0-0-0-0	0-0-0-0	4
13. PE/A	3-0-0-0	0-0-0-0	0-0-0-0	4-0-0-0	7
C. Comp.	100-19-3-26	5-0-0-2	1-2-0-0	68-1-2-5	234
Tot	315-44-6-74	30-0-0-5	3-2-1-1	186-7-18-23	714

Three confidence levels are used in the GEO-Rio landslide database to characterize each recorded landslide as a function of the level of uncertainty in estimating the date and hour of the landslide occurrence. The confidence level is assigned, on the basis of information from site survey reports, as follows: level 1, for landslides with both date and time of occurrence reported; level 2, for landslides for which only the date of occurrence is reported; level 3, for landslides with no information reported. The time associated to level 2 landslides is assigned by looking at the daily rainfall record of the closest rain gauge and assuming the peak of the recorded hourly intensity as the time of occurrence. If present in the survey report, the search is limited to a specified period of the day (morning, afternoon, evening). The time associated to level 3 landslides is computed by looking at the rainfall record of the closest rain gauge for the whole rainfall event and assuming, like before, the peak of recorder hourly intensity as the time of occurrence. Only the landslide occurrences characterized by confidence levels 1 and 2 are used for the analysis performed herein. For these analysis a "landslide event" is defined as one or more landslides occurring simultaneously, or within a relatively short time span, and triggered by the same rainfall event. A landslide event is assumed to include more than one landslide if the time difference among the single occurrences does not exceed 12h. In the period of analysis a total number of 132 landslide events occurred (Figure 3). The alert zone with the highest incidence of landslide events is Guanabara.

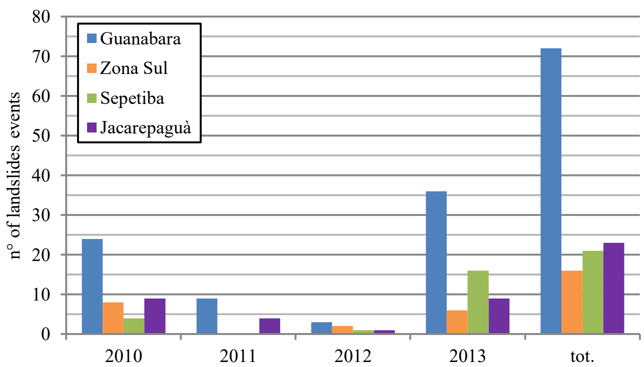

Figure 3 Landslide events recorded in 2010–2013, by year and alert zone.

1.3 WARNING LEVELS AND ALERT PHASES

The warning levels of Alerta-Rio are four and, as already discussed in the previous section, they are related to an expected spatial density of landslides as follows: low, when no rainfall-induced landslide occurrences are expected; medium, when occasional rainfall-induced landslides may occur; high, when diffuse landsliding may occur; very high, when widespread landsliding may occur. Warnings can either be issued for the whole metropolitan area of Rio de Janeiro or with reference to an individual alert zone. For the analysis developed herein, an “alert phase” is defined, following GEO-Rio criteria, as the time when the landslide warning level is equal to either high (diffuse landsliding possible within the alert zone) or very high (widespread landsliding possible within the alert zone).

A summary of the main information related to the alert phases issued by Alerta-Rio from 2010 to 2013, is reported in Table 3. The Table shows the alert phases issued with the indication of: the alert zone to which they refer, the starting and ending dates and times, the duration of the alerts. Most of the alerts were issued in 2010 and 2013 (28 out of 31), mainly for the Guanabara and the Zona Sul alert zones. Only in few cases, the alerts were issued at the same time for more than one zone. Only one rainfall event prompted a citywide alert lasting 5 to 6 days in all the alert zones (April 2010). Figure 4 shows a summary of the alert phases issued in 2010-2013 for each of the four alert zones. A total number of 31 alert phases were issued in the period of analysis, a little less than half of them (14/31) refer to the Guanabara alert zone.

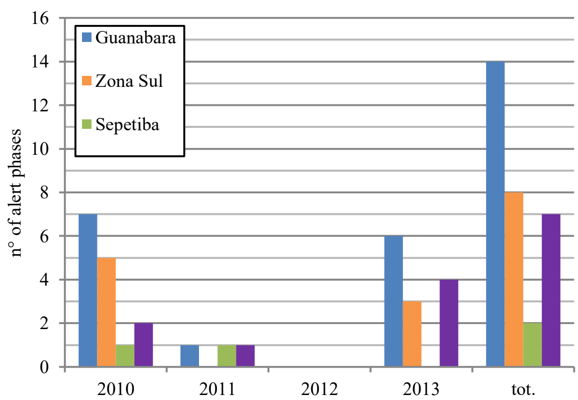

Figure 4 Alert phases issued in 2010–2013, by year and alert zone.

Table 3 Data on alert phases issued in 2010-2013: ID, alert zone, date and time of alert, duration.

ID	Alert Zone	Start		End		Alert duration [hh:mm]
		Date [yyyy-mm-dd]	**Time** [hh:mm]	**Date** [yyyy-mm-dd]	**Time** [hh:mm]	
ID 1	Guanabara	2010-01-15	23:30	2010-01-16	10:00	10:30
ID 2	Guanabara	2010-01-22	19:30	2010-01-23	09:00	13:30
ID 3	Zona Sul	2010-01-22	19:30	2010-01-23	09:00	13:30
ID 4	Guanabara	2010-01-25	18:20	2010-01-26	21:15	26:55
ID 5	Jacarepagua	2010-03-06	18:25	2010-03-08	07:20	36:55
ID 6	Zona Sul	2010-03-06	18:35	2010-03-08	07:20	36:45
ID 7	Guanabara	2010-03-06	18:35	2010-03-08	07:20	36:45
ID 8	Guanabara	2010-03-14	18:40	2010-03-15	00:20	5:40
ID 9	Zona Sul	2010-03-30	21:30	2010-04-01	10:30	37:00
ID 10	Jacarepagua	2010-04-05	18:10	2010-04-10	15:30	117:20
ID 11	Guanabara	2010-04-05	18:10	2010-04-10	15:30	117:20
ID 12	Zona Sul	2010-04-06	00:10	2010-04-10	15:30	111:20
ID 13	Sepetiba	2010-04-06	01:10	2010-04-10	15:30	110:20
ID 14	Zona Sul	2010-10-27	01:45	2010-10-27	09:35	7:50
ID 15	Guanabara	2010-12-05	21:40	2010-12-06	08:30	10:50
ID 16	Sepetiba	2011-04-24	16:25	2011-04-24	21:40	5:15
ID 17	Jacarepaguá	2011-04-24	16:25	2011-04-24	21:40	5:15
ID 18	Guanabara	2011-04-25	21:15	2011-04-27	05:30	32:15
ID 19	Guanabara	2013-01-15	20:08	2013-01-15	21:45	1:37
ID 20	Guanabara	2013-01-17	22:55	2013-01-18	00:55	2:00
ID 21	Guanabara	2013-01-19	22:38	2013-01-20	01:05	2:27
ID 22	Jacarepaguà	2013-01-19	22:38	2013-01-20	01:05	2:27
ID 23	Zona Sul	2013-01-19	22:38	2013-01-20	01:05	2:27
ID 24	Guanabara	2013-03-05	20:05	2013-03-05	23:00	2:55
ID 25	Jacarepaguà	2013-03-05	20:05	2013-03-05	23:00	2:55
ID 26	Zona Sul	2013-03-05	20:05	2013-03-05	23:00	2:55
ID 27	Jacarepagua	2013-12-05	21:47	2013-12-05	23:35	1:48
ID 28	Guanabara	2013-12-05	22:02	2013-12-05	23:35	1:33
ID 29	Zona Sul	2013-12-05	22:16	2013-12-05	23:35	1:19
ID 30	Guanabara	2013-12-11	04:50	2013-12-11	11:10	6:20
ID 31	Jacarepagua	2013-12-11	05:55	2013-12-11	11:10	5:15

1.4 LANDSLIDE OCCURRENCES AND ALERT PHASES

The main results of the analysis on the relationship among landslides and alert phases are reported in Figures 5 and 6. Figure 5 shows, for each alert zone and for each day in which at least one landslide occurred, two series in a bar chart reporting, respectively, the number of landslides which occurred during alert phases (in green) and the number of landslides which occurred when the alerts were not issued (in red). Despite the significant number of days during which landslides occurred without an alert phase being issued, the vast majority of landslides (502/714) occurred during alert phases. The year showing the highest percentage of landslides occurring while an alert was being issued is 2010. This is mainly the result of the behavior of the warning system during the single catastrophic landslide event which occurred in April 2010. During this event more than 350 landslides were recorded and the alert phase lasted for about 5 days (more than 110 hours) in all four alert zones. Another significant year is 2013, during which a total number of 234 landslides occurred, most of them when alerts were not issued. As shown in Table 4 the percentage of landslides occurring while an alert was being issued is lower than 50% and, in some alert zones, none or just few occurrences were concurrent with the alerts. Concerning this recorded behavior, it is important to highlight that not all these landslide occurrences (red bars in Figure 5) should be judged as missed alerts (MA). Most of them, indeed, occur as single phenomena in a given day and, therefore, they are not revealing the expected diffuse or widespread landsliding associated to an alert phase.

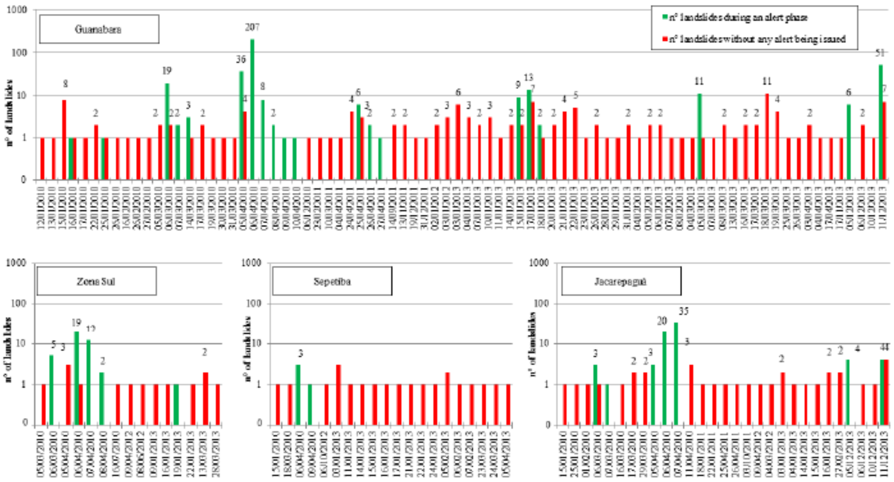

Figure 5: Landslides which occurred in 2010–2013 during alert phases (in green) and when alerts were not issued (in red), by day of occurrence and alert zone.

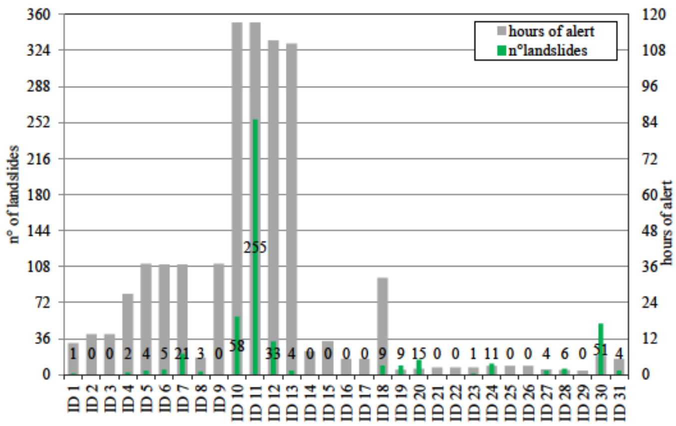

Figure 6 Hours of alert (grey) and number of landslides which occurred during the alert phases (green), by alert zone in increasing order of ID (see Table 6 for meaning of ID).

Table 4 Total number of landslide occurrences and landslides recorded during alert phases, by year of occurrence and alert zone.

Alert zone	2010		2011		2012		2013		Tot
	Total No. of landslides	No. of landslides during alert phase	Total No. of landslides	No. of landslides during alert phase	Total No. of landslides	No. of landslides during alert phase	Total No. of landslides	No. of landslides during alert phase	
Guanabara	315	282	30	9	2	0	186	98	533
Zona Sul	44	38	0	-	2	0	7	1	53
Sepetiba	6	4	0	-	1	0	18	0	25
Jacerepaguà	74	62	5	0	1	0	23	8	103
tot	439	386	35	9	6	0	234	107	714

A graphical comparison between the number of landslide occurrences and the duration of the alert phases (Fig. 6) shows significant differences between these indicators in the four alert zones. Out of fourteen alerts issued for the Guanabara zone, three of them may surely be defined false alerts (FA) as no landslides were recorded during these alert phases. For the other three zones, i.e. Zona Sul, Sepetiba and Jacarepagua, the number of such alerts is respectively five (out of eight), one (out of two) and three (out of seven). This numbers should interpreted as a lower bound of false alerts. Indeed, if during alert phases only few landslides occur, the expected diffuse or widespread landsliding associated to the alert phase does not manifest. Concerning the duration of the alert phases, alerts issued on 2013 (ID from 19 to 31) show an improved correspondence, with reference to the previous three years of analysis, between the length of the alert phases and the total number of landslides recorded within these phases.

Figure 7 shows the total number of landslides recorded during the years 2010-2013 (in blue) as well as the percentage of landslides which occurred within and outside an alert phase (in green and red, respectively), subdivided by typology. The most common typologies of landslide occurrences in the period of analysis are (see Tab. 2 for the adopted classification scheme): complex landslides including more than one type of phenomenon (typology C); earth slide on artificial slope (typology 1); earth slide on natural slope (typology 5); failure of engineered slope (typology 10); rock fall (typology 8). It is worth noting that high percentages of landslide occurrences during alert phases are reported for all the four most frequent landslide typologies, the highest being 85% for earth slides on natural slope. The fact that rock falls, which include block and slab failures, show a relatively low percentage of occurrences during alert phases (35%) is possibly indicative of phenomena which are not only triggered by intense rainfall events.

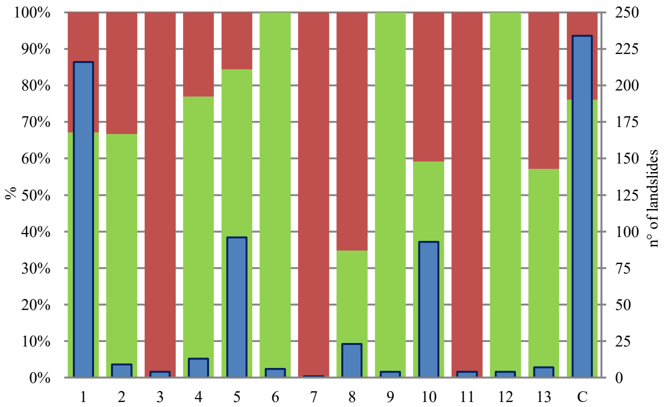

Figure 7 Landslides recorded in 2010–2013 (blue) and percentage of landslide occurrences during an alert phase (green) or without any alert being issued (red), by typology (see Table 4 for legend).

1.5 LANDSLIDE EVENTS AND ALERT PHASES

A simple way to define a false alert (FA) may be the following: alert phase during which no landslide occurrences are recorded. If we use this definition, the performed analyses indicate, with respect to the number of alerts issued over four years, a significant number of false alerts in Zona Sul, with a false alerts ratio equal to 0.63 (five false alerts out of eight alert phases), and a reasonably low number of false alerts in Guanabara (three false alerts out of fourteen alert phases). The results related to the Sepetiba zone are not very significant because the total number of alerts issued is too small (only two alert phases were issued). It is worth noting that the definition used above is very conservative because it minimizes the computed number of false alerts. Indeed, it considers an alert phase as a "good warning" as long as at least one landslide occurs during that phase and it does not consider the number of recorded landslide occurrences or the duration of the alert phase as criteria to judge the goodness of the alert. During some of the alert phases only one or two landslide occurrences were recorded. This number is much lower than the expected number of occurrences associated to the highest two warning levels (i.e. diffuse or widespread occurrence of landslides). Therefore, to better judge the relationship between alert phases and landslide events, one cannot neglect to consider the spatial density of the landslide events, which is related to number of occurrences within each alert zone.

Table 5 shows the number of alert phases issued in the four alert zones, differentiated so as to consider the following four classes of spatial density of the landslide event (LE): small, if only 1 landslide occurrence is recorded; intermediate, from 2 to 5 recorded occurrences; large, from 6 to 50 occurrences; very large, for more than 50 landslide occurrences. The results indicate that 15 high density landslide events (12 classified as large, and three classified as very large) occurred in 2010-2013, most of them within the Guanabara alert zone. Within the Alerta-Rio early warning system, alert phases are associated to diffuse or widespread landsliding. Thus, we may relate the alerts correctly issued by the system (CA) to the alert phases during which high density landslide events occur. The number of missed alerts (MA) may then be computed by counting the number of high density landslide events which occurred without an alert phase being issued. The results reported in the Table indicate only three missed alerts during the four years of analysis, all of them occurring in the Guanabara zone and none of them belonging to the highest class of spatial density. The Table also reports the number of alert phases issued without landslides recorded. These number, as discussed previously, should be considered a lower-bound estimate of the false alerts. Indeed, following the same argument employed to compute the missed alerts, the correct number of false alerts (FA) must be computed by counting the alert phases during which the number of landslide occurrences is lower than six. This means adding to the previous estimate the number of small and intermediate density landslide events which occurred during an alert phase. The results reported in the Table show that the total number of false alerts recorded between 2010 and 2013 is equal to 20. Six alerts were issued in Guanabara, with a false alert ratio equal to 0.43; seven alerts were issued in Zona Sul, with a false alert ratio equal to 0.88; two alerts were issued in Sepetiba, with a false alert ratio equal to 1; five alerts were issued in Jacarepaguà, with a false alert ratio equal to 0.71. These findings highlight the important role played by the warning levels thresholds used by GEO-Rio to activate an alert phase. The adopted criteria seem to be geared toward reducing at a minimum the number of missed alerts yet, for this same reason, they tend to produce a relevant number of false alerts.

Table 5 Number of landslide events (LE) and alert phases issued in the alert zones, by spatial density of landslide event. Alert zone legend: G=Guanabara, ZS=Zona Sul, S=Sepetiba, J=Jacarepagua

	Small spatial density (1 occurrence)					Intermediate spatial density (2-5 occurrences)				
Alert zone	No. of LE	No. of landslides	Alert phase issued	No. of LE during alert	No. of landslides during alert	No. of LE	No. of landslides	Alert phase issued	No. of LE during alert	No. of landslides during alert
G	37	37	1	1	1	24	63	2	2	4/9
ZS	12	12	1	1	1	2	7	1	1	5/5
S	19	19	0	0	1	2	6	1	1	3/3
J	13	13	0	0	0	8	23	2	2	8/10

	Large spatial density (6-50 occurrences)					Very large spatial density (>50 occurrences)					
Alert zone	No. of LE	No. of landslides	Alert phase issued	No. of LE during alert	No. of landslides during alert	No. of LE	No. of landslides	Alert phase issued	No. of LE during alert	No. of landslides during alert	Alert phases issued without LE
G	9	121	6	6	71/90	2	312	2	2	304/312	3
ZS	2	34	1	2	31/34	0	0	0	0	0	5
S	0	0	0	0	0	0	0	0	0	0	1
J	1	9	1	1	4/9	1	58	1	1	58/58	3

1.6 RAINFALL EVENTS, LANDSLIDE EVENTS AND ALERT PHASES FOR THE APRIL 2010 EVENT

The landslide events which occurred in the four alert zones between 5-10 April 2010 are herein analysed separately because of the relevant number of occurrences recorded during those days, which amount to about 50% of the total number of landslides recorded between 2010 and 2013. Figure 8 shows the cumulative number of landslides per landslide event (in blue), plotted together with the time deployment of the warning levels and the duration of the rainfall event (RE). The four warning levels employed by Alerta-Rio, i.e. small, medium, high and very high, are reported in the graphs with the numbers 0, 1, 2 and 3, respectively. Results clearly show than most of the landslides registered occur, correctly, during an alert phase (i.e. high or very high warning levels). Yet, two relevant issues emerge from a more detailed analysis of the data: warning level representativeness within an alert phase, duration of the alert phase. Concerning the first issue, the highest landslide time-density, expressed as number of landslides per hour, is obtained when a high warning level is issued for the first time and not, as it should be expected, during the very high warning level. This behaviour is registered, with slight differences, within all the 4 alert zones. Concerning the second issue, it is relevant to note that the warning levels were kept to very high or high for more than 4 days in all the zones, while most of the landslides occurred during the first two days of the event. This behavior is also confirmed by the significantly different temporal density—more than one order of magnitude—computed for the high warning levels issued, respectively, before and after the very high warning level.

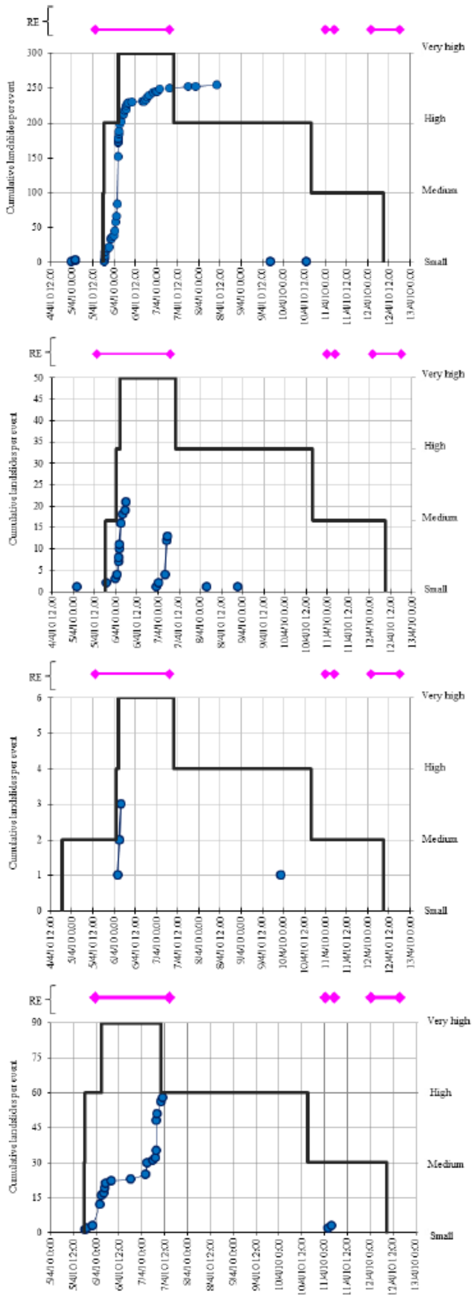

Figure 8 Cumulative number of landslides (blue), rainfall events (pink), and warning levels (black) between 5–10 April 2010, by alert zone: (a) Guanabara, (b) ZonaSul, (c) Sepetiba, (d) Jacarepaguà.

2 VARIABLES AND ACRONYMS USED IN TEXT

Acronym	Description
A	Area of analysis
AZ	Alert zone
CA	Correct Alert
EDuMaP	Event, Duration Matrix, Performance
ER	Error rate
FA	False Alert
FN	False Negative
FP	False Positive
Gre	Green error
HR_L	Hit Rate
I_{eff}	Efficiency Index
$L_{den(k)}$	Landslide density criterion
LE	Landslide event
LEWS	Landslide early warning system
L_{typ}	Landslide type
MA	Missed Alert
MR	Misclassification rate
OR	Odd Ratio
PP_W	Predictive Power
P_{SM}	Probability of Serious Mistakes
Pur	Purple error
RE	Rainfall event
ReCoL	Regional Correlation Law
Red	Red error
ReLWaM	Regional Landslide Warning Model
ReLEWS	Regional Landslide Early Warning System
R_{FA}	False Alert Rate
R_{MA}	Missed Alert Rate
t_{LEAD}	Lead time
t_{OVER}	Over time

TN	True Negative
TP	True Positive
TS	Threat Score
WE	Warning Event
WL	Warning Level
Yel	Yellow error
ΔA	Spatial discretization adopted for warnings
Δt_{LE}	Minimum interval between landslide events
Δt	Temporal discretization of analysis
ΔT	Time frame of analysis