Nat. Hazards Earth Syst. Sci. Discuss., 2, 7149–7179, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/7149/2014/
doi:10.5194/nhessd-2-7149-2014

Natural Hazards and Earth System Sciences
Open Access
Discussions

Monitoring and prediction in Early Warning Systems (EWS) for rapid mass movements

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Monitoring and prediction in Early Warning Systems (EWS) for rapid mass movements

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Received: 21 October 2014 – Accepted: 27 October 2014 – Published: 27 November 2014

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

Abstract

Rapid mass movements (RMM) pose a substantial risk to people and infrastructure. Reliable and cost-efficient measures have to be taken to reduce this risk. One of these measures includes establishing and advancing the State of Practice in the application of Early Warning Systems (EWS). EWS have been developed during the past decades and are rapidly increasing. In this document, we focus on the *technical part* of EWS, i.e. the prediction and timely recognition of imminent hazards, as well as on monitoring slopes at risk and released mass movements. Recent innovations in assessing spatial precipitation, as well as monitoring and modelling precursors, the triggering and deformation of RMM offer new opportunities for next-generation EWS. However, technical advancement can only be transferred into more reliable, operational EWS with an intense dialog between scientists, engineers and those in charge of warning. To this end, further experience with new comprehensive prototype systems jointly operated by scientists and practitioners will be essential.

1 Introduction

A sustainable risk management approach is preventive and includes reliable and cost-efficient risk mitigation measures. During the last decades, Early Warning Systems (EWS) for rapid mass movements have become an essential element of integral risk management worldwide (Glade and Nadim, 2014). Although they span a wide range of spatial scales and technological complexities, their ultimate goal is always the same: to alert people to imminent hazards and allowing them to get themselves to safety. Numerous EWS worldwide have been followed up by researchers and reported in the scientific literature (Fig. 1). Active systems and state-of-the-art technology installed for gravitative mass movement processes are summarized in Bell et al. (2010). The United Nations Environment Programme (UNEP, 2012) provided a worldwide compilation of EWS for different natural hazard processes. Baum and Godt (2010) summarized EWS

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of shallow landslides and debris flows in the USA. In Austria, an overview of EWS for snow avalanche and landslide processes was published by the Forestry Torrent and Avalanche Control (Forsttechnischer Dienst für Wildbach- und Lawinenverbauung, 2008). A recent overview of operational EWS in Europe was assembled for the EU FP7 project SafeLand (Michoud et al., 2013). Villagrán de León et al. (2013) presented a comparative review and discussed differences of warning and alarm frameworks. Successful implementation of EWS has also been reported for less-developed countries (Huggel et al., 2010).

Switzerland is a prominent example of a country that is prone to damage caused by Rapid Mass Movements (RMM) due to its topographic disposition. Here, the first automatic EWS for snow avalanches was operated in Mahnkinn in 1937 (Saettele and Meier, 2013) to detect spontaneous snow avalanches above an endangered railroad. Today, EWS are operated in a diversity of designs for various natural hazard processes. A collection of site specific EWS was first published by Eyer et al. (1998). Gubler (2000) described system components and experiences of site-specific EWS for snow avalanches, mudflows and rock fall. Hegg and Rhyner (2007) provided an overview of national warning products in Switzerland. Recently a common information platform for natural hazards was established to provide warning information from four Swiss warning centers in an integrated manner (Heil et al., 2014).

Integral EWS typically include four key elements (UNEP, 2012): (a) a comprehensive assessment of the risks, (b) a sensor-based monitoring and warning system, (c) a plan for the dissemination of alerts, and (d) strategies for the response of the people at risk. The present review article only discusses the state-of-the-art of the *technical part* of EWS, i.e. the prediction and timely recognition of imminent hazards, as well as the monitoring of slopes at risk, and released mass movements. The issue of disseminating warnings and response is deliberately not considered here. The paper aims at providing a useful basis for the design of next-generation EWS.

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2 Types and characteristics of existing Early Warning Systems

A recent study (Sättele et al., 2012) investigated the reliability of EWS, their comparability to alternative protection measures and their cost-efficiency. More than fifty active EWS in Switzerland were identified and analyzed to derive a classification of EWS. The study suggests that EWS can be classified into: (i) alarm, (ii) warning and (iii) forecasting systems. Pure monitoring systems, on the other hand, do not actively issue warning information, and are, accordingly, not considered as EWS.

i. *Alarm systems* detect process parameters of already ongoing hazard events to initiate an alarm automatically e.g. in the form of red flashing lights accompanied by sirens. The accuracy of the prediction is high, but the lead time is short. The alarm decision is based on a predefined threshold. One prominent example is the "Illgraben" debris flow alarm system in Canton Valais, which protects persons crossing the channel from debris flows as they have been detected (Fig. 2). Here, sensors are installed in the upper catchment to detect ground vibrations and flow depth increase of an ongoing debris flow; and to trigger an alarm in the form of flashing lights and audible signals at channel crossings further downstream, and text messages to local hazard managers (Badoux et al., 2009). Alarm systems are often installed to prevent damages caused by natural hazard processes that may be rapidly triggered such as debris flows, snow avalanches, glacier lake outburst floods and rock fall.

ii. *Warning systems* aim to detect significant changes in the environment (time dependent factors determining susceptibility with respect to mass release), e.g. crack opening, availability of loose debris material and potential triggering events (e.g. heavy rain) before the release occurs and thus allow experts to analyze the situation and implement appropriate intervention measures. The information content of the data is often lower in this early stage, but the lead time is extended. The initial warning is based on predefined thresholds. In Preonzo (Ticino, southern Switzerland), for instance, a warning system was installed to forecast an emerging rockfall. The velocities of the movement of a large body of rock at the top of the hillslope were measured, and a warning was sent when predefined thresholds were exceeded (Loew et al., 2012). Warning systems are mainly used for processes with progressive stages of failure, such as rock slides and deep-seated landslides.

iii. *Forecasting systems* predict the level of danger of a RMM process, typically at the regional scale and at regular intervals. In contrast to warning systems, the data interpretation is not based on a threshold, but is conducted on a broader basis. Experts analyze sensor data and consult models to forecast the regional danger levels, which are communicated widely in a bulletin. For example, the WSL Institute for Snow and Avalanche Research SLF operates a snow avalanche forecasting system and publishes a daily bulletin to predict the degree of avalanche danger for the next day (Rhyner, 2007). Similar systems are operated in many regions worldwide for other mass movements processes (e.g. Bell et al., 2010).

Independent of the category of an EWS, it must fulfill the following criteria (e.g. Michoud et al., 2013; Glantz, 2003 and UN/ISDR, 2006):

- Easy to implement: limited complexity of the technical system, as well as a thorough instruction of the people responsible (often laypersons) is essential.

- Comprehensible and manageable: thresholds (e.g. precipitation amount or runoff levels) have to be evident and comprehensible for those in charge of issuing warnings.

- Redundancy: the EWS may not depend on single sensors and transmission lines, but must be based on a range of different installations (and complementary parameters, if possible).

- Precision: the critical property defining the hazard level must be measured with sufficient precision.

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– Autonomy (electricity and data transfer): the system must need minimal maintenance and be functional in remote regions.

– Robustness: the instruments must be able to resist the expected range of environmental conditions, and, to some extent, mechanical perturbation.

– Affordable price: the costs of acquisition and operation have to be balanced with the expected risk reduction.

Researchers and practitioners in Switzerland discussed the needs of future EWS in a workshop in January 2013 with natural hazard experts responsible for the management of the debris flow EWS Spreitgraben (Tobler et al., 2012) and for several rock-fall EWS in central Switzerland (Wegmüller et al., 2013). The practitioners stated that they have to ensure that the specific technical components of such systems are suitable for the planned intervention measures. They have also experienced that a technical design is of low value without a clear distribution of responsibilities and organizational tasks enabling the effective management of emergencies.

A further concern for these experts is the abundance of sufficient information required to provide a comprehensive and complete risk assessment. But more measurements and data do not necessarily make risk management easier. Often, it is not the amount of data, but the understanding of the processes and the complex relationships between process measurements and probability of the onset of rapid mass movement that limits the success of an EWS.

3 Limitations of current EWS

The range of technologies used in current EWS to monitor environmental variables for recognizing critical states is very broad (Table 1). For each EWS, the specific choice of instrumentation depends on the type of imminent hazard, the area at risk, the know-how of the responsible authorities and the trade-off between costs and risk reduction.

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Common for most of the systems are measurements of precipitation, typically recorded at local weather stations. These measurements are often used to issue alerts as soon as site-specific thresholds of total amount and intensity are exceeded (e.g. Guzzetti et al., 2008). In alarm systems, often some combination of e.g. geophones, seismometers, trigger lines, flow-height sensors, are set up to detect the release or the passage of debris flows or rock fall (Sättele and Meier, 2013). For warning systems, in contrast, it is common to deploy sensors that depict the onset of movement such as extensometers, inclinometers or terrestrial radar systems (Caduff et al., 2014; Sättele and Meier, 2013). Finally, continuous measurements of soil water pressure, snow depth and spatial precipitation are used in forecast systems (Lehning et al., 1998).

In spite of the continuous worldwide progress of these technologies and the increasing experience obtained by operators and managers, we still face inherent shortcomings and limitations of current EWS:

Current EWS are sometimes too closely focused on simple thresholds. Thresholds (e.g. of measured precipitation) for the release of RMMs cannot be defined universally, but must be adapted to local conditions. The definition of local thresholds and corresponding warning levels is an iterative process that requires a long-term record of events. Newly-installed EWS or EWS set up to protect against only rare events do not provide a sufficient basis for defining plausible thresholds. In addition, thresholds can change over time, e.g. as critical geotechnical properties are changing (e.g. degrading permafrost) or as a consequence of previous events (e.g. slope erosion or raised saturation degree in the ground after a wet winter).

The observations used in current EWS are often not representative for site-specific processes. In many cases, the available measurements (e.g. rainfall data) used for the early warning of RMM are too far away from the critical area and therefore are not representative for site-specific processes. For example, recent work has illustrated the importance of the sensor position in the field in defining system performance (Sättele et al., 2013). Inclusion of additional sources of information (e.g. from private weather services or hydropower companies) could partly reduce this problem. Furthermore, the increasing availability of satellite-derived precipitation products at regional scales has driven important progress toward landslide nowcast assessments and warning. Several products of the Tropical Rainfall Measurement Mission (TRMM) have been improved over the past years, and have been evaluated for landslide warning purposes (Hong et al., 2007; Kirschbaum et al., 2012). Limitations arise from reduced accuracy of precipitation records at short time intervals (e.g. 3 hourly) and over complex mountain topography (Scheel et al., 2011).

Current EWS typically measure simple proxies of RMMs rather than the critical slope properties. Sensors typically measure environmental variables that affect the trigger process (e.g. rainfall, precipitation), but not the critical slope properties controlling the initiation of triggering (suction or pore water pressure, soil water content and saturation profiles, depth and stratigraphy of the snow cover). Depending on these variable dispositions, slope failure may occur in response to a large variety of precipitation intensity and duration (Zimmermann et al., 1997). Accordingly, the monitoring of precipitation may induce considerable uncertainty for the warning procedure.

Precursors of imminent hazards are scarcely considered in current EWS. Triggering failure will usually be preceded by development of local strains along the expected shear zones, which may occur gradually or as specific events very close to the time when the mass is triggered. So far, the relationship between these "precursor events" and the time and size of mass release is poorly understood.

Current EWS do not account for uncertainty in an appropriate way. Uncertainties are inherent to all EWS. Accounting for and managing uncertainty represents one of the main challenges for EWS. Uncertainties are related to the prediction/recognition of the triggering as well as to the transition of the mass, and thus directly affect success or failure of warning and effective risk reduction (avoidance of loss of life or damage). Unfortunately, uncertainty estimates (e.g. ensemble forecasts that give representative samples of the possible future states) are often missing, or only weakly represented, in current EWS. Furthermore, uncertainties are difficult to communicate to authorities and to the population that potentially may be affected. Past studies have shown that false

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alarms are less problematic if people have a better understanding of how the EWS works and what the thresholds are (Huggel et al., 2010).

4 Current innovations in modelling and observation of RMM

In cutting-edge research, a fundamental change is ongoing in assessing the probability of imminent release of rapid mass movements. New models and observation techniques are currently being developed that can be combined into an integral system that makes use of complementary information from various sources. In the following we summarize selected recent developments in technology relevant to technical aspects of EWS.

4.1 Precipitation patterns at fine scales

Accurate and timely knowledge of precipitation is a key for warning about impending RMM. The inherent problem with measuring and predicting precipitation is its large variability over a wide range of spatial and temporal scales. This variability needs to be properly taken into account in EWS. Traditional ways of monitoring precipitation using only few rain gauges over an entire catchment is far from optimal because rain gauges have a very limited spatial representativeness. Weather radar provides precipitation estimates that are more representative over large areas and can be used to better predict the distribution of RMMs within a given area (Crosta and Frattini, 2003; Chiang and Chang, 2009). Unfortunately, radar data are often too coarse to be used directly in EWS. New stochastic disaggregation techniques (Schleiss and Berne, 2012) are currently being developed that allow rain rate fields collected by radar or simulated by numerical weather prediction models to be downscaled, while preserving their main statistical properties (e.g. distribution, intermittency and structure). The intermittent nature of precipitation has been shown to have a profound impact on its variability (Schleiss et al., 2014). The proposed stochastic method can be used to generate large

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numbers of different outcomes for a single input field. These scenarios can then be applied to landscape models (Von Ruette et al., 2014) and used to determine the most vulnerable areas for a particular rain event. It can also be used to derive new rainfall thresholds for EWS and help to identify critical rainfall patterns that could trigger rapid mass movements.

4.2 Detection of precursors

Before a destabilized soil or snow mass is released, the progressive character of slip plane formation comprises many small scale mechanical failure events, such as the destruction of mechanical bonding agents (biological fibers, cemented grain contacts, plant roots, ice crystals), friction between grains, redistribution of internal stresses, or crack formation.

These local mechanical failure events cause release of energy that propagates through the porous medium as an elastic wave that can be measured as Acoustic Emissions (AE). Signals are generated at a high frequency because of the small size/scale of precursor failure events. Tests with natural soils revealed characteristic frequency ranges between 1 and 100 kHz for acoustic emissions associated with failure (Michlmayr et al., 2012). The range extends towards 1000 kHz for failure in permafrost specimens (Yamamoto and Springman, 2014). Providing the ability to detect single failure events down to the grain scale, acoustic emissions present a mechanical microscope for in-situ monitoring of progressive slope failure. Direct shear tests with different synthetic and natural granular media corroborated a coherent link between shear plane formation, micro-mechanical failure events, and synchronously observed acoustic emissions (Yamamoto and Springman, 2014; Michlmayr et al., 2013). Theoretical considerations based on granular material dynamics and wave propagation concepts allow the acoustic signature to be modelled and provide potential to interpret measured AE with respect to the material failure mode.

Acoustic precursory patterns are also investigated for snow avalanche release (van Herwijnen and Schweizer, 2011a; Reiweger and Schweizer, 2013). Snow slab avalanches are released as the result of crack formation and propagation in a buried weak snowpack layer. Laboratory fracture experiments with snow samples containing a weak snow layer confirmed that acoustic signals originate from within the weak layer (personal communication). The failure of a weak snow layer resembles a progressive transition into a critical state (Johansen and Sornette, 2000) that is manifested by typical power-law statistics. Such power-law behavior was also observed in snow samples and it was discovered that the distribution of the AE signals changed before, during, and after fracture (Reiweger and Schweizer, 2013). A similar change of precursory signals before mass release was also observed (Amitrano, 2005; Cohen et al., 2009) and simulated (Lehmann and Or, 2012) for other types of RMM. More specifically, the frequency distribution of the released energy follows a power law, with an exponent that changes before the mass release. The validity of power-laws in the precursory patterns is also an indication of the progressive material failure that is included in new types of models, as we will discuss in the following section.

4.3 Numerical models for triggering of mass movements

Recent advancements have also been made in modelling the triggering of rapid mass movements. For example, the change of hydro-mechanical material properties with increasing water content has been implemented in constitutive mechanical models to better represent the transition of soils from a partially to a fully water-saturated state (Nuth and Laloui, 2008). In this way, potential triggering of RMMs can be analysed in a systematic way by considering matric suction losses induced by rainfall infiltration (e.g. Eichenberger et al., 2013). The hydrology and saturation state at the catchment and regional scale must be represented appropriately in order to model the triggering of RMM.

Numerical and field experiments revealed that the spatial patterns at larger scale, including macro-permeability and the local hydrogeology, were key factors for the initiation of mass release. In a field study on triggering a shallow landslide by intense sprinkling (Springman et al., 2009), it was shown that exfiltration from the bedrock was an important destabilizing factor, whereas zones in which drainage into the bedrock prevented the water table from rising, remained stable (Askarinejad, 2013). The field study revealed as well that persisting positive pore pressures and high water saturation in large interconnected regions of the hillslope were required to initiate mass release (Lehmann et al., 2013).

An additional challenge for physically-based landslide triggering models is the abrupt mass release without clear precursors or additional "measurable" indication of changes in the system. New landslide triggering models based on a concept of self-organized criticality were developed to simulate abrupt mass release as progressive failure of interconnected soil columns (Lehmann and Or, 2012; Von Ruette et al., 2013). During intense rainfall events, "weak columns and connections" break and a rapid chain reaction culminating in mass release may be initiated. The weakening and local failure of soil was modelled explicitly using the framework of fiber bundle models (the mechanical strength is represented by a bundle of parallel fibers with load redistribution from broken weak fibers to stronger elements) to capture precursor statistics that change with imminence of mass release and comprise information that could be used in an EWS.

4.4 Monitoring slope deformation and flow propagation

Prediction of the triggering of debris flows remains a significant challenge, however, because it is rarely possible logistically or financially to install instruments at all possible failure locations. Broadband seismic networks, most commonly used for earthquake or other geological research, have recently been used to document numerous snow avalanches, several landslides and the transformation of one of these landslides into a debris flow (van Herwijnen and Schweizer, 2011b; Lacroix et al., 2012; Burtin et al., 2014). Recent work on snow avalanches suggests that an early warning based on accurate and near real-time avalanche activity monitoring is possible (Schweizer and van Herwijnen, 2013). Indeed, before periods of high wet-snow avalanche activity, the waiting time between avalanches clearly decreased towards peak avalanche activity. Prerequisites for applying the waiting time approach as an operational early warning tool are near real-time data transmission and automatic signal detection. We expect that this technology will be improved through the elaboration of seismic triggering thresholds and by cataloging seismic signals typically produced by various types of landslides, thereby eventually making it possible to automate the detection. Many examples already exist, e.g. typical seismic properties have already been observed for landslides (e.g. Suriñach et al., 2005; La Rocca et al., 2004; Ekström and Stark, 2013), debris flows (Burtin et al., 2009) and snow avalanches (e.g. Suriñach et al., 2005), however the density of seismic monitoring instruments must be relatively large to accurately identify the initiation zone (e.g. on the order of 1 station per 1 km^2 was used by Burtin et al., 2014) and algorithms to identify mass movements automatically have not, to the best of our knowledge, been developed or tested for their applicability to early warning. Of course, it will be necessary to identify precursor seismic signals for early warning, or at least the initial onset of movement, prior to the release of the main body of material.

Recent advances in portable ground-based radar interferometry using a new tripod-mounted radar instrument (Caduff et al., 2011) have reduced the amount of time necessary to determine the spatial distribution of movement of a hillslope by accounting for the influence of atmospheric disturbances on the radar signal, thereby increasing the usefulness of ground-based radar interferometry for early warning. For example, it was possible to measure rates of hillslope movement of 3 $mm\,day^{-1}$ for a landslide with an estimated volume of 500 000 m^3 at the Illgraben catchment (Canton VS, Switzerland). The radar interferometer can measure from several locations to permit construction of 3-D movement vectors of landslides. While the use of ground-based radar for measuring slope deformation has become relatively common (Caduff et al., 2014), work still needs to be done to develop general algorithms to process the radar data automatically to provide real-time warning of movement exceeding a user-defined threshold, especially during periods of strong atmospheric disturbance (Caduff et al., 2011).

4.5 Use of mass flow models in EWS

Progress in physically based mass flow models is important for several aspects of early warning. The design of an EWS requires understanding of the areas potentially affected by mass movements, especially in downstream areas where lives and infrastructure may be negatively impacted. Such models are based on principles of mass, momentum and energy conservation and many solve the shallow water equations adapted for granular flows, and include appropriate resistance terms to describe the flowing friction of a landslide. Examples are RAMMS (Christen et al., 2010), FLO-2D (O'Brien et al., 1993), or DAN-3D (Hungr and McDougall, 2009) which have been applied to a large range of RMM, including ice and rock avalanches, debris flows, lahars, or hyperconcentrated flows (e.g. Willenberg et al., 2009; Evans et al., 2009). Coupled or cascading RMM are a particular challenge to EWS and may include rock or ice avalanche impacts into lakes, generating displacement waves, and eventually lake outburst floods. Recent studies have coupled several models to simulate cascading processes and to provide an estimate of areas affected, including the generation of hazard maps as an input to EWS design (Schneider et al., 2014). Lead time for warning is a critical element for EWS and dynamic mass flow models are able to provide related estimates (Schneider et al., 2014) which can be improved by calibration using geophone, radar or lidar measurements (e.g. Badoux et al., 2009).

5 Main challenges

The transition from current well-established, but limited, EWS to future innovative EWS implies a number of challenges both to scientists developing the scientific basis, and to the natural hazard experts installing and operating such EWS. Some of these challenges were identified in the framework of the project SafeLand (EU FP7; Michoud et al., 2013), and corresponding strategies were proposed (Intieri et al., 2013). We are convinced that overcoming the following challenges will be essential in order to make

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significant advances towards effective next-generation EWS:

Obtaining *accurate, real-time high-resolution precipitation information* at a reasonable cost still represents a great challenge, especially in areas of complex topography and high relief (e.g. in the Alps), where the visibility of weather radar is strongly impeded. Spaceborne radars (e.g. the dual-frequency radar of the Global Precipitation Mission) provide useful precipitation information that complement ground-based data (if available). Fast and automatic disaggregation of ground-based and spaceborne radar data for EWS also represents a challenging task from the operational point of view and needs to be further investigated.

A fundamental *advance in the availability and use of information* about the *soil, snow and bedrock* will be the key for enabling numerical models to be used in operational EWS. For instance, at present, Switzerland still lacks a soil hydrological map that could be used to derive soil hydraulic properties. The spatial exploration of soil properties relevant for slope instabilities, as well as of the snow cover, requires substantial further development of non-invasive geophysical methods. Such information at the scale of slopes will become essential to translate precipitation fields into maps of water saturation, loads and soil/snow strengths for slope stability models. To ensure reliability of such derived soil-water fields, spatial measurements of water content and water pressure will have to be assimilated. This, on its part, will require considerable innovations in the development of (wireless) sensors and remote-sensing based methods.

A further challenge will be to *develop technical systems to measure precursors at affordable cost*. For example, the measurement of acoustic emission (AE) precursors in a field setting is today in a fledgling state. Numerous problems must be solved before AE devices become practical tools. For example, the strong attenuation of the high frequency elastic waves will have to be counteracted. A potential technology to overcome this problem could be fiber-optic AE sensing. Novel data acquisition methods can provide information on elastic waves impinging on a fiber-optic cable with a spatial resolution in the range of a few meters along a distance of several hundreds of meters.

Entire transects of a susceptible hillslope may be monitored with this method, and precursory AE events can be reported from failure-prone sections instantaneously. The feasibility of this technique at field scale will be tested in the near future.

Related to the implementation of future innovative EWS, a main challenge will be to *make the technical system comprehensible and usable by operators.* Typical operators of EWS may have a basic knowledge of the observed processes, but they are probably not scientists or engineers. Automated operation can be dangerous if the person responsible for security can not make a link between an automatically generated value and the process (e.g. warning level red, without knowing which values should generate a red level). The processes are normally too hazardous so that the necessary measures just can be deduced from an automatically generated value (e.g. a warn level). Therefore, interpretation is essential. But interpretation by locals is only possible if the EWS is not a black box, and clear guidance is provided about how the warning level must be interpreted.

Finally, the key-requirement of *redundancy and reliability of the technical system* remains a difficult task, which is also the case for future EWS. Current advances in remote sensing, e.g. by satellite-based radar systems, need to be better integrated into operational systems. Recent work in the Upper Reuss Valley (Switzerland) (Wegmüller et al., 2013), contracted by the Swiss Federal Railways (SBB), has shown that such observations could become a useful complement to ground-based measurements. Not least, the added value of numerical models running in a real-time mode (providing ensemble forecasts) for the redundancy and reliability of technical systems needs to be further explored.

6 How can we get there? Promising avenues towards future EWS

A substantial advance from current to next-generation technical systems for early warning of rapid mass movements will require fundamental investments in basic research, in the dialogue between researchers and EWS operators, as well as in the exploitation and exchange of experiences.

First of all, the basic research related to mechanisms, early detection and prediction of the initiation of rapid mass movements has to be further intensified. A substantial advance can only be achieved in an interdisciplinary setting. Our experiences suggest that most important will be new insights in how local observations – typically of very small scale – can be used to derive, over a short time and with high certainty, a risk estimation for the scale of slopes and regions. In this respect, innovations in the use of (complex) numerical models as a complement to observation systems will be of great importance.

Second, the knowledge increase at the research institutes has to be followed up and influenced by practitioners much more than in the past. A critical review of new research results by those in charge of or operating EWS will become essential. To this end, the dialogue between practitioners and scientists needs to be strengthened and institutionalized (e.g. Bründl et al., 2004). Establishing a common language will be a non-trivial prerequisite. A regular dialogue between practitioners, engineers and scientists will also help to foster a better understanding of the real problems and needs of operators.

Finally, gaining real experiences with new (prototype) EWS will be a key to developing confidence and to reduce skepticism of those making decisions and operating them. To this end, it would be necessary to install pioneer examples of functioning EWS that both constitute a real case of emergency with institutional need for action and which can serve as a playground for testing innovations. In the following paragraphs we sketch how such a novel EWS could be designed and work for shallow landslides:

For early recognition of shallow landslides, the concept would aim at detecting precursors occurring at a limited spatial scale, related to release of elastic energy in a frequency range defined as acoustic emission. Attenuation of released energy in the porous media requires a high spatial density of sensors across a long distance, a condition that can be met by new fiber-optic based acoustic emission (AE) sensors (Parker et al., 2014). With a cable installed in loops on a hillslope above a residential area or along a traffic pathway in steep terrain, small scale mechanical events (shearing particles, breaking roots and cementing agents) would be captured at appropriate scale (meters and seconds, respectively) by measuring (i) amplitudes of AE-signals, the waiting time in between and the frequency magnitude statistics collected over a time interval. As soon as these signal properties start to change towards more frequent events with high amplitudes, the system converges to a critical state and a warning would be released.

For a larger area (catchment scale) where continuous measurements and monitoring of precursors at high spatial resolution are not possible, local AE measurements would be combined with model predictions. For the modeling, information on surface terrain (digital elevation model), land use and soil type would be used, complemented by estimates of soil depth at selected spots. This "time invariant" information would initiate a triggering model computing the evolution of water content distribution and resulting mechanical loading and failure processes, using various time series of key properties like rainfall intensity, water content and precursor activity as input data (Fig. 3). With respect to rainfall data the prototype system would distinguish between measurements (radar data) with limited spatial resolution and the downscaling to high spatial resolution with appropriate disaggregation model. For each modeled time step the downscaled rainfall data would be used as input for the loading of the system. By maintaining a network of wireless sensors measuring water content and failure precursors (based on acoustic emission) the hydro-mechanical state at selected spots would be compared to model predictions and the measured values would be used to re-calibrate the model. The landslide model would then compute a series of realizations covering the uncertainty in input parameters. The resulting ensemble of predicted outcome would be used to make statements on the risk of landslide triggering (including information on location, time and volume of failure occurrence). Such prototype EWS could then be exploited for the training of practitioners, students and decision makers. A systematic collection of

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negative experiences from technical failures, false interpretations and wrong decisions in emergency measures will help further in improving future systems.

Acknowledgements. This document is a result of a workshop in January 2013 in the frame of the project TRAMM – Triggering of Rapid Mass Movements in Steep Terrain – financed by the ETH Competence Centre of Environment and Sustainability (CCES). We are grateful to the valuable discussion and remarks of Florian Frank (WSL), Jérome Faillettaz (ETH Zurich), Ueli Gruner (Kellerhals und Haefeli AG), Daniel Tobler (Geotest AG), Nils Hählen and Jörg Häberle (both at the department of natural hazards of the Canton Berne).

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Table 1. Technologies typically used in current EWS and proposed for future EWS.

Observed parameter		Technology	Type of EWS	References
Precipitation	Sum, intensity	Rain gauge	All	
		Precipitation radar	Forecasting systems	Panziera et al. (2011)
Snow cover	Depth		Forecasting systems	
	Wetness		Forecasting systems	
Soil moisture	Water content	TDR	Forecasting systems	
	Water suction/pressure	Tensiometer	Forecasting systems	
	Groundwater table	Piezometer	Forecasting systems	
Rock/Soil surface	Precursor of failure	Acoustic sensors	Warning system	Michlmayr et al. (2013)
	Displacement	Trigger line	Alarm systems	
		Extensometer, total stations	Warning systems	
		Inclinometer	Warning systems	
		Ground-based radar interferometry	Warning systems	Caduff et al. (2014)
		Satellite-based radar interferometry	Warning systems	Wegmüller et al. (2013)
Triggered mass movement	Vibration	Geophone	Alarm systems	
		Seismometer	Alarm systems	
	Flow surface height	Radar	Alarm systems	
	Flow characteristics	Video	Alarm and warning systems	

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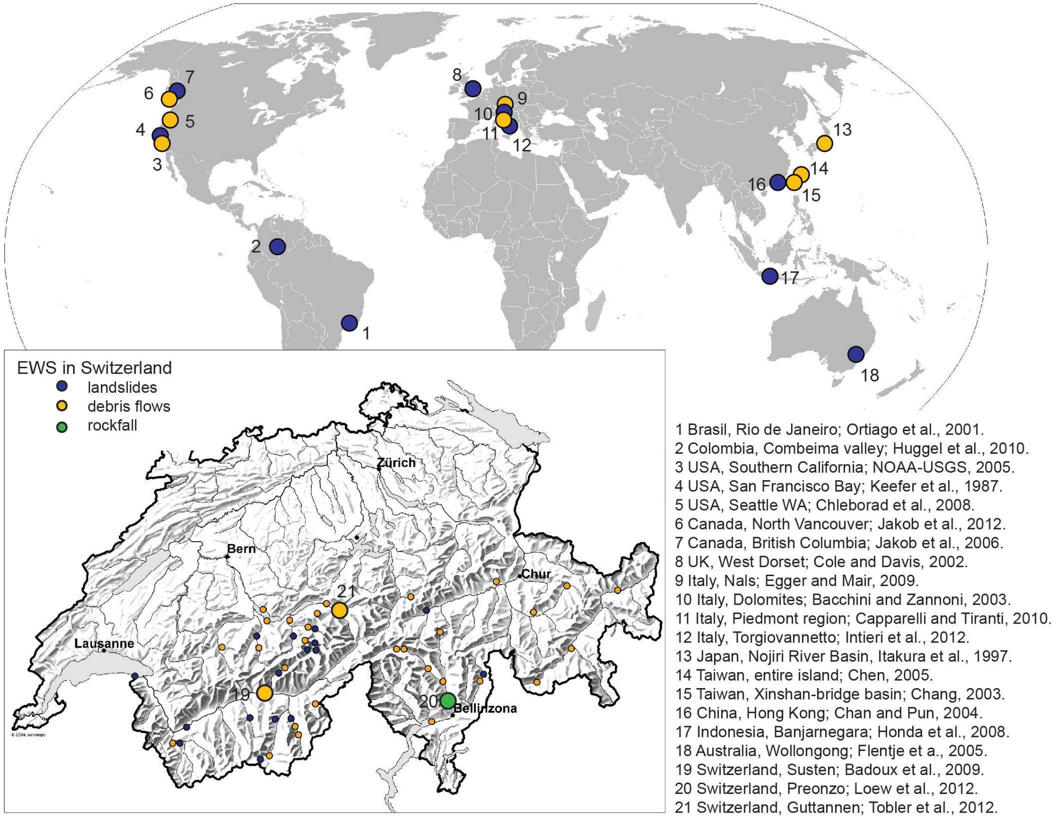

Figure 1. Map of selected EWS sites – worldwide and in Switzerland – reported in literature.

a)

b)

Figure 2. Debris flow EWS Illgraben (Canton VS, Switzerland): **(a)** debris flow detection system in the upper part of the catchment. **(b)** Lower part of the catchment with alerting system.

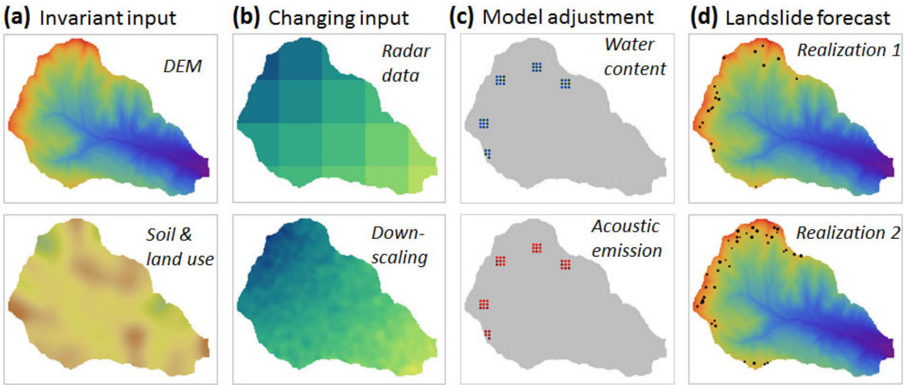

Figure 3. Example of possible future landslide forecasting system at catchment scale. Based on a digital elevation model (DEM) and information on soil type and land use **(a)**, the triggering model will compute the loading and failure patterns using rainfall data (radar values downscaled by disaggregation model) as input **(b)**. Water content and mechanical precursor values measured with a network of wireless sensors **(c)** can be compared to model predictions. In a series of model simulations the time, position and volume of the landslide triggering will be predicted. The ensemble of several realizations will be used to forecast the triggering **(d)**.

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