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Landslide Early Warning Systems: Resources or Problems?

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Abstract Recent estimates suggest that landslides occur in about 17.1% of the landmasses, that about 8.2% of the global population live in landslide prone areas, and that population exposure to landslides is expected to increase. It is threfore not surprising that landslide early warning is gaining attention in the scientific and the technical literature, and among decision makers. Thanks to important scientific and technological advancements, landslide prediction and early warning are now possible, and landslide early warning systems (LEWSs) are becoming valuable resources for risk mitigation. A review of geographical LEWSs examined 26 regional, national and global systems in the 44.5-year period from January 1977 to June 2019. The study relevaled that only five nations, 13 regions, and four metropolitan areas benefited from operational LEWSs, and that large areas where landslide risk to the population is high lack LEWS coverage. The review also revealed that the rate of LEWSs deployment has increased in the recent years, but remains low, and that reniewed efforts are needed to accelerate the deployment of LEWSs. Building on the review, recommendations for the further development and improvement of geographical LEWSs are proposed. The recommendations cover six areas, including design, deployment, and operation of LEWS; collection and analysis of landslide and rainfall data used to design, operate, and validate LEWSs; landslide forecast models and advisories used in LEWSs; LEWSs evaluation and performance assessment; operation and management; and communication and dissemination. LEWSs are complex and multi-faceted systems that require care in their design, implementation and operation. To avoid failures that can lead to loss of credibility and liability consequences, it is critical that the community of scientists and professionals who design, implement and operate LEWSs takes all necessary precautions, guided by rigorous scientific practices.

1 Introduction

Caused by meteorological and geophysical triggers – mostly precipitation and earthquakes [1] – and by a varierty of human actions, landslides of all types, including debris flows [2], sculpt the slopes of all mountain ranges, carrying sediments to rivers, lakes, and the seas. Recent estimates indicate that landslides occur in about 17.1% of the landmasses, that about 8.2% of the global population live in areas prone to landslides [3], and that population exposure to landslides is high [4]. Where they occur, landslide pose a severe threat to people, often claiming lives [5, 6]. Given these figures, it is not surprising that landslide early warning is gaining attention in the scientific and the technical literature [7, 8], and among government officials, decision makers, and the public.

In the talk, I shall discuss the main characteristics and limitations of early warning systems (EWSs), and specifically of landslide early warning systenns (LEWSs). This extended abstract, and the presentaion, are organized as follows. After an introduction on the terminology used for EWSs for various natural hazards, including landslides (section 2), I present the general assumptions for landslide early warning (section 3). Next, I summarize the results of a systematic review of 26, regional, national, and global LEWSs from 1977 to 2019, globally (section 4). Then, I present recommendations for the further development and improvement of geographical LEWSs, and to increase their reliability and credibility (section 5). I conclude (section 6) with remarks on the value and issues of LEWSs.

2 Terminology

There is no general agreement in the literature on the language to be used to describe early warning systems for natural hazards, including LEWSs. According to the Oxford Learner's English Dictionary, an "early-warning" is a "*thing that tells you in advance that something serious or dangerous is going to happen*", and an "early warning system" is "*a condition, system, or series of procedures indicating a potential development or impending problem*". With my co-authors [8], we defined an early warning system as "*a device, system or set of capacities that generates and disseminates timely and meaningful information to enable individuals, communities, and organizations threatened by a hazard to act timely and appropriately to avoid or to reduce the impact of the threat*" [8]. In the literature, when discussing LEWSs, the connotation of "*early*" depends on the type of hazard, and the perspective and responsibilities of the individuals and organizatios issuing, receiving, and using the "*warning*", which is an advice, recommendation, or order to take an action.

3 Early warning systems

Early warning systems are "*non-structural*" ("*soft*") measures designed, implemented, and operated to avoid or to minimize the impact posed by hazards [9]. Examples of EWSs exist for different natural hazards [9, 10] including *e.g.*, floods [11], volcanic eruptions [12], tsunamis [13], and snow avalanches [14], and are being investigate for earthquakes [15]. Landslide early warning systems are EWSs dedicated to landslides [7, 8].

3.1 Rationale for landslide early warning

Buildig upon ideas introduced originally by R.H. Cambell in 1975 [16], and firstly applied in Hong Kong [17] and in the San Francisco Bay Area, California (USA) [18, 19], the rationale for landslide early warning, and for the design, implementaion, and operation of LEWSs, relays on nine main assumptions [8].

The first two assumptions are that landslides can be predicted, in space and time, and that "*the past is the key to the future*" *i.e.*, the Uniformitarianism principle [20, 21], and hence that data and information on past landslide events can be used to construct landslide predictive models. Albeit there is nothing in the literature that prevents landslide prediction, these assumptions have not been demonstrated (or disproved), theoretically [22, 23]. Still, it is important to clarify the meaning of the term "*prediction*" [22], that the prediction must be scientifically based [24], and that one understands and accepts the limits of a prediction [25].

The next two assumptions are that rainfall is the primary trigger of (rainfall-induced) landslides, causing their initiation through infiltration of water into the slope; and that rainfall is a good proxy for the groundwater conditions that lead to slope instability [16, 19, 26, 27]. Further assumptions are that a rainfall or hydrological threshold is a reliable descriptor of the behaviour of a slope forced by rainfall [19, 26-28]; and that rainfall can be measured and forecasted with the spatial and temporal accuracy necessary to predict landslides [19, 29]. These assumptions are a clear simplification of the complex processes that cause a slope forced by precipitsion to fail.

The last three assumptions have to do with the efficacy of LEWSs, and postulate that landslide forecasts can be used to issue useful landslide advisories; and that based on a landslide advisory the population can take actions to minimize landslide risk [19]; and that there can be sufficient time to warn people leaving in potentially dangerous areas [19, 30]. These later assumptions appear reasonable, but also have not been proven [8].

3.2 Types of landslide early warning systems

Conceptually, LEWSs can be divided in two main, non-exclusive groups. A first group consists of systems that exploit the early detection of a landslide event when the event is already occurring *e.g.*, a monitored landslide is moving. The second group encompasses systems that attempt to anticipate the occurrence of a landslide event. LEWSs in the first group relay typically on direct or indirect measurments of physical properties of the moving mass *e.g.*, surface or sub-surface movements of a landslide [31, 32], seismic (acustic) noise produced by a moving debris flow in a channel [33, 34]. LEWSs in the second group use measurments of physical quantitites considered to be related to the (possible) landslide occurrence (*e.g.*, rainfall) to inform empirical [35-37] of physical [38-43] predictive models.

Another possible subdivision of LEWSs refers to the number of landslides that a system is designed (or expected) to anticipate – and, hence, the extent of the geographical area within which the systems operate. LEWSs are designed and operated to (i) monitor, early detect, and warn about the movement of a single (typically existing) landslide, or a debris flow in a single monitored channel; or (ii) to precict and warn about the possible occurrence of populations of landslides in a large or very large area *i.e.*, many landslides caused by a single trigger or a number of triggers in a relatively short period [22, 23]. The two groups work typically at very different spatial – and to some extent temporal – scales. The latter group encompasses LEWSs referred to as "*territorial*" [7] or "*geographical*" [8]. In the following (and in the talk), I concentrate on geographical LEWSs.

4 LEWS review

A recent review of geographical LEWSs [8] examined critically 26 regional (19), national (6), and global (1) LEWSs in the 44.5-year period from January 1977 to June 2019. The systematic study relevaled that, at the date of the ananlysis, only five nations, 13 regions, and four metropolitan areas benefited from operational LEWSs, and that large areas where fatal landslides are frequent and landslide risk to the population is high, lack LEWS coverage. The evidence is a problem for landslide risk mitigation. The review further revealed that the rate of LEWSs deployment has increased in the recent years, but remains slow.

Examination of the 26 LEWSs revealed that most systems have undergone some sort of verification, but also that no accepted standard exists to evaluate the performance and the forecasting skills of a LEWS. This is a limitation, because it limits the possibility to compare the performances of the existing and of future LEWSs.

5 Recommendations

Review of the 26 LEWSs globally allowed to propose a set of recommendations for the further development and improvement of geographical LEWSs, and to increase their reliability and credibility. The recommendations cover six main, equally relevant areas, namely: (i) design, deployment and operation of LEWSs, (ii) collection and analysis of relevant landslide and rainfall data used to design, operate, and validate the LEWSs, (iii) landslide models and advisories used in the LEWSs, (iv) LEWSs evaluation and performance assessment; (v) LEWSs operation and management, (vi) communication and dissemination.

5.1 Design, deployment and operation

Concerning the design, deployment, and operation of LEWSs, and based on the evidence that regional and national LEWSs cover a small part of the areas where landslides are expected, globally [3], the main recommendation is that it is important to increase the current (slow) rate of LEWSs deployment, implementing new LEWSs where landslide risk to the population is high and fatal landslide are frequent. It is equally important to maintain existing LEWSs, extending their operational life.

5.2 Landslide and rainfall data

Regarding the collection and analysis of relevant landslide and rainfall data to design, operate, and validate the LEWSs, a critical recommendation is to collect accurate information on the time of occurrence of landslides. This basic information is only apparently simple to collect [44-47], and a small landslide catalogue may result in large uncertainties, and in potentially inaccurate, or wrong threshold models [48, 49]. It is also important to establish strategies for landslide and rainfall data collection, to improve the quantification and comparison of landslide triggering rainfall fields, and to address – as much as possible – the inherent incompleteness and non-stationarity of landslide and rainfall records. These issues can possibly be mitigated using multiple sources of landslide and rainfall information.

5.3 Landslide models and advisories

Concerning the landslide prediction models, and the advisory systems and messages used in the LEWSs, the review revealed the lack of accepted standard methods for the defininiton of the landslide threshold models [26, 28, 37]. With this respect, the main recommendation is to decise and use open criteria to decide the number of the thresholds, and to adopt sound probabilistic approaches for landslide models, forecasts, and advisories. It is also important to explain how information on landslide susceptibility is used, or it can be used in operational LEWSs, and to investigate the role of climate and environmental changes on the landslide forecast models [50].

5.4 Evaluation and performance

The review outlined the lack of standards to evaluate the landslide forecast models. In this area, recommendations are multiple, and include using open criteria for the evaluation of the LEWSs skills and performance; evaluating all parts of the LEWSs, and not only the outcome; adopting optimization procedures to decide and revise the advisory levels; and assess the consequences of using external or general advisory schemes. It is also important to consider the – often unknown and difficult to quantify – uncertainties inherent to the landslide models, forecasts, and advisories, and the lack of landslide information when evaluating the LEWSs forecasts and advisories.

5.5 Operation and management

Regarding the operation and managemet of LEWSs, a recommendation is to log the system activity and events systematically, as this may contribute to the evaluation of the system performance, fostering transparency. Additional recommendations include the integration of site specific monitoring and physically-based models in LEWSs; the use of multiple models for the landslide forecasts and advisories; and the use of long-range weather forecasts for seasonal landslide forecasting.

5.6 Communication and dissemination

Concerning communication and dissemination, which are vital – too often undervalued – parts of any successful LEWS, the recommendations are to use simple, common, and standard language to construct the advisory messages; to define and adopt open standards for the design, implementation, maintenance, and evaluation of the LEWSs; and to stimulate the community of landslide and LEWSs scientists and practitioners to decide on, and disseminate open standards for LEWSs.

With this respect, it is worth noticing that on December 14, 2020, the – relatively small – community of scientists and professionals who design, implement, and manage landslide early warning systems joined to initiate LandAware [https://www.landaware.org/], an international network whose scope is to "*share experiences, needs, and innovations among experts and to develop and promote guidelines and best practices*" for existing and new landslide early warning systems [51].

6 Concluding remarks

Envisioned almost five decades ago [16], thanks to significant scientific and technological advancements, landslide prediction and early warning are now possible at all geographical scales, from local to global. As a result, LEWSs are becoming potentially valuable resources for landslide risk mitigation. This is particularly relevant as ongoing and projected climate and environmental changes are expected to increase landslide risk, and particularly the risk posed to the population by rainfall-induced landslides [50]. However, LEWSs are complex and multi-faceted systems that require care in their design, implementation, operation, and management. To avoid unnecessary failures that can lead to loss of credibility and legal liability and consequences, it is critical that the community of scientists and professionals who design, implement, and operate landslide warning systems takes all necessary precautions, guided by rigorous scientific criteria and practices [24]. To what extent the community will be able to do this will depend laregely on the community itself.

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