Landslide Warning Systems in High-Income Countries: Past Accomplishments and Expected Endeavours

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Abstract

Special emphasis has been given to the role Early Warning Systems (EWSs) can play as mechanisms for disaster risk reduction (DRR) around the globe. Along this line, the International Consortium on Landslides (ICL) has promoted several efforts to create regional and global network initiatives that include, among other relevant activities, landslides early warning systems (LEWSs). This task has actively involved the ICL community in supporting the implementation of the Sendai Framework for Disaster Risk Reduction (SFDRR) in all the nations included as members.

Despite the advances in the development of LEWSs, their successful implementation worldwide remains a challenge to be addressed. Building on earlier efforts, an overview of the diverse dimensions of LEWSs in High-Income Countries (HICs) is provided in this chapter.

Insights derived from a systematic literature review, are included in this document and organized into five sections. The introductory part focuses on the relevance of LEWSs in HICs and outlines the structure of the chapter. It is followed by a general reflection on hazard knowledge-based LEWSs. Details on the methodology used for this analysis are provided in the third section. The outcomes of the literature review are presented in the fourth section, while key messages are included at the end of the chapter.

Technology development for potential LEWSs, hazard analysis for LEWSs, and models and prototypes for LEWSs are the main thematic focus of research in the analyzed publications.

Keywords

Landslide Early Warning Systems · high-income countries · implementation · disaster risk reduction

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1 Introduction

The use of Early Warning Systems (EWSs) has increased since the establishment of the Sendai Framework for Disaster Risk Reduction (UNISDR 2015) as a fundamental mechanism to reduce disaster risk. The design, validation, and implementation of Landslide Early Warning Systems (LEWSs) have been strongly promoted by the International Consortium for Landslides (ICL) through an extensive array of collaboration and synergies among networks, Centres of Excellence, along with global strategies (Sassa 2015, 2016) and commitments (Alcántara-Ayala and Sassa 2021).

The Kyoto Landslide Commitment 2020 (KLC2020) is of particular relevance to this task. An effort that seeks to promote larger awareness of the need to implement people-centered early warning based on high accuracy and reliable prediction technology for landslides considering the context and challenges of a changing climate (Sassa 2019, 2020).

Just like any other type of EWSs, the development of LEWSs has been initiated in countries where human and financial capacities for the progress of science are not hindered by economic or political factors. Nonetheless, international scientific associations such as ICL have helped to enhance the dissemination of EWS around the world for the benefit of society.

In earlier works, insights regarding the application of LEWSs in low- and lower-middle-income countries (LICs and MICs) (Alcántara-Ayala and Garnica-Peña 2023a) and Upper Middle-Income Countries (UMICs) (Alcántara-Ayala and Garnica-Peña 2023b), from 1991 to 2021, have been presented. Building on these works, this chapter aims to offer a review of the implementation of LEWSs in High-Income Countries (HICs), during the same period. Excluding the introduction, this chapter comprises four sections: a brief account concerning the architecture of EWSs, the methodology, and results, and a final consideration of past accomplishments and expected endeavours.

2 Hazard Knowledge-Based Landslide Early Warning Systems

More than a decade ago, initial efforts took place to build people-centered EWSs (ISDR-PPEW 2005). Nonetheless, a very high percentage of EWSs are based on merely hazard perspectives. Instead of the balance tilting towards the role of the EWS being to guide practices for the formulation of policies that guarantee risk reduction, they have a highly technical nature that responds to humanitarian actions (Alcántara-Ayala and Oliver-Smith 2017, 2019).

Although it is essential to have hazard assessments that are as precise as possible, up to now elements of risk knowledge of the population exposed to the potential impact of landslides have not been incorporated.

LEWSs in HICs also show a clear tendency for their structure to focus on the landslide hazard dynamics. This includes rigorous scientific instrumentation, monitoring, and modeling and diverse methodologies that seek to estimate failure thresholds. Likewise, communication protocols are determined along with the dissemination of warnings to the population. Civil protection entities oversee providing access to the warning, action protocols, and response (Fig. 1).

There is no doubt that the increase in intensity and frequency of precipitation due to global warming will play an even greater role in landslide occurrence in the coming years (IPCC 2014; Cardona Arboleda et al. 2020; Adler et al. 2022). Therefore, additional efforts must consider moving from landslide hazard-based EWSs to integrated landslide disaster risk management (Alcántara-Ayala 2021). This will encourage strengthening alliances between the science and technology community and policy making.

3 Methodology

A systematic review of the literature was performed. The ISI Web of Science database data was used as the only source to conduct the analysis. This included the definition of the review scope, literature search, literature analysis, and synthesis. Past accomplishments and expected endeavours of LEWSs were also further explored.

In the same manner, as the analyses undertaken for low- and lower-middle-income countries (LICs and MICs) (Alcántara-Ayala and Garnica-Peña 2023a) and Upper Middle-Income Countries (UMICs) (Alcántara-Ayala and Garnica-Peña 2023b), the words "landslide", "warning system", and "early warning" in the title and abstract of the articles were considered in the search criteria and keywords for this study. The initial literature search for all countries was conducted between January and February 2022, and the analysis for HICs was performed in September 2022.

Fig. 1 The hazard knowledge-based nature of LEWSs

The years 1991–2021 were chosen as the publication period of analysis to avoid the incorporation of work in progress in 2022. A total of 1762 papers were included as search outputs (Fig. 2).

A filtering process was performed to exclude publications that did not have the full abstract available, were published in languages other than English, and were focused on LICs and MICs, and UMICs. The number of publications was reduced to 1159.

After removing publications that did not correspond to the objective of the literature review, as well as retracted publications, editorial material, and letters, the number of publications was reduced to 1009.

The last filter applied concerned the identification of publications in which LEWs were involved. Therefore, the number of documents included in this analysis was 584 (Fig. 2).

Like in the previous book chapters regarding LICs and MICs and UMICs, the examination and synthesis of the literature consisted of geographical analysis, timeframe of publications, institutions involved, research areas, methodological typology, and perspectives (Fig. 2). After the final selection of publications, exchanges, and discussion of perspectives by two researchers to confirm the relevance of
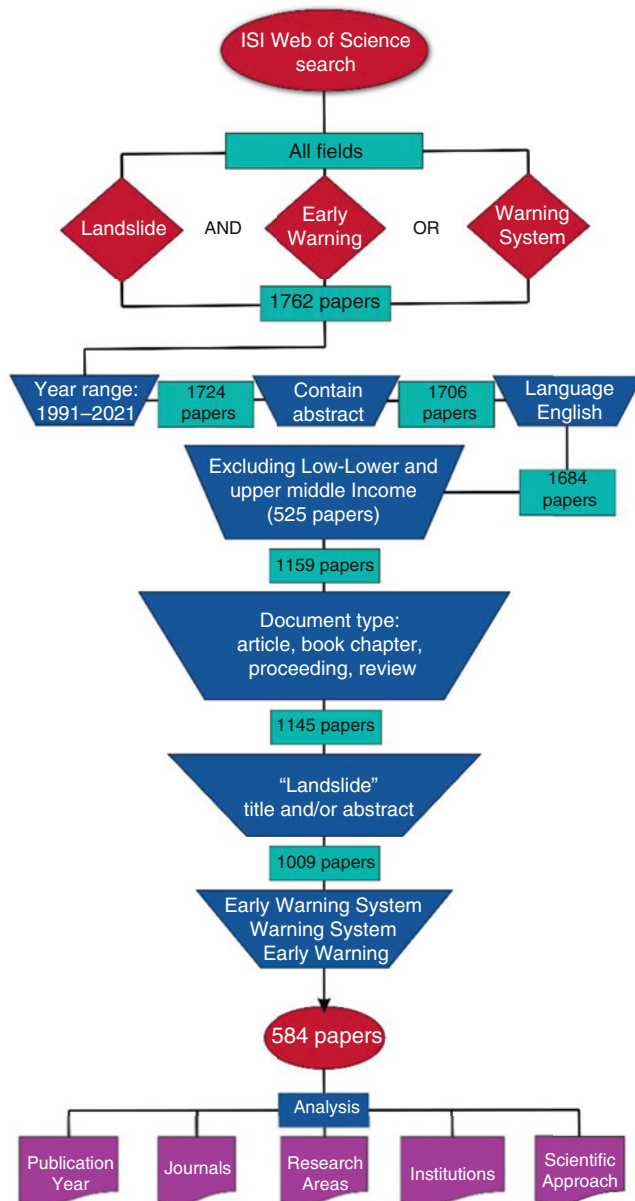
Fig. 2 Search strategy for systematic review

selected publications to the goal of the analysis was carried out.

Data were managed and analyzed by using Excel and HistCite. Past accomplishments and expected endeavours of LEWS in High-income countries (HICs) were shaped based on the insights derived from the analysis and the practical knowledge of the authors.

4 Results

Countries including Italy, the United States of America, Taiwan, Switzerland, the United Kingdom, Germany, Japan, Austria, Canada, France, Norway, Spain, the Republic

of Korea, Netherlands, Croatia, Poland, Slovenia, Australia, and the Czech Republic are the HICs where 96% of the total publications considered in the present literature review were developed.

The first two publications concerning LEWS included in ISI Web of Science were available in 1991, and they corresponded to publications generated in two of the HICs. Thus, the period of analysis considered in this chapter is 1991–2021 (Fig. 3).

Although there has been a growing tendency in the number of publications on LEWSs in HICs since 1991, 2003 was the first year when this increase was noted with the publication of eight papers. In 2010, there was a much clearer rise as 29 articles were published. Likewise, quite clearly, since the year 2015, when the Sendai Framework for Disaster Risk Reduction commenced, the temporal distribution of publications showed a marked surge. 2017 was the year with the highest number of publications produced by academicians working in HICs so far, which was in the order of 63 papers (Fig. 3).

The type of publications analyzed comprised articles (N = 399), conference proceedings (N = 155), book chapters (N = 9), and reviews (N = 21).

The publications focused on various fields of research in the diverse topic areas associated with landslides. Of the total publications, 23% was concentrated in the areas of engineering and geology (N = 135), followed by geology, meteorology, and water resources (N = 79), engineering (N = 57), and geology (N = 47). Additional relevant areas are physical geography and geology (N = 21), geochemistry and geophysics (N = 18), environmental science and ecology and water resources (N = 13), engineering, geology, and water resources (N = 10) environmental sciences and ecology and geology (N = 10) and geology and water resources (Fig. 4). Not a single publication produced by researchers in HICs was included in social sciences. Therefore, the total predominance of a technical perspective was documented.

The top four journals in which most of the papers were published included the Landslides Journal (N = 79), followed by Natural Hazards and Earth System Sciences (N = 47), Natural Hazards (N = 22), and Engineering Geology (N = 19). Additional articles were issued in publications such as Advancing the Culture of Living with Landslides (N = 12), Geomorphology (N = 12), Engineering Geology for Society and Territory (N = 11), Geophysical Research Letters (N = 11), Water (N = 11) Journal of Hydrology (N = 10) and Remote Sensing (N = 10) (Fig. 5).

Experts from 160 research institutions from HICs participated as contributors to more than one publication. The top institutions regarding participation in the largest number of publications were the University of Florence (N = 51), the National Research Council (CNR) of Italy (N = 41), the US Geological Survey (N = 22), University of Naples Federico II (N = 21), and the Swiss Federal

Fig. 3 Time analysis: number of publications analyzed concerning LEWSs in HICs
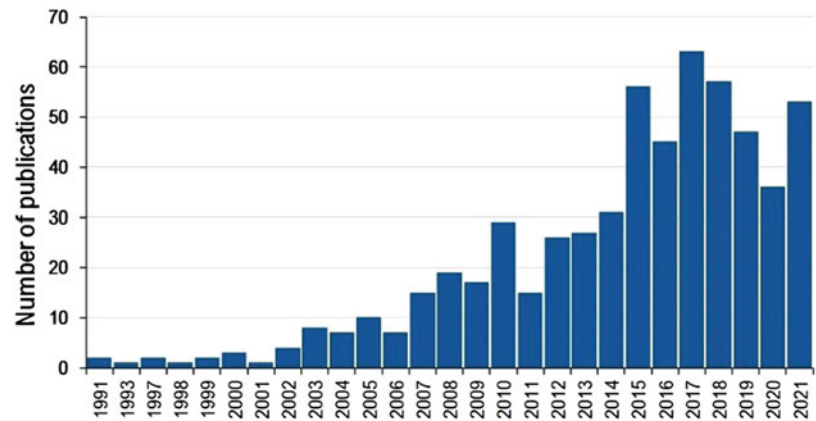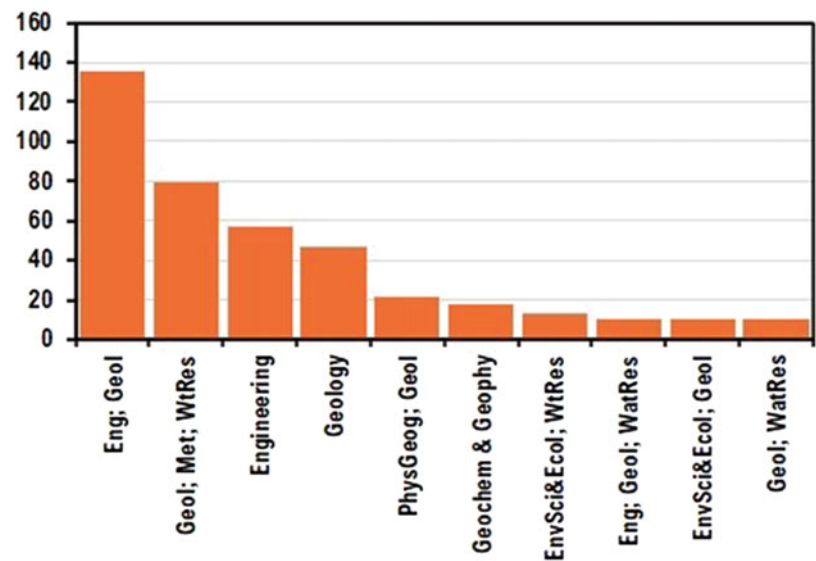

Fig. 4 Research areas concerning the publications analyzed on LEWSs HICs

Institute of Technology (N = 20) (Fig. 6). Quite clearly, through the work developed by the University of Florence and the National Research Council (CNR), Italy is at the top of the global production of papers on LEWSs.

Other institutions comprised at the top were the National Taiwan University (N = 16), University of Calabria (N = 16), University of Salerno (N = 16), National Institute of Geophysics and Volcanology (Istituto Nazionale di Geofisica e Vulcanologia, Italy) (N = 12), University of Roma La Sapienza (N = 12), University of Padua (N = 10), National Chiao Tung University (Taiwan) (N = 9), Norwegian Geotechnical Institute (N = 9), University of Perugia (N = 9) and University of Tokyo (N = 9) (Fig. 6).

The investigations included in the analyzed publications were concentrated on three main thematic lines of research. The highest percentage of publications was focused on diverse topics associated with technology development for potential LEWSs (N = 202, 34.5%). This was followed by

hazard analysis for LEWSs (N = 194, 33.2%). The third category included models and prototypes for LEWSs (N = 118, 20.2%) (Fig. 7).

The second group of themes comprised the actual implementation of LEWSs (N = 18, 33.2%), while the need to implement LEWSs (N = 14, 33.2%) and various aspects of landslide risk management (N = 11, 33.2%) followed (Fig. 7).

Further topics comprised surveys (N = 7, 1.1%), reviews (N = 5, 0.85%), ICL initiatives (N = 4, 0.68%), manual, guidelines and standards (N = 4, 0.68%), international efforts (N = 2, 0.34%), education (N = 3, 0.51%), barriers for implementation (N = 1, 0.17%), and technological and institutional capabilities (N = 1, 0.17%) (Fig. 7).

The research focused on the development and improvement of LEWSs in HICs has been extensive (Fig. 8).

Italy concentrates the largest number of study cases reported in the analyzed publications, followed by Taiwan and Switzerland (Fig. 9).

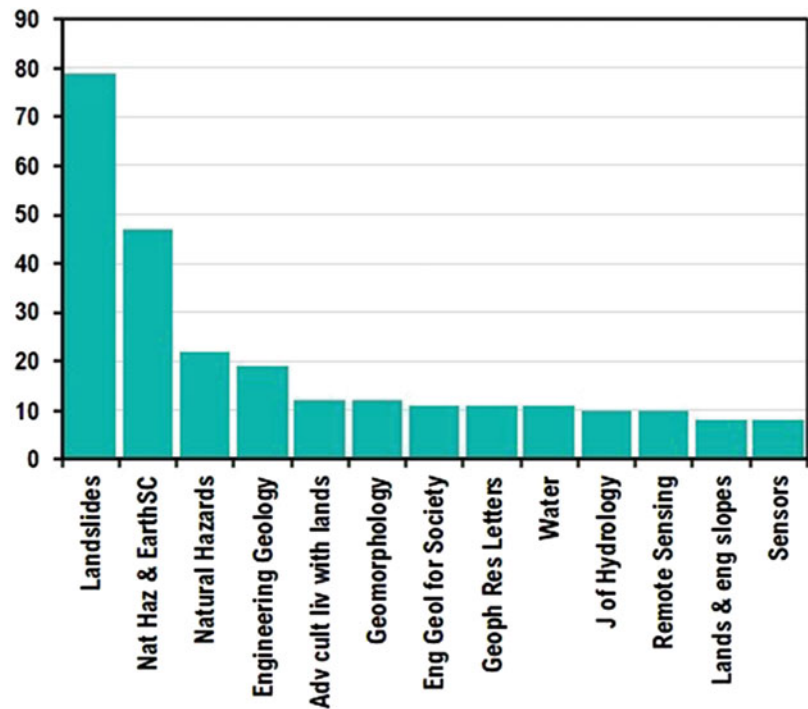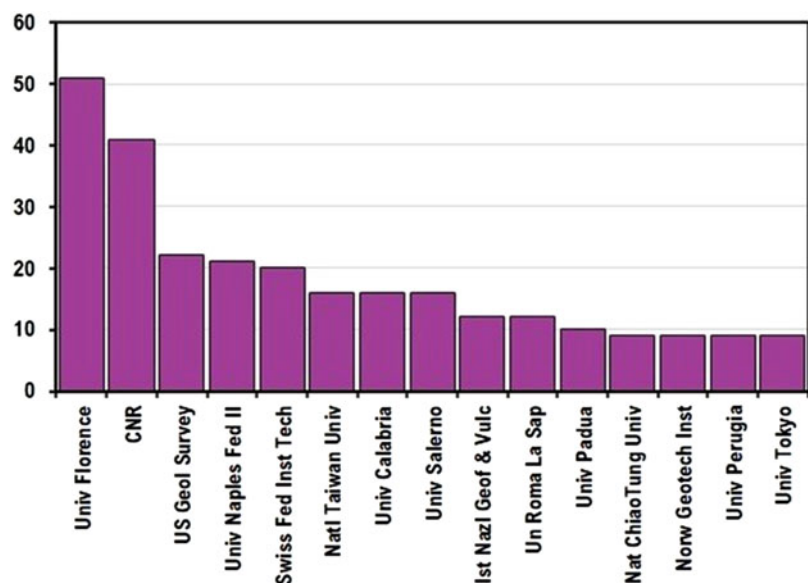**Fig. 5** Journals of publications regarding LEWSs in HICs

Fig. 6 Research and academic institutions to which the authors of the analyzed publications are affiliated

4.1 Technical Developments for Potential LEWSs

Quite clearly, due to the availability of resources and specific interest in improving EWSs, research in HICs is highly focused on technical developments for potential LEWSs. This includes to a major extent near-real-time monitoring of surface displacements, experimental application of distributed optical fiber sensors, techniques of optical remote sensing, acoustic sensing technology, geoelectrical, and seismic geophysical surveys, and three-dimensional experiments and modeling. A common feature is the use of a real-time GPS network, a ground-based interferometric linear synthetic aperture radar, LIDAR, and automated topographic monitoring systems.

Emphasis was also given to the use of low-cost ad hoc wireless sensor networks and flexible spatial web service technology, sensor networks for debris-flow monitoring and warning, time domain reflectometry for the continuous capture of dynamics and locations of shear deformations with
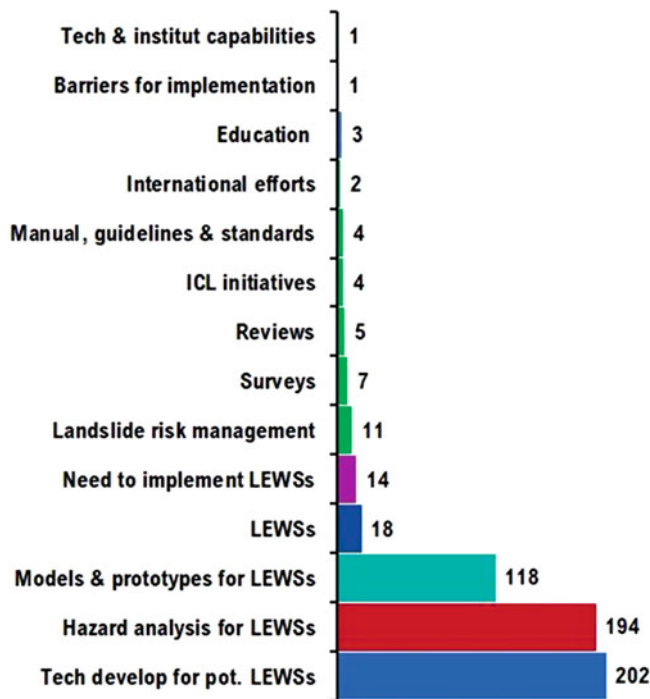
Fig. 7 Thematic lines of research associated with LEWSs in HICs, based on the systematic literature review

Tacheometry, and Low-Cost Global Navigation Satellite System, among others.

4.2 Hazard Analysis for LEWSs

Diverse characterizations of landslide hazards were also reported. A large amount of research was concentrated on the analysis of localized rainfall intensity, antecedent precipitation index, rainfall intensity-duration thresholds, and topography that affected the hydrologic processes.

Likewise, a wide diversity type of techniques and methodologies to understand the various aspects linked to the dynamics of landslides were used. This included numerical modeling, physics-based hydrology, slope stability models, multiple regression analysis, combined finite discrete element methods, the weight of evidence, analytic hierarchy process, fuzzy logic methods, multitemporal interferometry, optical Landsat TM images, Sentinel-1 SAR images, multi-satellite precipitation analysis, high-resolution three-dimensional laser scanning monitoring, Monte Carlo simulations, predictive models with machine-learning approaches, monitoring of slope displacements, dendrochronological based analysis of slope movements, and others.

Results from landslide hazard characterization dynamic were produced in terms of landslide rainfall thresholds, characterization of soil properties, hazard indexes, landslide susceptibility models, insights into the understanding of
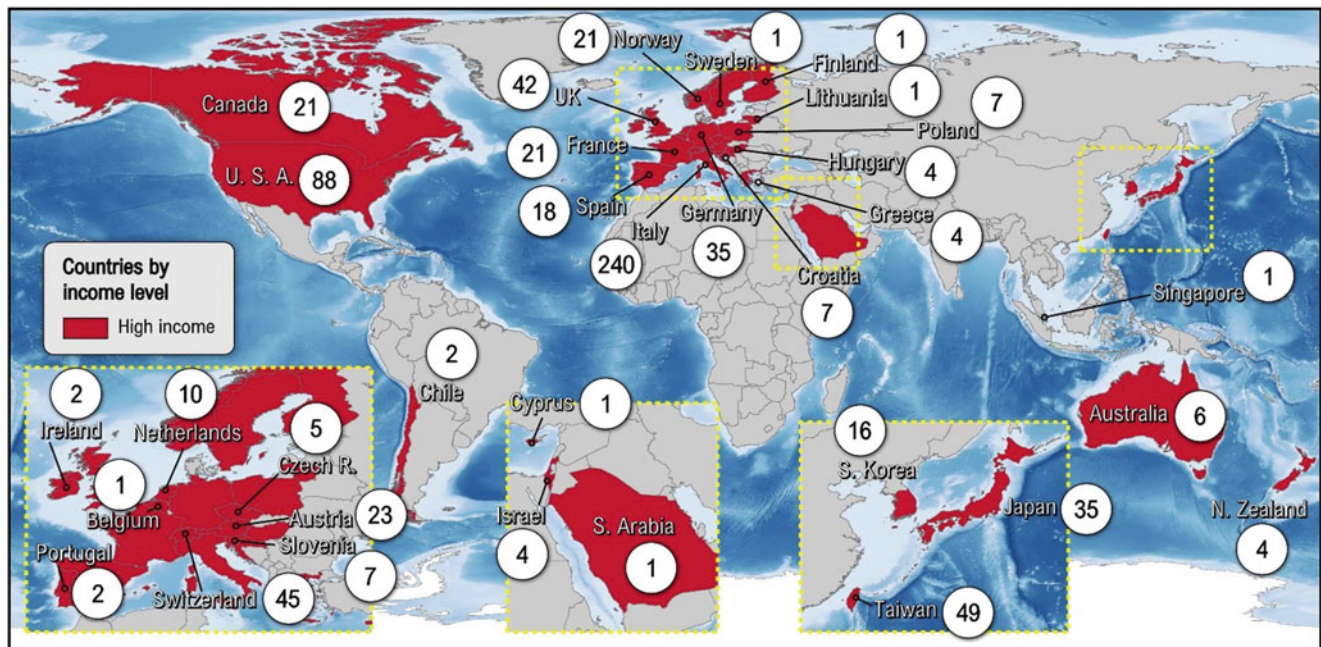
high temporal and spatial coverages, artificial intelligence camera prototypes, measurement of deformations by using Time Domain Reflectometry, Reflectorless Video

Fig. 8 Countries of the research and academic institutions to which the authors of the analyzed publications are affiliated. The number inside the circle represents the number of publications per country
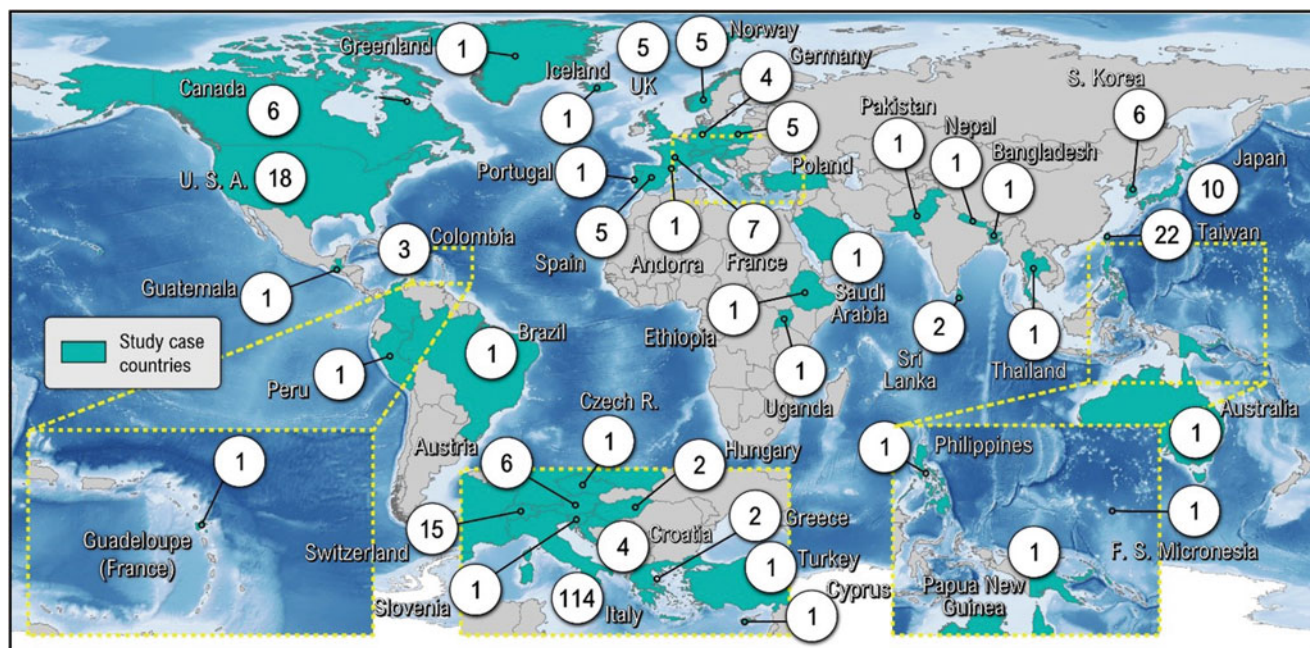
Fig. 9 Study case countries reported in the analyzed publications. The number inside the circle represents the number of study cases per country, including those which are not categorized as HICs

hydrological processes at slope scale, the evolution of surface deformation, the extent to which vegetation enhances slope stability, landslide potential maps, landslide-generated tsunami scenarios, and so forth.

4.3 Models and Prototypes

A series of models and prototypes have been developed in diverse institutions situated in HICs. Although it is not possible to make a follow-up on the implementation of those models and prototypes, its potential operation is higher than in other countries where resources are scarcer.

Some of these models include hydrological models such as the Forecasting of Landslides Induced by Rainfall (FLaIR), which is applicable for forecasting recurrent landslides and is based on the identification of a mobility function (Capparelli and Tiranti 2010; Capparelli and Versace 2011).

Likewise, mathematical models for LEWS have included different processes to provide rainfall and the occurrence evaluation of landslides (De Luca et al. 2010). The use of stochastic real-time predictors of rainfall-induced landslides has also helped to increase the time for successfully triggering risk mitigation procedures (Greco et al. 2013).

4.4 Operational LEWSs from Publications in HICs

The implementation of LEWs in diverse countries was reported in 18 publications, out of which 5 were from Italy, 2 from Canada, Norway, Switzerland, and the USA, and 1 from the Republic of Korea, Japan, Taiwan, Germany, and New Zealand.

Based on intensity-duration rainfall thresholds, a LEWS was established in the Tuscany region in Italy to provide alert levels for 25 distinct alert zones, for which specific thresholds were calculated (Segoni et al. 2015). Dei Cas et al. (2018) reported the monitoring undertaken in the Gallivaggio rock cliff in the San Giacomo Filippo district, thanks to which it was possible to successfully alert the Civil Protection Unit and the Municipality.

In 2005, after the Chichi Earthquake, a LEWS was created in Taiwan. It is based on the identification of rainfall threshold values derived from information produced by local weather stations and it is adapted according to specific geomorphologic context. The implementation of this LEWS has helped to reduce the casualties associated with landslide disasters (Chen and Huang 2010).

The Norwegian national LEWS initiated operations in 2013. It relays on rainfall thresholds, hydrometeorological

and real-time landslide observations, along with landslide inventory and susceptibility maps. The performance of this LEWS was recently evaluated and results indicate that the definition of the density criterion is a fundamental issue that system managers need to consider to be able to provide an idea of the expected number of landslides for every warning level in each warning zone (Piciullo et al. 2017).

A regional LEWS was put into operation by the government of Busan, the second-largest city in South Korea. Based on time-varying rainfall data, alerts are constructed through statistical, physically based, and geomorphological calculations. Analysis carried out to evaluate the LEWS revealed that close collaboration and feedback between researchers and operating authorities and clear divisions of legal responsibility are critical for its successful implementation and sustainable operation (Park et al. 2020).

Owing to the frequent impact of debris flows in the Swiss Alps, in the Canton of Valais, since the year 2000, a LEWS was in place. The system comprises community organizational planning, detection and alerting of events, geomorphological catchment observation, and development of an early warning system based on weather forecasting. According to an evaluation of its performance, out of the 20 automated alerts that have been issued, there was only 1 false alarm (Badoux et al. 2009).

References were also made to the need of implementing LEWS in different parts of the world. For example, in UNESCO cultural and natural World Heritage sites (Monteleone et al. 2016), flanks of active volcanoes, the Swiss Alpine region, and Croatia (Krkač et al. 2015), among others.

An important issue identified through the literature review was landslide disaster management. Thematic interests in this matter included the need to improve community resilience, the need to revise modes of risk governance, urban planning, and landslide insurance, and the need to develop and share new and best practices in the technical-scientific and regulation fields (Plagiara et al. 2017).

4.5 Additional Topics of Concern Related to LEWSs in UMICs

Further to the four lines of research mentioned earlier, the publications addressed topics of huge relevance for society.

When analyzing multi-risk governance for natural hazards, comprising landslides, in Naples and Guadeloupe, Scolobig et al. (2014) concluded that the main weaknesses were focused on the interagency communication and cooperation, and the use and dissemination of scientific knowledge at the time of the development of policies and practices. Nonetheless, warning systems and the assessment of hazards and exposure were considered major strengths.

In the same vein, within the context of mainstreaming multi-risk approaches into Policy, which included LEWS, Scolobig et al. (2017) identified that warning systems provide innovative and effective information, but also involve specific challenges to policymakers and practitioners associated with their transversal disciplinary aspects.

Regarding education, after the experience derived from the induced rainfall debris flow that occurred near Casita volcano, in Nicaragua, in 1998, where around 2000 people died, the term Education for Self-Warning and Evacuation was proposed as part of the mitigation measures (Scott 2000). Similarly, international efforts have been directed to encourage networking among members from specialized institutions and experts of EWS and LEWS. This includes diverse activities of ICL members (Bozzano et al. 2010; Zvelebil et al. 2010; Mikoš 2012; Tofani et al. 2017).

Inspired by a review and their own experience in the design, implementation, management, and verification of geographical LEWSs in Italy, Guzzetti et al. (2020) provided 30 recommendations to further develop and improve such systems and to enhance their reliability and credibility.

By undertaking semi-structured interviews, Lin and Chang (2020) found that local knowledge can improve early warning and build their capacities to respond to disasters. They suggested that local knowledge must be integrated into governmental scientific-based knowledge as a primordial insight for disaster risk management.

As a result of a survey applied in some countries of Europe and Asia, concerning the application and reliability of techniques for landslide site investigation, monitoring, and early warning, it was possible to identify that precipitation amount, pore-water pressure, and displacement monitored by wire extensometers, GPS, and total stations, accompanied by air temperature and EM-emissions monitoring and displacement monitored by crack gauges were considered the most promising parameters for early warning (Baroň and Supper 2013).

LEWS could be traditional when warnings are issued by watchful attendants or based on sophisticated electronic devices. Nonetheless, it is critical that all of them are applied by experts, regional and local authorities, and the population in the understanding that the alert should be transmitted to the people at risk, at the right time and provided accurate planning of emergency measures (Kienholz 2003).

4.6 Scientific International Collaborations

According to the literature review, a total of 725 collaborations were identified among HICs. Italy, the United States of America, and Taiwan are the HICs with the highest number of collaborations with 240, 88, and 49, correspondingly. In these three countries, 52% of the
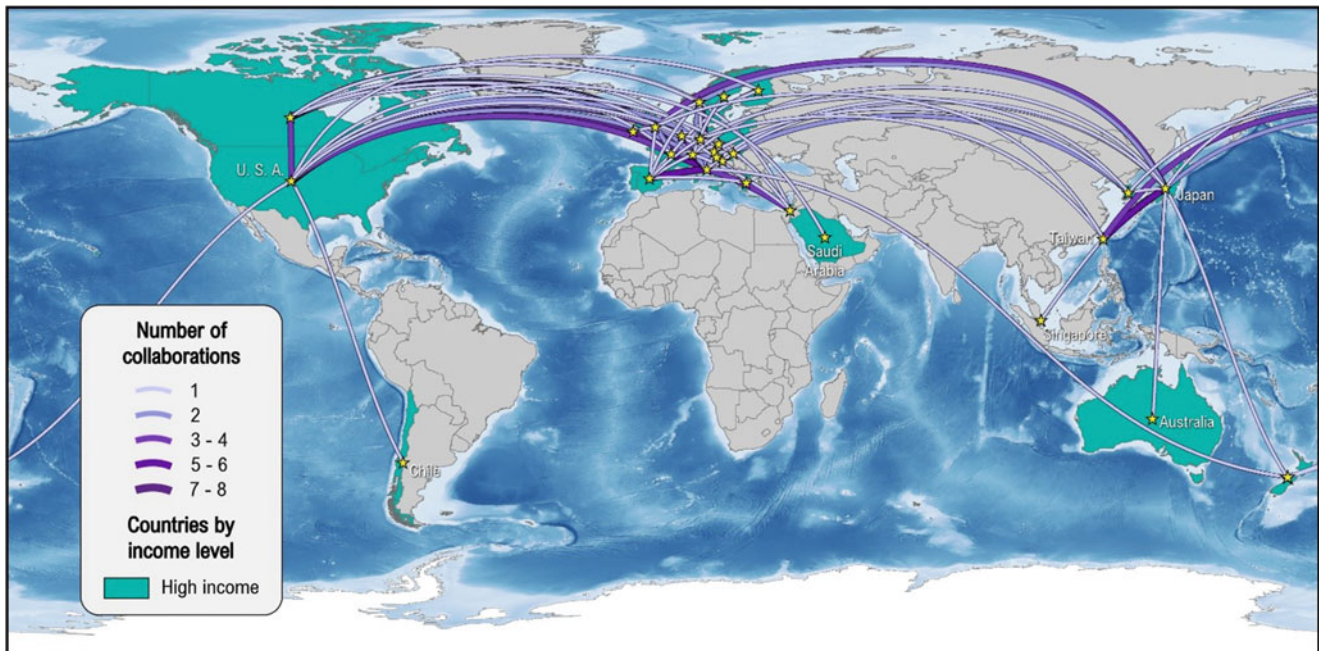
Fig. 10 Regional and international collaborations among HICs and other countries

total collaboration registered is concentrated. They are followed by Switzerland with 45, the United Kingdom with 42, and Germany and Japan with 35 each (Fig. 10).

A third group is formed by Austria (N = 21), Canada (N = 21), France (N = 21), Norway (N = 21), Spain (N = 18), and the Republic of Korea (N = 16). Netherlands (N = 10), Croatia (N = 7), Poland (N = 7), Slovenia (N = 7), Australia (N = 6), and the Czech Republic (N = 5) came after. Other countries also reported a minor number of collaborations (Fig. 10).

Italy and Norway have been collaborating through national and regional forecasting services for rainfall-induced landslides. These services use a combination of quantitative thresholds and daily rainfall forecasts and qualitative expert analysis to provide landslide hazard assessments. This type of collaboration is of significant relevance all the time, particularly when large low-pressure systems affect entire regions (Devoli et al. 2018).

The ICL Landslide Monitoring and Warning Thematic Network represents a productive collaboration among ICL member organizations and ICL supporters from eight countries. The main activity is sharing experiences and practices on monitoring and LEWSs (Mikoš 2012).

An ambitious collaboration reported an attempt to develop a global LEWS induced by rainfall and/or earthquakes. Beyond high-standard scientific models, its implementation will require wide interdisciplinary efforts and multi-agency collaboration (Hong and Adler 2007).

5 Discussion

The role of LEWS in strategies aimed at reducing risk around the world has been more evident in recent years, particularly in HICs.

A series of investigations have been devoted to characterizing the dynamics of landslide hazards, along with the development of new technologies, models, and prototypes to improve the accuracy of the understanding of landslide mechanisms and spatial-temporal predictions.

Key questions to be addressed as expected endeavours for the future concern varied components of implementation. When will the governments support the systematic implementation of LEWSs? How can the current technical dominant architecture of LEWSs be articulated with disaster risk knowledge and the diverse vulnerability dimensions of people at risk? How will the formulation of alliances and partnerships enhance the successful use of LEWSs in areas at risk? Will it be possible to have regional and global LEWSs that can be accessed by all people in the future? How can we strengthen the linkages between LEWSs and education? How can effective LEWS implementation go hand in hand with disaster risk governance?

These key questions are fundamental to advancing the relevance and usefulness of LEWSs as one of the components of Integrated Landslide Disaster Risk Management (ILDRIM) (Alcántara-Ayala 2021).

To accomplish such endeavours, stronger collaboration among disciplines along with wider interaction among the relevant disaster risk reduction stakeholders is necessary. In the same vein, sound strategies for ILDRIM call for multi-sectoral and multi-scale approaches and partnerships.

Future research on LEWSs would also benefit from integrating social and natural science approaches into mixed-method designs. This will allow us to build a holistic understanding of landslide disaster risk and implement LEWS based on risk scenarios, and not just hazard characterization.

6 Concluding Remarks

According to the systematic literature review presented here, there are a series of accomplishments made in the field of LEWSs in HICs.

Innumerable efforts have been made regarding technology development for potential LEWSs, hazard analysis for LEWSs, and models and prototypes for LEWSs. Likewise, implementation of LEWSs has increased and although the number of them is not as high as needed, current efforts show a positive tendency towards their enforcement.

A growing area of research concerning topics associated with the delineation and implementation of LEWS involves perspectives in the medium and short terms to strengthen desired successful warning outcomes for the benefit of societies.

After conducting a literature review of research related to LEWSs we came to three conclusions about the future expected endeavours that can be assigned to the implementation of LEWSs. First, we suggest that LEWSs need to be understood as a component of ILDRIM, but not as its replacement. Second, it is imperative that, at the same time as progress is made in understanding landslide hazards, there is also progress in integrating vulnerability concerns. Third, there is a complex relationship between the implementation of LEWSs and disaster risk governance.

Therefore, while one of the main functions of integrated disaster risk research is to support transdisciplinary processes, the implementation of LEWS requires a strong commitment from the scientific and technological community interested in reducing the risk of slope instability-related disasters to build transdisciplinary alliances and bridges aiming at the co-production of knowledge and mainstreaming integrated disaster risk management into local governments (Kirsch-Wood et al. 2022).

In highlighting research opportunities on the role of LEWSs in disaster risk management, the challenge posed by the Sendai Framework to move from managing disasters to managing disaster risk (UNISDR 2015) from an integrated perspective can be supported.

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