Nat. Hazards Earth Syst. Sci., 13, 85–90, 2013
www.nat-hazards-earth-syst-sci.net/13/85/2013/
doi:10.5194/nhess-13-85-2013

Natural Hazards and Earth System Sciences

Brief communication “Landslide Early Warning System: toolbox and general concepts”

E. Intrieri[1], **G. Gigli**[1], **N. Casagli**[1], **and F. Nadim**[2]

[1]Department of Earth Sciences, University of Studies of Florence, via La Pira 4, 50121, Florence, Italy
[2]NGI/ICG (Norwegian Geotechnical Institute/International Centre for Geohazards), P.O. Box 3930 Ullevål Stadion, 0806, Oslo, Norway

Correspondence to: E. Intrieri (emanuele.intrieri@unifi.it)

Received: 25 September 2012 – Revised: 18 December 2012 – Accepted: 27 December 2012 – Published: 18 January 2013

Abstract. We define landslide Early Warning Systems and present practical guidelines to assist end-users with limited experience in the design of landslide Early Warning Systems (EWSs).

In particular, two flow chart-based tools coming from the results of the SafeLand project (7th Framework Program) have been created to make them as simple and general as possible and in compliance with a variety of landslide types and settings at single slope scale. We point out that it is not possible to cover all the real landslide early warning situations that might occur, therefore it will be necessary for end-users to adapt the procedure to local peculiarities of the locations where the landslide EWS will be operated.

1 Introduction

Early Warning Systems (EWSs) have been applied to reduce the risk from natural hazards and are defined as “monitoring devices designed to avoid, or at least to minimize, the impact imposed by a threat on humans, damage to property, the environment, or/and to more basic elements like livelihoods” (Medina-Cetina and Nadim, 2008).

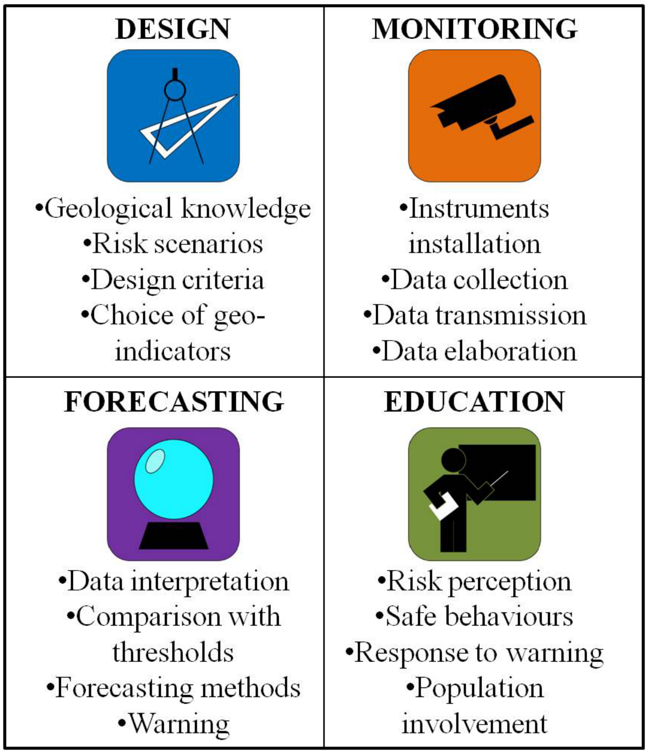
Landslide EWSs have become more applied in recent years (Anderson et al., 2011; Maskrey, 2011); they generally have lower economical and environmental impact than structural interventions, thanks to their capacity to reduce risk by alerting people exposed to the landslide hazard so that they can take action to avoid or reduce their risk and prepare for effective response. However, many EWSs suffer from imbalance among their components; for instance some of them may lack in the instrumental/technical element, some in the social/communication aspect or in the understanding of landslide occurrence and their triggers.

By elaborating the definitions furnished by UNISDR (2006) and DiBiagio and Kjekstad (2007) we can describe landslide EWSs as the balanced combination of four main activities: design, monitoring, forecasting and education (Fig. 1).

Establishing an operational landslide EWS requires careful planning due to their complex structure and the involvement of specialists from several different fields. The key tasks in the design phase of a landslide EWS are: (1) determining the needs and vulnerabilities of the population at risk, (2) identifying any impediments to the population taking action if a warning is issued, and (3) characterizing the geologic and meteorological setting and conditions that lead to landslide initiation. These conditions are referred to as the geo-indicators.

Monitoring, which includes instrument installation and data communication and analysis, is a crucial activity that must be performed throughout the life of the EWS. Monitoring is typically begun during the design phase to study landslide occurrence and behavior. Once the criteria for early warning have been developed during the design phase, the monitoring activities shift from research to operations. This shift in objectives generally requires a more robust and costly system that must operate under the most severe conditions. The operational monitoring system also provides information that can be used to issue the “all clear” once the threat of landslide occurrence has passed. This is the most technical part of the system a reference for which can be found in Reid et al. (2008).

Published by Copernicus Publications on behalf of the European Geosciences Union.



DESIGN
- Geological knowledge
- Risk scenarios
- Design criteria
- Choice of geo-indicators

MONITORING
- Instruments installation
- Data collection
- Data transmission
- Data elaboration

FORECASTING
- Data interpretation
- Comparison with thresholds
- Forecasting methods
- Warning

EDUCATION
- Risk perception
- Safe behaviours
- Response to warning
- Population involvement

Fig. 1. Subdivision of a generic EWS in its four fundamental components.

Forecasting represents the core element of an EWS as it includes the definition of thresholds (whose type depends on the specific case), models and all the activities that lead to a warning. It is also the most problematic one, not just for the intrinsic difficulty of predicting natural events, but also for severe social and legal implications. An excessively high threshold (of any type, for example a movement velocity or a rainfall intensity and duration threshold) value means that the lead time left for the emergency plans will be short and, in the worst case, that the event itself could be missed. Conversely, a threshold that is too conservative may lead to false alarms and to all the related problems. In other words: acceptable risk criteria and tolerability of false alarms are two sides of the same coin; their definition helps to determine the possible range within which the value of the threshold can be set (Nadim and Intrieri, 2011). In any case one has to keep in mind that the possibility of false alarms can be reduced, but cannot be completely nullified; therefore civil protection plans should encompass this chance as well.

Finally, education is necessary to cover the important social and logistic issues that every EWS must consider in order to be people-centered (Twigg, 2006). The main objectives of instruction are to increase the public risk perception and to explain correct behaviors to prevent damage or losses. Particular attention must be paid on how to recognize and react to false alarms and on conveying the message that, to a certain extent, they are bound to happen during the life of an EWS. Even though education is a very cost-effective means to reduce risk, its importance is still sometimes underrated, due to cultural and communication issues (this latter aspect is especially clear in larger communities, where it is more difficult to reach everyone).

One of the aims of the SafeLand project, a large-scale, integrating project of the European 7th Framework Programme that involved 27 partners from 12 European Countries, was to produce guidelines for landslide EWSs in Europe to contribute to the development of landslide EWSs. In this paper the focus is set on individual slope scale systems.

2 Guidelines

The SafeLand project was focused on developing generic quantitative risk assessment and management tools and strategies for landslides at local, regional, European and societal scales. It also aims at establishing the baseline for the risk associated with landslides in Europe, to improve our ability to forecast landslide hazard and detect hazard and risk zones. As a consequence, the purpose of the research done in one of the key areas of the SafeLand project was to develop a toolbox that can help end-users (such as civil protections and administrations) to create a landslide Early Warning System for every need (SafeLand, 2011).

Designing an EWS is a complex task. Many factors such as scale, type of landslide, risk scenarios, available resources, etc. must be considered. The variability that can be encountered when dealing with landslides is so large that it makes EWSs extremely site-specific. For this reason, a certain degree of simplification is required when building a general toolbox. Furthermore, EWSs must foster simplicity (Intrieri et al., 2012), as confusion and loss of time during emergencies can worsen the situation; thus the need for a simple and flexible toolbox based on graphic methods match end-users to the most suitable EWS. The idea behind this toolbox is to provide an easy-to-use tool for defining the main elements of an EWS, considering how several factors can vary. By applying the toolbox to a case study, the basic structure of the system is defined; further customization should also be considered in order to fit the system to the specific circumstances.

Using a flow chart was deemed to be the most suitable approach for fulfilling these needs (Figs. 2 and 3). By following the chart, the end-user is asked to provide information such as the types of landslides, some of their characteristics and the elements at risk. Depending on the answers given, this method provides a means to identify which instruments and procedures should be included in the EWS. The toolbox presented below is valid for designing an EWS for an individual slope.

The flow charts presented in Figs. 2 and 3 are constructed using two kinds of nodes: the ones written in *italics* indicate

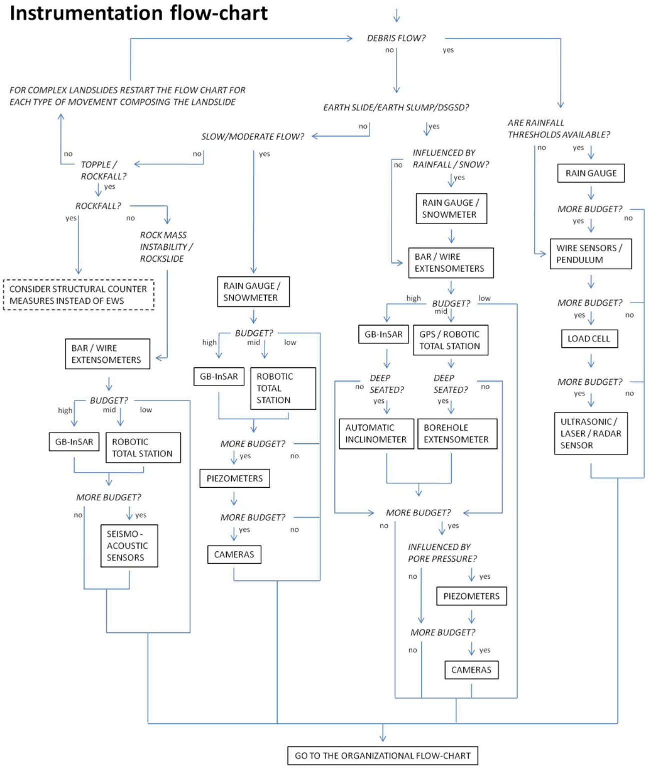


Fig. 2. Flow chart-based toolbox for the choice of instrumentation suitable for slope scale EWSs. The terms "earth slide" and "earth slump" follow the widely accepted classification of Cruden and Varnes (1996) and refers to rotational or translational landslides in granular or cohesive material. DSGSDs (Deep Seated Gravitational Slope Deformations) are defined by Agliardi et al. (2001) as slope movements occurring on high relief slopes and with relatively small displacements before the final phase of collapse. GB-InSAR (Ground-Based Interferometric Synthetic Aperture Radar) is an advanced remote sensing monitoring apparatus recently used in landslide EWSs (Del Ventisette et al., 2011; Intrieri et al., 2012).

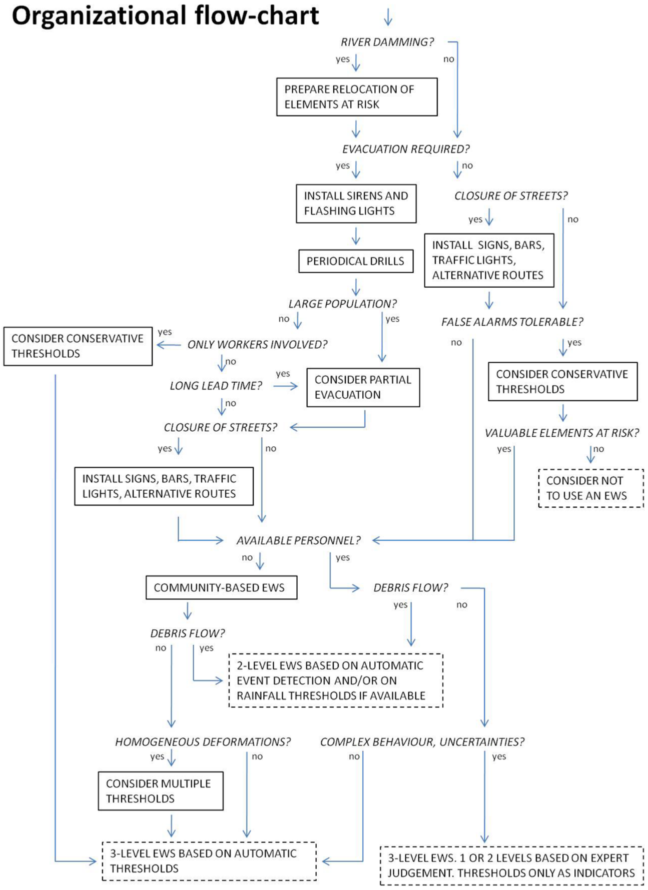


Fig. 3. Flow chart-based toolbox for the choice of organizational features in slope scale EWSs.

short questions posed to the end-user about the type of landslide and qualitative estimates of the budget available (Fig. 2), as well as questions about the elements at risk and risk scenarios (Fig. 3). These represent the constraints imposed by the case study. On the other hand, the nodes in boxes indicate possible features that should be introduced within the EWS to face the constraints. These are cumulative, which means that once the end-user has reached the end of the flow chart, all the suggestions furnished by the nodes in boxes encountered along the way should have been considered. The dashed nodes represent the ends of the flow chart.

The charts should be used in sequence: the first one (Fig. 2) helps in selecting the monitoring instruments, whose choice is mainly driven by the type of landslide and the budget. The second one (Fig. 3) concerns the organization of the system in general.

3 Discussion

The aim of this toolbox is to create a user-friendly instrument, keeping in mind that most end-users may not have experience with landslide EWSs, nor a deep knowledge of them. End-users may prefer instead to be led by an expert to an optimal solution through a series of guided choices. Hence the guidelines have been constructed to be practical, straightforward and almost automated.

The flow charts were calibrated using information from several operational EWSs working throughout the world and their validity was tested on well-known case studies, where efficient systems are described in literature (Iovine et al., 2006; Blikra, 2008; Lacasse and Nadim, 2008; Intrieri et al., 2012). The resulting EWSs are very similar to the real ones; they belong to one of the following types:

- 2-level EWSs: composed only of two different states (ordinary and alarm) and, although they are usually adopted at the regional scale, they can also be adopted for site-specific cases when it is not possible to assess a behavior between ordinary activity and failure (like for debris flows). The definition of "ordinary activity" is relative depending on the case; in general it may refer to inactive or suspended landslides (WP/WLI, 1993) or to active landslides experiencing low velocity and acceleration (for example landslides in the primary or secondary creep stage). 2-level EWSs are commonly associated with rainfall intensity/duration thresholds or movement sensors to detect the event.

- 3-level EWSs: differ from the 2-level EWSs in that they include a pre-alarm level, used when the landslide shows displacements above the seasonal oscillation. A pre-alarm indicates the need for increased monitoring and preparation for the alarm level. Medina-Cetina and Nadim (2008) found that three levels are usually enough for every landslide that shows some displacements before the failure (Rose and Hungr, 2007). In the event that qualified personnel are available, a system based on expert judgment, and not only on the rigid application of movement, rainfall or other types of thresholds, is suggested.

Each suggested choice presented in the flow charts is based on geological and geotechnical criteria that are concealed from the user in order not to confuse non-technical decision makers.

This toolbox is a flexible instrument that is applicable to a great variety of conditions and can be adapted to many different cases. Moreover, thanks to its modularity, it can be easily expanded in order to cover even more situations. For example, a component could be added in order to cover basin- or regional-scale EWSs; the flow charts themselves can be attached to a bigger tree (meant as guidelines) for landslide risk management, of which the EWS approach could represent just a branch. This approach could also be easily implemented as interactive software.

4 Developing a case-specific EWS

The method proposed here only provides a framework and the first input for designing an EWS because, given the huge variability of natural contexts, it cannot possibly encompass all the cases that might occur in reality. Hence, it may be necessary to adjust or complete some of the results according to the specific needs of the site. Therefore the end-user is encouraged to consider other possibilities for the EWS. For example, other monitoring instruments or devices to spread alarms, like SMS or radio broadcasting, can be used in addition to those indicated by the toolbox. Moreover, there are many other variables that can influence an EWS; some of them are listed as follows:

Rainfall thresholds: several types of rainfall thresholds exist, whether they consider antecedent rainfall/daily rainfall, intensity/duration or other relationships (e.g. Guzzetti et al., 2005). Rainfall thresholds can use the actual values of rainfall, the forecasted amounts or a combination of the two. In many cases EWSs operating with rainfall use only 2 levels (ordinary and alarm) with an automatic alarm that is triggered by the exceedance of the thresholds. However, depending on the reliability of the thresholds and the weather forecasts, expert judgment is often necessary to improve the accuracy of the alarm. The value used as a threshold depends on the type of landslide, the geological material, land use and the climate.

Scale: the guidelines are mostly focused on Early Warning Systems at slope scale. However, regional/basinal EWSs are often the most cost-effective if not the only counter-measure against landslides over a wide area. The typical situation for this kind of system is a very large area with diffuse instability problems where there is no possibility to monitor each landslide individually. Usually EWSs are much more reliable over broad regions than at the slope scale because thresholds are calibrated on landslides that happened in the past, rather than on reactivation periods and accelerations. Debris flows are an example of a landslide for which the regional/basin scale EWSs are implemented, because the occurrence of debris flows is often controlled by rainfall intensity and are not easily monitored by other means. Also, because debris flows move at high velocity, when they occur, they allow little time for those at risk to take action. Therefore weather forecasts play a very important role for debris flow EWSs. In the case of alarm, all emergency units can be alerted and access to dangerous areas can be forbidden or restricted. Large scale EWSs or systems managed by centralized structures, instead of communities, may take advantage of SMS and public broadcast media, like radio and television, to disseminate the alarm; communication, in fact, is a key element in early warning. However, relying only on such technologies may not be enough, as they become ineffective when electricity supplies are cut off. Moreover they are not typically tailored to spread the information only to the specific areas affected (Garcia and Fearnley, 2012). In the future, interesting outcomes may result from the use of social media; Sakaki et al. (2010) report that their system is capable of delivering earthquake notifications on Twitter to registered users mostly within a minute (sometimes within 20 s), faster than the announcements broadcast operated by the Japanese Meteorological Agency (which, on average, is 6 min).

Type of trigger: the main triggers are encompassed in the flow chart of Fig. 2, including the case of landslides triggered by rainfall, rising porewater pressure or accelerating movement. Kinematic thresholds (based on absolute displacement, movement velocity or acceleration) are usually suggested, except for those situations where rainfall and rising porewater pressure play a major role and can be easily monitored. However there are many other possible triggers, which should be studied in detail for every landslide. Some of the most common triggers are earthquakes, volcanic activity, human work, flood, erosion, snowmelt and change in reservoir level. Different triggers may require different monitoring systems; for example landslides triggered by volcanic activity could include instruments and monitoring parameters typical of volcanic environments. EWSs for landslides placed above reservoirs should monitor parameters like the water level in reservoir or the flow (see the Lake Sarez rockslide described by DiBiagio and Kjekstad, 2007). Custom-made approaches may be required for landslides with particular behaviors, such as the Séchilienne landslide where it is not possible to establish a fixed velocity threshold due to its continuous acceleration. For this reason, a method based on relative changes of past velocity has been adopted (Durville et al., 2011). These observations show that detailed geological and geomechanical studies are the first fundamental step of every EWS.

Risk: EWSs are strongly influenced by the risk scenario. For example, the presence of structural countermeasures that mitigate the risk can lead to less conservative thresholds. On the other hand, highly vulnerable elements at risk (such as hospitals, schools, power stations) may require lower thresholds. Even associated risks must be considered for setting an alarm and civil protection plans, because a landslide can cause many different kinds of collateral damage (tsunami, fire, river damming, pollution, damaging of structures that may become unstable, triggering other landslides, etc.) depending on the settings. In each case the most appropriate counter-measures must be planned in advance and people must be trained specifically for each situation. Also, the possible evolution of the landslide in terms of style and distribution of activity must be taken into account, as it might exhibit different types of movement (complex and composite landslides) or affect larger areas by experiencing retrogression, widening (WP/WLI, 1993). Obviously, the most hazardous change would be the transition from slow- to rapidly moving, such as the transition to debris flow or catastrophic failure.

5 Conclusions

Although the important role of EWSs is clear to the scientific community, they still struggle to reach full recognition by Governments and decision makers as a viable risk mitigation tool. This may be due to their relative novelty and to the constant and specialized effort that the set up and maintenance of an EWS require. Therefore it is important to foster such approach by implementing new methods like the toolbox presented here, a simple and versatile flow chart which aims at guiding inexperienced users to the development of an EWS. Similar tools, together with a better comprehension of this complex subject, will hopefully help to create new systems and improve the existing ones, thus reducing the number of victims and losses caused by natural catastrophes all around the world.

Acknowledgements. The work described in this paper was partially supported by the SafeLand project: "Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies" under Grant Agreement No. 226479 in the 7th Framework Programme of the European Commission.

We are very thankful to Jonathan Godt, Matjaž Mikoš and editor Mario Parise for their work of review and Emilio Intrieri and Patrizia Musina for their language revision.

Edited by: M. Parise
Reviewed by: J. Godt and M. Mikos

References

Agliardi, A., Crosta, G., and Zanchi, A.: Structural constraints on deep-seated slope deformation kinematics, Eng. Geol., 59, 83–102, 2001.

Anderson, M. G., Holcombe, E., Blake, J. R., Ghesquire, F., Holm-Nielsen, N., and Fisseha, T.: Reducing landslide risk in communities: Evidence from the Eastern Caribbean, Appl. Geogr., 31, 590–599, 2011.

Blikra, L. H.: The Åknes rockslide: Monitoring, threshold values and early-warning, 10th International Symposium on Landslides and Engineered Slopes, Xian, China, 30 June–4 July, 1089–1094, 2008.

Cruden D. M. and Varnes D. J.: Landslide types and processes, in: Landslides: Investigation and Mitigation, edited by: Turner A. K., Shuster R. L., Transportation Research Board, Natural academy of Science, Spec. Rep. 247, 36–75, 1996.

Del Ventisette, C., Intrieri, E., Luzi, G., Casagli, N., Fanti, R., and Leva, D.: Using ground based radar interferometry during emergency: the case of the A3 motorway (Calabria Region, Italy) threatened by a landslide, Nat. Hazards Earth Syst. Sci., 11, 2483–2495, doi:10.5194/nhess-11-2483-2011, 2011.

DiBiagio, E. and Kjekstad, O.: Early Warning, Instrumentation and Monitoring Landslides, 2nd Regional Training Course, RECLAIM II, Phuket, Thailand, 29 January–2 February 2007, 1–24, 2007.

Durville, J.-L., Bonnard, C., and Pothérat, P.: The Séchilienne (France) landslide: a non-typical progressive failure implying major risks, J. Mt. Sci., 8, 117–123, 2011.

Garcia, C. and Fearnley, C. J.: Evaluating critical links in early warning systems for natural hazards, Environ. Hazards, 11, 123–137, 2012.

Guzzetti, F., Peruccacci, S., and Rossi, M.: Definition of critical threshold for different scenarios (WP 1.16), RISK-AWARE: Advance Weather forecast system to Advice on Risk Events and management, Action 1.16, 38 pp., available at: http://www.smr.arpa.emr.it/riskaware/get.php?file=_Report_WP1.16.pdf, 2005.

Intrieri, E., Gigli, G., Mugnai, F., Fanti, R., and Casagli, N.: Design and implementation of a landslide early warning system, Eng. Geol., 147–148, 124–136, available at: http://www.sciencedirect.com/science/article/pii/S001379521200230X, 2012.

Iovine, G., Petrucci, O., Rizzo, V., and Tansi, C.: The March 7th 2005 Cavallerizzo (Cerzeto) landslide in Calabria – Southern Italy, Proceedings of the 10th IAEG Congress, Nottingham, Great Britain, 6–10 September 2006, 785, 1–12, 2006.

Lacasse, S. and Nadim, F.: Landslide risk assessment and mitigation strategy, in: The First World Landslide Forum, United Nations University, Tokyo, Japan, 18–21 November 2008, 31–61, 2008.

Maskrey, A.: Revisiting community-based disaster risk management, Environ. Hazards, 10, 42–52, 2011.

Medina-Cetina, Z. and Nadim, F.: Stochastic design of an early warning system, Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 2, 223–236, 2008.

Nadim, F. and Intrieri, E.: Early warning systems for landslides: challenges and new monitoring technologies, 5th Canadian Conference on Geotechnique and Natural Hazards, Kelowna, B. C., Canada, 15–17 May, 1–15, 2011.

Reid, M. E., Baum, R .L., LaHusen, R. G., and Ellis, W. L.: Capturing landslide dynamics and hydrologic triggers using near-real-time monitoring, in: Landslides and Engineered Slopes, edited by: Chen, Z., Zhang, J., Li, Z., Wu, F., and Ho, K., Taylor and Francis Group, London, 179–191, available at: http://landslides.usgs.gov/docs/reid/Reid_etal_ISL_2008.pdf, 2008.

Rose, N. D. and Hungr, O.: Forecasting potential rock slope failure in open pit mines using the inverse velocity method, Int. J. Rock Mech. Mining Sci., 44, 308–320, 2007.

SafeLand: Deliverable 4.8: Guidelines for landslide monitoring and early warning systems in Europe: design and required technology, December, 2011.

Sakaki, T., Okazaki, M., and Matsuo, Y.: Earthquake shakes Twitter users: real-time event detection by social sensors, WWW 2010 Proceedings of the 19th international conference on World Wide Web, ACM New York, NY, USA, 851–860, 2010.

Twigg, J.: Disaster Early Warning Systems: People, Politics and Economics, Benfield Hazard Research Centre Disaster Studies, Working Paper 16, 1–4, 2006.

UNISDR (United Nations International Strategy For Disaster Reduction): The International Early Warning Programme – The four elements of effective early warning systems – Brochure, Platform for the Promotion of Early Warning (PPEW), 4 pp., available at: http://www.unisdr.org/2006/ppew/iewp/IEWP-brochure.pdf, 2006.

WP/WLI (International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory): Multilingual landslide glossary, The Canadian Geotechnical Society, BiTech Publishers Ltd., Richmond, B. C., Canada, ISBN 0-920 505-10-4, 32 pp., available at: http://www.cgs.ca/pdf/heritage/Landslide%20Glossary.pdf, 1993.