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 28 Lo-LEWSs have been retrieved from: peer-reviewed articles published in scientific journals, proceeding of technical conferences, books, reports, and institutional web pages. The first part of the paper describes the characteristics of these systems according to the following three modules: landslide model, warning model and risk management. 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 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 monitored parameters and monitoring 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 properties around the world every year *(e.g., Petley, 2012).* Landslide risk can be reduced adopting different mitigation methods, classifiable in 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 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);* 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 due to landslide events by informing 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, 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 local LEWSs (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 LEWSs 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 to identify the main components of an early warning system for weather-induced landslides distinguishing three different modules: landslide model, warning model, 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 warning levels and the decision-making procedures required for issuing the warnings. The warning system embeds the warning model and includes the following risk management elements: warning dissemination, communication and education, community involvement, and emergency plan.

The efficiency of a landslide model developed for warning purposes—i.e. the capability to properly assess the relationship between triggering and predisposing factors and landslide events—strongly depends on the characterization 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 28 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 28 Lo-LEWS worldwide. Little experiences have been gathered from LEWS at slope scale before 2000 (AS_1977_N, AS_1991_P, EU_1995_P, EU_1997_A). The first reported successful application refers to a system employed in Xiling Gorge, China. On May 12 1985 the system, operational since 1977, was able to predict 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).* In the past 20 years, numerous 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 Àknes 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 kept under observation year-round employing a variety of monitoring instruments. Many 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, the successful operation of this system depends on the face-to-face relationships established between the experts and the residents of the area most threatened by the tsunami. Other particularly well-known and well-described operational systems are dealing with: debris flows occurring 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; a complex slow-moving phenomenon in the South 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). The former terminated in 1985, because of the failure of the Xintan slope, which destroyed the historical town located in front of 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 in: Nojiri River Basin, Japan (AS_1991_P); Moscardo catchment, Italy (EU_1995_P); 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, 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: Nojiri River Basin, Japan (AS_1991_P) and Wollongong, Australia (OC_2005_P). The information on the 28 Lo-LEWS was retrieved from different sources: international journals and publications, scientific reports, web pages and grey literature. Of course, the Authors are aware that besides the 28 Lo-LEWS herein described, there are many more operational warning systems designed to address potentially unstable slopes in various contexts, such as railway embankments, pipelines and open pit mines. If they have not been included in this review, it means that information on these systems is not available, it was not found or it is privately disclosed in internal reports.

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 28 Lo-LEWS reviewed herein.

Covered area

All the systems have been designed 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 one is a peculiar 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), started in 2002 as a debris flow monitoring project aiming at improving the capability of collecting debris flow field data. According to a survey by SWCB, there are 1503 potential debris flow torrents in Taiwan. The system originally employed 17 on-site monitoring stations located in the vicinity of the potential debris flow posing the highest risk to nearby communities; since 2004, three more mobile monitoring stations were added to the system *(Yin et al., 2010).*

Landslide cause(s)

As expected, 25 of the 28 reported systems deal with weather-induced landslides (triggered by rainfall, snow melting or a combination of both). 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 sea abrasion and water erosion. The landslides addressed in the second system are lahars (a type of debris flow) possibly generated by the failure of a tephra (volcanic material) dam by retrogressive landsliding in the crater of the Mt Ruapehu in New Zealand. No information is available on the landslide cause for the system deployed in the Northern Italian community of Nals (EU_2002_A). On this issue, peculiar is the system deployed in Wushan Town (AS_2004_A), for which the monitored landslide may be activated by seasonal changes in the regime of both rainfall and the Three Gorges Dam reservoir located at the toe of the landslide.

Type(s) of landslide

Figure 2a displays the types of landslides that have been monitored within each system. Debris flows (7) and rockslides (6) are the most investigated classes of landslides. The information is not available in 6 cases. It is worth nothing that the majority of the systems deals with a single landslide typology. This is to be expected, since 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 to generically state 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.

Monitoring system

The monitored parameters and the monitoring instruments will be thoroughly analysed in Section 3.

2.3. Warning model

The landslide model is part of a warning model. **Table 3** lists the main characteristics of the warning models adopted within the 28 Lo-LEWS reviewed herein.

Warning parameters

Most of the warning parameters used in the adopted warning models are displacements—in terms of rate of movements, velocity, acceleration (15 cases)—since they show a direct evidence of the state of activity of the landslide. In addition to them, meteorological parameters (8 cases) are also widely considered, mainly because a significant number of mass movements are weather-induced landslides. In a good number of systems (9 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.

Warning criteria

Warning criteria are needed to establish a connection between a landslide model and a set of warning levels. A warning 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—26 out of 28—employ empirical models (**Figure 2b**). The remaining two systems are: 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 in: heuristic methods (18 cases), wherein thresholds are identified without employing any rigorous mathematical or statistical criterion; and correlation laws (8 cases), wherein 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 rates 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 have been established based on data from many similar phenomena occurring in 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).* 8 Lo-LEWS are based on correlation laws derived from statistical analyses on historical data. For rainfall-induced landslides, the thresholds are usually obtained by drawing lower-bound lines 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 phenomena may show "accelerating creep" *(Crosta and Agliardi, 2003; Loew et al., 2016)*. The only application of a probabilistic model for the definition of the thresholds is the prototype system that has been operational in Vancouver between 2009 and 2011 (NA_2009_N). A discriminant analysis analysis was therein conducted 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 warning levels

Figure 2c highlights that the majority of the Lo-LEWS reviewed herein employs two (8 cases) or three (9 cases) warning levels. The definition of many different thresholds does not necessarily improve the performance of a warning model and often results in a pointless loss of simplicity *(Medina-Cedina and Nadim, 2008)*. However, starting from the beginning of the 2000s, a significant number of systems have been designed considering four warning levels (6 cases) or more (4 cases). The highest number of warning 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%. In the system employed in North Vancouver, Canada (NA_2009_N), the transitions between the four warning levels—i.e. no watch, watch I/watch II, warning I, warning II—has been designed to ensure that each warning level is always preceded or followed by a level that is either one step higher or one step lower. Moreover, each level is typically set to be maintained for at least six consecutive hours. When this is not possible, an override is 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 warning levels adopted 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, warning dissemination, communication and education, community involvement, and an emergency plan. 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 risk reduction measures 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 very short, in the order of second or minutes. Warning and forecasting systems 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). 14 cases can be considered warning systems, as the lead time varies from 1 to 24 hours. They typically deal with active landslides that move slowly but can be characterized by movement rates rapidly increasing before a general failure stage (e.g., mid- and high-magnitude rockslides, deep-seated landslides). 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. In these cases, the warnings are targeted to: politicians, scientists, government institutions, civil protection agencies, infrastructure authorities. As an example, in the system designed for the Ancona Landslide, Italy (EU_2008_A), a team of engineers, geologists, technical experts and urban planners can 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 procedures 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 intersectorial structure involving experts from different municipality departments as well as experts of other local Institution and organizations. In the remaining 16 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 SMS, are the most used tool (12 cases), probably because they allow a very fast emergency notification-delivery and they reach numerous recipients at once. In 8 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 coupled in 23% of the cases and more than two techniques in only 11% of the cases. An exception is represented by the system developed in Àknes, Norway (EU_2004_A), where 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—are combined and several evacuation tests have been conducted throughout the years.

Decision about issuing or cancelling an alert

Although this information is not available for many systems, it should be noted that warnings are almost always issued manually. 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; and North Vancouver (NA_2009_N), where the warning levels were hourly updated 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 warning 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 28 (**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 landslide 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 appropriate, also because the instrumental errors cases could be filtered out by means of a manual check. In the prototype system operational in North Vancouver, Canada (NA_2009_N) the performance was evaluated during the whole period of activity. A total of nine debris flows were documented during five storms, during which the warning level was reached in four cases and the watch II level was exceeded for 26 consecutive hours in the remaining case. No debris flows were recorded during watch I or lower levels. The severe warning level was also never reached. In nine other cases a warning 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 analysis *(Sättele et al., 2015; Sättele et al., 2016)*. According to this scheme, the 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. 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. *Intrieri et al. (2013)* point out the important role of monitoring in the design and operational phases of a LEWS. Monitoring of triggering parameters is necessary to study landslide occurrence and behaviour, as well as to define thresholds and warning 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 able of trigger 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 parameters, activities and methods of monitoring (**Table 6**). This classification is herein adopted 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, 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 certain 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, 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 can be defined as indicators or factors related to the slope of interest that can be quantified and monitored in time *(Baroň et al., 2012)*. A key issue for any LEWS operational at local scale is the understanding of the behaviour of such site-specific parameters and, particularly, the evaluation of their role as early warning indicators. The latter necessarily implies an advanced knowledge of their temporal evolution towards the identification of properly-defined critical values (i.e., thresholds). **Figure 3a** displays the parameters monitored in the 28 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—26 out of 28—is based on deformation monitoring, expressed in terms of displacement (15 cases), velocity (8 cases), acoustic emissions (7 cases), cracking (4), acceleration (2) and strain (1). This is due to the fact that most of the monitored landslides show evidence of active deformations. In most cases the main indicator is the cumulated displacement; velocity and acceleration are used as kinematic indicators mainly 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 represented by the system deployed in Mt. Ruapehu, New Zealand (OC_2000_A), for which the volcanic activity is directly responsible for the occurrence of landslides since lahars may only occur in tephra deposits in the aftermath of magmatic eruptions. 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 markedly different depending on the type of soils involved. 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 if 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. Nowadays, 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 28 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 20 cases out of 28. 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 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 (12 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—has been investigated and monitored employing different 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 warning 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 (39) 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 occurrences. 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.

The overview of the monitoring strategies performed herein 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 phenomena 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 14 cases of the 28 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 28 (86%) monitor different classes of parameters and 23 out of 28 (82%) 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 28 (25%) 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 (25%) 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) or only one (EU_1995_N, NA_2009_N, EU_2010_A) of these aspects are present.

5. Concluding remarks

The main components of 28 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 to derive statistical significant conclusions, these valuable experiences allowed the description and the analysis of all the elements playing a 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.

References

Arattano M (1999) On the Use of Seismic Detectors as Monitoring and Warning Systems for Debris Flows. Nat Hazards 20: 197–213. https://doi.org/10.1023/A:1008061916445

Arattano M, Marchi L (2008) Systems and sensors for debris-flow monitoring and warning. Sensors 8(4): 2436–2452. https://doi.org/10.3390/s8042436

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

Baroň I, Supper R (2013) Application and reliability of techniques for landslide site investigation, monitoring and early warning—outcomes from a questionnaire study. Nat Hazards Earth Sys 13: 3157–3168. https://doi.org/10.5194/nhess-13-3157-2013

Baroň I, Supper R, Ottowitz D (2012) SafeLand deliverable 4.6.: Report on evaluation of mass movement indicators. European Project SafeLand, Grant Agreement No. 226479, 382 pp. Available at: http://www.safeland-fp7.eu

Blikra LH, Kristensen L, Lovisolo M (2013) Subsurface monitoring of large rockslides in Norway: a key requirement for early warning. Ital J Eng Geol Environ 6: 307–314. https://doi.org/10.4408/IJEGE.2013-06.B-28

Broccolato M (2010) I grandi movimenti di massa sul territorio valdostano: Il sistema di monitoraggio (In Italian). In: Conference presentation, Barzio, Italy

Calvello M (2017) Early warning strategies to cope with landslide risk. Rivista Italiana di Geotecnica 2: 63-91. https://doi.org/10.19199/2017.2.0557-1405.063

Calvello M, Pecoraro G (2018) FraneItalia: a catalog of recent Italian landslides. Geoenvironmental Disasters. Manuscript under review.

Calvello M, Peduto D, Arena L (2017). Combined use of statistical and DInSAR data analyses to define the state of activity of slow-moving landslides. Landslides, 14:473-489. https://doi.org/10.1007/s10346-016-0722-6

Calvello M, Piciullo L (2016) Assessing the performance of regional landslide early warning models: the EDuMaP method. Nat Hazards Earth Sys 16: 103-122. https://doi.org/10.5194/nhess-16-103-2016

Cardellini S, Osimani P (2008) Living with landslide: the Ancona case history and early warning system. In: Proc of the 1st World Landslide Forum, Tokyo, pp 473–476

Cardinaletti M, Cardellini S, Ninivaggi A (2011) The Integrate Landslide Managing System of Ancona. UNISDR PreventionWeb.

https://www.preventionweb.net/applications/hfa/lgsat/en/image/href/512. Accessed 23 October 2017

Chae BG, Park HJ, Catani F et al. (2017) Landslide prediction, monitoring and early warning: a concise review of state-of-the-art. Geosci J 21: 1033–1070. https://doi.org/10.1007/s12303-017-0049-x

Clark AR, Moore R, Palmer JS (1996) Slope monitoring and early warning systems: application to coastal landslide on the south and east coast of England, UK. In: Senneset K (ed) Landslides, 7th International Symposium on Landslides. Balkema, Rotterdam, pp 1531–1538

ClimChAlp (2017) Available at http://www.alpine-space.org/2000-2006/climchalp.html. Accessed 23 October 2017

Cotecchia V (2006) The Second Hans Cloos Lecture. Experience drawn from the great Ancona landslide of 1982. Bull Eng Geol Environ 45: 1–41. https://doi.org/10.1007/s10064-005-0024-z

Crosta GB, Agliardi F (2003) Failure forecast for large rock slides by surface displacement measurements. Can Geotech J 40: 176–191. https://doi.org/10.1139/t02-085

Crosta GB, Agliardi F, Rivolta C et al (2017) Long-term evolution and early warning strategies for complex rockslides by real-time monitoring. Landslides 4(5): 1615–1632. https://doi.org/10.1007/s10346-017-0817-8

Crosta GB, di Prisco C, Frattini P et al (2014) Chasing a complete understanding of the triggering mechanisms of a large rapidly evolving rockslide. Landslides 11: 747–764. https://doi.org/10.1007/s10346-013-0433-1

Crosta GB, Frattini P, Castellanza R et al (2015) Investigation, monitoring and modelling of a rapidly evolving rockslide: the Mt. de la Saxe case study. In: Engineering geology for society and territory—vol 2. Springer, Berlin, pp 349–354. https://doi.org/10.1007/978-3-319-09057-3_54

Del Ventisette C, Casagli N, Fortuny-Guasch J, Tarchi D (2012) Ruinon landslide (Valfurva, Italy) activity in relation to rainfall by means of GBInSAR monitoring. Landslides 9:497–509. https://doi.org/10.1007/s10346-011-0307-3Di Biagio E, Kjekstad O (2007) Early warning, instrumentation and monitoring landslides. In: Proc of the 2nd Regional Training Course, RECLAIM II. Phulet, Thailand

Fathani TF, Karnawati D, Wilopo W (2016) An integrated methodology to develop a standard for landslide early warning systems. Nat Hazards Earth Sys 16(9): 2123–2135. http://dx.doi.org/10.5194/nhess-16-2123-2016

Flentje P, Chowdhury RN (2005) Managing landslide hazards on the Illawarra escarpment. In: Proc of the GeoQuest Symp on Planning for Nat Hazards, pp 65–78

Flentje P, Chowdhury RN (2006) Observational approach for urban landslide management, engineering geology for tomorrow's cities. In: Proc of the 10th International Association of Engineering Geology and the Environment Congress, Nottingham (Paper no. 522).

Froese CR, Moreno F (2014) Structure and components for the emergency response and warning system on Turtle Mountain, Alberta, Canada. Nat Hazards 70: 1689–1712. https://doi.org/10.1007/s11069-011-9714-y

Giuliani A, Bonetto S, Castagna S et al (2010) A Monitoring System for Mitigation Planning: The Case of "Bagnaschino" Landslide in Northern Italy. Am J Environ Sci 6(6): 516–522. http://dx.doi.org/10.3844/ajessp.2010.516.522Haque U, Blum P, da Silva PF et al (2016) Fatal landslides in Europe. Landslides 13(6): 1545–1554. https://doi.org/10.1007/s10346-016-0689-3

Haque U, Blum P, da Silva PF et al (2016) Fatal landslides in Europe. Landslides 13(6): 1545–1554. https://doi.org/10.1007/s10346-016-0689-3

Honda K, Aadit S, Rassarin C et al (2008) Landslide early warning system for rural community as an application of Sensor Asia. In: Proc of the World Conference on Agricultural Information. Tokyo, pp 283–288

Huang R, Huang J, Ju N, He C, Li W (2013) WebGIS-based information management system for landslides triggered by Wenchuan earthquake. Nat Hazards 65: 1507–1517. https://doi.org/10.1007/s11069-012-0424-x

Intrieri E, Gigli G, Casagli N, Nadim F (2013) Landslide early warning system: toolbox and general concepts. Nat Hazards Earth Sys 13: 85–90. https://doi.org/10.5194/nhess-13-85-2013

Intrieri E, Gigli G, Mugnai F et al (2012) Design and implementation of a landslide early warning system. Eng Geol 147: 124–136. https://doi.org/10.1016/j.enggeo.2012.07.017

Itakura Y, Fujii N, Sawada T (2000) Basic characteristics of ground vibration sensors for the detection of debris flow. Phys Chem Earth, Part B 25(9):717–720. https://doi.org/10.1016/S1464-1909(00)00091-5

Jakob M, Owen T, Simpson T (2012) A regional real-time debris-flow warning system for the District of North Vancouver, Canada. Landslides 9(2): 165–178. https://doi.org/10.1007/s10346-011-0282-8

Ju NP, Huang J, Huang RQ et al (2015) A real-time monitoring and early warning system for landslide in southwest China. J Mt Sci 12(5): 1219–1228. https://doi.org/10.1007/s11629-014-3307-7

Keys HJR, Green PM (2008) Ruapehu Lahar New Zealand 18 March 2007: Lessons for Hazard Assessment and Risk Mitigation 1995-2007. J Disaster Res 3: 284–285. https://doi.org/10.20965/jdr.2008.p0284

Klima2050 (2017) Available at http://www.klima2050.no/. Accessed 23 October 2017

Komac M, Jemec M, Šinigoj J et al (2008) Slope monitoring methods: a state of the art report. ClimChAlp project, Deliverable WP6, 165 pp. https://www.lfu.bayern.de/geologie/massenbewegungen/projekte/climchalp/doc/engl_report_6.pdf. Accessed 23 October 2017

Kristensen L, Blikra LH, Hole J (2010) Àknes: State of Instrumentation and Data Analysis (Àknes Report 02 2010). County Governor - Fylkesmannen.no, 43 pp.

Kristensen L, Blikra LH (2011) Monitoring displacement on the Mannen rockslide in Western Norway. In: Proc of the 2nd World Landslide Forum, Rome, 8 pp

Lacasse S, Nadim F (2011) Learning to live with geohazards: from research to practice. In: Proc of GeoRisk 2011, 26–28 June, Atlanta, pp 64–116. https://doi.org/10.1061/41183(418)4

LEMONADE (2017) Available at http://lemonade.mountainresearch.at/. Accessed 23 October 2017

Li D, Meng S, Sun J (2016) Prediction Analysis of Large-scale Landslides in the Three Gorges Reservoir. EJGE 21: 2053–2063

Loew S, Gischig V, Moore J, Keller-Signer A (2012) Monitoring of potentially catastrophic rockslides. In: Proc of the 11th International & 2nd North Am Symp on Landslides. Taylor & Francis, London, pp 101–116

Loew S, Gschwind S, Gischig V et al (2016) Monitoring and early warning of the 2012 Preonzo catastrophic rockslope failure. Landslides 14: 141–154. https://doi.org/10.1007/s10346-016-0701-y

Lu P, Catani F, Tofani V, Casagli N (2014). Quantitative hazard and risk assessment for slow-moving landslides from Persistent Scatterer Interferometry. Landslides 11: 685-696. https://doi.org/10.1007/s10346-013-0432-2

Manconi A, Giordan D (2015) Landslide early warning based on failure forecast models: the example of the Mt. de la Saxe rockslide, northern Italy. Nat Hazards Earth Syst Sci 15(7):1639–1644. https://doi.org/10.5194/nhess-15-1639-2015

Massey C, Manville V, Hancox GT et al (2010) Out-burst flood (lahar) triggered by retrogressive landsliding, 18 March 2007 at Mt. Ruapehu, New Zealand—a successful early warning. Landslides 7: 303–315. https://doi.org/10.1007/s10346-009-0180-5

McArdell BW, Bartelt P, Kowalski J (2007) Field observations of basal forces and fluid pore pressure in a debris flow. Geophys Res Lett 34(L07406). https://doi.org/10.1029/2006GL029183

Medina-Cetina Z, Nadim F (2008) Stochastic design of an early warning system. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards 2: 223–236. https://doi.org/10.1080/17499510802086777

Michoud C, Abellán A, Derron MH, Jaboyedoff M (2012) SafeLand deliverable 4.1.: Review of Techniques for Landslide Detection, Fast Characterization, Rapid Mapping and Long-Term Monitoring. European Project SafeLand, Grant Agreement No. 226479, 401 pp. Available at: http://www.safeland-fp7.eu

Michoud C, Bazin S, Blikra LH et al (2013) Experiences from site-specific landslide early warning systems. Nat Hazards Earth Sys 13: 2659–2673. https://doi.org/10.5194/nhess-13-2659-2013

Mikkelsen PE (1996) Field Instrumentation. In: Turner AK, Schuster RL (eds), Landslides investigation and mitigation, Special report 247. National Academy Press, Washington, DC, pp 278–316

Moreno F and Froese CR (2010) ERCB/AGS Roles and Responsibilities Manual for the Turtle Mountain Monitoring Project, Alberta. ERCB. http://ags.aer.ca/publications/OFR_2017_04.html. Accessed 23 October 2017

Olivieri W, Lovisolo M, Crosta GB (2012) Continuous geotechnical monitoring for alert thresholds and hazard management. In: Landslides and Engineered Slopes, CRC Press, Taylor and Francis Group, pp. 1929–1934

OMIV (2017) Available at http://omiv2.u-strasbg.fr/monitored_lavalette.php. Accessed 23 October 2017

Peduto D, Ferlisi S, Nicodemo G, Reale D, Pisciotta G, Gullà G (2017). Empirical fragility and vulnerability curves for buildings exposed to slow-moving landslides at medium and large scales. Landslides, 14: 1993-2007. https://doi.org/10.1007/s10346-017-0826-7

Petley D (2012) Global patterns of loss of life from landslides. Geology 40(10): 927–930. https://doi.org/10.1130/G33217.1

Piciullo L, Calvello M, Cepeda JM (2018) Territorial early warning systems for rainfall-induced landslides. Earth Sci Rev 179: 228–247. https://doi.org/10.1016/j.earscirev.2018.02.013

Piciullo L, Dahl M-P, Devoli G, Colleuille H, Calvello M, (2017a) Adaptation of the EDuMaP method for the performance evaluation of the alerts issued on variable warning zones. Nat. Hazards Earth Syst. Sci. 17 (6), 817–831. http://dx.doi.org/10. 5194/nhess-17-817-2017.

Piciullo L, Gariano SL, Melillo M et al (2017b) Definition and performance of a threshold-based regional early warning model for rainfall-induced landslides. Landslides 14: 995–1008. https://doi.org/10.1007/s10346-016-0750-2

Read RS, Langenberg W, Cruden D et al (2005) Frank Slide a century later: the Turtle Mountain monitoring project. In: Hungr O, Fell R, Couture RR, Eberhardt (eds), Landslide Risk Management. Balkema, Rotterdam, pp 713–723

SafeLand (2017) Available at http://esdac.jrc.ec.europa.eu/projects/safeland. Accessed 23 October 2017

Sassa K, Luciano P, Yin YP (2009) Monitoring, prediction and early warning. In: Proceedings of the 1st World Landslide Forum. Tokyo, pp 351–375

Sättele M, Bründla M, Straubb D (2015) Reliability and effectiveness of early warning systems for natural hazards: concept and application to debris flow warning. Rel Eng Syst Safety 142:192–202. https://doi.org/10.1016/j.ress.2015.05.003

Sättele M, Bründl M, Straub D (2016) Quantifying the effectiveness of early warning systems for natural hazards. Nat Hazards Earth Syst Sci 16:149–166. https://doi.org/10.5194/nhess-16-149-2016Savvaidis PD (2003) Existing landslide monitoring systems and techniques. In Proceedings of the conference from stars to earth and culture. Thessaloniki, pp 242–258

Segoni S, Rossi G, Rosi A, Catani F (2014) Landslides triggered by rainfall: a semiautomated procedure to define consistent intensity-duration thresholds. Comput. Geosci. 63, 123–131. http://dx.doi.org/10.1016/j.cageo.2013.10.009

Scaioni M, Longoni L, Melillo V, Papini M (2014) Remote sensing for landslide investigations: an overview of recent achievements and perspectives. Remote Sens 6(10): 9600–9652. https://doi.org/10.3390/rs6109600

Stähli M, Sättele M, Huggel C et al (2015) Monitoring and prediction in early warning systems for rapid mass movements. Nat Hazards Earth Syst Sci 15: 905–917. https://doi.org/10.5194/nhess-15-905-2015

Stumpf A, Kerle N, Malet JP (2012) SafeLand deliverable 4.4: Guidelines for the selection of appropriate remote sensing technologies for monitoring different types of landslides. European Project SafeLand, Grant Agreement No. 226479, 91 pp. Available at: http://www.safeland-fp7.eu

Takeshi T (2011) Evolution of debris-flow monitoring methods on Sakurajima. Int J Erosion Cont Eng. 4: 21–31. https://doi.org/10.13101/ijece.4.21

Tamburini A (2005) EYDENET: A Real Time Decision Support System. In: Conference presentation, "RiskHydrogeo", Aosta, Italy.

Tamburini A, Martelli D (2006) Displacement and rainfall threshold values for large landslide forecast in real time: the example of the "Becca di Nona" Landslide (Aosta). Conference presentation, RiskYdrogeo, Saint Vincent, Italy

Thiebes B (2011) Landslide analysis and early warning – Local and regional case study in the Swabian Alb, Germany. PhD dissertation, University of Vienna

Thiebes B, Bell R, Glade T et al (2014) Integration of a limit-equilibrium model into a landslide early warning system. Landslides 11(5): 859–875. https://doi.org/10.1007/s10346-013-0416-2

Thiebes B, Glade T (2016) Landslide early warning systems – fundamental concepts and innovative application. In: Aversa S, Cascini L, Picarelli L, Scavia C (eds), Landslides and Engineered Slopes. Experience, Theory and Practice. CRC Press, Napoli, pp 1903–1911

Thiebes B, Glade T, Bell R (2012) Landslide analysis and integrative early warning-local and regional case studies. In: Eberhardt E, Froese CR, Turner AK, Leroueil S (eds), Proc of the 11th International & 2nd North American Symposium on Landslides. Taylor & Francis, London, pp 1915–1921

Tofani V, Segoni S, Catani F, Casagli N (2012) SafeLand deliverable 4.5: Evaluation report on innovative monitoring and remote sensing methods and future technology. European Project SafeLand, Grant Agreement No. 226479, 280 pp. Available at: http://www.safeland-fp7.eu

UNISDR (2006) Available at: http://www.unisdr.org/2006/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf. Accessed 23 October 2017

Wang FW, Zhang YM, Huo ZT et al (2008) Movement of the Shuping landslide in the first four years after the initial impoundment of the Three Gorges Dam Reservoir, China. Landslides 5: 321–329. https://doi.org/10.1007/s10346-008-0128-1

Wang S (2009) Time prediction of the Xintan landslide in Xiling Gorge, the Yangtze River. In: Wang F, Li T (eds) Landslide disaster mitigation in Three Gorges Reservoir, China, environmental science and engineering. Springer, Berlin, pp 411–431

Yin HY, Huang CJ, Chen CY et al (2011) The present development of debris flow monitoring technology in Taiwan - a case study presentation. Ital J Eng Geol Environ, Special issue: 307–314. https://doi.org/10.4408/IJEGE.2011-03.B-068

Yin Y, Wang H, Gao Y, Li X (2010) Real-time monitoring and early warning of landslides at relocated Wushan Town, the Three Gorges Reservoir, China. Landslides 7: 339–349. https://doi.org/10.1007/s10346-010-0220-1