Monitoring strategies for local landslide early warning systems

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Abstract

The main aim of this study is the description and the analysis of the monitoring strategies implemented within local landslide early warning systems (Lo-LEWS) operational all around the world. Relevant information on 29 Lo-LEWS have been retrieved from: peer-reviewed articles published in scientific journals and proceedings of technical conferences, books, reports, and institutional web pages. The first part of the paper describes the characteristics of these early warning systems considering their different components. The main characteristics of each system are summarized using tables with the aim of providing easily accessible information for technicians, experts, and stakeholders involved in the design and operation of Lo-LEWSs. The second part of the paper describes the monitoring networks adopted within the considered systems. Monitoring strategies are classified in terms of monitored activities and methods detailing the parameters and instruments adopted. The latter are classified as a function of the type of landslide being monitored. The discussion focuses on issues relevant for early warning, including appropriateness of the measurements, redundancy of monitoring methods, data analysis and performance. Moreover, a description of the most used monitoring parameters and instruments for issuing warnings is presented.

1. Introduction

Landslides are a major natural hazard causing thousands of deaths and injuries as well as significant damage to property and infrastructure around the world every year *(e.g., Petley, 2012).* Landslide risk can be reduced by adopting different mitigation methods, classifiable into two main categories: structural works, i.e. active measures reducing the probability of occurrence of landslides or engineering works decreasing the vulnerability of the elements at risk; and non-structural actions. Among the latter, landslide early warning systems (LEWS) are being increasingly applied worldwide, mainly because of: their lower economic costs and environmental impact compared to structural measures (*e.g., Intrieri et al., 2012; Thiebes and Glade, 2016);* the continuous development of new technologies for landslide monitoring (*e.g., Chae et al., 2017; Crosta et al., 2017);* and increasing availability of reliable databases to calibrate the warning models *(e.g., Haque et al., 2016; Calvello and Pecoraro, 2018).* LEWS aim at reducing the loss-of-life probability and other adverse consequences from landslide events by informing individuals, communities, and organizations threatened by landslides to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss (*UNISDR, 2006*). LEWS can be designed and employed at two scales *(e.g., Thiebes et al., 2012; Calvello and Piciullo, 2016).* Systems addressing single landslides at slope scale can be named as local (Lo-LEWSs), systems operating over wide areas at regional scale are referred to as territorial systems (Te-LEWS), i.e. they can be employed over a basin, a municipality, a region or a nation (*Piciullo et al., 2017*). At both scales of operation LEWS can be schematized as an interrelation of different components, as stated by many authors *(UNISDR, 2006; Di Biagio and Kjelstad, 2007; Intrieri et al., 2013; Fathani et al., 2016; Piciullo et al., 2017, 2018;* among others). *Calvello (2017)* introduces a framework based on a clear distinction among landslide models, warning models and warning systems, wherein a landslide model is one of the components of a warning model and the latter is one of the components of a early warning system. The landslide model can be defined as a functional relationship between weather characteristics and landslide events considering monitoring data and the geological, geomorphological, hydrogeological and geotechnical features of the area of interest. The warning model includes the landslide model, and it defines a set of decision-making procedures required for issuing the alert levels. The warning system embeds the warning model and includes the following risk management elements: warning dissemination, communication and education, community involvement, and emergency action plan.

The efficiency of a landslide model developed for warning purposes—the capability to properly assess the relationship between triggering and predisposing factors and landslide events—strongly depends on the character (e.g. size, possible precursors, potential velocity) of the landslide under surveillance and on the monitoring strategies adopted. Adequate knowledge of the active or potential landslide(s) in the warning area necessarily calls for a thorough site investigation, which may be performed by a variety of methods and techniques, and the long-term monitoring of event precursors and descriptors *(Baroň and Supper, 2013;*

Michoud et al., 2013; Stähli et al., 2015). In this context, the main goal of this study is the description and the analysis of the monitoring strategies implemented within Lo-LEWS worldwide. The first part of the paper describes the main characteristics of 29 Lo-LEWS as a function of the three main modules of the scheme proposed by *Calvello (2017).* The second part of the paper presents and discusses the monitoring networks adopted among the systems.

2. Review on Local Landslide Early Warning Systems

2.1. Location, period and state of activity

Figure 1 shows the period of activity and the location of 29 Lo-LEWS worldwide for which published information is available. Little experience has been gathered from LEWS at slope scale before 2000 (AS_1977_N, AS_1991_P, EU_1995_P, EU_1997_A, NA_1998_A). The first reported successful application refers to a system employed in Xiling Gorge, China. On 12 May 1985 the system, operational since 1977, was able to provide sufficient warning of a large colluvial landslide that occurred on the north bank of the Yangtze River and all the 1,371 inhabitants of the surrounding area were safely evacuated before the failure *(Wang, 2009).* The system developed by USGS at Mt. Rainier, USA (NA_1998_A) employs a network of geophones for detecting lahars. This methodology has been applied to many lahar-hazard areas in the world such as USA, Indonesia, Philippines, Ecuador, Mexico and Japan. In the past 20 years, twenty-four systems have been designed and employed, principally in Asia and Europe. In Europe, an important example is the system deployed in Norway, since 2004, in the Storfjord region. The system deals with a massive rockslide, known as the Åknes landslide, representing a threat to the communities located along the fjord for the potential of the landslide failure to trigger a tsunami. The landslide is observed year-round using a variety of monitoring instruments. Nine corner reflectors and measuring rods have been installed along the slope, and movements are measured by GPS, laser, radar, and seismic sensors. Besides the technical components, successful operation of this system depends on the trust established between the experts making the observations and operating the system and the residents of the area most threatened by the tsunami. Other particularly well-known and well-described operational systems are addressing: debris flows in the Illgraben catchment in Switzerland since 2000 (EU_2000b_A); the Turtle Mountain landslide in Canada since 2005 (NA_2005_A); the site of the Frank Slide that buried parts of the town of Frank killing over 70 people in 1903; and a complex slow-moving landslide in the Southern French Alps known as La Valette landslide since 2007 (EU_2007_A). Only two of the operational Lo-LEWS reviewed herein are no longer active: Xiling Gorge, China (AS_1977_N) and North Vancouver, Canada (NA_2009_N). Operation of the former ended in 1985 because of the failure of the Xintan slope, which destroyed the historical town located below the landslide *(Li et al., 2016).* The latter, Canada's first real-time debris flow warning system, operated in the District of the North Vancouver for three years, from 2009 to 2011 *(Jakob et al., 2012).*

Some of the Lo-LEWS considered are prototype systems. In these cases, the main aim of the system is to test innovative monitoring sensors or to collect data for future real-case applications, like those in the Nojiri River Basin, Japan (AS_1991_P), Moscardo catchment, Italy (EU_1995_P), and Wollongong, Australia (OC_2005_P).

Table 1 provides a summary of the country where the system has been employed, the institution operating the system, the source of information used for the analyses and the year of the latest available information. In the majority of cases, Lo-LEWS are managed either by government institutions, often directly involved in civil defence and landslide risk management, or by civil protection agencies operating at national or regional levels. Only two prototype systems are managed by university research groups: the Nojiri River Basin, Japan (AS_1991_P) and Wollongong, Australia (OC_2005_P). The information on the 29 Lo-LEWS was retrieved from different sources: international journals and publications, scientific reports, web pages and grey literature. The authors are aware that besides the 29 Lo-LEWS herein described, many other operational warning systems designed to address potentially unstable slopes in various contexts, such as railway embankments, pipelines and open pit mines. However, information on these systems is not readily available, in the published literature.

2.2. Landslide model

A landslide model may be described as a functional relationship between landslide causes (weather, geomorphological, anthropic) and landslide events, taking into account the geological, geomorphological and hydrogeological features of the slope and the data provided by monitoring instruments. **Table 2** reports the main characteristics of the landslide models used by the 29 Lo-LEWS reviewed herein.

Covered area

All the systems have been designed to operate at local scale, yet the areas under surveillance range from less than 0.1 km^2 for systems dealing with single landslides to more than 1 km^2 for systems monitoring large destructive phenomena or several landslides on a slope. The smallest and largest warning areas are covered by the LEWS operating, respectively, in Longjingwan, China (AS_2014_P) and in Taiwan (AS_2002_A). The latter is an unusual Lo-LEWS, as it comprises multiple local EWS for a series of debris flows located in various areas of the country, some of them designed to operate permanently, others installed for a short period of time. The system, operated by the Taiwanese Council of Agriculture Soil and Water Conservation Bureau (SWCB), was established in 2002 as a debris flow monitoring project aimed at improving the capability of collecting field data on debris flows. According to a survey by SWCB, there are 1’503 potential debris flow torrents in Taiwan. The system originally employed 17 on-site monitoring stations located in the vicinity of potential debris flows posing the highest risk to nearby communities; since 2004, three more mobile monitoring stations have been added to the system *(Yin et al., 2010).*

Landslide cause(s)

Twenty-six of the 29 identified systems address weather-induced landslides (triggered by rainfall, snow melt or a combination of both). It is worth mentioning that at Mt. Rainier, USA (NA_1998_A), the lahars (volcanic debris flows) under investigation are triggered principally by snowmelt and sometimes by volcanic eruptions. In two of the three remaining cases, EU_1997_A and OC_2000_A, the landslide cause is well identified and described. The focus of the first system are cliff top recessions along the southern and eastern coasts of England, which are mainly caused by wave erosion. The landslides addressed in the second system are lahars generated by the failure of a tephra (volcanic material) dam by retrogressive landsliding in the crater of the Mt. Ruapehu in New Zealand. The system deployed in Wushan Town, China (AS_2004_A) is unusual in that the monitored landslide may be activated by seasonal changes in the regime of both rainfall and variations in the pool level of the reservoir behind the Three Gorges Dam. No information is available on the landslide cause for the system deployed in the Northern Italian community of Nals (EU_2002_A).

Type(s) of landslide

Figure 2a displays the types of landslides that have been monitored by each system. Debris flows (8) and rockslides (6) are the most investigated type. For six cases information on the type of landslide or style of movement is not available. It is worth nothing that the majority of the systems deals with a single landslide type. This is to be expected, because a LEWS operational at slope scale requires site-specific choices for its design and management depending on the characteristics of the landslide under surveillance. In two cases (AS_2014_P and OC_2005_P), the information available only allows a generic statement that the Lo-LEWS addresses rainfall-induced landslides. In Preonzo, Switzerland (EU_2010c_A), two types of landslides are addressed as the operational system has been designed to cope with a series of retrogressive rockslides and rock avalanches that are parts of an extremely complex phenomenon.

2.3. Warning model

As already mentioned, according to *Calvello (2017)*, the warning model includes the landslide model, and it defines a set of decision-making procedures required for issuing the alert levels. **Table 3** lists the main characteristics of the warning models adopted within the 29 Lo-LEWS reviewed in what follows.

Alert parameters

The primary alert parameter used in the adopted warning models is displacement—in terms of rate of movements, velocity, acceleration (15 cases)—because displacement provides a direct evidence of the state of activity of the landslide. In addition to displacement, meteorological parameters (8 cases) are also considered, mainly because a significant number of mass movements are weather-induced landslides. In most of the systems (21 out of 29 cases), parameters not explicitly included in the warning model are also monitored. The need for additional information on the behaviour of the landslides could be attributed to the following good practice by system managers: willingness to evaluate the adopted landslide model over time, towards possible updates of the adopted warning model.

Alert criteria

Alert criteria are needed to establish a connection between a landslide model and a set of alert levels. An alert criterion may be defined as a functional relationship between the investigated landslide and the monitored parameters (e.g. displacements, rainfall). The large majority of the systems—27 out of 29—employ empirical models (**Figure 2b**); the remaining two systems, Vancouver, Canada (NA_2009_N), where a probabilistic model has been adopted, and the Barcelonnette basin, France (EU_2007_A), for which no information is available.

Empirical models can be further subdivided into heuristic methods (19 cases), for which thresholds are identified without employing any rigorous mathematical or statistical criterion, and correlation laws (8 cases), for which thresholds are defined considering one or more combinations of the monitored parameters (e.g., displacements, rainfall) that have led to a slope movement or not. Several parameters may be included in the models, depending on the characteristics and the complexity of the phenomenon. Heuristic threshold values are defined by considering historical observations and monitoring data, as well as expert judgement. For instance, in the prototype system operational in Torgiovannetto, Italy (EU_2007b_P) movement rate thresholds (mm/day) have been assigned considering measures coming from a network of extensometers. The thresholds have been defined by analysing the most critical periods of the monitoring dataset with support from expert judgment and interpretation. The system has been designed to be flexible so that, if necessary, thresholds can be changed as soon as new data become available *(Intrieri et al., 2012).* In the relocated Wushan town in the Three Gorges Reservoir area, China (AS_2004_A), the threshold values employed for the investigated deep-seated colluvial landslide are based on data from many similar landslides occurring on the banks of the Three Gorges Reservoir. The thresholds have been heuristically defined considering different monitoring parameters: ground displacements, deep displacements, pore water pressures and soil strains *(Yin et al., 2010).*

Eight Lo-LEWS are based on correlation laws derived from statistical analyses of historical data. For rainfall-induced landslides, thresholds are usually obtained by estimating lower-bound limits to the rainfall conditions that resulted in landslides considering Cartesian, semi-logarithmic, or logarithmic charts of two relevant rainfall indicators. If information on rainfall conditions that did not result in slope failures is also available, thresholds are typically defined as the best separators between rainfall conditions that produce or did not produce slope instabilities. In 4 cases—Taiwan torrents (AS_2002_A), Illgraben catchment (EU_2000b_A), Bagnaschino (EU_2010b_A), Wollongong (OC_2005_P)—intensity-duration (ID) thresholds have been employed. In the system developed in Taiwan

(AS_2002_A), two thresholds were considered to evaluate the possible occurrence of debris flows: an intensity-duration threshold (10 mm/h) in combination with accumulated rainfall (100 mm within 24 hours). In the prototype system employed in Banjarnegara (AS_2007_P), an algorithm based on two different monitoring parameters is applied: antecedent rainfall in 24 and 72 hours and cumulative displacements.

For two large rock landslides—Ruinon (EU_2006_P), Preonzo (EU_2010c_A)—the adopted relationships were derived looking at the observed displacements, starting from the basic assumption that the slope movement may show "accelerating creep" which presumably would precede catastrophic movement *(Crosta and Agliardi, 2003; Loew et al., 2016).*

The only application of a probabilistic model to define thresholds is the prototype system that has been operational in Vancouver between 2009 and 2011 (NA_2009_N). A discriminant analysis was applied to identify, for a given storm, the rainfall parameters that provided the best discriminatory power and variance. A given case was classified into either the landslide-triggering (LS) or non-landslide-triggering (NLS) group based on classification scores computed considering these parameters. The difference between the classification scores obtained from LS and NLS, termed ΔCS, has been interpreted as a reasonable proxy for the likelihood of shallow landslides and debris flows *(Jakob et al., 2012).*

Number of alert levels

Figure 2c highlights that the majority of the Lo-LEWS employ two (8 cases) or three (10 cases) alert levels. The definition of many thresholds does not necessarily improve the performance of a warning model and often results in needless complexity *(Medina-Cedina and Nadim, 2008).* However, at the beginning of the 2000s, a significant number of systems began using four alert levels (6 cases) or more (4 cases). The highest number of alert levels is adopted in Mt. Ruapehu, New Zealand (OC_2000_A), from base level to level 5, the latter associated to a risk with a conditional probability of 100%. For the system employed in North Vancouver, Canada (NA_2009_N), the transitions between the four alert levels—i.e. no watch, watch I/watch II, warning I, warning II—was designed to ensure that each alert level was preceded or followed by a level that was either one step higher or one step lower. Moreover, each level was typically maintained for at least six consecutive hours. When this was not possible, an override was issued and specifically communicated to the users to avoid confusion *(Jakob et al., 2012).* For the system dealing with La Valette landslide (EU_2007_A), the number of alert levels used is not known.

2.4. Warning system

The warning system embeds the landslide and warning model and includes other essential elements of the risk mitigation strategy adopted in Lo-LEWS, such as: lead time, alert dissemination, communication and education, community involvement, and an emergency response plan. A reliable early warning system can be described as the interaction between both technical and social aspects, such as public statements, public response and education. A breakdown in the process can result in an ineffective warning, even if each individual component is properly performing its internal role *(Sorensen, 2000; Piciullo et al., 2018).* For instance, if the people at risk are not adequately informed during a warning event, either because they are not reached by the warning messages or because the meaning of these messages is not clear, they will not react as the system managers expect them to. The lead time, the warning methods and the media employed to spread warning information, as well as the public informed, vary significantly depending both on the level of warning issued and on the aim of the system (**Table 4**).

Lead time

The lead time of LEWS can be identified as the interval between the time a warning is issued and the beginning of the forecasted landslide event. That interval must necessarily be longer that the time needed to put in place the appropriate response actions adopted in the LEWS (e.g., evacuation). Many authors *(Stähli et al., 2015; Sättele et al., 2016; Calvello, 2017;* among others), suggest that LEWS can be classified into three main categories: alarm systems, warning systems and forecasting systems. Alarm systems detect process parameters (e.g., acoustic emissions) of ongoing landslides, thus the lead time is typically very short, on the order of seconds or minutes. Warning and forecasting systems typically monitor triggering parameters (e.g., rainfall) before the occurrence of the landslides, thus ensuring a longer lead time; typically more than 1 hour for warning systems and more than one day for forecasting systems. Among the Lo-LEWS reviewed herein, 8 LEWS can be considered alarm systems, as the lead time varies from few seconds to several minutes. In most of these cases, the systems deal with debris flows (AS_1991_P, AS_2002_A, EU_1995_N, EU_2000b_A, OC_2000_A). Fifteen cases can be considered warning systems, as the lead time varies from 1 to 24 hours. These typically deal with active landslides that move slowly but can be characterized by movement rates rapidly increasing before a general failure stage (e.g., large rockslides, deep-seated landslides). For example, the lead time is expected to be longer than 1 day in Mannen Norway (EU_2009b_A) where the rockslide under surveillance is expected to provide clear signs of acceleration days to weeks in advance of a catastrophic collapse. In the remaining 6 cases information on the assumed lead time is not available.

Warning statements

Table 4 shows that in 12 cases only internal statements are planned with warnings are targeted to: politicians, scientists, government institutions, civil protection agencies or infrastructure authorities. As an example, in the system designed for the Ancona Landslide in Italy (EU_2008_A), a team of engineers, geologists, technical experts and urban planners have access year-round the values of the monitored parameters. Tasks and responsibilities are clearly assigned, according to an Emergency Plan. A special task-force, named “Centro Operativo di Controllo” (COC), is in charge of coordinating the emergency actions established to reduce the risk exposure of the citizens *(Cardinaletti et al., 2011).* The COC starts operating as soon as an early warning is issued. The COC is an interagency structure involving experts from different municipality departments as well as experts of other local Institution and organizations. In the remaining 17 cases, the systems directly inform and warn people of the possible occurrence of a landslide, in order to reduce the number of people exposed in pre-defined areas. Detailed descriptions of the procedures adopted to issue the warning statements are available for the systems operating in Wushan Town, China (AS_2004_A), in the Illgraben catchment, Switzerland (EU_2000_A) and in Wollongong, Australia (OC_2005_P).

Information tools

Many communication channels are available for warning dissemination, such as warning messages, warning signals, phone calls and internet tools (**Figures 2d, 2e**). Warning messages, usually sent as an SMS, are the most used tool (13 cases), because the message is "pushed" from the warning organization to end users and the latency between a decision to alert to message receipt is minimized. In 9 cases warning signals, such as traffic lights and sirens, are employed on road and railway lines crossing mountainous regions threated by landslides. Manually or automated phone calls have also been used in the oldest Lo-LEWS, while internet-based tools, such as web pages and emails, are adopted in 6 more recent systems. Communication strategies are rarely redundant in the considered Lo-LEWS—2 techniques are combined for just 21% of the cases and more than two techniques in only 14% of the cases. Two relevant exceptions are represented by the systems developed in Åknes, Norway (EU_2004_A), and at Mt. Rainier, USA (NA_1998_A). In both of them several techniques of information—SMS sent in Norwegian, English and German, warning messages on website, automated phone calls, newspapers, radio/televisions news ads, warning sirens in the former; warning messages, radio/television news ads, warning sirens in the latter—are combined and several evacuation drills have been conducted.

Decision about issuing or cancelling an alert

Although the information on decision process or criteria for issuing or cancelling an alert are not available for many systems, it should be noted that warnings are almost always issued manually that is they are issued by an individual or group. The only documented exceptions are represented by the system employed in: Illgraben catchment (EU_2000_A), for which alert signs are activated by a detection system; Preonzo (EU_2010c_A), where the highest level of warning is issued by cantonal officials supported by an automated alert system based on crack meters; Mt. Rainier (NA_1998_A), where the alerts are issued by a computer base station, after analyzing the signals from the field stations; and North Vancouver (NA_2009_N), where the alert levels were updated hourly combining rainfall measures from a rain gauge and rainfall forecasts.

2.5. Performance evaluation

The performance of a LEWS can be described as the system capability to timely detect a landslide event. Standard requirements do not exist for assessing the performance of LEWS.

Calvello and Piciullo (2016) state that many questions need to be addressed to deal with this issue, among which: how are false and missed alerts defined when the warning model includes more than two alert levels? The presence of false and missed alerts reduces the performance of LEWS (e.g., *Wilson, 2004; Segoni et al., 2014; Piciullo et al., 2017a,b).* However, in operational conditions these errors cannot be avoided, thus, as stated by *Sättele et al. (2016)*, an optimal trade-off between detected events and false alarms needs to be identified. Among the Lo-LEWS reviewed herein, only in 7 cases out of 29 (**Table 5**) the performance of the system has been evaluated, adopting two different approaches.

Five evaluations (AS_2014_P, EU_1995_N, EU_2006_P, EU_2007b_P, NA_2009_N) have been carried out by analysing the activity of the landslide(s) under surveillance during specific time frames *(Ju et al., 2015; Arattano, 1999; Del Ventisette et al., 2012; Intrieri et al., 2012; Jakob et al., 2012).* Such an analysis allows a qualitative evaluation of the performance of the adopted warning model, yet it does not provide any statistical indicator to assess the weight of the correct predictions in relation to the model errors. In Longjingwan, China (AS_2014_P), the effects of rainfall on the landslide activity were evaluated from May to September 2012 (i.e. the rainy season in China). A comparison between the movement rates and the daily and cumulative rainfall allowed the authors to calibrate the thresholds of the warning model. In the Moscardo catchment, Italy (EU_1995_P), a performance evaluation was carried out for the summer seasons 1995 and 1996, during which three debris flows occurred. Four seismometers placed along the channel detected all three events, whereas an estimation of the velocity of the flowing mass was possible only in one case. In Ruinon, Italy (EU_2006_P), the velocities of the rockslide under surveillance and the rainfall data were compared for 1 year. The best-performing rainfall thresholds were defined by separating events that induced different dynamic behaviours of the rockslide in relation to rainfall. The reliability of the thresholds employed in the prototype system operational in Torgiovannetto, Italy (EU_2007b_P) was verified by performing a back analysis which showed that the attention level was reached only 7 times in 2.5 years, due to heavy rains, or, in few occurrences, to instrumental errors. The performance has been considered adequate also because the instrumental errors cases could be filtered out by means of a manual check. For the prototype system operational in North Vancouver, Canada (NA_2009_N) performance was evaluated during the whole period of activity. A total of nine debris flows were documented during five storms, the alert level was reached for four cases and the watch II level was exceeded for 26 consecutive hours for the remaining case. No debris flows were recorded during watch I or lower levels. The severe alert level was also never reached during the time the system was operated. For nine other cases the warning I level was reached but no debris flows were documented.

The two remaining evaluations (EU_2000b_A, EU_2010c_A) accounted for several aspects of the systems: technical reliability, inherent reliability and effectiveness *(Sättele et al., 2015; Sättele et al., 2016).* According to this scheme, system performance was derived using two statistical indicators: the probability of detection (POD) and the probability of false alarm

(PFA). To identify a well-balanced warning model the optimal trade-off was identified by means of an utility ratio defined as the ratio between PFA and POD. The optimal balance will be a function of exposure, elements at risk, risk tolerance of the affected community, and will vary substantially based on cultural expectations and norms. A warning strategy that maximizes the performance of the system should produce values of utility ratio between 0.7 and 0.9. Based on the performed analyses, the warning model adopted within the system operational in the Illgraben catchment in Switzerland (EU_2000b_A) has been considered reliable. In this case, the results also highlighted that the performance of the system decreases faster with increasing PFA than with decreasing POD. In the semi-automated system operational in Preonzo, Switzerland (EU_2010c_A), the probability of detection has been calculated for two risk types (i.e. less risk tolerant and more risk tolerant decision makers) as a function of the initially installed sensors, from 5 to 50. The probabilistic analysis revealed that even with a high number of sensors, the probability of the risk-tolerant decision-maker detecting the event never exceeded 0.85.

3. Monitoring strategies

3.1. Classification of monitoring instruments

Monitoring is a crucial continuous activity within a LEWS. Monitoring of triggering parameters is necessary to study landslide occurrence and behaviour, as well as to define thresholds and alert criteria to be employed in a LEWS. In the operational phase, triggering parameters need to be continuously monitored to evaluate the probability of thresholds exceedance. According to *Mikkelsen (1996),* different measurements can be evaluated and the monitoring equipment can be classified based on whether the measurements are performed manually or automatically. *Savvaidis (2003)* defined five different types of techniques of monitoring landslides: remote sensing, photogrammetric, ground-based geodetic, satellite-based geodetic and geotechnical. The author stated that the techniques vary from case to case, depending on expected risk, accessibility of the area, potential for damage, and availability of resources. In a report of the ClimChAlp project, *Komac et al. (2008)* classified slope monitoring methods in four main categories: geodetic, geotechnical, geophysical and remote sensing. The authors also provided a quick overview on the possible fields of application, by introducing characteristics such as surface extension, coverage and predominant morphology. Recently, *Stähli et al. (2015)* presented an overview on the technologies, typically used in EWS for weather-induced landslides, to monitor environmental parameters that contribute to the triggering of landslides. They also discuss the applicability of such technologies to different types of EWS. Besides global reviews of monitoring strategies for early warning purposes, literature contributions also exist on selected issues, such as devices for specific types of landslides *(Arattano and Marchi, 2008; Stumpf et al., 2012; Scaioni et al., 2014)* or particular classes of monitoring instruments *(Tofani et al., 2012; Baroň et al., 2012; Michoud et al., 2012).*

By elaborating on the many schemes already available, *Calvello (2017)* classified the landslide monitoring instruments in terms of observed parameters, and activities and methods of monitoring (**Table 6**). This classification is adopted here to comment on the monitoring strategies used within the reviewed Lo-LEWS. Monitoring can be classified into three main categories: i) deformation, i.e. direct monitoring of the kinematic behaviour of a landslide; ii) groundwater and soil moisture, i.e. monitoring of the pore water characteristics leading to the initiation or an acceleration of a landslide; iii) trigger, i.e. monitoring the external processes responsible for activating or accelerating a landslide. For each activity a number of monitoring parameters can be defined. The monitoring methods are classified in six categories: i) geotechnical, identifying direct measurements of ground displacements, soil deformation, soil moisture, groundwater level and total stress in the soil; ii) hydrologic, measuring the distribution and movement of water on and below the ground surface; iii) geophysical, monitoring changes in the landslide mass by observing physical parameters of soil or rock masses (e.g., density, acoustic/elastic parameters, resistivity); iv) geodetic, assessing landslide displacements by measuring angles and distances or by tracking GPS satellites signals; v) remote sensing, monitoring surface displacements and other ground properties without any physical contact with the landslide body; vi) meteorological, measuring weather parameters that may trigger a landslide (e.g., precipitation, snowmelt) and/or influence its behaviour (e.g., wind, air temperature).

3.2. Activities monitored and parameters

Monitored parameters are indicators or factors related to the slope or landslide of interest that can be quantified and observed with time *(Baroň et al., 2012).* A key issue for any LEWS operating at local scale is the understanding of the behaviour of such site-specific parameters and, moreover the evaluation of their role as early warning indicators. The latter necessarily implies advanced knowledge of the temporal evolution of a given indicator or parameter towards the identification of properly-defined critical values (i.e., thresholds). **Figure 3a** displays the parameters monitored in the 29 Lo-LEWS and presents this information in terms of monitored activities, according to the classification proposed in **Table 6**. As expected, the large majority of the systems—27 out of 29—are based on deformation monitoring, expressed in terms of displacement (15 cases), velocity (8 cases), acoustic emissions (8 cases), cracking (4), acceleration (2) and strain (1). This is due to the fact that most of the monitored landslides were previously recognized and show evidence of active deformation. In most cases the main indicator compared with threshold criteria is the cumulated displacement; velocity and acceleration are more commonly used as kinematic indicators for landslides in rock. A large number of Lo-LEWS also monitor triggering parameters (21 cases), essentially rainfall data (20 cases). A relevant exception is the system deployed at Mt. Ruapehu, New Zealand (OC_2000_A), where the level of the lake is used as the alert parameter, since the explosive ejection of lake water has been recognized as the main trigger for the possible occurrence of lahars.

Groundwater conditions are monitored in 16 systems. Pore water pressures (in 8 cases) and water levels (in 7 cases) are the most commonly monitored parameters. The groundwater response to a rainfall event in a slope is dependent on the hydrological properties of the materials involved and the initial soil moisture and groundwater conditions. In particular, the groundwater regime may display rapid response to intense rainfall or a gradual rise/decline of the groundwater level during wet/dry seasons. For this reason, groundwater levels and/or pore water pressures are typically recorded at intervals related to the period of the year and to the soil characteristics. Monitoring of other activities is not frequent in the reviewed systems (5 cases). A relevant example to mention is the system developed at Lake Sarez, eastern Tajikistan (AS_2005_A), where the fluctuations of the lake level and the turbidity of the water represent significant landslide precursors. Further analyses have been carried out in order to investigate the monitored activities as a function of the types of landslide under surveillance (**Figure 3b**). Deformation activity is considered for all types of landslides.

The two most common landslide typologies, i.e. debris flows and rockslides, use very different monitoring parameters even though the activity monitored is the same. Two parameters are concurrently or alternatively investigated for debris flows: rainfall (trigger activity), to predict an event before its occurrence; acoustic emissions (deformation activity), to detect a debris flow while in progress recording the ground vibration produced by the moving mass of water and debris. On the contrary, the monitoring systems developed for rockslides always employ displacement and velocity parameters to define the deformation activity. In the majority of cases, independently on the type of landslide addressed, groundwater and meteorological parameters are also investigated. In these cases, redundancy in the number of monitored parameters is typically justified as a way to better understand the behaviour and the spatial-temporal evolution of the monitored phenomena and to produce predictions that are more reliable.

3.3. Monitoring methods

The monitoring methods employed in Lo-LEWS are correlated to the site-specific conditions of the slope to be monitored and, as a consequence, to the parameters investigated. In particular, suitable parameters for monitoring must be identified and the most appropriate monitoring instruments selected according to a set of criteria, such as: simplicity, robustness, reliability and cost. A wide spectrum of instruments is available to LEWS designers and managers. **Figure 4a** shows the monitoring methods and instruments that are used within the 29 Lo-LEWS reviewed, following the classification proposed in **Table 6**. As already mentioned, redundancy is a crucial aspect for developing monitoring strategies. The large number of Lo-LEWS employing more than one monitoring method confirm the previous statement. As an example, the system implemented at Wushan Town, China (AS_2004_A), addressing a deep-seated colluvial landslide, employs geotechnical and geodetic methods (i.e. inclinometers, GPS) integrated by hydrologic (i.e. water level meter), geophysical (i.e. TDR) and meteorological ones (i.e. a network of rain gauges).

Geotechnical and meteorological methods are widely employed—both methods are considered in 21 cases. Geotechnical data include deformation and groundwater measurements. In general, inclinometers, piezometers, perforated standpipes and extensometers are widely used, since these sensors deliver reliable data and are robust and cheap. Systems addressing large and complex phenomena often implement expensive instruments, such as differential monitoring of stability (DMS) columns (6 cases) consisting of a large number of inclination and settlement sensors providing profiles of horizontal and vertical displacements along monitored boreholes. Meteorological monitoring methods are also crucial for early warning purposes, as demonstrated by the large number of rain gauges (12 cases) and weather stations (10 cases) employed within the considered systems. Geotechnical monitoring is combined in several applications with geodetic monitoring, in order to achieve reliable information on the absolute displacements of the landslide with respect to some reference points. For the large majority of applications (11) GPS monitoring is preferred over conventional terrestrial methods because it provides greater flexibility—e.g., measurements possible also during the night and under bad weather conditions—and the results are typically more reliable. Remote sensing techniques, especially cameras and Ground-based Synthetic Aperture Radars (GbSAR), are also widely applied (13 cases), although these sensors are quite expensive and do not provide real-time data usable to issue warnings. Indeed, they are typically used to understand and update the state of knowledge on the long-term landslide kinematic behaviour.

Figure 4b shows the monitoring methods employed in the reviewed systems in relation to the different types of landslide. Geotechnical monitoring is widely used for all landslides with the exception of debris flows. In these cases, the monitoring strategies are mainly based on meteorological methods or geophysical methods, the latter to warn about phenomena that are already occurring. Geophysical methods are also often employed to monitor rockslides, in combination with geotechnical methods. For a certain number of cases, additional information is also acquired by means of remote sensing methods. In particular, cameras are used for debris flows, and GbSAR and Interferometric Synthetic Aperture Radars (InSAR) for large and destructive phenomena, such as rockslides and deep-seated colluvial landslides.

4. Discussion

A great variety of slope instabilities—comprising debris flows, rockslides, rock avalanches, deep seated colluvial landslides, cliff top recessions, rockfalls and mudslides—have been investigated and monitored employing a range of strategies. Often one or more parameters are monitored for the same landslide, and different monitoring methods and instruments are employed. However, some parameters are more reliable than others for issuing warnings. **Figure 5** presents the number and the type of monitored parameters and instruments directly used to issue alert levels (in red colour in the Figure), which is a subset of the parameters and instruments composing the monitoring network of the reviewed Lo-LEWS (in blue colour in the Figure). In 7 systems the exceedance of more than one triggering parameter is considered to issue a warning. For these reasons, the total number of parameters employed for warning purposes (40) exceeds the number of Lo-LEWS reviewed herein. As expected, displacements and derived quantities (velocity and acceleration) are the parameters most widely adopted, with 25 examples. In particular, displacement and velocity are considered the main warning parameters in 18 cases. Displacement monitoring is performed adopting a variety of sensors, among which the highest warning potential can be attributed to: GPS devices (9 cases), embedded extensometers (6 cases) and inclinometers (5 cases). The widespread application of GPS is quite surprising as other literature contributions *(Baroň and Supper, 2013; Michoud et al., 2013)* indicate inclinometers and extensometers as the most reliable displacement measuring devices. Rainfall is also widely monitored (20 cases) as a crucial parameter for landslide warning, since most of the investigated mass movements are weather-induced landslides. Rainfall are typically monitored either by a network of rain gauges or by weather stations, when additional weather parameters (e.g., snowmelt or temperature) are deemed to be important, such as for systems dealing with rockslides in mountainous environments. Acoustic emissions are also frequently monitored, especially by means of geophones, which have demonstrated to be robust and reliable sensors in a good number of applications *(e.g., Arattano and Marchi, 2008).* The early warning potential of this parameter is mainly related to the detection of debris flows in their initial stages. However, a good number of instruments, although part of Lo-LEWS monitoring networks, are not explicitly used for issuing warnings. For instance, data coming from cameras, GbSAR, InSAR and LIDAR (Light Detection and Ranging)—i.e. monitoring by remote sensing often reported as a promising method for warning purposes—are not included in any warning model. According to *Baroň and Supper (2013),* these technologies are still not mature enough for geotechnical applications yet they have a high warning potential.

This overview of the monitoring strategies reveals that a crucial aspect of operational Lo-LEWS is redundancy. In particular, rockslides, rock avalanches, rockfalls and deep seated colluvial landslides are usually monitored by combining geotechnical, geophysical, meteorological and remote sensing techniques. The latter can be helpful during pre-investigation phases and can also provide LEWSs with complementary information on the landslide activity. In particular, satellite-based techniques are mainly useful for an overview of slope stability issues in the area of interest (*e.g., Lu et al., 2014; Calvello et al., 2017; Peduto et al., 2017*), whereas ground-based techniques typically provide greater details for local investigations *(e.g., Stumpf et al., 2012; Michoud et al., 2013; Scaioni et al., 2014).* Redundancy of the measures also allows a continuous check on the working conditions of the instruments and, therefore, a prompt reaction in case of malfunctioning of some devices *(Federici, 2008; Intrieri et al., 2012).* Redundancy is not possible, however, for landslides that do not show clear warning signs in the pre-failure stage. In case of debris flows, for instance, the monitoring strategies are typically focused on the investigation of only one or two parameters: the triggering factor (e.g., rainfall) and/or the evidence of a phenomenon already in progress (e.g., acoustic signals).

The redundancy of monitoring strategy is only one of the aspects to be addressed for evaluating the success or the failure of a Lo-LEWS. Indeed, the reliability of a system should be defined in terms of efficiency and effectiveness (*Piciullo et al., 2018*). *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. The analysis of the effectiveness of the reviewed Lo-LEWS is beyond the scope of this paper. However, among all the aspects influencing the effectiveness of Lo-LEWS it is important to mention the lead time. Longer lead times mean better opportunities for the system managers and for the actors involved in the emergency plan to react adequately to the warnings issued. In 15 cases of the 29 reviewed Lo-LEWS the occurrence of the landslide is forecasted using triggering parameters and, thus, a lead time longer than 1 hour is to be expected.

Many aspects may be associated to the efficiency of a Lo-LEWS. As already mentioned, redundancy of the monitored parameters and of the monitoring methods are crucial aspects. Indeed, they can provide useful data to be considered in the decisional phase, as well as allowing a continuous check on the working conditions of the instruments and, therefore, a prompt reaction in case of malfunctioning of some devices. Among the reviewed systems, 24 out of 29 (83%) monitor different classes of parameters and 23 out of 29 (79%) employ several monitoring methods (**Figure 6a**). For instance, in Wushan Town, China (AS_2004_A), all the monitored activities are considered (i.e. deformation, groundwater, trigger, other) and five different groups of monitoring methods are employed (i.e. geotechnical, hydrologic, geophysical, geodetic and meteorological). The definition of thresholds considering more than one activity also leads to an increased efficiency of a system, as it supports the decision of whether to issue or not to issue a warning. Only in 7 cases out of 29 (24%) multiple thresholds have been considered. Finally, the evaluation of the warning model performance is another important aspect related to the efficiency of a warning system. As highlighted in the section 2.5, this issue is often overlooked by system managers, indeed only 7 (24%) of the considered systems underwent some formal performance evaluation. **Figure 6b** summarises, for each Lo-LEWS, the presence or absence of each one of the four aspects previously associated to the efficiency of Lo-LEWS. The reviewed systems are ordered by the number of aspects considered. None of the systems is considering all four aspects, yet at least two aspects have been addressed in a good number of systems. On the other end of the spectrum, there are systems for which no one (AS_1991_P, EU_2002_A, NA_1998_A) or only one (EU_1995_N, NA_2009_N, EU_2010_A) of these aspects are present.

5. Concluding remarks

The main components of 29 Lo-LEWS operational worldwide have been presented, summarized in tables and discussed in relation to a conceptual model comprising three main modules: landslide model, warning model and warning system. Lo-LEWS are mainly managed by government institutions and by civil protection agencies, thus complete and thorough information on their characteristics is not always available in the scientific literature. When existing, publications often describe innovative monitoring techniques, compare measured and predicted data and/or correlate landslide movements with monitoring data. However, they often do not adequately present the features of the monitoring network in relation to the warning model adopted within the considered Lo-LEWS. For this reason, information on the reviewed systems was gathered from different sources including, besides peer-reviewed scientific articles, grey literature reports and web pages.

To design and manage—i.e. efficient and effective—LEWS operating at local scale, it is important to address a variety of issues. Indeed, omitting or underestimating any component of the system may lead to the failure of the whole system. In this context, monitoring strategies (i.e. monitored parameters and monitoring methods) play a central role, both in the design and in the operational phase of a LEWS. Although the limited number of systems reviewed does not allow us to derive quantitative conclusions, these valuable experiences provide the means to describe the elements and their role in the success (or in the failure) of operational Lo-LEWS. The classification of the monitoring network of the reviewed Lo-LEWS in terms of parameters, activities and methods of monitoring, showed that: rainfall and displacements were the parameters most widely measured; and rain gauges, GPS, weather stations and inclinometers were highly employed as monitoring instruments. However, considering only the parameters and the instruments directly used to issue the warnings: displacement and velocity resulted the main monitored parameters; and GPS, embedded extensometers, total stations and inclinometers were the main monitoring instruments. This review also revealed an absence of standard procedures for developing monitoring strategies for Lo-LEWS, which are indeed a function of many local factors, such as landslide hazard and risk settings and socio-economic constrains. Future research work in this area is thus needed, and should be directed at highlighting the main requirements that system managers have to consider when designing their monitoring strategies within a Lo-LEWS. Of great benefit to future work would be increased documentation of the performance and operational aspects of existing systems, particularly those operated by private interests.

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Table 1. Local landslide early warning systems reviewed: country, managing institution, source of information, year of most recent information.

ID	Location	Country	Institution	Source of information	Latest information
AS_1977_N	Xintan Town	China	No info	Wang (2009), Li et al. (2016)	2016
AS_1991_P	Nojiri River Basin	Japan	Kyoto University	Itakura et al. (2000), Takeshi (2011)	2004
AS_2002_A	Taiwan torrents	Taiwan	Soil and Water Conservation Bureau	Yin et al. (2011)	2011
AS_2004_A	Wushan Town	China	Ministry of Land and Resource	Wang et al. (2008), Yin et al. (2010)	2010
AS_2005_A	Lake Sarez	Tajikistan	Ministry of defense	Di Biagio and Kjekstad (2007)	2007
AS_2007_P	Banjarnegara	Indonesia	Asian Institute of Technology	Honda et al. (2008), Sassa et al. (2009)	2009
AS_2014_P	Longjingwan	China	State Key Laboratory of Geohazard Prevention and Geoenvironment Protection	Huang et al. (2013), Ju et al. (2015)	2015
EU_1995_P	Moscardo catchment	Italy	Forest Service of Friuli-Venezia Giulia Region	Arattano (1999)	1996
EU_1997_A	Coastal areas	England	No info	Clark et al. (1996), Stähli et al. (2015)	2015
EU_2000_A	Nals	Italy	Civil Defence	Thiebes (2011), Stähli et al. (2015)	2015
EU_2000b_A	Illgraben catchment	Switzerland	Cantonal Crisis Unit of the Canton of Valais	McArdell et al. (2007), Badoux et al. (2009)	2009
EU_2002_A	South-west	Germany	No info	Thiebes (2011)	2002
EU_2003_A	Aosta Valley	Italy	Aosta Control Centre	Broccolato (2010), Tamburini (2005), Tamburini and Martelli (2006)	2010
EU_2004_A	Åknes	Norway	Åknes/Tafjord Early Warning Centre	Baroň et al. (2012), Blikra et al. (2013), Kristensen et al. (2010), Lacasse and Nadim (2011)	2013
EU_2006_P	Ruinon	Italy	ARPA Lombardia Early Warning Centre	Crosta and Agliardi (2003), Baroň et al. (2012)	2006
EU_2007_A	La Valette	France	Service de Restauration des Terrains en Montagne	Web page from OMIV (Accessed: 23 October 2017)	2017
EU_2007b_P	Torgiovannetto	Italy	No info	Intrieri et al. (2012)	2007
EU_2007c_P	Swabian Alb	Germany	German Federal Ministry of Education and Research	Thiebes et al. (2014)	2008
EU_2008_A	Ancona	Italy	Ancona Monitoring Center	Cotecchia (2006), Cardellini and Osimani (2011), Cardinaletti et al. (2011), Baroň et al. (2012)	2012
EU_2009_A	Mont de La Saxe	Italy	Geological Survey of Aosta Valley Region	Crosta et al. (2014), Crosta et al. (2015), Manconi and Giordan (2015)	2015
EU_2009b_A	Mannen	Norway	Åknes/Tafjord Early Warning Centre	Kristensen and Blikra (2011), Baroň et al. (2012), Blikra et al. (2013)	2013
EU_2010_A	Alice Bel Colle	Italy	Alice Bel Colle municipality	Olivieri et al. (2012)	2010
EU_2010b_A	Bagnaschino	Italy	Geological Bureau of the Province of Cuneo	Giuliani et al. (2010), Baroň et al. (2012)	2012
EU_2010c_A	Preonzo	Switzerland	Department of Territory - Canton of Ticino	Loew et al. (2012), Loew et al. (2016)	2016
NA_1998_A	Mt. Rainier	USA	United States Geological Survey (USGS) and Pierce County Emergency Management (PCEM)	LaHusen (1998), Pierson et al. (2014), web pages from USGS and PCEM (Accessed: 05 September 2018)	2018
NA_2005_A	Turtle Mountain	Canada	Alberta Geological Survey	Read et al. (2005), Moreno and Froese (2010), Froese and Moreno (2014)	2014

NA_2009_N	Vancouver	Canada	British Columbia Ministry of Forests	Jakob et al. (2012)	2011
OC_2000_A	Mt. Ruapehu	New Zealand	Department of Conservation	Keys and Green (2008), Massey et al. (2010)	2010
OC_2005_P	Wollongong	Australia	University of Wollongong	Flentje and Chowdhury (2005), Flentje and Chowdhury (2006)	2005

Table 2. Lo-LEWS reviewed: information on landslide models. (Legend: The: Theodolite; TotS: Total station; Crack: Crackmeter; Mic: Microphone; RG: Rain gauge; Cam: Camera; Geoph: Geophone; WLM: Water level meter; WS: Weather station; Bar: Barometer; GPS: Global positioning system; TDR: Time domain reflectometer; Inc: Inclinometer; Hyd: Hydrometer; PT: Pressure transducer; OptF: Optic fiber; Acc: Accelerometer; TM: Turbidity mteter; EExt: Embedded Extensometer; BExt: Borehole Extensometer; Seis: Seismometer; Tilt: Tiltmeter; Sat: Satellite sensor; GbSAR: Ground-based synthetic aperture radar; DMS: "Differential monitoring of instability" column; InSAR: Interferometric synthetic aperture radar; LiDAR: Light detection and ranging; Tens: Tensiometer)

ID	**Covered area**	**Type(s) of landslide**	**N° (and volume) of landslides**	**Landslide cause(s)**	**Monitoring system**
AS_1977_N	0.75 km^2	Rock avalanche	1 (30M m^3)	Rainfall	The, Crack, WLM
AS_1991_P	10 km^2	Debris flows	Several	Rainfall	Geoph
AS_2002_A	17 + 3 sites (35,980 km^2)	Debris flows	Several	Rainfall	*17 on-site + 3 mobile stations:* RG, Cam, Geoph, Hyd, WS
AS_2004_A	0.75 km^2	Deep-seated colluvial	1 (90M m^3)	Rainfall and human activity	GPS, TDR, Inc, Piez, RG, OptF, WLM
AS_2005_A	1.5 km^2	No info	1	Rainfall	WLM, Acc, GPS, SprS, WS
AS_2007_P	1 km^2	No info	1	Rainfall	EExt, RG, Piez, Cam
AS_2014_P	0.008 km^2	Rainfall-induced	1	Rainfall	RG, Inc, Piez
EU_1995_P	4.1 km^2	Debris flows	No info	Rainfall	Seis
EU_1997_A	6 sites (1 km^2)	Cliff top recession	No info	Sea activity	Tilt, EExt, PS, GPS, Inc
EU_2000_A	App. 0.3 km^2	Debris flows	No info	Rainfall	Geoph, Piez, RG, Cam
EU_2000b_A	9.5 km^2	Debris flow	No info	Rainfall	Geoph, Sat, Cam, RG
EU_2002_A	0.035 km^2	No info	1 (700K m^3)	No info	GPS
EU_2003_A	4 * < 1 km^2	No info	4	Rainfall and snowmelt	*Becca di Nona:* EExt, GPS, WS *Vollein:* TotS, WS, GPS *Bosmatto:* EExt, GPS, WS, Piez *Citrin:* EExt, WS, GPS, GbSAR
EU_2004_A	0.75 km^2	Rockslide	1 (54M m^3)	Rainfall and snowmelt	GPS, TotS, GbSAR, BExt, Crack, Tilt, Geoph, WS, DMS, PS
EU_2006_P	0.26 km^2	Rockslide	1 (13M m^3)	Rainfall	EExt, TotS, WS, GPS, InSAR
EU_2007_A	0.5 km^2	Mudslide	3,5M m^3	Rainfall	WS, Inc, Piez, BExt, GPS, Cam, LiDAR
EU_2007b_P	0.03 km^2	Rockslide	1 (182K m^3)	Rainfall	EExt, RG, Cam
EU_2007c_P	0.4 km^2	Rockfall	No info	Rainfall	Inc, Tilt, TDR, Tens, WS, Piez
EU_2008_A	App. 3 km^2	No info	No info	Rainfall	TotS, GPS, RG, DMS, PS
EU_2009_A	0.15 km^2	Rockslide	1	Rainfall and snowmelt	*Surface:* InSAR, GPS, TotS *Deep:* Inc, BExt, PS, DMS
EU_2009b_A	0.25 km^2	Rockslide	1 (20M m^3)	Rainfall and snowmelt	BExt, GPS, GbSAR, DMS, PS, WS
EU_2010_A	App. 0.45 km^2	No info	No info	Rainfall	DMS, Inc, PS
EU_2010b_A	0.15 km^2	Deep-seated roto-translational	(1,2M m^3: flow part)	Rainfall and snowmelt	DMS, PS, TotS, WS, Inc
EU_2010c_A	0.01 km^2	Rockslides and rock avalanches	1 (140K m^3)	Rainfall	EExt, RG, TotS, Crack, GbSAR
NA_1998_A	App. 100 km^2	Lahars (debris flows)	Several (potentially 40M m^3)	Snowmelt and volcanic activity	Geoph
NA_2005_A	0.5 km^2	Rock avalanche	Several	Rainfall	Tilt, BExt, Crack, WS, RG, TDR
NA_2009_N	160.76 km^2	Debris flows	No info	Rainfall	RG
OC_2000_A	0.2 km^2	Lahars (debris flows)	Several	Dam break	3 Geoph, WLM
OC_2005_P	2 sites	Rainfall-induced	2	Rainfall	Inc, Piez, RG

Table 3. Lo-LEWS reviewed: information on warning models. (Legend: HM: Heuristic method; CL: Correlation law; PM: Probabilistic model)

ID	Alert criterion	Alert parameters	Other parameters monitored	Alert levels
AS_1977_N	Power law: velocity vs. failure time (CL)	Velocity	Displacement, stream flow, cracking	2
AS_1991_P	Empirical correlation with acoustic emission (HM)	Acoustic emission	None	2
AS_2002_A	Rainfall intensity or accumulated rainfall (CL)	Rainfall intensity or accumulated rainfall	Acoustic emission, steam flow	2
AS_2004_A	Empirical correlation with displacement, pore water pressure, strains (HM)	Displacement, pore water pressure, strains	Soil water content, rainfall, stream flow	4
AS_2005_A	Empirical correlation with seismic acceleration, stream flow, displacement, water quality, rainfall (HM)	Seismic acceleration, stream flow, displacement, water quality, rainfall	None	3
AS_2007_P	Correlation with antecedent rainfall and displacement (CL)	Antecedent rainfall, displacement	Pore water pressure	3
AS_2014_P	Empirical velocity thresholds (HM)	Velocity	Rainfall, pore water pressure	4
EU_1995_P	Empirical correlation with acoustic emission (HM)	Acoustic emission	None	2
EU_1997_A	Empirical thresholds (HM)	Displacement, groundwater level	None	2
EU_2000_A	Empirical correlation with acoustic emission (HM)	Acoustic emission	Pore water pressure, rainfall	2
EU_2000b_A	Rainfall intensity-duration (CL)	Rainfall	Acoustic emission	2
EU_2002_A	Pre-defined thresholds based on rate of movement (HM)	Displacement	No info	3
EU_2003_A	Rainfall and displacement thresholds (HM)	Rainfall, displacement	Pore water pressure	3
EU_2004_A	Velocity level (HM)	Velocity	Acceleration, rainfall, snowmelt, acoustic emission, groundwater level, cracking	5
EU_2006_P	Power law: velocity vs. failure time (CL)	Velocity	Rainfall	3
EU_2007_A	No info	No info	Rainfall, displacement, pore water pressure	No info
EU_2007b_P	Empirical velocity thresholds (HM)	Velocity	Rainfall	3
EU_2007c_P	Empirical correlation with pore water pressure and displacement (HM)	Pore water pressure, displacement	Suction, soil water content, rainfall	3
EU_2008_A	Empirical thresholds (HM)	Displacement, rainfall, groundwater level	None	5
EU_2009_A	Empirical displacement thresholds (HM)	Displacement	Groundwater level	3
EU_2009b_A	Velocity level (HM)	Velocity	Acceleration, rainfall, snowmelt, groundwater level	5
EU_2010_A	Empirical displacement thresholds (HM)	Displacement	Groundwater level	4
EU_2010b_A	Rain intensity-duration law (CL)	Rainfall	Displacement, groundwater level	2
EU_2010c_A	Correlation law: velocity vs. time of failure (CL)	Velocity	Rainfall, cracking, soil water content	4
NA_1998_A	Empirical correlation with acoustic emission (HM)	Acoustic emission	None	3
NA_2005_A	Empirical velocity-based thresholds (HM)	Velocity	Displacement, rainfall, cracking	4
NA_2009_N	Discriminant analysis of rainfall events (PM)	Rainfall	None	5
OC_2000_A	Empirical correlation with abs. lake level (HM)	Absolute lake level	Stream flow, volcanic activity	6

OC_2005_P	Intensity-duration (CL)	Rainfall	Pore water pressure, displacement	3

Table 4. Lo-LEWS reviewed: information on warning system.

ID	Lead time	Warning statement	Information tools	Persons informed	Decision about issuing or cancelling an alert
AS_1977_A	24 hours	Public	No info	Residents	No info
AS_1991_P	Few seconds	Internal	No info	No info	No info
AS_2002_A	< 1 hour	Internal	Triggering signal	Debris Flows Disaster Management Center	No info
AS_2004_A	No info	Public	Website	Internet users	Government
AS_2005_A	< 1 hour	Public	Warning messages	Office in Dushbane, local control center and villages downstream	Office in Dushanbe or local control center
AS_2007_P	1 to 24 hours	Public	Web pages	Public	No info
AS_2014_P	24 hours	Public	Web pages	Experts and citizens	Experts judgement
EU_1995_N	Few seconds	Internal	No info	Researchers	No info
EU_1997_A	No info	Internal	Automatic telephone calls	Experts	No info
EU_2000_A	20 to 60 minutes	Public	Flood lights	Citizens	No info
EU_2000b_A	Few seconds	Public	Flashing lights, sirens	Pedestrians, inhabitants in the valley	Automated alert signals
EU_2002_A	No info	Internal	Automatic telephone calls	Experts	Road authorities
EU_2003_A	24 hours	Internal	Warning messages	Experts	Expert group
EU_2004_A	24 hours	Public	Web pages, public meetings, newspapers, television, radio, sirens, automatic phone calls	The public	Early Warning Centre
EU_2006_P	24 hours	Public	No info	No info	No info
EU_2007_A	No info	Public	No info	No info	Local risk managers
EU_2007b_P	24 hours	Internal	Automatic notification	Personnel in charge of monitoring	No info
EU_2007c_P	24 hours	Public	Two traffic lights, SMS	Drivers and road maintenance service, police, rescue forces, regional geological department	Experts
EU_2008_A	1 to 3 hours	Internal	Warning SMS, direct call	Ancona Monitoring Centre	Civil Protection Department of the Ancona Municipality
EU_2009_A	1 hour	Public	Warning messages, traffic lights	Civil protection, road users, residents	Civil Protection
EU_2009b_A	> 24 hours	Public	SMS, emails, electronic warning siren	Early Warning Centre, police, county governor, municipalities, road authorities, coast guard, power companies, inhabitants	Early Warning Centre
EU_2010_A	No info	Internal	SMS, direct call	Staff on duty at the monitoring centre	Technical personnel of the Alice Bel Colle Municipality
EU_2010b_A	No info	Public	No info	No info	No info
EU_2010c_A	> 1 hour	Internal	SMS	Landslide experts	Cantonal officers and automatic alarms
NA_1998_A	40 minutes to 3 hours	Public	Warning messages, television, radio, sirens	Schools, public and commercial facilities, citizens	Automated system
NA_2005_A	24 hours	Internal	Warning messages, phone calls	Turtle Mountain Staff	Municipal and provincial emergency management officials
NA_2009_N	6 hours	Public	Warning messages	No info	Warnings updated automatically
OC_2000_A	5 to 30	Internal	Pagers, phone calls,	Experts	Decision-making

	minutes		internet		authorities
OC_2005_P	6 hours	Public	Web pages	Landslide research team	No info

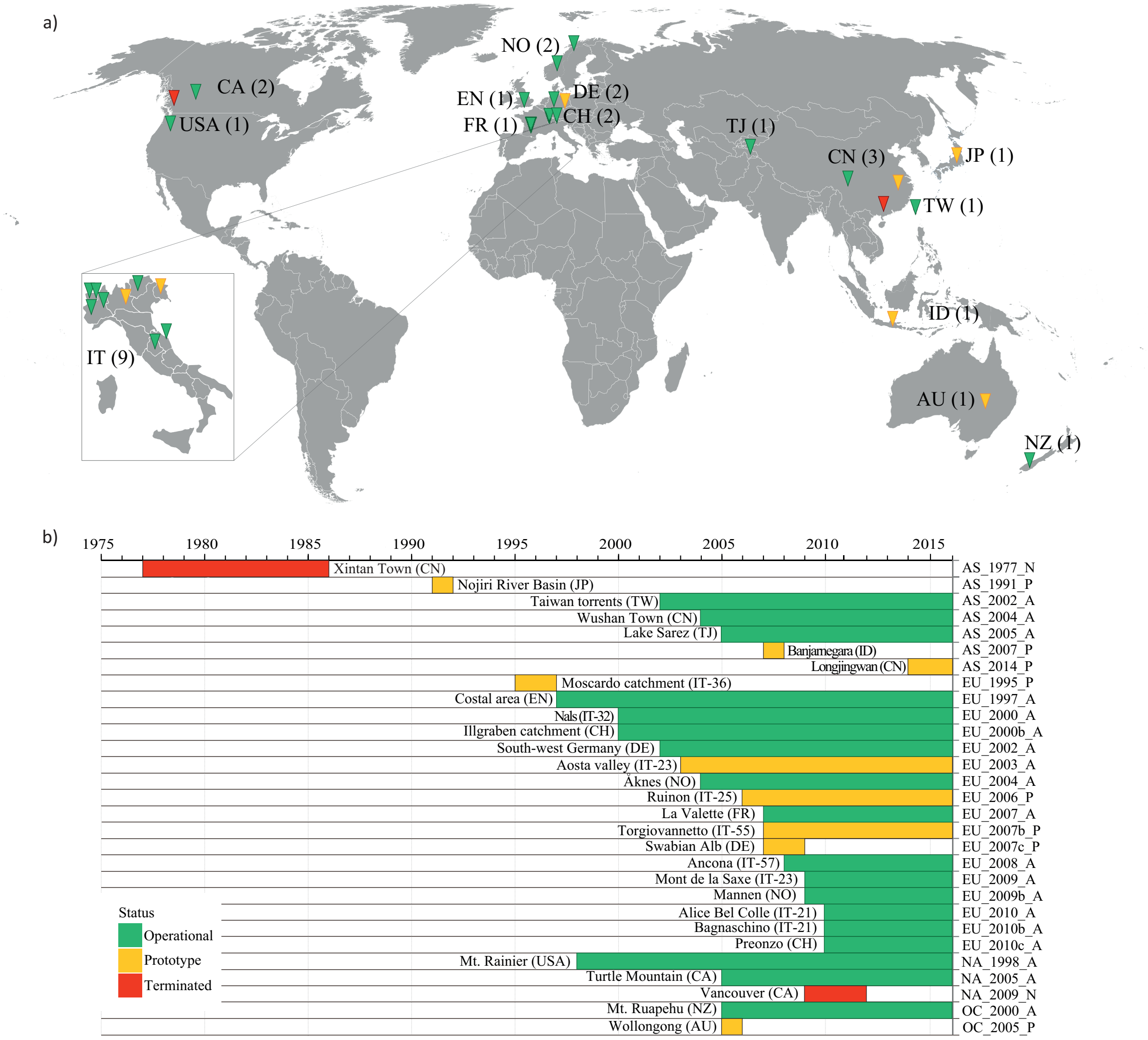
Table 5. Performance evaluation methods developed for the Lo-LEWS for which the information is available.

ID	Performance evaluation method	Through…
AS_2014_P	Comparison between landslide activity and warnings issued	Time frame analysis
EU_1995_N	Comparison between predicted and reported landslides	Time frame analysis
EU_2000b_A	Reliability analysis	Statistical indicators
EU_2006_P	Comparison between landslide activity and warnings issued	Time frame analysis
EU_2007b_P	Comparison between landslide activity and warnings issued	Time frame analysis
EU_2010c_A	Reliability analysis	Statistical indicators
NA_2009_N	Comparison between predicted and reported landslides	Time frame analysis

Table 6. Instruments used for landslide monitoring within LEWS, classified considering the parameters and the activities monitored and the monitoring methods (after Calvello, 2017). (Legend: Inc: Inclinometer; BExt: Borehole extensometer; DMS: “Differential monitoring of stability” column; Tilt: Tiltmeter; GPS: Global positioning satellite; Int: Interferometer; TotS: Total station; Cam: Camera; GbLiD: Ground-based LIDAR; ALiD: Airborne LIDAR; GbSAR: Ground-based synthetic aperture radar; InSAR: Interferometric synthetic aperture radar; UAV: Unmanned air vehicle; OptF: Optic fiber; EExt: Embedded extensometer; Geoph: Geophone; Crack: Crackmeter; Acc: Accelerometer; Seis: Seismometer; GPR: Ground penetrating radar; Piez: Piezometer; PS: Perforated standpipe; Tens: Tensiometer; TPsy: Thermocouple psychrometer; ElCS: Electrical conductivity sensor; ThCS: Thermal conductivity sensor; TDR: Time domain reflectometer; Sat: Satellite sensor; RG: Rain gauge; WS: Weather Station; Bar: Barometer; WLM: Water level meter; Hyd: Hydrometer; SprS: Spring sampling).

Monitored activity	Monitored parameter	Monitoring method					
		Geotechnical	Hydrologic	Geophysical	Geodetic	Remote sensing	Meteorological
Deformation	Displacements	Inc BExt EExt DMS Tilt			GPS Int TotS	Cam GbLiD ALiD GbSAR InSAR UAV	
	Strains	OptF EExt		Geoph			
	Cracking	Crack				GbLiD ALiD	
	Mass balance					GbLiD ALiD	
	Microseismicity / Acoustic emission			Acc Seis Geoph		GPR	
	Rockfall event frequency					GbLiD ALiD	
Groundwater	Pore water pressure	Piez					
	Groundwater level	PS					
	Suction	Tens TPsy		ElCS ThCS			
	Soil water content			TDR		Sat	
Trigger	Weather					Sat	RG WS
	Earthquake			Acc Seis Geoph			
	Volcanic activity			Acc Seis Geoph		InSAR	
Other	Atmospheric tides						Bar
	Stream flow		WLM Hyd				
	Water quality		SprS				

fig.1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Xintan Town (CN)
Nojiri River Basin (JP)
Taiwan torrents (TW)
Wushan Town (CN)
Lake Sarez (TJ)
Banjarnegara (ID)
Longjingwan (CN)
Moscardo catchment (IT-36)
Costal area (EN)
Nals (IT-32)
Illgraben catchment (CH)
South-west Germany (DE)
Aosta valley (IT-23)
Åknes (NO)
Ruinon (IT-25)
La Valette (FR)
Torgiovannetto (IT-55)
Swabian Alb (DE)
Ancona (IT-57)
Mont de la Saxe (IT-23)
Mannen (NO)
Alice Bel Colle (IT-21)
Bagnaschino (IT-21)
Preonzo (CH)
Mt. Rainier (USA)
Turtle Mountain (CA)
Vancouver (CA)
Mt. Ruapehu (NZ)
Wollongong (AU)
AS_1977_N
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Status
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Prototype
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fig.2

Click here to access/download;Figure;fig.2-LO-LEWS_Tavola disegno 1.eps

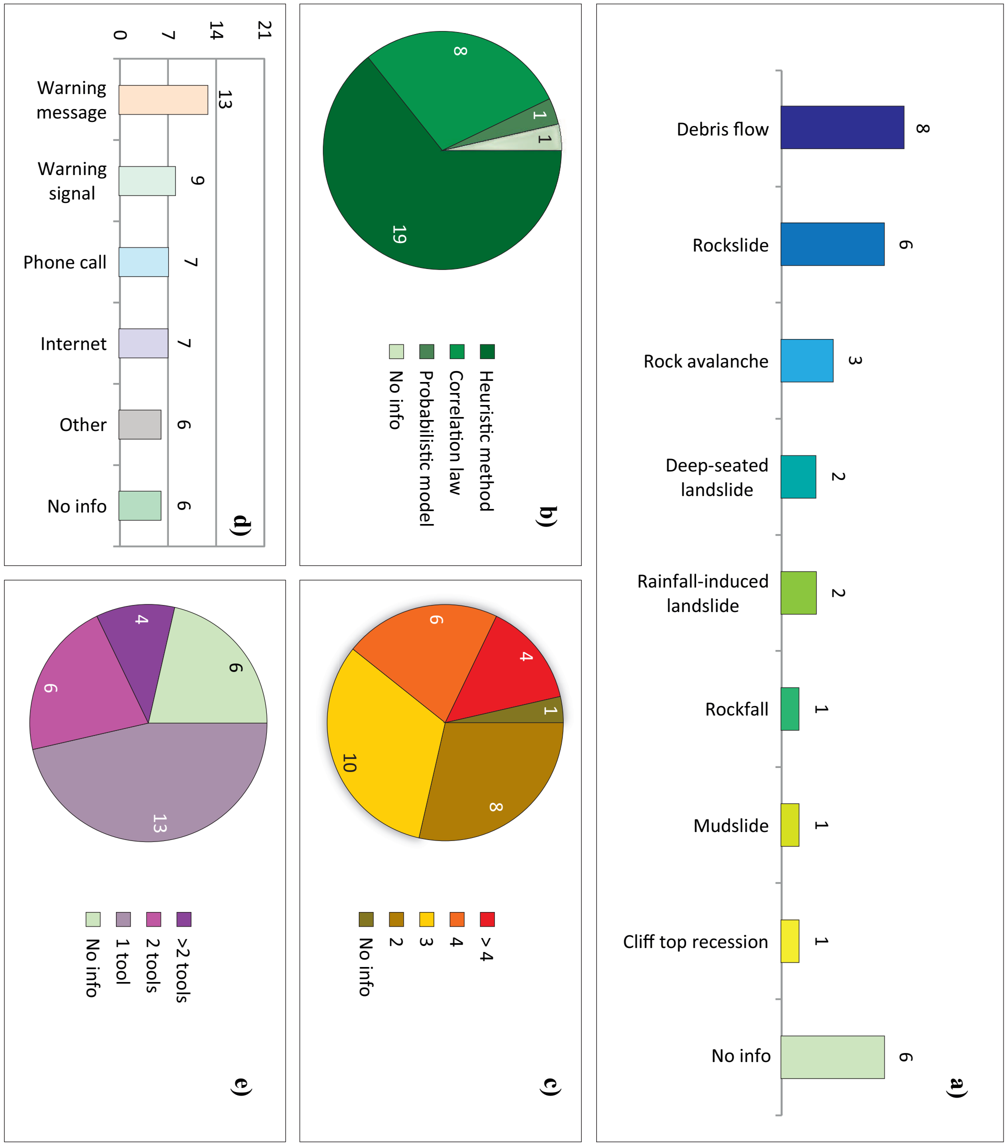
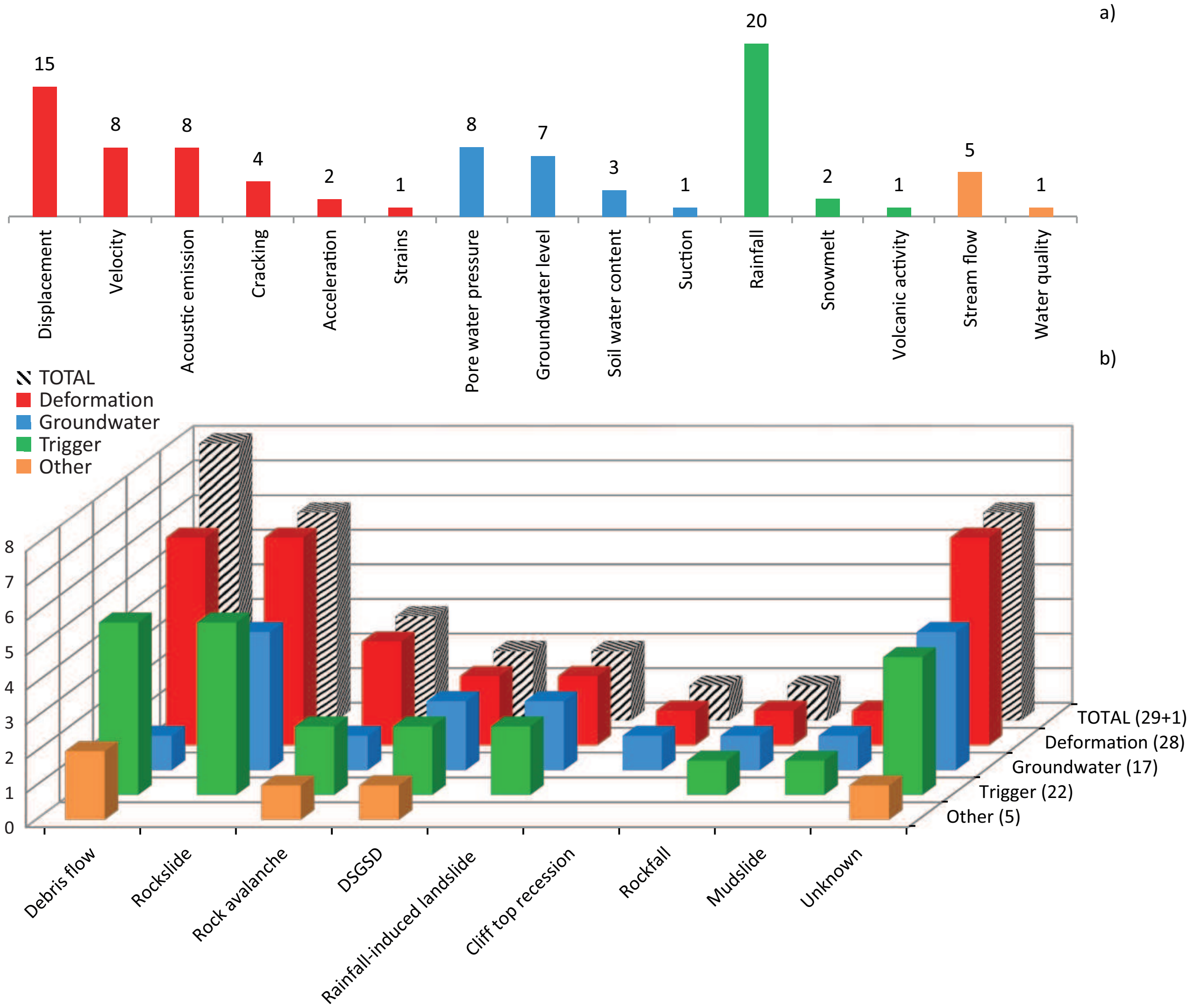


fig.3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Pore water pressure
Groundwater level
Soil water content
Suction
Rainfall
Snowmelt
Volcanic activity
Stream flow
Water quality
b)
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Deformation (28)
Groundwater (17)
Trigger (22)
Other (5)
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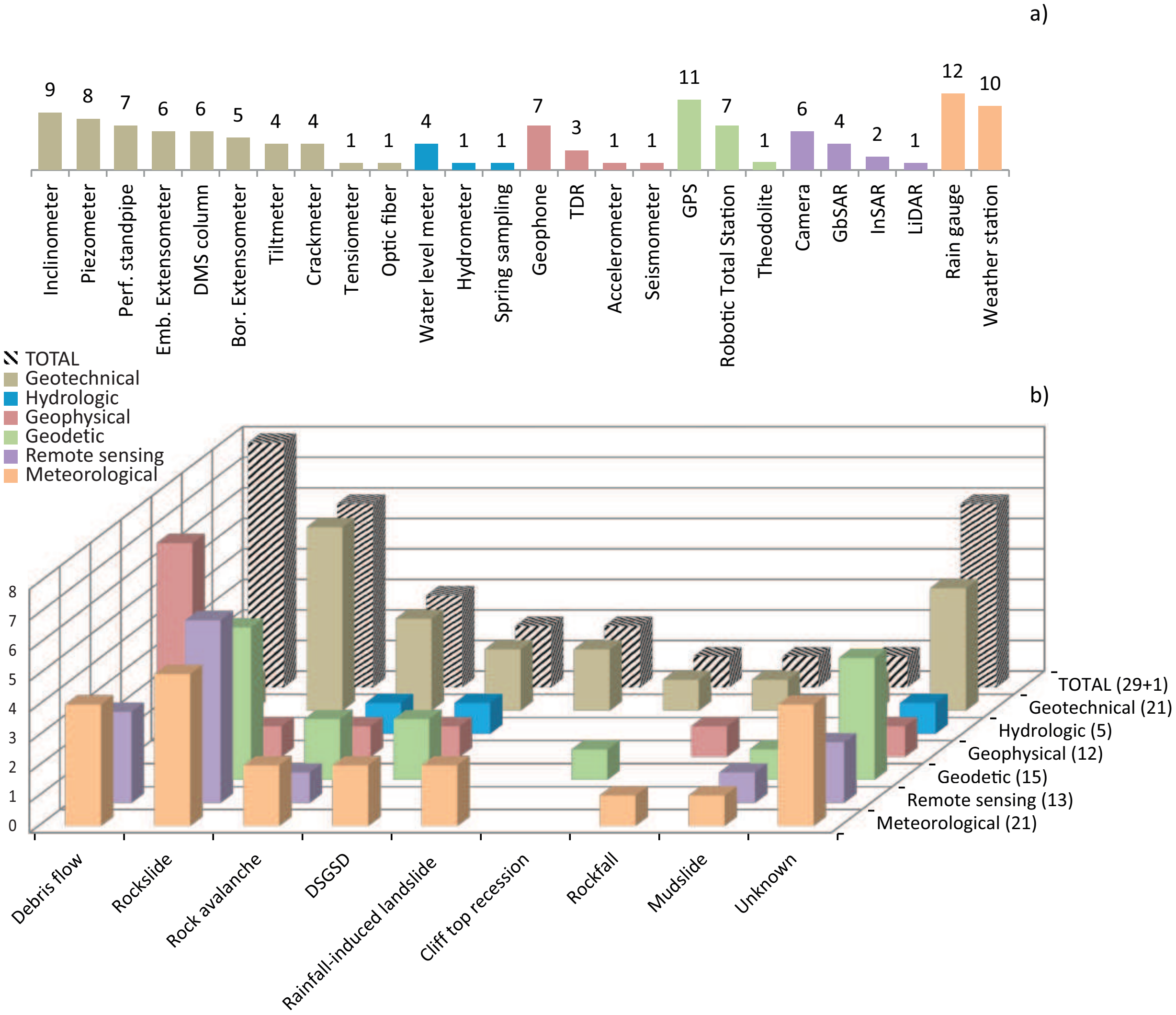
Rockslide
Rock avalanche
DSGSD
Rainfall-induced landslide
Cliff top recession
Rockfall
Mudslide
Unknown

fig.4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Perf. standpipe
Emb. Extensometer
DMS column
Bor. Extensometer
Tiltmeter
Crackmeter
Tensiometer
Optic fiber
Water level meter
Hydrometer
Spring sampling
Geophone
TDR
Accelerometer
Seismometer
GPS
Robotic Total Station
Theodolite
Camera
GbSAR
InSAR
LiDAR
Rain gauge
Weather station
b)
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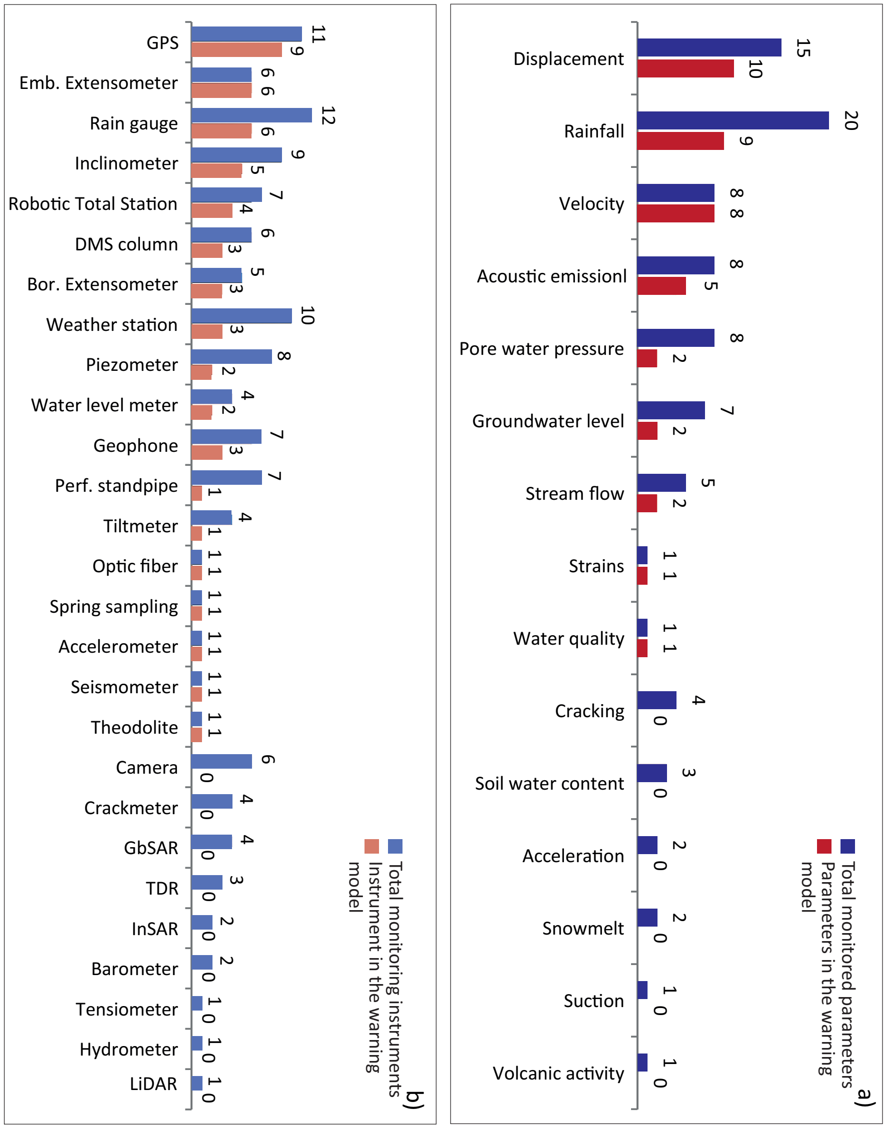
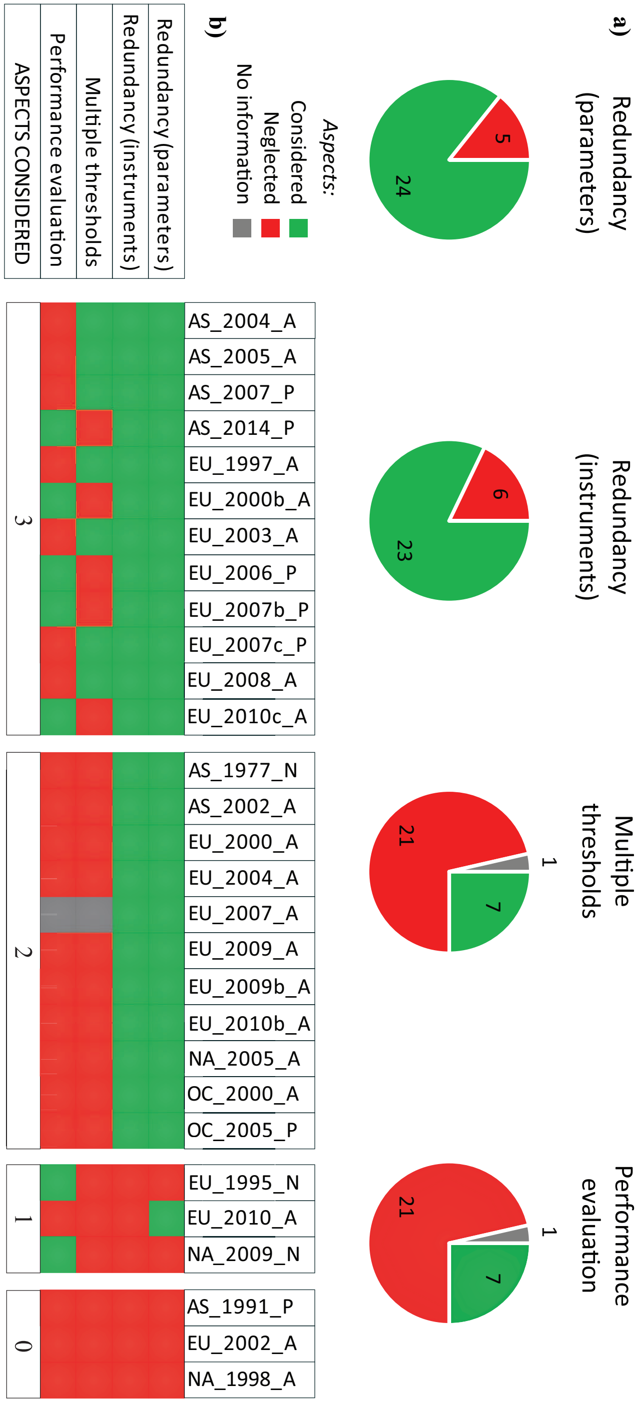
Hydrologic
Geophysical
Geodetic
Remote sensing
Meteorological
8
7
6
5
4
3
2
1
0
TOTAL (29+1)
Geotechnical (21)
Hydrologic (5)
Geophysical (12)
Geodetic (15)
Remote sensing (13)
Meteorological (21)
Debris flow
Rockslide
Rock avalanche
DSGSD
Rainfall-induced landslide
Cliff top recession
Rockfall
Mudslide
Unknown

fig.5


a)
Total monitored parameters
Parameters in the warning model
Displacement 15 10
Rainfall 20 9
Velocity 8 8
Acoustic emissionl 8 5
Pore water pressure 8 2
Groundwater level 7 2
Stream flow 5 2
Strains 1 1
Water quality 1 1
Cracking 4 0
Soil water content 3 0
Acceleration 2 0
Snowmelt 2 0
Suction 1 0
Volcanic activity 1 0
b)
Total monitoring instruments
Instrument in the warning model
GPS 11 9
Emb. Extensometer 6 6
Rain gauge 12 6
Inclinometer 9 5
Robotic Total Station 7 4
DMS column 6 3
Bor. Extensometer 5 3
Weather station 10 3
Piezometer 8 2
Water level meter 4 2
Geophone 7 3
Perf. standpipe 7 1
Tiltmeter 4 1
Optic fiber 1 1
Spring sampling 1 1
Accelerometer 1 1
Seismometer 1 1
Theodolite 1 1
Camera 6 0
Crackmeter 4 0
GbSAR 4 0
TDR 3 0
InSAR 2 0
Barometer 2 0
Tensiometer 1 0
Hydrometer 1 0
LiDAR 1 0



	Redundancy (parameters)	Redundancy (instruments)	Multiple thresholds	Performance evaluation	ASPECTS CONSIDERED
AS_2004_A	🟩	🟩	🟩	🟥	3
AS_2005_A	🟩	🟩	🟩	🟥	
AS_2007_P	🟩	🟩	🟩	🟥	
AS_2014_P	🟩	🟩	🟥	🟩	
EU_1997_A	🟩	🟩	🟩	🟥	
EU_2000b_A	🟩	🟩	🟥	🟩	
EU_2003_A	🟩	🟩	🟩	🟥	
EU_2006_P	🟩	🟩	🟥	🟩	
EU_2007b_P	🟩	🟩	🟥	🟩	
EU_2007c_P	🟩	🟩	🟩	🟥	
EU_2008_A	🟩	🟩	🟩	🟥	
EU_2010c_A	🟩	🟩	🟥	🟩	
AS_1977_N	🟩	🟩	🟥	🟥	2
AS_2002_A	🟩	🟩	🟥	🟥	
EU_2000_A	🟩	🟩	🟥	🟥	
EU_2004_A	🟩	🟩	🟥	🟥	
EU_2007_A	🟩	🟩	⬜	⬜	
EU_2009_A	🟩	🟩	🟥	🟥	
EU_2009b_A	🟩	🟩	🟥	🟥	
EU_2010b_A	🟩	🟩	🟥	🟥	
NA_2005_A	🟩	🟩	🟥	🟥	
OC_2000_A	🟩	🟩	🟥	🟥	
OC_2005_P	🟩	🟩	🟥	🟥	
EU_1995_N	🟥	🟥	🟥	🟩	1
EU_2010_A	🟩	🟥	🟥	🟥	
NA_2009_N	🟥	🟥	🟥	🟩	
AS_1991_P	🟥	🟥	🟥	🟥	0
EU_2002_A	🟥	🟥	🟥	🟥	
NA_1998_A	🟥	🟥	🟥	🟥	

Figure 1. Local landslide early warning systems considered in this review: a) national distribution; b) location and period of activity.

Figure 2. a) Type of landslide under surveillance (total is higher than 29, i.e. the total number of reviewed Lo-LEWSs, because two different type of landslides are considered in EU_2010c_A); b) alert criteria adopted; c) number of alert levels; d) communication tools used to send warning; and e) redundancy of the tools used.

Figure 3. a) Inventory of the parameters monitored and b) monitored activities in relation to the type of landslide and to the group of parameter according to the classification of Table 5 (totals are higher than 29, i.e. the total number of reviewed Lo-LEWS, because multiple parameters are monitored in some systems and two different types of landslides are considered in EU_2010c_A).

Figure 4. a) Number of monitoring instruments, and b) monitoring methods grouped in relation to the type of landslide and to the group of instruments according to the classification of Table 5 (totals are higher than 29, i.e. the total number of reviewed Lo-LEWS, because multiple monitoring methods are employed in some systems and two different types of landslides are considered in EU_2010c_A).

Figure 5. a) Total number of monitored parameters composing the monitoring networks (in blue) and monitored parameters directly used to issue the warnings (in red). b) Total number of instruments composing the monitoring networks (in blue) and instruments directly used to issue the warnings (in red).

Figure 6. a) Important aspects associated to the efficiency of Lo-LEWS: redundancy (parameters); redundancy (instruments); multiple thresholds; performance evaluation. b) Identification of systems for which these aspects: have been considered (green); have not been considered (red); or information is not available (grey).