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Territorial early warning systems for rainfall-induced landslides

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A B S T R A C T

Among the many mitigation measures available for reducing the risk to life related to landslides, early warning systems certainly constitute a significant option available to the authorities in charge of risk management and governance. Two categories of landslide early warning systems (LEWSs) can be defined as a function of the scale of analysis. Systems addressing single landslides at slope scale can be named local LEWSs (Lo-LEWSs), systems operating over wide areas at regional scale are herein referred to as territorial systems (Te-LEWSs). In the literature there are several proposals schematizing the structure of LEWSs. They highlight the importance of the interconnection among different know-how and system components, as well as the key role played by the actors involved in the design and deployment of these systems. This worldwide review is organized describing and discussing the main components of 24 Te-LEWSs, following an original conceptual model based on four main tiles: setting, modelling, warning and response. Te-LEWSs are predominantly managed by governmental institutions, thus information is often difficult to find in the literature and, when available, it is not always complete and thorough. The information considered herein has been retrieved from different sources: articles published in the scientific literature, grey literature, personal contacts with system managers, and web pages. Te-LEWSs mainly deal with rainfall-induced landslides, thus pluviometers are the main monitoring instruments. Intensity duration thresholds are typically employed and meteorological modelling is often used to forecast the expected amount of rainfall in order to issue a warning with a given lead time. Public or internal statements are disseminated for increasing the preparedness of both the public and institutions or agencies. Since the beginning of the 21st century, Te-LEWSs are slowly becoming a commonly used risk mitigation option, employed worldwide, for landslide risk management over wide areas. Considerations and insights on key-points for the success or the failure of Te-LEWSs are presented, differentiating among issues related to the efficiency and the effectiveness of the system. Among them, the important role played by performance analyses of the warning model for increasing the system efficiency is thoroughly discussed.

1. Introduction

Over the last decades, significant consequences in terms of economic losses and fatalities have been caused by natural hazards worldwide (Barredo, 2009; European Environment Agency, 2010; CRED, 2011; Alfieri et al., 2012). Many natural disasters are related to extreme weather events, which are continuously increasing in many parts of the world due to climate change and global warning (Easterling et al., 2000; Morss et al., 2011; IPCC, 2014). Landslides are natural hazardous phenomena often connected with severe social and economic consequences. The geographical pattern of fatal landslides and hazardous landslide areas depend largely on relief, precipitation and the distribution and abundance of the population (Gariano and Guzzetti, 2016). Operational landslide early warning systems (LEWSs) aim at reducing the loss-of-life probability by inviting people to act properly in populated areas characterized, at specific times, by an intolerable level of landslide hazard (Calvello, 2017). Within the landslide risk management framework proposed by Fell et al. (2005), landslide early warning systems (LEWSs) may be considered a non-structural passive mitigation measure. LEWSs differ widely depending on: the type of landslides and their predisposing and triggering factors; the scale of operation—i.e. the size of the area covered by the system. The scale of operation influences several aspects connected to the design and employment of a LEWS, such as: stakeholders involved, monitoring network, type of landslides addressed, variables to be considered for the warning model, the process of disseminating information, emergency plan, education activity. Two categories of LEWSs can be defined considering the scale of analysis (Bazin, 2012; Thiebes et al., 2012; Calvello et al., 2015). Systems addressing single landslides at slope scale are herein referred to as local LEWSs (Lo-LEWSs), and systems dealing with

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the possible occurrence of multiple landslides at regional scale are named territorial systems (Te-LEWSs). The adjective “territorial” is herein preferred over the most commonly used adjective “regional” to provide a more general name for all the LEWSs employed over a wide area, e.g. a nation, a region, a municipal territory, a river catchment.

In recent years scientists, governmental agencies and NGOs have shown an increasing interest on Te-LEWSs and several cooperative projects have been funded worldwide on this topic. However, at the present stage, a state of art paper on Te-LEWSs is still missing from the literature. In the first part, this review provides a summary of the schemes proposed in literature to describe structure and elements of a LEWS. From this synthesis, an original conceptual model of the main tiles necessary to develop and manage an operational system is introduced. Then, the review summarizes all the available information collected on Te-LEWSs operational worldwide, in relation to the four main tiles of the conceptual model proposed: setting, modelling, warning and response. The material herein reviewed is presented by means of summary tables in order to provide easily accessible information to stakeholders interested or involved in different aspects of Te-LEWSs. Finally, considerations on key-points of success and/or failure of these systems, together with some insights on how to design and operate a reliable LEWS, are provided.

2. Landslide risk management with early warning systems

2.1. Warning systems as people-oriented risk mitigation measures

In general terms, an early warning systems (EWS) is an important, dynamic and non-structural mitigation alternative, upgradable over time to reduce the risk for human life associated to the occurrence of hazardous events. Early warning constitutes a process where information generated from tailored observations of natural phenomena is provided to communities at risk, or to institutions which are involved in emergency response operations, so that certain tasks may be executed before a catastrophic event impacts such communities (Villagrán de León et al., 2013). EWSs can be 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 is rather concise yet it highlights the importance assumed, within such systems, by the people as elements at risk. In the Hyogo framework for Action 2005–2015 (UNISDR, 2005), EWSs were recognized as important tools for disaster risk reduction and for achieving sustainable development and livelihoods. The succeeding Sendai Framework for Disaster Risk Reduction 2015-2030 (UN, 2015) corroborates this idea by defining one of its seven global targets as follows: “substantially increase the availability and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030.”

According to UNISDR (2006), people-oriented EWSs always comprise, independently from the type of threat, few essential interrelated elements: i) knowledge of risks; ii) monitoring, analysis and forecasting of hazards; iii) communication and dissemination of alerts and warnings; and iv) local capabilities to respond to warnings. Knowledge of risks means the study of hazards and vulnerabilities in a given area aimed at defining a level of risk. Monitoring deals with the collection of data necessary to control, in time, the trend of variables which significantly affect the hazard and the risk level. To this end, the equipment used can be very different depending on the purpose, the characteristics and the scale of the warning system. Communication and dissemination of warnings aims at informing people at risk. Finally, response capability may be associated to the education of the population, to the information provided on how to act in areas at risk and to specific procedures adopted for handling emergency situations.

Basher (2006) outlines that the setup of a people-oriented EWS requires many systematic approaches and diverse activities spanning the four elements previously described. These activities need to be oriented firstly at identifying target populations potentially at risk, then at increasing the human understanding of warnings and, finally, at generating public information tailored to target groups and making innovative use of the media and education systems. The term “early” in EWSs does not simply mean doing things faster but, just as importantly, doing things effectively (Hall, 2007), i.e. the elements at risk need to react to a warning appropriately and timely. Many reports of the World Bank (WDR, 2014; World Bank and GFDRR, 2013) outline the importance of EWS in reducing fatalities and providing cost-effective means of mitigating the damage from natural hazards. The benefits may exceed costs by a margin of four to one at the global level (Rogers and Tsirkunov, 2010; Teisberg and Weiher, 2009). In the past decades, EWSs have been developed around the world for a wide range of natural hazards, such as: extreme weather events, earthquakes, tsunamis, floods, volcanic eruptions, droughts, snow avalanches, and landslides.

2.2. Proposed schemes on the structure of landslide early warning systems

The continuous urbanization process in landslide prone areas and the increasing number of extreme atmospheric phenomena have drastically raised, worldwide, the exposure of people affected by rainfall-induced landslides. A variety of options are available to mitigate landslide risk: active measures addressing the reduction of the probability of occurrence of landslides (e.g., modification of slope profile; lowering of the water level and pore water pressure, reinforcements); structural engineering works designed to decrease the vulnerability of elements at risk (e.g., barriers, basins, protections); non-structural risk mitigation measures (e.g., landslide early warning systems, land-use planning, awareness, acceptance). Among the many mitigation measures available for reducing the risk to life related to rainfall-induced landslides, landslide EWSs (LEWSs) certainly constitute a significant option available to the authorities in charge of risk management and governance.

The first scheme of the structure of LEWSs presented in the literature (Di Biagio and Kjekstad, 2007) employs a flow chart to outline four main sequential activities for such systems: monitoring, analysis and forecasting, warning, and response. According to this scheme, the key technical issue for the operation of an effective LEWS is the identification, measurement and monitoring of precursors of the occurrence of landslides. The choice of precursors varies with the type of landslides to be monitored (Lacasse and Nadim, 2009) and with the system objectives. Typical examples of precursors for rainfall-induced landslides are heavy rains, rapid increase of pore water pressures, displacements, velocities and accelerations of existing phenomena. Depending on the type of precursor, typical instruments used within the monitoring network of a landslide warning system include: pluviometers, inclinometers, extensometers and other devices measuring ground or subsurface movements, geophones, piezometers and water-content gauges.

The importance attributed to people in LEWSs emerged in the ILEWS project (Integrative Landslide Early Warning Systems), funded by the German Federal Ministry of Education and Research in the period 2007–2010 (Bell et al., 2009; Thiebes et al., 2012). The overall goal of the project was to develop and implement a transferable early warning concept starting with sensors in the field and modelling of early warning, and ending with user-optimized action advice embedded in a holistic risk management strategy. The general structure of ILEWS clearly distinguished natural-scientific interrelations from social systems and it was based on three modules: monitoring, modelling and implementation. The main aim of the first module was the definition and operation of a monitoring system at the Swabian Alb, south-west Germany, for hydrological and slope movement purposes. The modelling module focused on data analysis providing reliable information on future slope behaviour based on a range of modelling approaches. The