Early Warning Systems for Landslides: Challenges and New Monitoring Technologies

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**ABSTRACT**

This paper discusses the practical issues related to design and implementation of early warning systems for landslides, the challenges for the future, and possible solutions to the common problems encountered. The problems related to setting the thresholds for warning and in using forecasting methods and expert judgment are discussed in detail. The main challenge in choosing the threshold values for an early warning system is to balance the conflicting requirements of capturing the critical events with a sufficient margin of reliability while avoiding false alarms. New monitoring and characterization technologies that could be implemented as part of early warning systems for different types of landslides are discussed. The integrated use of innovative instruments, thresholds, public education campaigns and other important aspects are exemplified by two very different case studies: the Åknes rockslide in western Norway and the landslip warning system for Hong Kong City.

**1 INTRODUCTION**

An early warning system (EWS) is defined as “the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss.” (UNISDR, 2009). This definition encompasses a wide range of factors that, if effective, will contribute to successful responses to warnings. It also emphasizes the point that an early warning system involves considerably more than just accurate predictions. This need for more than just accurate predictions was stated in the Hyogo Framework for Action (HFA) 2005-2015 (ISDR, 2005), which stressed that early warning systems should be “people centered” and that warnings need to be “timely and understandable to those at risk” and to “take into account the demographic, gender, cultural and livelihood characteristics of the target audiences”. Warnings also need to include “guidance on how to act upon warnings”. The focus of early warning systems should be to warn and inform the citizens and governments of changes on a seamless timescale stretching from minutes, for immediate threats requiring urgent evasive action, to weeks, for more advanced preparedness.

A typical EWS consists of both scientific/technological and social/organizational aspects (Figure 1). The first part comprises monitoring, installation of instruments, data transmission and elaboration, choice of appropriate indicators and thresholds and so on. The second part consists of public education to increase the awareness of the risk, decision making and communication among authorities (e.g. government agencies, local authorities, police/fire department), development of the form and content of warnings issued (how these are understood and relayed to the population at risk), social aspects of how a population responds, implementation of emergency plans and services to assist the population, and finally plans for reconstruction/recovery when the emergency is over.

Installing the technological part of an early warning system without considering the social aspects, in particular without considering the public response, results in an incomplete system, which may in practice create a new type of emergency (e.g. evacuating a village because sensors indicate an eminent landslide, but without providing the village population any place to go, shelter or means to live). Although geologists and engineers are not directly involved in the “human factor” part of the total system development, these needs cannot be ignored and one must not underestimate the importance of the work. Clearly there can be failures in the technology and
maintenance, but failures in communication and response are also common.

![Block diagram of a typical landslide early warning system (DiBiagio & Kjekstad, 2007).](image)

Depending on the needs, an early warning system can be implemented as a temporary or as a permanent solution. A temporary installation may be appropriate where an immediate and short-term risk reduction is required, for example where the event causing the risk is short lived (e.g. monitoring an unstable slope during a construction excavation), or where other permanent remedial efforts are being implemented (e.g. monitoring avalanche danger while a permanent avalanche barrier is designed and installed). A permanent installation may be appropriate when the cost of building and maintaining the EWS has a better cost/benefit for risk reduction than other remedial techniques, or where there is no possibility of remedial action (e.g. dealing with the risk posed by a huge potential rockslide).

Various technical and social issues related to monitoring and early warning systems will be illustrated through the EWS operating at the Åknes rock slope in western Norway and the Hong Kong landslip warning system. Also, some possible guidelines for choosing the most suitable early warning system for landslides will be discussed.

2 SCIENTIFIC BASIS FOR THE WARNING: THRESHOLDS AND EXPERT JUDGMENT

In order to issue an alarm, one must make a prediction of what is about to happen. It is also necessary that sufficient lead time is available to be able to take an effective action. Making a prediction requires an understanding of the physical process being evaluated (a quantitative understanding allowing modelling) or sufficient experience to make correlations (qualitative understanding built on statistical analysis of previous events).

It is also necessary to define which parameters are most indicative for assessing the stability of the slope(s) being monitored (e.g. rainfall, water levels, pore pressures, vibrations, surficial movements, displacements at some depth and so on). There is no strict rule for what indicators are to be used as this depends on many factors, such as the scale of interest (regional vs. individual slope), the type of landslide, etc. In any case the relevant indicators must be measured accurately regardless of whether the implementation is based on a quantitative or a qualitative model. Once the key indicators are identified, the appropriate technology for monitoring must be selected.

The major problem in designing an early warning system is the specification of reliable and effective threshold values. Usually this is done based on past experience.

For an EWS operating at a regional scale it is sometimes possible to assess what are the characteristics of rainfall events that have triggered landslides in the past, if sufficient high-quality data are available. The relationship between rainfall and slope failure can be represented in many ways, for instance by using rainfall intensity-duration curves, absolute rainfall values, antecedent rainfalls, or combinations of these.

For a slope scale EWS (i.e. an EWS monitoring an individual slope), the thresholds derived from this approach are based primarily on personal experience (so-called "expert judgment"), past trends in the measurements and the knowledge of the rupture mechanism(s), rather than in objective data. This is because in most cases, even for reactivated landslides, there is no measured record of the indicators preceding failure. Therefore, considering the uncertainties in the rainfall thresholds specified for a slope scale EWS, these thresholds should be used carefully, and there is no justification to define too many warning levels or too precise limits. For a slope scale EWS, thresholds derived from kinematic indicators (displacement, velocity, acceleration) and pore pressure/water table measurements are preferable to rainfall intensity since they are more directly correlated with the stability conditions of the slope. Rainfall thresholds could be implemented as well, but mainly as a support to decision makers or as simple prewarnings. On the other hand at a regional scale or for landslides which do not have clear kinematic indicators (such as debris flows), rainfall (and snow melt) thresholds are probably the best, if not the only, option available. In any case, the design of the early warning system must be flexible such that the threshold parameters can be changed as more information is gathered on the performance of the monitoring system and on the behaviour of the slope or the region being monitored.

Some slope scale EWS are designed to use forecasting methods to issue warnings. The few empirical models that are generally used for forecasting the timing of a slope failure (Saito, 1965; Fukuzono, 1985; Azimi et
al., 1988; Voight, 1989; Mufundirwa et al., 2010) are all based on the assumption that once a landslide enters the tertiary creep phase, it will be subject to an acceleration eventually leading to failure. According to the approach of Fukuzono (1985), assuming that the landslide will theoretically reach a velocity value equal to infinity at the moment of collapse and plotting the inverse of velocity (1/v) against time, it is possible to predict the time of failure by interpolating the line until it intersects the time axis, corresponding to 1/v = 0 that is to v = ∞ (Figure 2). This type of behavior (linear decrease of 1/v vs. time until failure is reached) is sometimes referred to as Saito's hypothesis (Saito, 1965).

![Figure 2](image)

Figure 2. Plot of the inverse velocity against time. At time t_f (time of failure) 1/v is equal to 0 and v is theoretically infinite.

The EWS based on forecasting methods have proved valuable in more than one occasion (Rose & Hungr 2006; Casagli et al. 2009, Gigli et al. in review). Nevertheless their use, which is limited only to slope scale early warning systems, is not immune to false alarms and does not always guarantee an acceptable result. Therefore, a good deal of interpretation and expert judgment should be included as well when such methods are used. However, the advantages are considerable. First of all, the time left before the failure occurs can be estimated. This allows the stakeholders involved in civil protection plans to organize their emergency work. Moreover they can be implemented even when it is not possible to establish reliable thresholds because of the lack of relevant historical data.

2.1 False alarms and missed events

The selection of threshold levels for issuing a warning must take into account not just scientific but also social considerations. Indeed, an excessively high threshold value means that the lead time left for emergency plans will be short and, in the worst case, that the event itself can be missed. Conversely, a too conservative threshold may lead to false alarms and to all the related problems. In fact, a population subject to an alarm reacts the first time, the second time, and maybe a third time; but quickly becomes tired of the false alarms and the warning system loses credibility. Initially an implicit trust exists between the affected population and the “experts”, or at least an acknowledgment of the system can exist, which can eventually lead to trust. However, that initial trust is quickly destroyed by system failure (false alarms), and the trust will be difficult, or impossible, to win back completely.

In other words acceptable risk criteria and tolerability of false alarms are two faces of the same coin; their definition helps to determine the possible range within which the value of the threshold can be set (Figure 3).

![Figure 3](image)

Figure 3. Conceptual scheme showing how the definitions of tolerability of both risk and false alarms can help to set thresholds.

Medina-Cetina and Nadim (2008) presented a method for stochastic design of an early warning system that accounts for the uncertainties in the thresholds and consequences of false alarms. This method introduces a risk measure as the reference variable that integrates the effects of each of the warning information sources, serves as a rational index for the definition of warning thresholds, and naturally incorporates EWS within a decision-making framework. Following the work by Sousa and Einstein on ‘Warning Systems for Natural Threats’ (2006), the engineering definition of Risk R for a specific state of information is:

\[
R = P[T] \cdot u(C) \quad [1]
\]

where \( P[T] \) is the hazard or probability of occurrence of possible threats T, and \( u(C) \) is the loss or utility of a set of consequences C that are all certain to happen to some
extent. In the case where the loss or utility is weighted by a link term that conditions the occurrence of $C$ to certain level of intensity of $T$, the risk concept is redefined as:

$$R = P[T] \cdot P[C \mid T] \cdot u(C)$$

where the link factor $P[C \mid T]$ maybe interpreted as the vulnerability of the element(s) at risk.

An EWS is considered a risk mitigation agent within a decision-making framework. In this case, the risk mitigation mechanism is illustrated in Figure 4, which shows that the impact of early warning can be due to Active Countermeasures $AC$ acting on the hazard reduction (i.e. influencing directly to reduce or avoid the threat), and/or due to Passive Countermeasures $PC$ acting on the vulnerability reduction (i.e. influencing directly to reduce or avoid the vulnerability or the consequences). The implementation of either one of them generates the costs $u(AC)$ and $u(PC)$ respectively. Therefore, the trade-off between the savings induced by the hazard or vulnerability reduction and the costs associated to their implementation is what defines the risk measure, and consequently the warning levels.

Due to the stochastic nature of EWS, the risk measure $R$ can be defined as a stochastic process, either referenced only to time:

$$R(t) = P[T(t)] \cdot P[C(t) \mid T(t)] \cdot u(C(t))$$

or to time and space:

$$R(t, X) = P[T(t, X)] \cdot P[C(t, X) \mid T(t, X)] \cdot u(C(t, X))$$

where $X$ represents the spatial parameters and $t$ the time parameter. Such definitions implicitly assume that the threat and the consequences are stochastic processes. For instance, the impact of a meteorological condition, such as a hurricane, varies in time and location. Similarly, consequences such as traffic due to commuting are also a function of location and time. In this way, the complexity of warning systems can be in some cases resolved properly if adequate references of space and time are defined (e.g. stochastic risk maps), and if data assimilation tools capable of dealing with spatio-temporal analyses are available (i.e. those capable of managing extreme stochastic conditions such as non-Gaussianity and non-stationarity). Additionally, the integration of a system with temporal or spatio-temporal characteristics demands an efficient representation and of the dynamics of the decision-making under the presence of EWS. Figure 5 shows a simple scheme that illustrates the sequence for estimating the different information sources that integrate the risk measure, including the updating effect introduced by the EWS.

It is worth mentioning that although the concept of risk has proved to be a consistent and robust parameter in many engineering fields, there is a growing interest in many social, environmental and economic disciplines to extend its definition with the aim to make it more people-oriented. A specific shift on the risk definition is observed for including some of non-physical factors, particularly related to risk and vulnerability. The structure for estimating a risk measure as suggested in Eq. 4 is flexible enough as to incorporate risk components such as exposure and coping capacity, and to manage different information levels (i.e. individual, local, regional, national and international).

Although validation of the EWS cannot be performed unless there is data available triggered by actual events, simulations of the system under extreme conditions can be performed as a way to test the inference system and the decision making. Medina-Cetina and Nadim (2008) recommended using Bayesian Networks (BN) (Heckerman et al., 2000) for testing the performance of the designed EWS and obtaining the thresholds that minimize the risk measure. The simulated system in the BN model should include data exploration for the definition of the probability states of each of the events considered in the network, and should have access to computational resources for the smoothing, forecasting, and the updating of the risk measure given by the BN. An example of the BN simulating the EWS for the Åknes rock slope is presented later in the paper.

Figure 4. Update of the risk measure under the presence of EWS.

Figure 5. Sequence of risk measure assessment under a decision-making framework containing the influence of EWS.
3  EARLY WARNING SYSTEMS FOR LANDSLIDES

4 EXAMPLES OF OPERATIVE EARLY WARNING SYSTEMS FOR LANDSLIDES

4.1 EWS at slope scale: Åknes rock slope in Norway

Rock falls and rockslides are among the most dangerous natural hazards in Norway, mainly because of their tsunamigenic potential. The three most dramatic natural disasters in Norway in the 20th century were tsunamis triggered by massive rockslides into fjords or lakes (Loen in 1905 and 1936, and Tafjord in 1934), causing more than 170 fatalities (Bjerrum & Jørstad, 1968, Anda & Blikra, 1998). As public attention on natural hazards increases, the potential rockslides in the Storfjord region in western Norway have earned renewed focus. A massive rockslide at Åknes could be catastrophic as the rockslide-triggered tsunami is a threat to all the communities around the fjord. The Åknes/Tafjord project was initiated in 2005 by the municipalities, with funding from the Norwegian government, to investigate rockslides, establish monitoring systems and implement a warning system and evacuation plan to prevent fatalities, should a massive rockslide take place.

Åknes is a rock slope over a fjord arm on the west coast of Norway (Figure 6). The area is characterized by frequent rockslides, usually with volumes between 0.5 and 5 million m³. Massive slides have occurred in the region, e.g. the Loen and Tafjord disasters. Bathymetric surveys of the fjord bottom deposits show that numerous and gigantic rockslides have occurred many thousands of years ago. The Åknes/Tafjord project (www.aknes-tafjord.no) includes site investigations, monitoring, and an early warning system for the potentially unstable rock slopes at Åknes in Stranda County and at Hegguraksia in Norddal County. The project also comprehends a regional susceptibility and hazard analysis for the inner Storfjord region, which includes Tafjord, Norddalstjord, Sunnnylvsfjord and Geirangerfjord. The potential disaster
associated with a rockslide and tsunami involves many parties, with differing opinions and perceptions. Figure 7 shows some of the displacements observed at the upper crack. The displacements appear to move linearly with time. The total annual displacements vary from less than 2 cm up to about 10 cm.

As part of the on-going hazard and risk assessment and validation of the early warning system, event trees were prepared by pooling the opinion of engineers, scientists and stakeholders. The objective was to reach consensus on the hazard and risk associated with a massive rockslide at Åknes (Lacasse et al., 2008).

![Sliding volume scenarios](modified from Blikra et al., 2007).

Area I: Slide volume 10-15 millions m$^3$, displacement=6-10 cm/yr
Area II: Slide volume 25-80 millions m$^3$, displacement=2-4 cm/yr

Figure 6. Sliding volume scenarios. Superficial area and cross-section. (modified from Blikra et al., 2007).

4.2 Instrumentation and monitoring of Åknes rock slope

The large variations in weather and atmospheric conditions in the fjord and mountain areas pose unusual challenges to the instrumentation. For example, the hazard due to snow avalanche and rock bursts is high in most of the monitored area. Solar panels do not provide sufficient electricity, and energy has to be obtained from several sources to ensure a stable and reliable supply. Significant effort is underway to deploy robust instruments and improve data communication during periods of adverse weather. An Emergency Preparedness Centre is located in Stranda. The monitoring data is integrated into a database that forms the basis for the on-going analyses. Based on the experience with similar projects and the specific needs in Storfjord, the overall monitoring system has been equipped with:

**Surface monitoring**
- GPS-network with 8 antennas
- total station with 30 prisms
- ground-based radar with 10 reflectors
- 5 extensometers measuring crack opening
- geophones that measure vibrations
- 2 lasers measuring opening of the 2 largest cracks
- Ground-based interferometric radar

**Monitoring in borehole**
- inclinometers for measuring horizontal displacements
- piezometers measuring pore pressure
- specially designed instruments such as Differential Monitoring of Stability (DMS)
- temperature

![Displacements from extensometers 1, 2, 3, 4 and 5 at the top scarp at Åknes](Kveldsvik et al., 2006).

Figure 7. Displacements from extensometers 1, 2, 3, 4 and 5 at the top scarp at Åknes (Kveldsvik et al., 2006).
– electrical resistivity of water

**Meteorological station**
– temperature
– precipitation and snow depth
– wind speed
– ground temperature
– radiation

Light Detection and Ranging (LiDAR) mapping was also done. Several independent systems were installed to ensure continuous operation at all times, and different communication systems were implemented to ensure continuous contact with the Emergency Preparedness Centre in Stranda.

The warning is based on 5 levels each corresponding to a different velocity of the landslide (Figure 8). When an empirical velocity threshold is exceeded the next level is entered. The response and the description of each level are summarized in Table 1.

Medina-Cetina and Nadim (2008) did a crude simulation of the EWS for the Åknes rock slope using the BN shown on Figure 9. Although the costs of consequences used in their simulation were rather

<table>
<thead>
<tr>
<th>Alarm level</th>
<th>Activities and alarms</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 Normal situation</td>
<td>Minor seasonal variations No alarm</td>
<td>EPC staff only Technical maintenance</td>
</tr>
<tr>
<td>Level 2 Awareness</td>
<td>Important seasonal fluctuations for individual and multiple sensors &lt; upper thresholds for Level 2</td>
<td>Increase frequency of data review, compare different sensors Call in geotechnical/geological/monitoring experts</td>
</tr>
<tr>
<td>Level 3 Increase awareness</td>
<td>Increased displacement velocity, seen on from several individual sensors &lt; upper thresholds for Level 3</td>
<td>Do continuous review, do field survey, geo-expert team at EPC full time Inform police and emergency/preparedness teams in municipalities</td>
</tr>
<tr>
<td>Level 4 High hazard</td>
<td>Accelerating displacement velocity observed on multiple sensors &lt; upper thresholds for Level 4</td>
<td>Increase preparedness, continuous data analysis Alert municipalities to prepare for evacuation</td>
</tr>
<tr>
<td>Level 5 Critical situation</td>
<td>Continuous displacement acceleration Values &gt; upper thresholds for Level 4</td>
<td>Evacuation</td>
</tr>
</tbody>
</table>

EPC = Emergency Preparedness Centre in Stranda

Table 1. Sketch of alarm levels and response indicated in Figure 8 (Blikra, 2008).

![Figure 8](image-url) Illustration of the alarm levels as function of displacement velocities (vertical axis: displacement rate in mm/day; horizontal axis: relative time before failure). It should be noted that the curve represented here has just a visual meaning as it helps to show approximately how the landslide is expected to behave before failure (Blikra, 2008).
arbitrary, the simulations implied that three threshold levels for issuing warnings would be more cost-effective than the current five levels. Considering the uncertainties in our knowledge about the mechanisms that might lead to the failure of this slope, one might consider merging Levels 2 and 3, and Levels 4 and 5.

4.3 A regional scale EWS based on rainfall values: the Hong Kong Landslip Warning System

Slope instability represents a huge problem for Hong Kong with its 7 million inhabitants and over 60% of hilly terrain. It has been estimated that 300 landslides occur every year in Hong Kong (Mak et al., 2007). The Geotechnical Engineering Office (GEO) of the Civil Engineering Department (CED) and the Hong Kong Observatory (HKO) of the Government of Hong Kong Special Administrative Region operate an EWS, called Landslip Warning System, focusing on man-made slopes (Yu et al., 2004).

The system relies mainly on two strong points: a sophisticated threshold system based on decades of data analysis and a massive public education program. The instrumental part of the system consists of a network of 110 automatic rain gauges, powered by solar panels that provide data every 5 minutes and transmit them by private telephone line to the Central Control Centre for further analysis and assessment.

The research at GEO on the correlation between rainfall and landslides started by selecting 118 rainfall events that exceeded 50 mm/day; then for each of them an isohyets map has been elaborated. The city area has been divided into about 700 spatial grid cells (Pang et al., 2000). Starting from the first map, for each cell the number of landslides caused by that particular event has been counted; by knowing the number of man-made slopes, a landslide frequency, classified by the type of slope (soil cut, rock cut, fill, retaining wall), has been obtained for each cell. Then frequencies, still divided by type, have been averaged for the whole map. In this way each of the 118 maps had a single value of landslide frequency for each type of slope.

At this point a correlation between rain values and number of landslides has been made. The 118 events have been grouped in rainfall classes (0-50 mm, 50-100 mm, 100-150 mm, 150-200 mm, 250-300 mm, 300-350 mm, 350-400 mm, 400-450 mm, ≥ 450 mm). The frequencies previously obtained for each map have then been averaged within every rainfall class so that now, to each rainfall class, 4 frequencies correspond (one for every type of slope) (Figure 10).

Figure 9. Proposed Bayesian network for representing the key influencing events of the Åknes' warning system (Medina-Cetina & Nadim, 2008).
The warning is issued by using the rainfall value of the 21 previous hours plus the forecasted value of the next 3 hours (the so called rolling 24-hour rainfall). In this way, by knowing the rolling 24-hour rainfall value for a certain cell, it is possible to assess the corresponding frequency for each type of slope (that is the probability of occurrence) for that particular cell; then, by knowing the number of slopes, it can be determined how many landslides would probably occur in that cell. By summing the results of each cell an estimation of the total number of landslides for the whole monitored territory can be carried out.

The warning is issued when the number of landslides in the region is expected to exceed 15. This is due to the observation that, on the average, for every 15 landslides there is a major one (i.e. with a volume greater than 50 m$^3$).

The aim of the Landslip Warning is to alert the public to reduce their exposure and to avoid certain areas as well as to trigger the operation of an emergency system within government departments that mobilizes staff and resources to deal with landslide incidents (Yu et al. 2004).

4.3.1 Public education in Hong Kong

One of the characteristics that make the EWS operating in Hong Kong stand out is its massive awareness campaign (Mak et al., 2007). Public education is by far less expensive than engineering works and in Hong Kong has two main purposes: to encourage private owners to maintain their slopes and to teach people about landslide risk and how to reduce their exposure during heavy rain.

Surveys show that in Hong Kong the most effective way to convey the slope safety message is by means of television. GEO periodically engages professional film production companies in order to realize always new announcements able to strike the population.

GEO operates also on a more specific level, by addressing targeted groups, mainly students (by introducing the subject of landslides in the geography curriculum and by organizing talks and exhibitions) and children (by producing cartoon books, films, games, accessories and so on, all related to slope safety).

Education campaigns are also organized as well as

![Figure 10. Correlations between landslide frequencies (Y axis) and rolling 24-hour rainfall (X axis) for each type of slope (Yu et al. 2004).](image_url)
other activities aiming at encouraging participation from the community (exhibitions, expos, open competitions, seminars, public demonstrations, contests etc.). Some of them also involve partnering with non-government organizations (such as the Hong Kong Red Cross).

As stated before, the other important aspect is to motivate private owners to maintain their private slopes, which are around one third of the total in Hong Kong. This is firstly achieved by letting them know their responsibilities as owners from the very moment they purchase a new property. Technical assistance, advisory services and financial assistance are also provided to those who may not possess the required knowledge or money.

Since it was found that 80% of landslide fatalities in the last years were associated with squatters, pedestrians and motorists, specific warning signs have been installed to alert these people to move to safer places or to avoid certain areas (such as road cuts, steep slopes etc.) when the Landslip Warning is issued.

Given the importance of communication a dedicated unit has been set up to deal with the media questions and a website containing information about all the 57000 registered man-made slopes is accessible to the public. Independent surveys showed that the awareness of owners’ responsibility and the public concern with slope safety grew during the years, though remarkable drops occurred during dry years, when the annual number of landslides was far below the average, regardless of the efforts put in the awareness campaigns.

5 CHOOSING THE APPROPRIATE EWS FOR LANDSLIDES

Given the complexity of such systems, it has been felt the need to develop guidelines to help the end users (like Civil Protection and public administrations) to design the EWS that can suit their necessities. This is one of the aims of SafeLand project, a large, integrating European project in the 7th Framework Programme that started on 1 May 2009. SafeLand involves 27 partners from 12 European countries and is coordinated by the International Centre for Geohazards in Norway.

One of the main problems of this task is that early warning systems are very site specific and it is not possible to come up with an “ultimate recipe” valid in every case. So the guidelines must be flexible enough to allow the end-users to adapt them to their specific needs. Moreover they have to be as simple as possible in order to meet the requirements of users who may not be experts of this subject.

Work in this direction is still in progress but a first approach that seems to satisfy these requirements is to use graphic methods that can be easily implemented as software. An example is the flow-chart shown in Figure 11. (SafeLand 2011).

Flow-charts are already used in some design processes and represent a valuable tool to easily check the most common issues that can be encountered and to come up with corresponding solutions.

In this case the end-user is asked for relevant information about the landslide, the elements at risk etc. and depending on the answers it indicates what instruments, procedures, and so on should be introduced in the EWS.

The example reported here represents just a part of the procedure that can be implemented in the final interactive software. More flow-charts can be chained to this one thus creating a really flexible tool able to be expanded to include regional scale EWS, different types of landslides, suggestion about monitoring systems and so on, all by keeping a simple and straight-forward interface. Eventually the end-user will be provided with the main features to be included in the warning system.

However, the user will generally have to make some adjustments and/or additions to the final system design in order to deal with the inevitable site specific details that differ from case to case.

6 LOOKING FORWARD: NEW MONITORING AND CHARACTERIZATION TECHNOLOGIES

A state-of-the-art survey of monitoring systems was done in the SafeLand project (2010). The latest developments in monitoring technologies were reviewed for (a) landslide detection (new landslides recognition from space or airborne imagery), (b) fast characterization (retrieving information on failure mechanism and volume involved), (c) rapid mapping (fast semi-automatic image processing for changes detection and/or target detection; hotspot mapping), and (d) long-term monitoring (processing data for retrieving deformation patterns and time-series), were reviewed.

The methods reviewed are categorized as shown in Figure 12 and include: (1) optical images from ground-based and space borne sensors, (2) airborne and terrestrial laser scanning, (3) ground-based and space borne radar interferometry, (4) ground-based, airborne and underwater geophysical investigations, (5) geotechnical ground-based monitoring systems, and (6) global navigation satellite systems.
Slope scale: choice of type of alarm system

Figure 11. Flow-chart approach to help in the choice of the most appropriate EWS (work in progress from the ongoing SafeLand project; SafeLand, 2011).
Promising technologies include both hardware and software developments. Examples of algorithm development can be found in the field of interferometric monitoring. In the case of DInSAR techniques a lot of effort has been put into procedures for processing and interpretation of data. For instance the SqueeSARTM algorithm developed by T.R.E. (Novali et al. 2009) allows one to drastically increase the number of permanent scatterers in mountainous areas, keeping a very high spatial resolution. This would prove useful to improve the knowledge of the risk and to better characterize unstable slopes, both essential parts for the first stage of every early warning system.

Also hardware and instrumental research have shown interesting advancements in the last few years. For example, with respect to portability and ease of use, a new terrestrial laser scanner, the LYNX Mobile Mapper, has been developed by Optech. It can be mounted on a car and allows scanning along the road from the moving car (Figure 13). This can be very useful to assess the rockfall susceptibility along transportation corridors and reduce the time needed for the point cloud acquisition and post-processing (Carrera et al. 2010).

A relatively new instrument that can be fruitfully adopted in an early warning system is the DMS (Differential Monitoring of Stability) (Lovisolo & Della Giusta 2005). It is an in place monitoring tool that consists of a series of modular cylinders connected together for installation in boreholes. The DMS string of instruments enables continuous measurements of differential displacement 2D/3D along the borehole as well as other physical and mechanical parameters, such as piezometric level, pore pressure, vibrations and temperature.

As far as software developments are concerned, current efforts are focused on creating more user-friendly programs, especially in the field of radar images and interferometry processing. For instance the ESA, in collaboration with the Delft University of Technology, is presently developing NEST-DORIS, a complete toolbox for radar images and interferometry processing. It will soon be available for free (Marinkovic et al. 2009).

Another example is the software Coltop 3D, being developed at IGAR (University of Lausanne) for post-processing of terrestrial laser scanning datasets (e.g. Figure 14). It enables analysis of huge datasets and can perform structural analysis, identify discontinuities, make dip measurement and color code rock faces (Jaboyedoff et al., 2007).

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**Figure 12. Structure of the major chapter of the deliverable exploring the state of the art and the theory of remote sensing and ground based techniques applied to landslides detection, fast characterization, rapid mapping and long-term monitoring.**

- **Remote Sensing**
  - Passive optical sensors *(ground-based photography, satellite imaging, etc.)*
  - Active optical sensors *(ALS, TLS, etc.)*
  - Active microwave sensors *(InSAR, PS, DInSAR, etc.)*
  - Ground-Based *(electromagnetic, micro-seismicity, etc.)*
  - Offshore *(multibeam, 3D high resolution seismic, etc.)*
  - Airborne
    - Extensometer *(wire, probe, fixed)*
    - Inclinometer *(probe, in place)*
    - Other *(piezometers, contact earth pressure cells)*

- **Geophysics**
- **Geotechnique**
- **Other**
- **GNSS**
- **Core Logging**
ESA is developing five new missions called Sentinels specifically for the operational needs of the joint European Commission-ESA GMES programme. (http://www.esa.int/esaLP/SEMBRS4KXMF_LPgmes_0.html).

In 2012, the first of the two satellites of the Sentinel-1 constellation is scheduled to be launched. The Sentinel-1 European Radar Observatory is a polar-orbiting satellite system for the continuation of Synthetic Aperture Radar (SAR) operational applications. It will operate in C-band and is meant to substitute and give continuation to the current ERS mission. The characteristics of Sentinel-1 will be based on feedbacks from users who stressed the importance of continuity of data, frequent revisits, geographical coverage and timeliness. For example, at present, the services encompassing interferometry and cover classification have a global coverage of at most once every 2 weeks. The Sentinel-1 pair is expected to provide coverage over Europe and Canada in less than two days, independent of weather conditions. Radar data will be delivered within an hour of acquisition – a vast improvement over existing SAR systems.

The primary applications of this polar orbiting satellite system will be:
- monitoring sea ice zones and the arctic environment;
- surveillance of marine environment;
- monitoring land surface motion risks;
- mapping of land surfaces: forest, water and soil, agriculture;
- mapping in support of humanitarian aid in crisis situations.

On the global scale, the TRMM (Tropical Rainfall Measuring Mission) joint space mission between NASA and JAXA (Japan) has implemented an algorithm to estimate potential landslide areas (http://trmm.gsfc.nasa.gov/publications_dir/potential_landslide.html). This algorithm yields classes of landslide potential using a global landslide susceptibility map, an intensity-duration precipitation threshold, and 1-, 3-, and 7-day estimates of cumulative rainfall based on satellite measurements. Tests of the algorithm using a global landslide catalogue indicate a need for substantial improvements of its predictive performance (Kirschbaum et al., 2010). These improvements will mainly depend on enhanced calibrations of the thresholds and the susceptibility map. Previous experiences and the ongoing work for implementing such calibrations indicate that the algorithm has potential for practical application to landslide early warning on the global scale.

7 CONCLUDING REMARKS

There is an urgent need to improve the strategies for landslide risk management and the professions’ ability to reduce the risks to acceptable levels. In many situations an early warning system is an effective, and sometimes the only, tool available for accomplishing this goal. Early warning systems mitigate risk by giving sufficient lead time to move the elements at risk out of the harm’s way. Monitoring and early warning systems are more than just an implementation of a technological/scientific solution; the human factors, social elements and information communication are essential parts. That is, an early warning system is not just sensors and data transfer, it is also public education, decision making, social aspects of how a population responds, civil protection plans and finally plans for reconstruction/recovery when the emergency is over. A failure at any point in this chain can compromise the whole system. Although geologists and engineers are not directly involved in the social part of the total system development, these needs cannot be ignored and their importance must not be underestimated.

Landslide monitoring programs incorporating physical measurements and human observations provide the information needed to design EWS. That is why landslide monitoring has become such an important activity worldwide. Without physical measurements and visual
observations, landslide assessment would be reduced to intelligent guessing. Reliability of measurements is paramount in any monitoring system but particularly so in an early warning system. Thus, redundancy and alternate measurement methods should be considered to avoid false alarms. Frequent false alarms destroy the initial trust of the affected population in the system, the trust will be difficult, or impossible, to win back completely.

In order to avoid the occurrence of false alarms, well thought-through thresholds should be adopted for an EWS. Automatic application of these thresholds for issuing a public alarm should only be done when there are no other possibilities.

During the past decade innovative applications in monitoring and remote sensing techniques have been developed. The possibility of acquiring terrain information (height, displacement, land use, etc.) with high accuracy and high spatial resolution is currently opening up new ways of visualizing, modelling and interpreting Earth surface processes such as landslides, debris flows, rockfalls, etc. These new sensors can be mounted on terrestrial, aerial and/or satellite instrumental, covering a full spectra of accuracies, resolutions, points of view, etc. Geophysical and geotechnical investigations can also bring additional information on subsurface processes and movements, which are essential for monitoring and early-warning systems.

Methodological innovations are also contributing to significant improvements in the EWS for landslides. The use of stochastic methods based on Bayesian networks for continuously integrating different information sources and consequently updating the risk measure looks promising. Furthermore, within the framework of the ongoing European project SafeLand, guidelines for designing landslide early warning systems are being developed. These guidelines make use of simple, graphic methods, such as flow-charts, to help the end-user in the choice of the most appropriate system.

Important lessons can be learned from existing EWS operating throughout the world, both from operational systems like those presented in this paper, and from systems that have failed. Examples of the latter are not easy to find in literature because few people are willing to describe negative experiences.

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