# Review ~~article~~Article: Rainfall-Induced Landslide Early Warning System through the Lens of Early Warnings for All Framework: Advances, Gaps, and Perspectives

**Roquia Salam [1], Bayes Ahmed [1], Peter Sammonds [1]**

[1] Department of Risk and Disaster Reduction (RDR), University College London (UCL), Gower Street, London, WC1E 6BT, UK

*Correspondence to:* Roquia Salam (roquia.salam.22@ucl.ac.uk; roquiasalam@gmail.com)

## Abstract

This review is necessary ~~at this time~~ to provide a comprehensive evaluation of ~~the~~ rainfall-induced landslide early warning systems (LEWS) through the lens of the United Nations 'Early Warnings for All' (EW4All) framework. This study integrates EW4All pillars, ~~incorporates overlooked literature,~~ examines information sharing in academic publications~~,~~ and official websites/portals, and evaluates the global feasibility of implementing EW4All for LEWS. Of ~~61~~ 45 rainfall-induced ~~LEWS~~ systems~~identified in the literature covering 23 countries~~, 27~~14~~ (26 LEWS and one Forecasting-focused system) were ~~are~~ found~~considered~~ operational (benefiting 19 countries), meaning they ~~are~~ were~~currently~~ implemented and actively used for warning purposes when this paper was prepared~~, across only 10 countries~~. Some forecasting-focused systems were misleadingly described as early warning systems. Among ~~local~~Local, ~~regional~~Regional, and ~~national~~ National systems, ~~local~~ Local ~~LEWS~~ systems ~~is~~ were often less scalable and more resource-intensive. Operational systems were mainly National, followed by Regional. Most operational systems ~~target debris flows and shallow landslides and~~ rely~~ied mainly~~ on rainfall thresholds. ~~While~~ S~~s~~ome included susceptibility maps, risk maps ~~are~~ were largely absent. Real-time sensor data ~~are~~ were used in some systems; however, high maintenance costs limited scalability. Reliability ~~is~~ was further constrained by data scarcity, limited forecast verification, and suboptimal use of Artificial Intelligence~~, and the lack of standardised forecasting approaches~~. Community engagement was infrequently documented in the reviewed systems.~~Community engagement and multi-hazard integration remain limited.~~ Although EW4All is transformative, implementing effective LEWS ~~in~~ across rainfall-induced landslide-prone areas worldwide by 2027 remains impractical without localised approaches, sufficient ~~funds~~funding, community engagement, and enhanced institutional capacity~~resources~~.

**Keywords:** Rainfall-induced landslides early warning system, early warning for all, rainfall threshold, risk map, community reflection



**Formatted:** Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Width: 21 cm, Height: 29.7 cm
**Formatted:** Font: (Default) Arial, Font color: Text 1
**Formatted:** Font: (Default) Arial, Font color: Text 1
**Formatted:** Font: (Default) Arial, Font color: Text 1
**Formatted:** Font: (Default) Arial, Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Font color: Text 1

# 1 Introduction

## 1.1 The early warning for all (EW4All) framework

Several initiatives have been undertaken since 1989 to develop ~~an~~ effective early warning system(s) (EWS), with the ~~aiming to minimise~~aim of minimising human suffering and disruption (Fig. 1). The first global ~~initial~~ effort ~~for~~ towards disaster risk reduction (DRR) began in 1989, when the UN declared the 'International Decade for Natural Disaster Reduction' (IDNDR) (1989–1999) to enhance DRR activities.

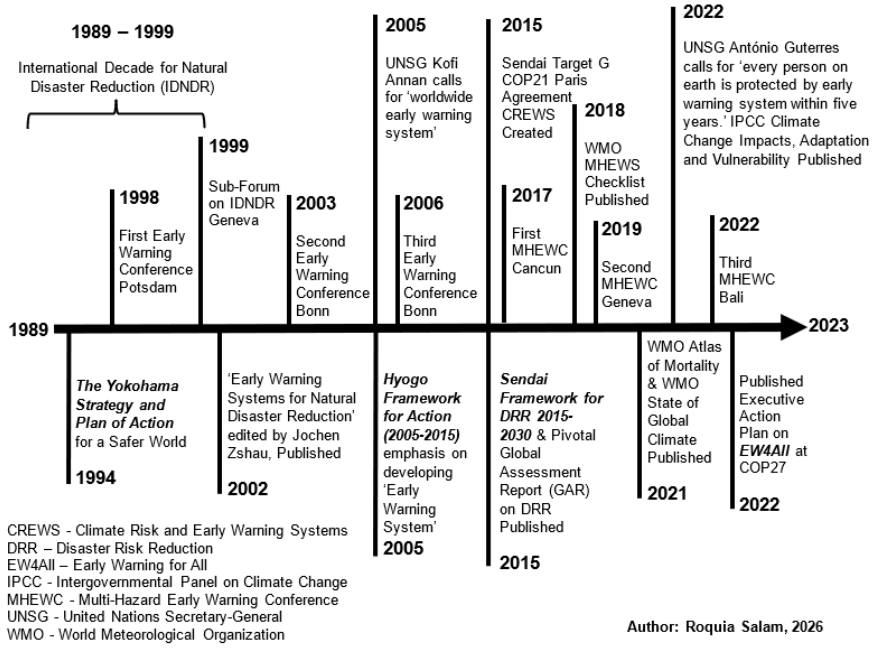



**Figure 1:** A brief history of ~~event~~events, ~~publication~~publications, ~~and announcement~~announcements, and other milestones in the development of early warning systems from 1989 to the present day [Figure modified after UN (2023)].

~~Within~~ During the IDNDR, the first landmark ~~guidance and~~ international guidance and framework for DRR, the 'Yokohama Strategy and Plan of Action for a Safer World' was launched in 1994. Under the principles of this framework, early warning (EW) was identified as a key factor in effective disaster prevention and preparedness activities (UNISDR, 1994). However, EW was still a nascent concept ~~in~~ within this framework, ~~that~~ which lacked a detailed and clearly defined mechanism ~~of~~ for EWS implementation (UNISDR, 2005). The tragic catastrophe of the Indian Ocean t~~T~~sunami in December 2004, which killed more than 230,000 people around the Indian Ocean (Lay, 2012), made the international DRR community realise that ~~an~~ EWS could save thousands of lives (UNISDR, 2006). ~~Therefore~~Consequently, soon after ~~this~~ the tsunami, the first global blueprint for DRR, the 'Hyogo Framework for Action (HFA) 2005–2015', was adopted in January 2005 by the global DRR community.

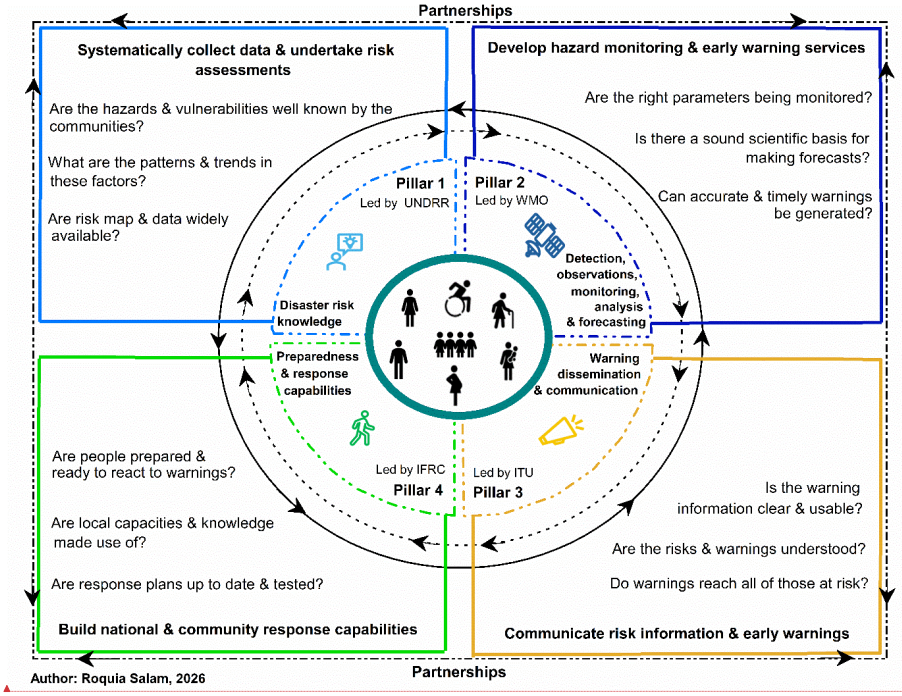



**Figure 2**: UN defined four pillars of the people-centred multi-hazards EW4All framework~~s~~ [Figure slightly modified after UN (2023)].

Among the ~~5~~ five priorities for action, ~~p~~Priority ~~number~~ ~~2~~ two was 'identify, assess and monitor disaster risks and enhance early warning', ~~where~~ with an emphasis on developing an EWS ~~was emphasised~~ (UNISDR, 2005). However, several limitations were identified (UNISDR, 2015), such as the HFA emphasising the development of~~ing~~ sector-specific (single-hazard) rather than integrated (multi-hazard) EWS.

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

~~Besides~~Furthermore, the engagement of all sectors (e.g., public, private, civil, academia, and scientific) was not ensured. Moreover, the HFA lacked a people-centred EWS. ~~Furthermore, the~~The HFA also treated the EWS as a siloed system (which was not ~~exclusively~~ explicitly incorporated into disaster risk management plans and policies~~y~~) that limits its effectiveness in ~~tackling~~ addressing the causal (e.g., climate change, and unplanned urbanisation) and compounding (e.g., demographic change, and poor institutional capacity) factors of disaster risk~~s~~. Additionally, the small island developing countries (SIDs), least developed countries (LDCs), and landlocked developing countries (LLDCs) ~~were~~ faci~~ng~~ ed multifaceted ~~issues~~ challenges in ~~arranging~~ securing financial, technical, and institutional resources. These limitations of the HFA led to the adoption of a more comprehensive framework for DRR, the 'Sendai Framework for Disaster Risk Reduction (2015–2030)', in 2015 (UNISDR, 2015). While people-centred multi-hazard EWS (MHEWS) ~~is~~ are ~~focused on~~emphasised in the Sendai Framework under Target G, the implementation of MHEWS ~~was~~ has remained slow and uneven under this policy framework. In 2022, it was reported that fewer than half of the countries worldwide ~~less than half of the countries in the world~~ lacked ~~proper~~ MHEWS coverage (UNDRR and WMO, 2022). Therefore, a more targeted initiative to accelerate the operationalisation of the MHEWS ~~under the priorities of~~in line with Target G ~~has been~~was launched in 2022, ~~which is called~~known as ~~early warning~~Early Warnings for ~~all~~ All (EW4All) (UN, 2023).

EW4All is a groundbreaking initiative, and its main objective is to ensure that by the end of 2027, every human being on ~~this~~ the planet is ~~safeguarded~~ protected from ~~any form of~~ hazardous weather, water, ~~or~~ and climate events through timely ~~alerts~~ warnings provided by ~~from~~ EWS.

The EW4All initiative has three main targets, ~~which are~~as follows (UN, 2023):

- **i.** global coverage,
- **ii.** multi-hazard impact-based EWS, and
- **iii.** people-centred EWS.

Although EWS exist in some parts of the world, global coverage of these systems ~~is~~ has not yet been ensured (UN, 2023). Some parts of the world ~~are fully deprived of~~remain without adequate EWS coverage, ~~such as in~~particularly LDCs and SIDs, ~~and it is the worst~~with the situation being most severe in Africa (Guterres, 2022). Fig. 2 portrays the UN-defined framework of ~~the~~ people-centred multi-hazard~~s~~ early warning systems (MHEWS) for all (EW4All), ~~with~~ comprising four pillars. Several organisations contribute~~d~~ to leading each pillar. EW4All has four pillars, ~~which are~~ as follows (UN, 2023):

Pillar 1: Disaster risk knowledge: Systematically collect data and undertake risk assessments.

Pillar 2: Detection, observation, monitoring, analysis, and forecasting: Develop hazard monitoring and early warning services.

Pillar 3: Warning dissemination and communication: Communicate risk information and early warnings.

Pillar 4: Preparedness and response capabilities: Build national and community response capabilities.

### 1.2 The necessity of the early warning system

Since the United Nations (UN) initiated systematic efforts ~~for~~ towards DRR activities in 1989, significant progress has been made (UN, 2023). ~~People are now more aware of when and how to deal with harsh environments than they were before. However, there is barely a single week when no devastating hazards or disasters responsible for catastrophic impacts are broadcast or reported.~~ However, increasing concentrations ~~Due to the increase~~ of human-induced greenhouse gases in the atmosphere have disrupted climatic and ~~that imbalances the~~ meteorological ~~cycle~~processes, contributing to increases in the intensity and frequency of extreme climate-related~~the intensity and frequency of extreme climatic~~ events (e.g., floods, landslides, droughts, cyclones, heatwaves, and ~~so on~~others), which are expected to intensify ~~have increased over the period, and are expected to grow~~ further (Lee et al., 2023). As the frequency of climatic extremes increases over time (Fig. 3), so does the number of people affected ~~people~~. Numerous adverse~~Countless~~ impacts, including death, injury, property damage, and loss of livelihoods, are recorded every day. Moreover~~Besides~~, the environment is severely ~~impacted~~affected, creating conditions that may further exacerbate the risks associated with subsequent ~~which makes the situation favourable for escalating the risks arising from further~~ hazards. These extreme events may be associated ~~are correlated~~ with ~~one~~ single or multiple hazards, thereby creating ~~giving them a~~ multi-hazard risk ~~status~~. ~~It~~ This means that two or more hazardous events may occur in an area simultaneously (e.g., flash floods and landslides), or cumulatively (e.g., recurrent flash flooding~~s~~), or sequentially (e.g., tropical storms and landslides), resulting in ~~responsible for a higher degree of~~ disproportionately severe~~disastrous~~ impacts on people and ~~their~~ property ~~on the earth~~ (Lee et al., 2024).

Formatted: Font color: Text 1

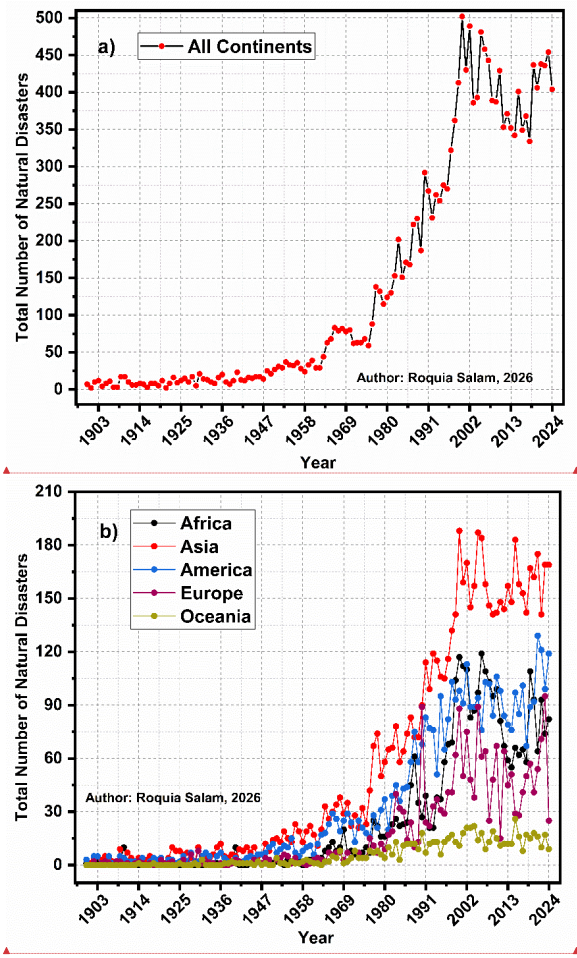



**Figure 3:** Temporal trends ~~of~~ in the total number of natural disasters between 1900 and 2024, a) cumulative trend ~~including~~ across all continents, and b) continent-specific trends (Data source: EM-DAT).

It is very challenging to reduce or avoid hazards completely; however, a recognised way to reduce their potential impacts is to ensure that people have access to EWS and, therefore, the opportunity to take appropriate anticipatory action before a hazardous event occurs~~have the opportunity to take some beneficial anticipatory action ahead of the hazards' occurrence~~. More specifically, ~~an~~ an EWS is "an integrated system of hazard monitoring, forecasting, and prediction, disaster risk assessment, communication, and preparedness activities systems and processes that enables individuals, communities, governments, businesses, and others to take timely action to reduce disaster risks in advance of hazardous events" (UNDRR, 2017).

Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font color: Text 1

Some affected people have access to timely warnings through EWS, allowing them to prepare for upcoming events.

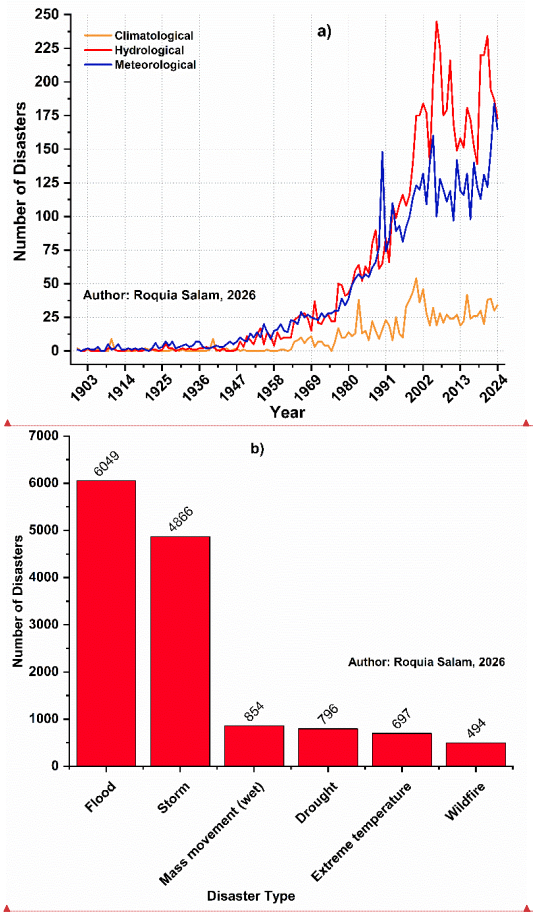



**Figure 4:** a) Temporal trends ~~of~~ in the total number of climatological, hydrological, and meteorological disasters and b) ~~specific~~ individual disasters ~~by~~ types between 1900 and 2024 (Data source: EM-DAT).

MoreoverBesides, rapid urbanisation has forced people in low- and middle-income ~~nations~~ countries to reside in vulnerable and hazardous ~~land~~ areas, ~~like~~ such as industrial areas, unstable slopes, and floodplains (Ozturk et al., 2022). These people are often economically marginalised, and ~~struggling~~ struggle to afford homes in safer and more stable areas due to higher land prices. As displacement ~~is increasing~~increases, more and more people are migrating to urban areas, often settling ~~ending up~~ in these vulnerable and hazardous ~~land areas~~locations. This contributes ~~These lead~~ to a rapid increase in informal settlements characterised by~~with~~

Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font color: Text 1

low-quality housing materials, unstable political governance (Werthmann et al., 2024), and inadequate ~~numbers of~~ road networks~~s~~, drainage facilities, and other essential infrastructure. Therefore, ~~in times of an~~during emergenciesy~~s~~, people ~~who are~~ living in such areas are often unable to evacuate safely, increasing the potential for disastrous consequences~~leading to a disaster~~. EWS are therefore particularly important for these communities to minimise potential~~is badly needed for these people to minimise their overall~~ loss and damage.

However, one-third of the world's population, especially those living in ~~from the~~ LDCs ~~as well as~~and SIDS, does not have access to timely ~~or proper~~and effective EWS ~~to~~ that would enable ~~themselves~~ them to prepare for ~~the~~ upcoming hazardous events, resulting in increased loss and damage ~~leading to an accelerated loss, which is unacceptable~~ (UN, 2023). Hence, there is a need ~~to have~~for ~~an~~ EWS that ~~must be~~can provide and ~~disseminated to alert~~disseminate timely warnings to all local ~~people~~ communities~~on time~~, enabling them to take appropriate action ~~act properly~~ to reduce the impacts.

### 1.3 Why are rainfall-induced landslides a concern?

A significant upward trend is observed in the occurrence of hydrological disasters (Fig. 4a), and hydrological disasters account for about 90% globally (Perera et al., 2019). Among these, rainfall-induced landslides (mass movement - wet) are identified as the third most common hydrological disaster globally (Fig. 4b). Recent studies ~~showed~~ have shown that human activities ~~like~~ such as construction, illegal hill cutting, and mining, largely associated with ~~activities mainly for~~ urbanisation, are increasingly ~~driving~~ contributing to fatal landslides ~~nowadays~~ (Alcántara-Ayala, 2025; Ozturk et al., 2022; Froude and Petley, 2018; Petley, 2009). Between 1998 and 2017, an estimated 4.8 million people were affected by landslides, resulting in more than 18,000 ~~human~~ deaths (WHO, 2025). Therefore, the combined effects of ~~the greenhouse~~climate ~~effect~~ change and rapid urban ~~sprawl~~ expansion are expected to increase landslide risk~~s~~ globally, leaving ~~a huge~~large number~~s~~ of people residing in informal settlements at higher risk (Werthmann et al., 2024; Ozturk et al., 2022). Despite their prevalence and significant social, economic, and environmental impacts, rainfall-induced landslides frequently receive less attention than more visibly catastrophic events such as floods, tsunamis, volcanic eruptions~~oes~~, and earthquakes (Guzzetti, 2021).

According to Varnes (1978), 'landslide is the downslope movement of soil, rock, and organic materials under the effects of gravity, which occurs when the gravitational driving forces exceed the frictional resistance of the material resisting on the slope'. Depending on the type of material~~s~~ involved in the movement, landslides are classified into six major categories as follows: flow, fall, topple, spread, slide, and complex (Varnes, 1978). Global inventories of fatal landslides covering 1995–2014 (Haque et al., 2019) and 2004–2016 (Froude and Petley, 2018) demonstrate a strong association between rainfall and fatal landslide occurrence. Froude and Petley (2018) reported that 79% of non-seismic fatal landslide events were triggered by rainfall, while Haque et al. (2019) found that more than half of the recorded deadly landslide events occurred

Formatted: Font color: Text 1

in areas exposed to extreme rainfall. ~~Among them, most of the landslides (88%) are rainfall-triggered (Haque et al., 2019; Froude and Petley, 2018).~~ The Intergovernmental Panel on Climate Change (IPCC) has reported that increased concentrations of greenhouse gases in the atmosphere are ~~disturbing~~disrupting the global water cycle and, subsequently, intensifying ~~the unevenly distributed~~ extreme rainfall events that are unevenly distributed across the globe (Seneviratne et al., 2021). Extreme rainfall events cause slopes to become ~~over~~saturated with water~~.~~ ~~Therefore~~, increasing pore water pressure ~~increases,~~ ~~leading to~~and reducing slope ~~instability~~stability, ~~and finally,~~which may ultimately lead to slope failure ~~occurs~~. Landslides usually occur ~~close to the~~near weak points in slopes, such as joints, cracks, drainage channels, and fault lines, of the slopes. ~~First~~ Initial failures usually occur at these weak points, often triggered by factors such as rainfall, and unplanned urbanisation, ~~and others,~~ contributes to ~~which are responsible for~~ slope destabilisation. Such initial failures may further destabilise the slope, increasing its susceptibility to subsequent ~~Thus, the occurrence of the second failure accelerates and renders the area more susceptible to further~~ landslides. This process can create ~~Therefore,~~ a feedback loop in which successive failures further weaken the slope and potentially contribute to ~~is created that triggers~~ additional and larger landslides in that area.

Landslide risk is associated with the interaction between exposure, hazard, and vulnerability. When an external hazard factor, ~~like~~ such as rainfall, is coupled with high exposure in vulnerable areas, it can ~~results~~ result in ~~varying degrees of~~ landslides of varying severity. Therefore, the current ~~growing~~ expansion of urban ~~sprawl~~ areas into vulnerable ~~areas~~ locations amplifies ~~the risks of landslides~~landslide risk in the absence of an adequate EWS. Landslides are often associated with compound or cascading ~~hazard~~ hazards ~~to~~ involving floods and storms; they ~~have~~ also present specific challenges, particularly ~~around~~ in relation to uncertainties, forecasting, communication, and governance. These challenges are further complicated by the fact ~~, which are made additionally challenging given~~ that 'landslides' is an umbrella term encompassing multiple landslide types, each posing its own challenges in the EW4All context. Although EWS ~~is~~ have proven effective in ~~mitigating~~ reducing disaster impacts~~s~~, the application of ~~the~~ rainfall-induced landslide early warning system(s) (LEWS) remains geographically limited and fragmented (Guzzetti et al., 2020). ~~B~~Moreover~~esides~~, rainfall-induced LEWS are not always ~~successful due to~~effective for several reasons, ~~like~~ including the absence of risk-based mapping and community ~~reflection~~engagement, a lack of impact-based forecasting, and the absence of anticipatory action plans. Existing literature on LEWS provides information on rainfall thresholds, monitoring approaches, statistical modelling, and spatial scales. These contributions largely focus on forecasting. In particular, less attention has been given to operational and governance dimensions, including institutional responsibility, warning dissemination, community preparedness, response capacity, and implementation feasibility. Therefore, adopting the EW4All framework allows this review to reinterpret existing LEWS studies beyond technical performance and to assess the extent to which they address the wider requirements of effective early

warning. An effective LEWS can contribute significantly to reducing potential loss and damage from rainfall-induced landslides; however, its effectiveness depends on wider risk reduction measures, including land-use planning, governance structures, exposure reduction, vulnerability reduction, and preparedness planning. ~~Only an effective LWES can mitigate the overall potential loss and damage arising from rainfall-induced landslides.~~

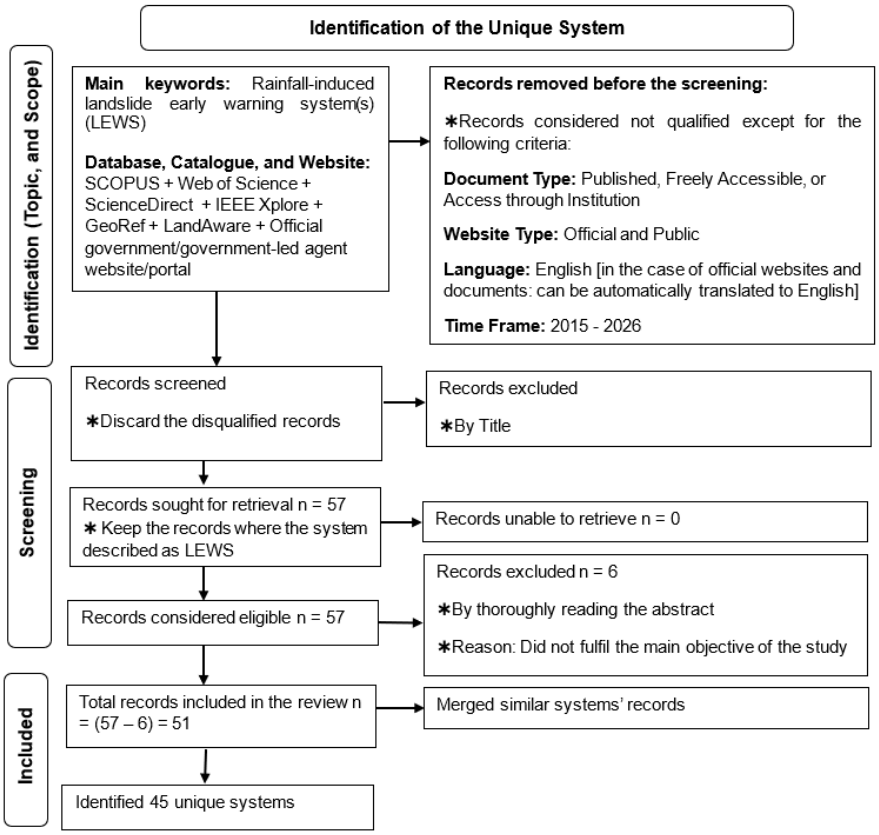
### 1.4 Novelty and originality

This study advances research on rainfall-induced LEWS by explicitly reframing the field ~~through~~ within the United Nations EW4All framework. Although previous reviews have compared LEWS across local, regional, and national scales, they have generally focused on specific technical dimensions, such as thresholds, scale, or modelling approaches (Piciullo et al., 2018; Guzzetti et al., 2020). The distinct contribution of this review lies in its integrative and evaluative perspective, which considers LEWS through the EW4All pillars and assesses their implications for implementation. Rather than merely compiling published LEWS studies, this review reinterprets them through the operational and governance dimensions of EW4All, including institutional responsibility, warning dissemination, preparedness, response capability, and implementation feasibility. In addition, this review ~~incorporates relevant literature not considered in earlier syntheses, broadening the evidence base used to evaluate current practice. It also~~ examines the extent to which LEWS-related information is shared in academic publications. Finally, it evaluates the feasibility of applying the EW4All framework, in its current form, to the development of LEWS ~~development~~ worldwide. The novelty does not lie in identifying each individual technical or operational limitation for the first time; rather, it lies in examining how these established limitations interact across the complete warning chain represented by the EW4All framework.

Accordingly, the core objectives of this study are two-fold: first, to identify the main challenges and areas requiring improvement in the development ~~for~~ of rainfall-induced LEWS ~~development~~ through the EW4All lens; and second, to assess the feasibility of applying the EW4All framework to the development of rainfall-induced ~~LEWS development globally~~LEWS globally.

**Formatted:** Font color: Text 1

## 2 Selection process of the ~~articles~~ system for the systematic literature review




~~This literature review is mainly systematically conducted, as some criteria must be maintained. As the PRISMA 2020 methodology provides a standardised framework for identifying, screening, and selecting relevant studies, it has been adopted in this study for selecting the relevant articles (Fig. 5). Articles have been collected from six databases: SCOPUS, Web of Science (WoS), ScienceDirect, PubMed, the Institute of Electrical and Electronics Engineers (IEEE), and grey literature sources (e.g., ResearchGate, national websites).~~

**Formatted:** Font color: Text 1

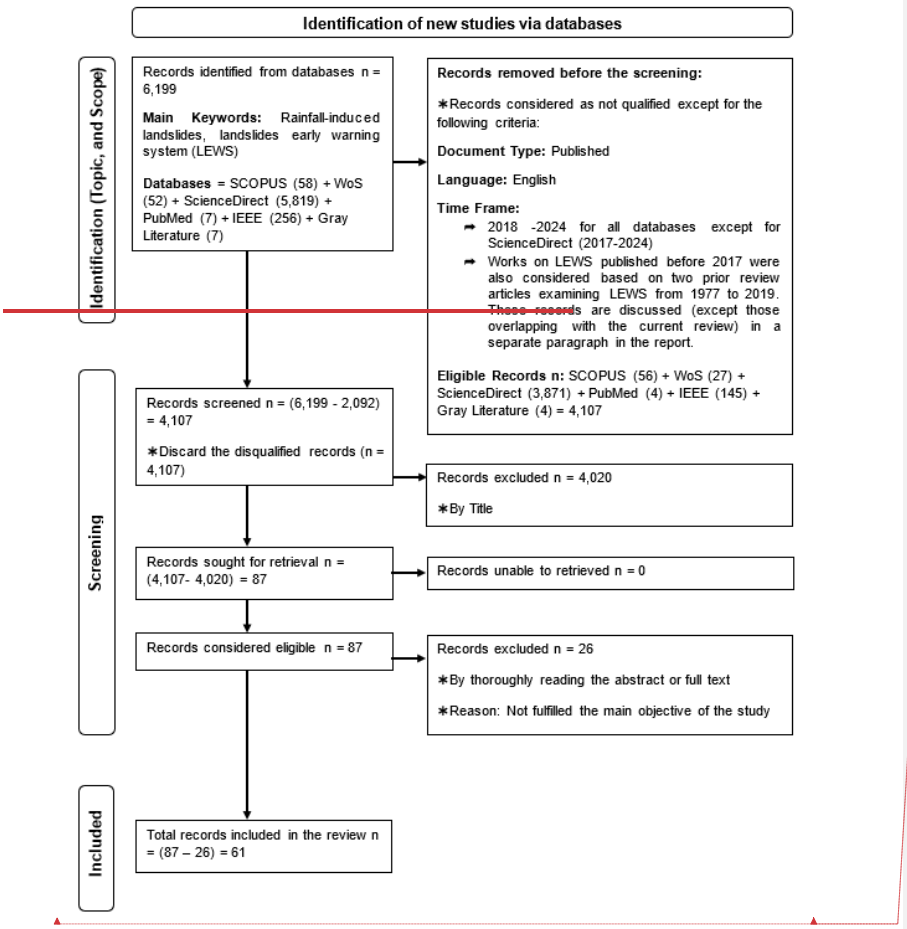



**Figure 5**: In alignment with PRISMA 2020 methodology, the selection process was used to identify unique systems for inclusion in the literature review. ~~In alignment with the methodology of PRISMA 2020, the selection process was used to select the articles for the literature review on LEWS.~~

This literature review ~~is mainly systematically conducted~~was conducted systematically, following predefined selection ~~as some~~ criteria ~~must be maintained~~. As the PRISMA 2020 methodology provides a standardised framework for identifying, screening, and selecting relevant studies, it ~~has been~~was adopted in this study ~~for~~to select~~ing the~~ relevant articles and websites (Fig. 5). Articles ~~have been~~were ~~collected~~retrieved from ~~six~~five databases: S~~COPUS~~copus, Web of Science ~~(WoS)~~, ScienceDirect, ~~PubMed~~GeoRef, and~~,~~ the Institute of Electrical and Electronics Engineers (IEEE) Xplore~~, and grey literature sources (e.g., ResearchGate, national websites)~~. The

Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font color: Text 1

LandAware catalogue, together with official government and agency websites/portals, was used to supplement the literature records. This supplementary grey-literature search was conducted in a targeted manner. These sources were used to verify the operational status of each system, collect evidence to inform the assessment of Pillars 3 and 4, and identify operational LEWS that were not captured in the filtered literature. Only publicly available supplementary information meeting the defined language (English) criteria was utilised.

There is a clear distinction~~difference~~ between 'forecasting' and an 'early warning system'. Forecasting is an integral ~~part~~ component of EWS. ~~Forecasting~~ Forecasting is a definite statement or statistical estimate of the likely occurrence of a future event or conditions for a specific area (UNISDR, 2009)~~the prediction (e.g., upcoming hazards) of the near future (up to a few days)~~. However, EWS ~~is~~ is an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities, systems and processes that enables stakeholders to take timely action to reduce disaster risk before hazardous events occur (UNDRR, 2017)~~the dissemination of this forecast information to the right people at the right time with an understandable message so that the people can take appropriate actions to avoid unwanted impacts~~. In the~~ journal~~ published literature~~articles~~, many authors ~~frequently~~ have used the term 'EWS' to ~~explain~~ describe their work, although they ~~only~~ discussed only ~~up to~~ the forecasting ~~part~~component. This review paper considers both articles ~~where~~ in which LEWS (all pillars of landslide EWS were present) and ~~the forecasting~~forecasting-focused systems (only those where the systems were described as LEWS) ~~of landslides are~~were discussed. Therefore, the term 'system' is used throughout this review to encompass records of both LEWS and forecasting-focused systems. A system classified as LEWS had evidence, from publications, official websites, portals, or blogs, of a complete EWS chain. A system classified as forecasting-focused lacked evidence of a complete EWS chain.

The ~~keywords~~search term used to search for the potential ~~articles~~ records ~~are~~ was 'Rainfall-induced landslide~~s', and 'landslides~~ early warning systems.' ~~Where needed, the Boolean search query is used with the following query: '(landslide* AND (early warning OR forecasting) AND (real time OR "real time") AND "rainfall induced")'.~~ Landslides can also be triggered by ~~occur from~~ earthquakes ~~as well~~. However, ~~there is no widely agreed-upon, reliable, and near-accurate system for forecasting earthquakes so far (Jarah et al., 2023). So, LEWS for earthquake induced landslides is not that reliable~~this review focused exclusively on rainfall-induced landslides.~~.~~ Therefore, systems addressing~~in this article selection process,~~ earthquake-induced landslides ~~LEWS is~~ were excluded during the selection process.~~.~~

~~After searching for potential articles using the mentioned keywords and query, a number of articles were found (a total of 6,199) in each database, such as 58 in SCOPUS, 52 in WoS, 5,819 in ScienceDirect, seven in PubMed, 256 in IEEE, and~~

~~seven in grey literature. At this stage, several criteria were followed to select the articles, which are the documents that should be published, be written in English, and the time of publication between 2018 and 2024 (except for ScienceDirect, where the time frame applied between 2017 and 2024). This is because some articles related to LEWS found in ScienceDirect and published in 2017 are not featured in the existing review papers.~~

Systems discussed in articles published between 2015 and 2026 were considered for this study. Therefore, systems with no relevant publication during this period were not included in the main dataset. This may have excluded some older but still operational systems. This approach enabled the review to focus on current published evidence, recent methodological and operational challenges, and the gap between what is reported in recent literature and what is required for a complete EW4All-aligned LEWS. ~~There are two review articles where LEWS that cover the time between 1977 and 2019, are discussed (Piciullo et al., 2018; Guzzetti et al., 2020). These articles are not completely excluded from discussion in this study. However, these are not included in this article selection process and are discussed in a separate section after getting the overall idea from the published review articles.~~

Next, the~~ article~~ screening process was initiated. After applying all the ~~above-mentioned~~ criteria specified in Fig. 5 and scrutinising the titles of the articles, documents, and websites, ~~, the total number of articles from all databases was 4,105~~7 records remained. ~~Then, after scrutinising the titles of the articles, 4,020 articles were eliminated from the list. Next, out of~~Of these ~~87~~ 57 ~~articles~~records, ~~26~~six were subsequently excluded ~~as~~ because they did not meet the main objective of this study. ~~The final inclusion and exclusion were conducted by reading the abstracts of the 87 articles, and if the main objectives were unclear from the abstract, the full texts were read.~~ Finally, ~~61~~ 51 ~~articles~~ system records ~~have been~~were selected ~~for the literature review on LEWS~~. Among these ~~61~~ 51 ~~articles~~records, ~~there~~ multiple ~~are some LEWS developed for the same area~~records describing the same system were merged. After this consolidation, a total of 45 unique systems were identified. ~~However, the authors have used different methods and techniques to develop the LEWS. So, all of them are considered for this review.~~

For each unique system, a structured data-extraction protocol was used to extract information on country; locality; areal coverage; system scale (National, Regional, or Local); system type (LEWS or Forecasting-focused); operational evidence; strength of the evidence (High or Moderate); Pillar 1 (P1) assignment source, Pillar 2 (P2) assignment source, Pillar 3 (P3) assignment source, and Pillar 4 (P4) assignment source; source of the pillar assignments; and references (Appendix I). 'High' strength was assigned where explicit information was provided in the relevant articles or official websites/portals. 'Moderate' strength was assigned where explicit information was not found in the relevant articles or official websites/portals. 'Operational' status was assigned to systems for which current routine warning dissemination was demonstrated, either in published literature or supplementary official blogs, portals, or

websites. ‘Non-operational’ status was assigned to systems for which current routine warning dissemination was not demonstrated. This category included systems that were designed, prototyped, experimentally tested, validated, or recommended for future implementation. Systems designed to monitor and disseminate warnings for a specific slope, site, catchment, or settlement were defined as ‘Local’. Systems designed to monitor and disseminate warnings for a subnational area, such as a municipality, city, district, province, or region, were defined as ‘Regional’. Systems designed to monitor and disseminate warnings for multiple landslide-prone regions or municipalities, or for an entire country, were defined as ‘National’.

In addition to technical and methodological considerations, LEWS development is strongly influenced by institutional ownership and operational responsibility. In many contexts, geological surveys or comparable technical agencies may lack either the continuous operational capacity required for warning services or the formal mandate to issue warnings. Consequently, LEWS may emerge through community-led initiatives or be developed by sector-specific actors, such as transport agencies, that face recurrent ~~landslide~~ disruption from landslides. These forms of locally embedded practice are often insufficiently captured in academic publications~~, yet they~~. Yet, they are directly relevant to EW4All, whose implementation framework ~~emphasizes~~ emphasises social inclusion, local engagement, and people-centred warning systems.

## 3 Results and Discussion

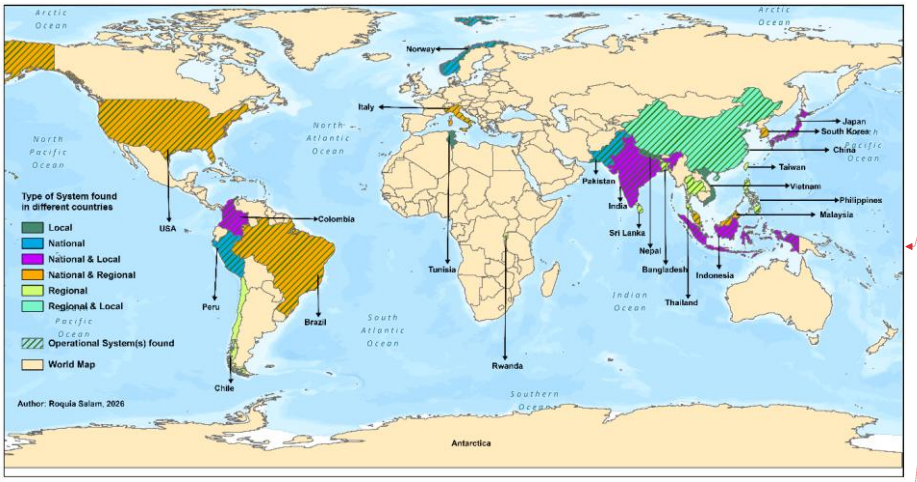



**Figure 6:** Geographical distribution and type of system identified from the selected 45 systems.

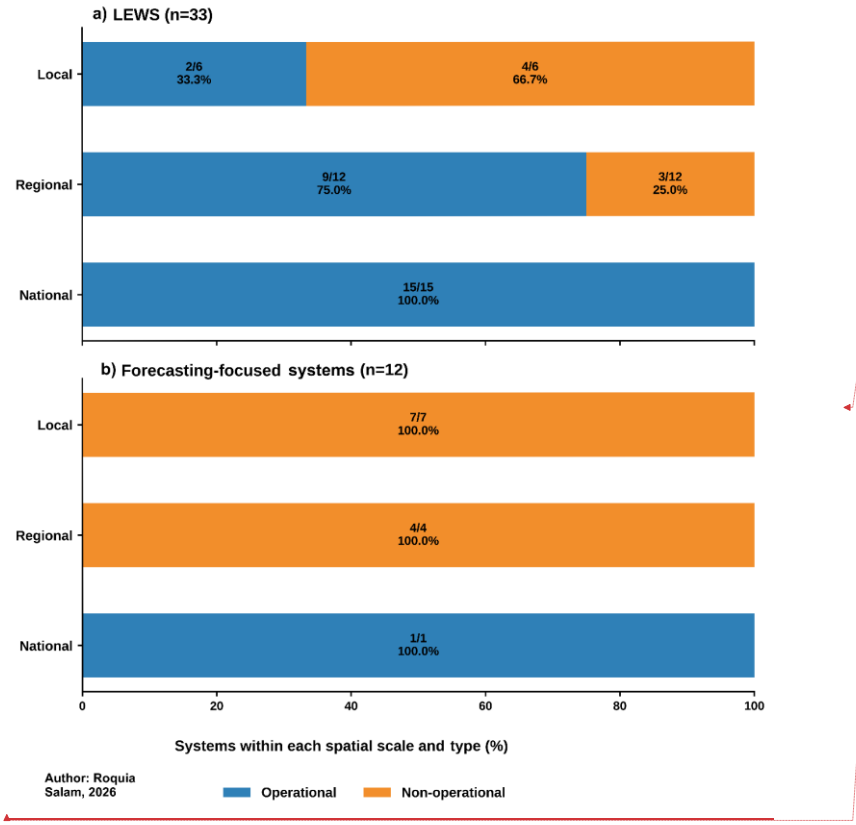
The information on the 45 ~~LEWS~~ systems presented in this section ~~is~~ was derived exclusively from the referenced publications, websites, portals, and official blogs. Only details explicitly reported and supported by evidence from these supplementary sources ~~by the authors a~~were included. Where relevant information was not



Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Centered
Formatted: Font: (Default) Arial, Bold, Font color: Text 1
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Normal
Formatted: Font: Not Bold
Formatted: Font color: Text 1
Formatted: Normal, Justified

~~included~~found, it was treated as ~~not included~~ not reported for that ~~LEWS~~ system in this analysis. Furthermore, because the study selection process involved several filtering stages, some potentially relevant publications may have been~~were~~ excluded. As a result, the plots and associated discussion may reflect some degree of missing or incomplete information. This limitation highlights an important aspect of global comparison. Some studies described technical forecasting methods in detail, while others provided limited information on institutional mandates, warning dissemination, preparedness actions, operational status, or community engagement. For this reason, comparisons among systems developed across different countries and scales may partly reflect differences in reporting practices, rather than solely differences in the actual performance or maturity of the systems.

## 43.1 Pillar 1: Landslide risk knowledge




## ~~Geographical distribution and the type of the selected LEWS~~

~~The selected articles discussed LEWS covering 23 countries worldwide (Table 1 and Fig. 6). Among 61 publications, the majority (42) discuss LEWS of Asia. Fig. 6 depicts the geographical distribution and the type of LEWS. There are three types of LEWS:~~

Formatted: Font: Not Bold, Italic

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Centered

Formatted: Font color: Text 1

national, regional, and local. More than one type of LEWS is found in six countries (China, Colombia, India, Italy, Norway, and Spain). All types of LEWS, national, regional, and local found in two countries, Italy and Norway. Regional and local LEWS are found in four countries: China, Colombia, India, and Spain. In Indonesia, national and local LEWS were found. The rest of the countries have a single type of LEWS.

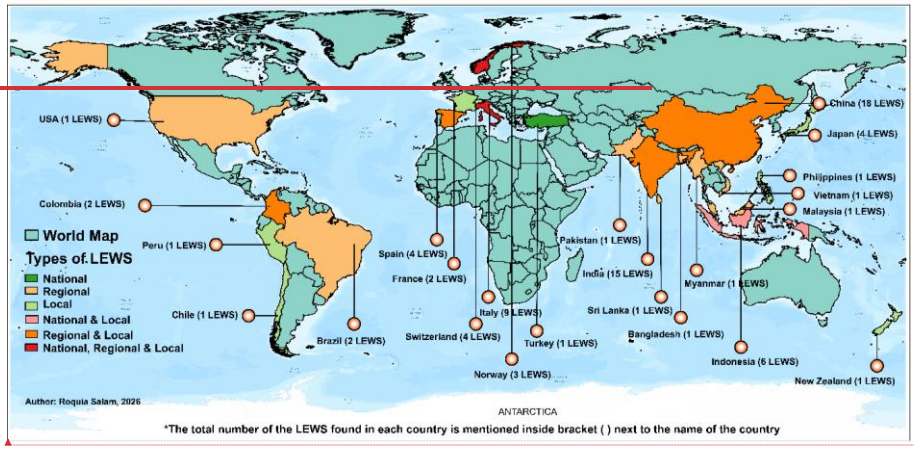



**Figure 6**: Geographical distribution and the type of LEWS found in the referenced publications.

**Table 1**: Published studies reviewed for rainfall-induced LEWS, with study location, assigned code (not mentioned in the publication), and EW4All pillars addressed in each publication

| ID | Location/Region | Country | Code | EW4All Pillars | Reference |
|---|---|---|---|---|---|
| 1 | Cox's Bazar | Bangladesh | BD | 1, 2, 3, 4 | Ahmed et al., (2020) |
| 2 | Blumenau, Petrópolis, and Nova Friburgo | Brazil | BR1 | 1, 2, 3 | Andrade et al., (2023) |
| 3 | Guaruja and Recife cities | Brazil | BR2 | 1, 2 | Sousa et al., (2023) |
| 4 | Wangmiao | China | CN1 | 1, 2 | Li et al., (2017) |
| 5 | Yunyang County | China | CN2 | 1, 2 | Guo et al., (2019) |
| 6 | Sichuan and Heifangtai area of Gansu Provinces | China | CN3 | 1, 2 | Dai et al., (2020) |
| 7 | No info | China | CN4 | 1, 2 | Wang. (2020) |
| 8 | Bazhou district | China | CN5 | 1, 2 | Li et al., (2020) |
| 9 | Tibetan Bank of the Jinsha River at the junction of Baige Village, Boro Township, Jiangda County, Tibet Autonomous Region, and Zeba Village, Ronggai Township, Baiyu County, Sichuan Province | China | CN6 | 1, 2 | Wu et al., (2020) |
| 10 | Southwest China | China | CN7 | 1, 2 | Ju et al., (2020) |
| 11 | Loess Plateau | China | CN8 | 1, 2, 3, 4 | Xu et al., (2020) |
| 12 | Quanzhou city, Fujian Province | China | CN9 | 1, 2 | Liu et al., (2021) |
| 13 | Zizhou County, Yulin City, Shaanxi Province | China | CN10 | 1, 2 | Yang et al., (2021) |
| 14 | Nanping city, Fujian Province | China | CN11 | 1, 2 | Cao et al., (2022) |
| 15 | Huaihua City, Hunan Province | China | CN12 | 1, 2 | Liu et al., (2023) |
| 16 | Chongqing | China | CN13 | 1, 2 | Liu et al., (2024) |

**Formatted:** Font: (Default) Arial, Font color: Text 1

**Formatted:** Font: (Default) Arial, Font color: Text 1

**Formatted:** Centered, Line spacing: Multiple 1.15 li

**Formatted:** Font color: Text 1

| ID | Location/Region | Country | Code | EW4All Pillars | Reference |
|---|---|---|---|---|---|
| 17 | No info | China, Chile, Japan | ML1 | 1, 2 | Du et al., (2023) |
| 18 | Puigcercós, Nevis Bluff, Bomba site, Otomura, Ca' Lita, Kunimi, Xintan, Masseria Marino, Preonzo, Roesgrenda, Baishuihe, Kagemori landslides | China, Italy, Japan, Spain, Switzerland, Norway, New Zealand | ML2 | 1, 2 | Zhang et al., (2022) |
| 19 | Saleshan, Maoxian, Xintan, Vajont, Baishuihe, Muyubao, Shiliushubao, La Frasse, La Saxe, Shuping | China, Italy, Switzerland | ML3 | 1, 2 | Zhang et al., (2024) |
| 20 | Muping, La Clapie`re, New Wolongsi, Huangci, Saleshan, Puigcerco`s, Ohto, Mt Beni, Maoxian, Xintan, Vajont, Baishuihe, Muyubao, Shiliushubao, La Frasse, La Saxe | China, Japan, France, Spain, Italy, Switzerland | ML4 | 1, 2 | Zhang et al., (2024a) |
| 21 | Muping, La Clapie`re, New Wolongsi, Huangci, Saleshan, Puigcerco`s, Ohto, Mt Beni, Maoxian, Xintan, Vajont, Baishuihe, Muyubao, Shiliushubao, La Frasse, La Saxe | China, Japan, France, Spain, Italy, Switzerland | ML5 | 1, 2 | Zhang et al., (2024b) |
| 22 | Bello Oriente neighborhood in Medellín | Colombia | CO1 | 1, 2 | Gamperl et al., (2021) |
| 23 | Bello Oriente neighborhood, located on the urban–rural border of Medellín | Colombia | CO2 | 1, 2, 3, 4 | Werthmann et al., (2024) |
| 24 | Nilgiri district | India | IN1 | 1, 2 | Renuga et al., (2017) |
| 25 | Amboori, Kerala | India | IN2 | 1, 2 | Naidu et al., (2018) |
| 26 | Chamoli-Joshimath Corridor on the Rishikesh-Badrinath Highway, Garhwal, Himalaya, Uttarakhand | India | IN3 | 1, 2 | Joshi et al., (2019) |
| 27 | Himachal Pradesh | India | IN4 | 1, 2 | Prakasam et al., (2021) |
| 28 | Chamoli-Joshimath Corridor on the Rishikesh-Badrinath Highway, Garhwal, Himalaya, Uttarakhand | India | IN5 | 1, 2 | Joshi et al., (2022) |
| 29 | Nilgiris District | India | IN6 | 1, 2 | Chinamuttevi et al., (2022) |
| 30 | Chandmari, Sikkim | India | IN7 | 1, 2, 3 | Kumar and Ramesh (2022) |
| 31 | Uttarakhand state | India | IN8 | 1, 2 | Thomas et al., (2023) |
| 32 | Narender Nagar, Uttarakhand | India | IN9 | 1, 2 | Kumar et al., (2023) |
| 33 | Pakhi landslide site in Garhwal, Himalayas, Uttarakhand | India | IN10 | 1, 2 | Joshi et al., (2023) |
| 34 | Uttarakhand, Himachal Pradesh, and Jammu and Kashmir | India | IN11 | 1, 2 | Amune et al., (2023) |
| 35 | Uttarakhand, Himachal Pradesh, and Jammu and Kashmir | India | IN12 | 1, 2 | Kumar et al., (2024) |
| 36 | South-eastern region | India | IN13 | 1, 2 | Singha et al., (2024) |
| 37 | Lambagad Landslide Zone near the Joshimath Badrinath Highway in Uttarakhand | India | IN14 | 1, 2 | Gupta and Satyam (2024) |
| 38 | Kalimpong, Darjeeling, West Bengal, Tamil Nadu, Himachal Pradesh, Karnataka, Assam, Meghalaya, Mizoram, Uttarakhand, Kerala, Sikkim, Kolkata, and Nilgiri | India | IN15 | 1, 2, 3, 4 | GSI (2024) |
| 39 | Indonesia | Indonesia | ID1 | 1, 2 | Amelia et al., (2018) |
| 40 | Tulungrejo Village, Batu City | Indonesia | ID2 | 1, 2 | Wardana et al., (2018) |
| 41 | Indonesia | Indonesia | ID3 | 1, 2, 3 | Hidayat et al., (2019) |
| 42 | Indonesia | Indonesia | ID4 | 1, 2 | Sofwan and Azka (2019) |
| 43 | Indonesia | Indonesia | ID5 | 1, 2 | Fatimah et al., (2020) |
| 44 | Siantar-Parapat highway | Indonesia | ID6 | 1, 2 | Sigiro et al., (2023) |
| 45 | Italy | Italy | IT1 | 1, 2, 3, 4 | Rossi et al., (2018) |
| 46 | Aosta Valley | Italy | IT2 | 1, 2 | Ponziani et al., (2020) |
| 47 | Metropolitan City of Florence, Tuscany | Italy | IT3 | 1, 2 | Collini et al., (2022) |
| 48 | Umbria Region | Italy | IT4 | 1, 2 | Ponziani et al., (2023) |
| 49 | Italy | Italy | IT5 | 1, 2 | Guzzetti et al., (2024) |
| 50 | Pulau Pinang, Genting Highlands, and Tanjung Bungah, Penang Island | Malaysia | MY | 1, 2 | Nong et al., (2023) |

**Formatted:** Font color: Text 1

| ID | Location/Region | Country | Code | EW4All Pillars | Reference |
|---|---|---|---|---|---|
| 51 | Mon State | Myanmar | MM | 1, 2 | Thein et al., (2020) |
| 52 | Vestlandet, Western Norway | Norway | NO1 | 1, 2, 3 | Piciullo et al., (2017) |
| 53 | Norway | Norway | NO2 | 1, 2,3, 4 | Krøgli et al., (2018) |
| 54 | Muzaffarabad | Pakistan | PK | 1, 2 | Binu et al., (2024) |
| 55 | Chanchamayo district | Peru | PE | 1, 2 | Curipaco et al., (2023) |
| 56 | Subic Bay Freeport Zone | Philippines | PH | 1, 2 | Sejera et al., (2020) |
| 57 | Catalonia | Spain | ES | 1, 2 | Palao et al., (2023) |
| 58 | No info | Sri Lanka | LK | 1, 2, 3, 4 | Konagai et al., (2023) |
| 59 | Turkey | Turkey | TR | 1, 2 | Fang et al., (2023) |
| 60 | Sitka, southeast Alaska | USA | US | 1, 2, 3, 4 | Patton et al., (2023) |
| 61 | Quang Ninh | Vietnam | VN | 1, 2 | Nguyen et al., (2024) |

**Figure 7:** Operational status of the reviewed systems by spatial scale.

The 45 unique systems covered 23 countries worldwide (Fig. 6, Appendix I). Of these 45 systems, 33 were classified as LEWS, while the remaining 12 were classified as forecasting-focused (Table 1). LEWS accounted for six (46.2%) of 13 Local systems, 12 (75.0%) of 16 Regional systems, and 15 (93.75%) of 16 National systems. Previous studies found that although there are operational nNational, rRegional, or lLocal LEWS in some countries, many areas at very high-risk of landslides affected areas, where losses and damages are very highsubstantial, are notremain uncovered by any of these LEWS (Guzzetti et al., 2020; Froude and PetleyFroude et al., 2018). The LEWS that arsremain inat the validatednon-operational stage arshave been recommended by their authors for operational implementation to be practically implemented (Liu et al., 2024; Guo et al., 2019). In thissuch cases, these LEWS mightay not have been operationally practically implemented due tobecause of the limitationlimitations ofin successfuleffective coordination and collaboration withamong the relevant departments, agencies, or authorities.

Fig. 7 shows the operational status of the 45 reviewed systems according to their spatial scale. Among the 45 systems, 27 were identified as operational, while the remaining 18 were identified as non-operational. A relatively balanced distribution of systems was observed across the three spatial scales: 16 National, 16 Regional, and 13 Local. However, operational status differed markedly across spatial scales within this sample. Only 15.4% of Local systems were operational, compared with 56.25% of Regional systems and 100% of National systems. This distinction may indicate that most National systems benefit from established institutional mandates that support their operationalisation. Both National and Regional systems are comparatively more scalable and may be easier to sustain institutionally. Each slope is distinct because offrom others due to its unique geological and geomorphological characteristics, which may that require a tailored monitoring approach (Khan et al., 2021; Wieczorek and Snyder, 2009). Local LEWS are therefore often designed around site-specific monitoring strategies, with monitoring parameters and instruments selected according to the characteristics of the landslide being monitored (Pecoraro et al., 2019). Accordingly, some systems had been developed to focus on individual slopes;

Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: Bold, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: Bold, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Justified, Line spacing: Multiple 1.15 li
Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font color: Text 1

however, most remained at the non-operational stage. This may be partly because implementing a Local LEWS for a single community on a specific slope is not always economically feasible, as cost–benefit analyses may indicate that the associated costs outweigh the potential benefits (Sapena et al., 2023). ~~Considering this, some LEWS were developed focusing on individual slopes; however, most of them are prototypes or are in the development stage. Out of 19 local LEWS, only one is operational for providing EW to a community residing on a slope in Southwest China (Ju et al., 2020). This occurs because implementing local LEWS for a single community on a specific slope may not be feasible, as the cost benefit analysis indicates the associated cost outweighs the potential benefits (Sapena et al., 2023).~~ Local systems require slope-specific instruments to be installed, along with continuous monitoring, calibration, maintenance, technical expertise, and secure funding. Therefore, although Local systems may provide highly localised and relevant landslide warnings, ensuring their scalability is difficult (Sapena et al., 2023). This highlights a major gap in the transition from the development of prototype systems to operational implementation. The scale comparison therefore reveals an operational trade-off between local accuracy and wider transferability rather than a simple hierarchy of system quality. Several systems (12) were developed primarily to demonstrate rainfall thresholds, monitoring approaches, or forecasting methods. For instance, only one forecasting-focused system, which operated at the National scale, was identified as operational. Local systems had a comparatively higher number of forecasting-focused systems (seven). However, making a system operational requires continuous data availability, maintenance funding, institutional responsibility, legal authority to issue warnings, adequate financial resources, skilled personnel, clear communication and response protocols, and an appropriate mandate (Krøgli et al., 2018). These requirements are not always considered or addressed in academic research. As a result, many developed systems remain at the prototype or experimental stage and are therefore classified as forecasting-focused, rather than being fully operational.

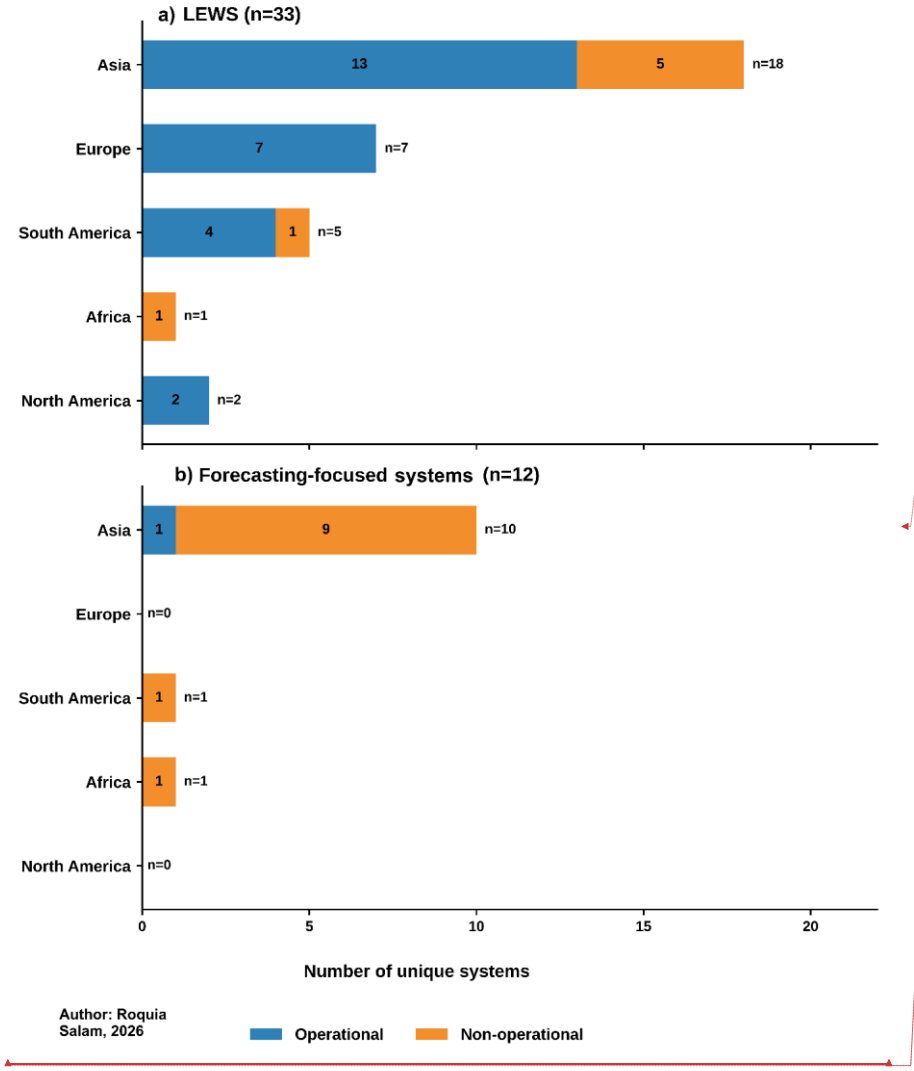



**Figure 8:** Geographical distribution of the 45 systems, together with their operational status.

Fig. 8 shows the uneven geographical distribution of the 45 systems. Among the 45 systems, 28 were in Asia, followed by seven in Europe, six in South America, two in Africa, and two in North America (Fig. 6, Fig. 8). A total of 14 systems (13 LEWS and one forecasting-focused) in Asia were operational, followed by seven in Europe (all LEWS), four in South America (all LEWS), none in Africa, and two in North America (both LEWS). These operational systems do not cover all landslide-affected areas within their respective countries; rather, most cover only parts of the landslide-affected

Formatted: Font: (Default) Arial, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Centered, Line spacing: Multiple 1.16 li
Formatted: Font: Bold, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: Bold, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1

zones (Appendix I). The operational systems span 19 countries: Bangladesh, Brazil, Colombia, Hong Kong (China), India, Indonesia, Italy, Japan, Malaysia, Nepal, Norway, Pakistan, Peru, the Philippines, South Korea, Sri Lanka, Taiwan, Thailand, and the United States (Fig.6, Appendix I). Together, they provide EW coverage for only a small fraction of landslide-affected areas worldwide. However, this does not reflect a complete inventory of operational systems worldwide.~~All these operational LEWS do not cover the whole landslide affected areas of the respective nations, rather most of them cover a part of the landslide affected zones. Together, they are disseminating EW in a tiny~~

Most focused landslides on the reviewed systems were shallow landslides and debris flows. Debris flow is one of the most destructive rainfall-induced landslides. It is observed from the selected systems (Table 1) that 25 systems used a static susceptibility map. Among them, 23 were categorised as LEWS (19 operational), and two were forecasting-focused (both non-operational). Of these 25 systems (55.5% of the total sample), 19 (76%) (comprising one Local, six Regional, and 12 National systems) were operational. However, among the 20 systems that did not integrate a susceptibility map, ten were forecasting-focused, while eight (40%) systems (of them one Local and one forecasting-focused) were identified as operational. These descriptive results do not demonstrate that susceptibility mapping causes operationalisation.

The uneven use of susceptibility maps indicates that some operational systems remain dominated by rainfall-threshold approaches. Rainfall thresholds are comparatively easier to develop, validate, and integrate into systems, particularly where other data, technical expertise, and institutional resources are limited. However, systems that integrate only rainfall thresholds may provide more generalised warnings, as they have a limited capacity to account for spatial variations in landslide susceptibility and risk. Landslide susceptibility levels vary considerably within a landslide-affected locality, area, or region. A susceptibility map can provide spatial information on landslide susceptibility across an area through susceptibility levels (e.g., very low, low, medium, high, very high) to indicate the relative likelihood of landslide occurrence in different locations (Azarafza et al., 2021). Therefore, incorporating a susceptibility map into Regional and National systems can enhance forecasting capability by enabling the prioritisation of specific high-risk zones for targeted EW, rather than providing generalised warnings across the entire affected area (Singh et al., 2024). This may help to reduce false alarms. Moreover, making susceptibility maps accessible to communities may support more informed and proactive preparedness measures.

Formatted: Font color: Text 1

Formatted: Font color: Text 1

fraction of the total landslide-affected area worldwide.

Table 1 exhibits the country codes of the countries for easy identification in the graphs. Here, internationally accepted codes (ISO codes) are used (ISO, n.d.). However, as there is more than one work covering the same country in multiple studies, a number is added to the ISO code to differentiate them. For instance, the country code of Italy is IT, and there are five different studies discussing LEWS of Italy; so, the country code for these studies is assigned as IT1, IT2, IT3, IT4, and IT5. In 5 studies, multiple (ML) countries' LEWS were discussed. In such cases, ML is assigned as the base code, and the numeric number is added to the base code (e.g., ML1, ML2, ML3, ML4, and ML5) to differentiate each study. These country codes are used subsequently in this study to reference specific studies.

Table 1 also illustrates the EW4All pillars addressed by each study. Mostly, this information has been extracted from the referenced articles. In some cases, additional documents or national websites were analysed to better understand and obtain this information. It is explored that eight countries have addressed four pillars of the EW4All framework: Bangladesh, China, Colombia, India, Italy, Norway, Sri Lanka, and the USA. Out of 23 countries, four addressed the first three pillars: Brazil (Blumenau, Petrópolis, and Nova Friburgo), India (Chandmari, Sikkim), Indonesia, and Norway (Vestlandet, Western Norway). The rest of the countries, Brazil, Chile, France, Japan, Malaysia, Myanmar, New Zealand, Pakistan, Peru, Philippines, Spain, Switzerland, Turkey, and Vietnam, addressed the first two pillars. All the elements under each pillar are not addressed by a single country, indicating the requirement for improvement of the existing systems and implementing them in a way that would be actionable.

# 4 Results and Discussion

## 4.1 Pillar 1: Landslide risk knowledge

Within the EW4All framework, Pillar 1 emphasises disaster risk knowledge as the foundation of effective EW. When people take the initiative to assess the type of landslides, their susceptibility, or seek to develop an LEWS, it indicates an awareness of existing hazards and their potential consequences. Such actions demonstrate that communities possess, or are beginning to acquire, the knowledge required to recognise landslide risk and to support informed preparedness and risk reduction measures.

Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Heading 3, Left

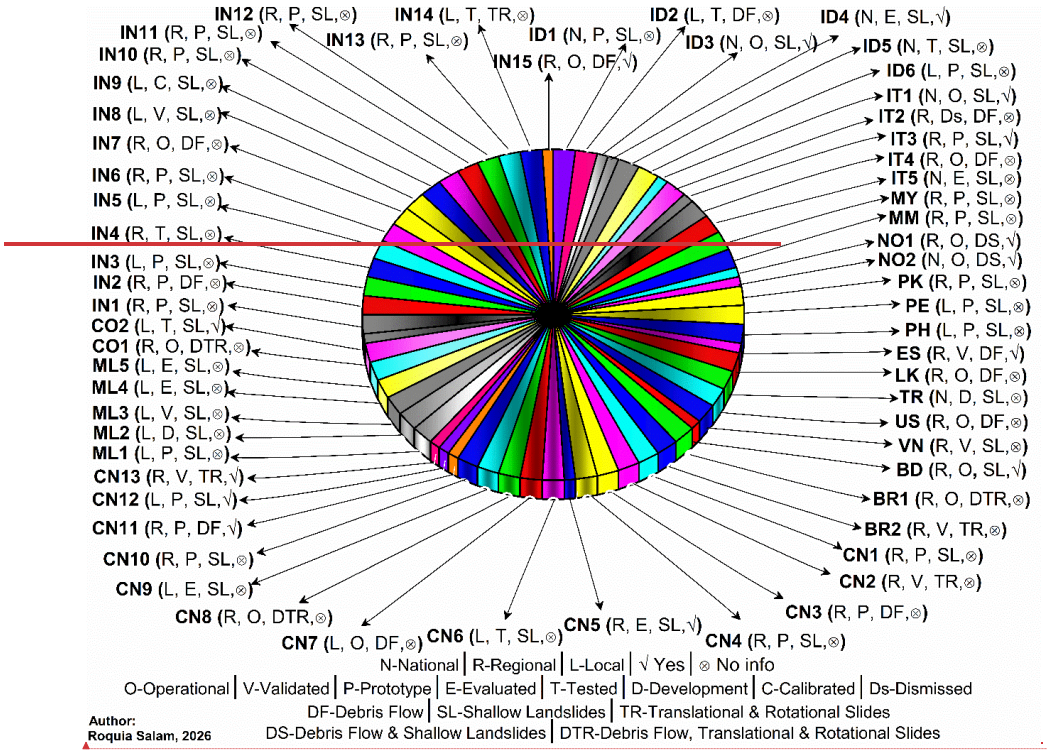
Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Heading 4

Formatted: Font color: Text 1

~~Fig. 7 shows the status, stages, types of landslides, and the integration of the susceptibility map for the selected countries' LEWS. It is found from the reviewed articles that out of 61 LEWS, only 14 are operational, benefiting 10 countries in Bangladesh, Brazil, China, Colombia, India, Indonesia, Italy, Norway, Sri Lanka, and the USA.~~




**Formatted:** Font: (Default) Arial, Font color: Text 1

~~**Figure 7**: Respectively (in brackets from left to right), the status, stages, types of landslides, and integration of the susceptibility map for the selected countries' LEWS.~~

~~Previous studies found that although there are operational national, regional, or local LEWS in some countries, many very high risk landslide-affected areas, where losses and damages are very high, are not covered by any of these LEWS (Guzzetti et al., 2020; Froude et al., 2018). The LEWS that are in the validated stage are recommended by the authors to be practically implemented (Liu et al., 2024; Guo et al., 2019). In this case, these LEWS might not be practically implemented due to the limitation of successful coordination and collaboration with the relevant departments, agencies, or authorities.~~

~~Each slope is distinct from others due to its unique geological and geomorphological characteristics that require a tailored monitoring approach (Khan et al., 2021; Wieczorek and Snyder, 2009). Considering this, some LEWS were developed focusing on individual slopes; however, most of them are prototypes or are in the development stage. Out of 19 local LEWS, only one is operational for providing EW to a community residing on a slope in Southwest China (Ju et al., 2020). This occurs because implementing local LEWS for a single community on a specific slope may not be feasible, as the cost-benefit analysis indicates the associated cost outweighs the potential benefits (Sapena et al., 2023).~~

~~The selected LEWS were developed to provide EW for four types of landslides: debris flow, translational slides, rotational slides, and shallow landslides (Fig. 7). Approximately 66.66% of LEWS were developed only for shallow landslides. However, out of 14 operational LEWS, only three were developed for shallow landslides; six for debris flow; three for both debris flow, translational slides, and rotational slides; and two for debris flow and shallow landslides.~~

~~It is explored from the selected literature that so far, no LEWS has incorporated a landslide risk map; therefore, lacking impact-based modelling. However, some LEWS (14) used a static susceptibility map. Out of these 14 LEWS, six are operational.~~ Table 1: Distribution of operational status and spatial scale across key system characteristics, stratified by system type.

**Formatted:** Font color: Text 1

**Formatted:** Left, Line spacing: Multiple 1.16 li

| Characteristic | Category | Category total n | Type of the System | Type n (% of category) | Local | | Regional | | National | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Operational n (%) | Non-operational n (%) | Operational n (%) | Non-operational n (%) | Operational n (%) | Non-operational n (%) |
| Type of the System | | | LEWS | 33 (73.3%) | 2 (6.1%) | 4 (12.1%) | 9 (27.3%) | 3 (9.1%) | 15 (45.5%) | 0 (0.0%) |
| | | | Forecasting-focused | 12 (26.7%) | 0 (0.0%) | 7 (58.3%) | 0 (0.0%) | 4 (33.3%) | 1 (8.3%) | 0 (0.0%) |
| Integrate Susceptibility Map | Yes | 25 | LEWS | 23 (92.0%) | 1 (4.0%) | 1 (4.0%) | 6 (24.0%) | 3 (12.0%) | 12 (48.0%) | 0 (0.0%) |
| | | | Forecasting-focused | 2 (8.0%) | 0 (0.0%) | 1 (4.0%) | 0 (0.0%) | 1 (4.0%) | 0 (0.0%) | 0 (0.0%) |
| | No | 20 | LEWS | 10 (50.0%) | 1 (5.0%) | 3 (15.0%) | 3 (15.0%) | 0 (0.0%) | 3 (15.0%) | 0 (0.0%) |
| | | | Forecasting-focused | 10 (50.0%) | 0 (0.0%) | 6 (30.0%) | 0 (0.0%) | 3 (15.0%) | 1 (5.0%) | 0 (0.0%) |
| Integrate Rainfall Threshold | Yes | 31 | LEWS | 24 (77.4%) | 1 (3.2%) | 2 (6.5%) | 9 (29.0%) | 2 (6.5%) | 10 (32.3%) | 0 (0.0%) |
| | | | Forecasting-focused | 7 (22.6%) | 0 (0.0%) | 4 (12.9%) | 0 (0.0%) | 2 (6.5%) | 1 (3.2%) | 0 (0.0%) |
| | No | 14 | LEWS | 9 (64.3%) | 1 (7.1%) | 2 (14.3%) | 0 (0.0%) | 1 (7.1%) | 5 (35.7%) | 0 (0.0%) |
| | | | Forecasting-focused | 5 (35.7%) | 0 (0.0%) | 3 (21.4%) | 0 (0.0%) | 2 (14.3%) | 0 (0.0%) | 0 (0.0%) |
| Use Sensor Data | Yes | 38 | LEWS | 30 (78.9%) | 2 (5.3%) | 4 (10.5%) | 8 (21.1%) | 1 (2.6%) | 15 (39.5%) | 0 (0.0%) |
| | | | Forecasting-focused | 8 (21.1%) | 0 (0.0%) | 6 (15.8%) | 0 (0.0%) | 2 (5.3%) | 0 (0.0%) | 0 (0.0%) |
| | No | 7 | LEWS | 3 (42.9%) | 0 (0.0%) | 0 (0.0%) | 1 (14.3%) | 2 (28.6%) | 0 (0.0%) | 0 (0.0%) |
| | | | Forecasting-focused | 4 (57.1%) | 0 (0.0%) | 1 (14.3%) | 0 (0.0%) | 2 (28.6%) | 1 (14.3%) | 0 (0.0%) |
| Use AI / ML | Yes | 5 | LEWS | 3 (60.0%) | 0 (0.0%) | 0 (0.0%) | 1 (20.0%) | 2 (40.0%) | 0 (0.0%) | 0 (0.0%) |
| | | | Forecasting-focused | 2 (40.0%) | 0 (0.0%) | 2 (40.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| | No | 40 | LEWS | 30 (75.0%) | 2 (5.0%) | 4 (10.0%) | 8 (20.0%) | 1 (2.5%) | 15 (37.5%) | 0 (0.0%) |
| | | | Forecasting-focused | 10 (25.0%) | 0 (0.0%) | 5 (12.5%) | 0 (0.0%) | 4 (10.0%) | 1 (2.5%) | 0 (0.0%) |
| Use API Data | Yes | 8 | LEWS | 6 (75.0%) | 1 (12.5%) | 0 (0.0%) | 2 (25.0%) | 1 (12.5%) | 2 (25.0%) | 0 (0.0%) |
| | | | Forecasting-focused | 2 (25.0%) | 0 (0.0%) | 1 (12.5%) | 0 (0.0%) | 1 (12.5%) | 0 (0.0%) | 0 (0.0%) |
| | No | 37 | LEWS | 27 (73.0%) | 1 (2.7%) | 4 (10.8%) | 7 (18.9%) | 2 (5.4%) | 13 (35.1%) | 0 (0.0%) |

| Characteristic | Category | Category total n | Type of the System | Type n (% of category) | Local | | Regional | | National | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Operational n (%) | Non-operational n (%) | Operational n (%) | Non-operational n (%) | Operational n (%) | Non-operational n (%) |
| | | | Forecasting-focused | 10 (27.0%) | 0 (0.0%) | 6 (16.2%) | 0 (0.0%) | 3 (8.1%) | 1 (2.7%) | 0 (0.0%) |
| Use IoT | Yes | 7 | LEWS | 6 (85.7%) | 1 (14.3%) | 4 (57.1%) | 1 (14.3%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| | | | Forecasting-focused | 1 (14.3%) | 0 (0.0%) | 1 (14.3%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| | No | 38 | LEWS | 27 (71.1%) | 1 (2.6%) | 0 (0.0%) | 8 (21.1%) | 3 (7.9%) | 15 (39.5%) | 0 (0.0%) |
| | | | Forecasting-focused | 11 (28.9%) | 0 (0.0%) | 6 (15.8%) | 0 (0.0%) | 4 (10.5%) | 1 (2.6%) | 0 (0.0%) |
| Utilise Remote Sensing | Yes | 17 | LEWS | 11 (64.7%) | 1 (5.9%) | 2 (11.8%) | 4 (23.5%) | 2 (11.8%) | 2 (11.8%) | 0 (0.0%) |
| | | | Forecasting-focused | 6 (35.3%) | 0 (0.0%) | 3 (17.6%) | 0 (0.0%) | 2 (11.8%) | 1 (5.9%) | 0 (0.0%) |
| | No | 28 | LEWS | 22 (78.6%) | 1 (3.6%) | 2 (7.1%) | 5 (17.9%) | 1 (3.6%) | 13 (46.4%) | 0 (0.0%) |
| | | | Forecasting-focused | 6 (21.4%) | 0 (0.0%) | 4 (14.3%) | 0 (0.0%) | 2 (7.1%) | 0 (0.0%) | 0 (0.0%) |

**Note:** Percentages in "Type n" are calculated using the corresponding characteristic-category total as the denominator. Percentages in the Local, Regional, and National columns use the same characteristic-category denominator. All values refer to the reviewed sample.

Formatted: Font color: Text 1
Formatted Table
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: Not Bold, Font color: Text 1
Formatted: Font: 8 pt, Bold, Font color: Text 1
Formatted: Font color: Text 1

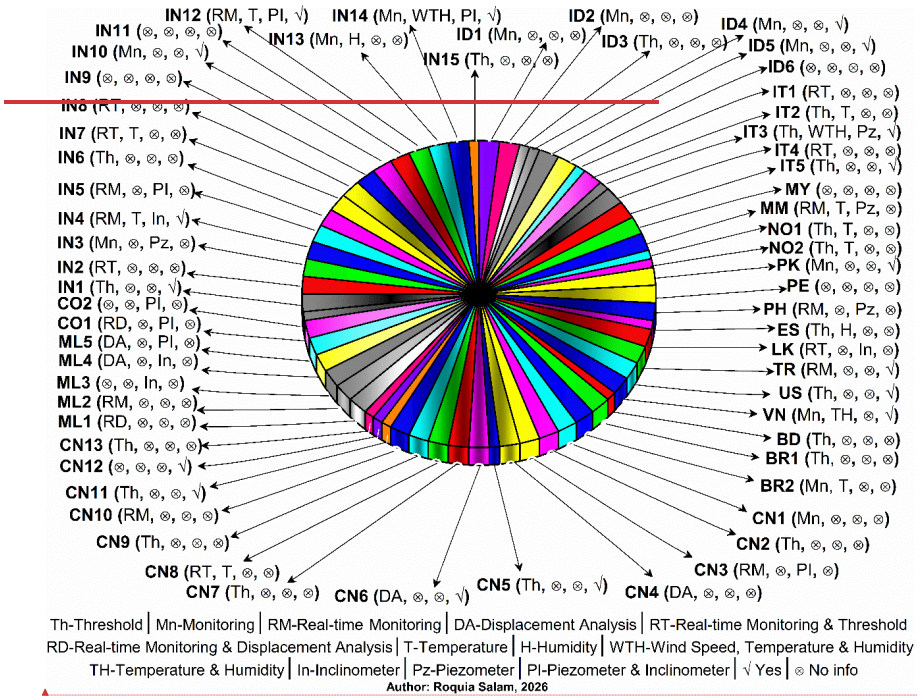
~~It is comparatively easier to monitor the factors of debris flow, and the early sign of the event occurrence can be detected by utilising the rainfall threshold techniques that help to develop more effective LEWS (Segoni et al., 2018; USGS, 2018).Except for an individual point, incorporating the susceptibility map into LEWS enhances forecasting capability (Singh et al., 2024). Landslide susceptibility levels are not equal everywhere in a landslide-affected locality, area, or region. These vary from slope to slope and catchment to catchment based on land use patterns, soil composition, geology, human intervention, hydrology, slope, amount of rainfall received, presence of any weak point (e.g., fault, joint, cracks, drainage channels), and so on. A susceptibility map can integrate all these conditions and provide the spatial information of the respective area through susceptibility levels (e.g., very low, low, medium, high, very high) to the occurrence of landslides in different parts of the study area (Azarafza et al., 2021). Therefore, incorporating a susceptibility map into the LEWS enhances the forecasting capabilities of the LEWS as it can prioritise specific zones (high risks) in providing targeted EW rather than a generalised EW for the whole affected area. This helps to reduce the number of false alarms. Moreover, having an accessible susceptibility map can enable the community to take proactive measures. However, human modifications on hills like unplanned urbanisation and deforestation are ongoing issues (Hidayat et al., 2019) that change the susceptibility levels of an area dynamically. In most areas, the authority has no control over these human modifications. Therefore, a static susceptibility map cannot precisely represent the actual ground scenarios.~~Additionally, susceptibility-based systems involve important trade-offs between accuracy, transferability, and operational scalability (Piciullo et al., 2018; Sapena et al., 2023). Local systems may not require a susceptibility map; however, they can generate more precise warnings for specific slopes. As Local systems require monitoring instruments, regular maintenance and updating, technical expertise, funding, and other resources, they may be less transferable (Sapena et al., 2023). However, National and Regional systems are more scalable and may be easier to operationalise. Therefore, susceptibility maps should be integrated into National and Regional systems to improve their capacity to issue more spatially targeted and reliable warnings. Without such integration, these systems may overlook important spatial variations in susceptibility and risk, reflecting a broader operational challenge in LEWS development. Therefore, having an accessible risk or susceptibility map is important to help communities understand the potential and spatially specific impacts of landslides on their livelihoods and resources, and to support appropriate preparedness measures (UNDRR and WMO, 2025).~~Lastly, a risk map is important to have in hand so that the community can understand the potential and specific impact of landslides on their livelihoods and resources and be prepared for them.~~

~~From the above analysis, it can be stated that there is a data gap in many countries that hinders them from incorporating the risk map or even the susceptibility map into the LEWS. Even the basic data is unavailable in the data-sparse regions. For instance, in the case of landslides, sometimes it is not possible to record the event areas immediately after the event due to the extreme weather, inadequate and unavailability~~

**Formatted:** Font color: Text 1

~~of communication networks, and so on (Salam et al., 2024). Nowadays, artificial intelligence (AI) is used extensively to fill this data gap in several ways (Pfeiffer et al., 2024). For example, AI can support identifying landslide locations in remote areas by using Earth Observation (EO) data. Besides, a large amount of data for better achieving landslide risk knowledge can be processed swiftly with the help of AI, which is otherwise very difficult to implement. Although AI is a very powerful tool for performing tasks, it is necessary to provide the correct commands to the AI by obtaining reliable information from the local community. Moreover, AI cannot be useful in detecting landslides in areas of high cloud coverage, especially during the monsoon. Lastly, a risk map is important to have in hand so that the community can understand the potential and specific impact of landslides on their livelihoods and resources and be prepared for them.~~

## 43.2 Pillar 2: Landslide detection, observation, monitoring, analysis, and forecasting




~~**Figure 8**: Countries used, respectively (in brackets from left to right), types of rainfall monitoring and analysis, other meteorological parameters, use of the Inclinometer and Piezometer, and utilising AI for creating LEWS.~~

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

After establishing an appropriate understanding ~~developing the proper knowledge~~ of landslide risks, the next stage involves ~~it is time for~~ detection, observation, monitoring, analysis, and forecasting, which constitute the second pillar of the EW4All framework, led by the World Meteorological Organization (WMO). The elements incorporated into~~used for developing the~~ LEWS are important to ~~study~~ examine, as selecting and integrating appropriate~~because integrating the right~~ elements ~~into the system~~ can improve the effectiveness and reliability of ~~provide more efficient~~ warnings (Calvello, 2017). From an operational perspective, the choice of monitoring strategy directly affects warning reliability, lead time, maintenance requirements, and the scalability of LEWS. Table 1 presents a comparison of the operational status of the selected systems and their key characteristics. Appendix II provides supplementary information. The information shown in Table 1 and Appendix II should be interpreted as descriptive cross-tabulations only. ~~Fig. 8 demonstrates, respectively (in brackets from left to right), the types of rainfall monitoring and analysis, other meteorological parameters, use of equipment such as the Inclinometer and Piezometer, and utilising AI for developing LEWS.~~

~~A precise observation is the foundation of accurate monitoring and analysis of landslides. Many countries in the world still have serious challenges in observing landslides due to data shortages in surface and space, such as countries in the global south, Africa, western Latin America, and the Pacific (UN, 2023). This data scarcity is a major hindrance to developing LEWS in these countries. Even forecast verification is not possible due to the lack of adequate data. Moreover, the right parameters for landslides are not always available to monitor, affecting the development of a reliable forecasting system.~~The cross-tabulation indicates that technical availability and operational status vary markedly across spatial scales.

Reliable monitoring depends on sustained observations and data continuity. Rainfall monitoring was found to be the primary hydrometeorological trigger. A total of 31 out of 45 systems used a rainfall threshold. Among these 31 systems (including seven forecasting-focused systems), 21 (67.7%) were operational (including one forecasting-focused system) (Table 1, Appendix II). By contrast, among the 14 systems that did not integrate a rainfall threshold, six (42.9%) were operational (none of which were forecasting-focused) (Table 1, Appendix II). The scale-based pattern is also informative. Among the 31 systems that used a rainfall threshold, one Local system (out of seven), nine Regional systems (out of 13), and 11 National systems were operational. Among the 14 systems without a rainfall threshold, one Local system (out of six), none of the three Regional systems, and all five National systems were operational. This pattern indicates that integration of rainfall thresholds was more common among Regional and National systems.

~~Monitoring and analysing rainfall is very important as it is one of the most significant triggering factors of rainfall-induced landslides. There are four types of rainfall monitoring and analysis methods found in existing LEWS: monitoring (no information found on what type of monitoring), real-time monitoring, threshold, and displacement~~

**Formatted:** Line spacing: Multiple 1.16 li

~~analysis. Some LEWS are developed by utilising a single rainfall monitoring method, and some are based on multiple rainfall monitoring methods. The most popular threshold is intensity–duration (I-D), and another method is the antecedent rainfall threshold (Naidu et al., 2018; Ahmed et al., 2020; Liu et al., 2021; Cao et al., 2022; Andrade et al., 2023).~~

~~Among the 61 selected LEWS, rainfall is not included in eight LEWS as an element; perhaps, due to data limitations. However, none of these eight LEWS is operational. About 21 LEWS utilised threshold, 12 monitoring, four displacement analysis, nine real-time monitoring, five both real-time monitoring and threshold, and two real-time monitoring and displacement analysis.~~

~~Interestingly, out of 14 operational LEWS, except one (which used real-time monitoring and displacement analysis), in 13 LEWS, thresholds were used to analyse rainfall.~~ In this threshold calculation~~ing~~ approach, both historical rainfall and past landslide data are used to identify a critical rainfall level associated with previous landslide occurrences~~find a critical rainfall level that has previously triggered the occurrence of landslides~~ (Satyaningsih et al., 2023). This critical rainfall level is ~~called~~ defined as the threshold, and ~~it is then~~subsequently used as ~~the~~ a benchmark ~~in LEWS~~. Therefore, when rainfall is forecast to approach or exceed ~~about to reach or cross~~ this threshold level, the system issues a warning indicating the potential ~~for the probable~~ occurrence of landslides. This threshold level is not the same everywhere in the world. It varies from country to country, region to region, place to place, and even from slope to slope (Barthélemy et al., 2024). Therefore~~So~~, identifying the appropriate~~correct~~ threshold level for the specific place or region is ~~the most~~a crucial aspect of developing an effective and reliable ~~LEWS~~ system for that ~~respective place or region~~area (Harilal et al., 2019). However, thresholds developed for Local systems may have limited transferability (Harilal et al., 2019).~~Apart from rainfall, in some LEWS (14 out of 61, and among these 14, four are operational), other meteorological parameters like temperature, humidity, and wind speed were also analysed. However, these parameters are not the primary factor of rainfall-induced landslides and are less crucial to consider when developing LEWS (Werthmann et al., 2024; Abbate et al., 2021).~~

Field sensors were used in 38 of the 45 systems, eight of which were forecasting-focused, and none of these eight were operational. This indicates that in situ monitoring was one of the most common technical characteristics of the reviewed systems. A total of 25 (65.8%) of these 38 systems were operational (Appendix II). The cross-tabulation of operational status by spatial scale shows uneven sensor use among these 25 operational systems (Table 1). Two of the 12 Local systems, eight of the 11 Regional systems, and all 15 National systems were operational. The sensors ~~Out of 61 selected LEWS, only four~~ used included rain gauges, piezometers[1], ~~four~~

**Formatted:** Font color: Text 1

**Formatted:** Font color: Text 1

[1] Piezometer is a geotechnical instrument used for measuring pore water pressure or groundwater pressure in the surrounding soil and rock.

~~used~~ inclinometers[2], tilt sensors, displacement monitoring devices, and other instruments~~seven used both piezometers and inclinometers (Fig. 8)~~. ~~However, only two LEWS are operational among these 15 LEWS.~~ Monitoring pore water pressure[3] is important as it can decrease the soil's shear strength and slope stability. Pore water pressure can increase due to external factors ~~like~~ such as rainfall, changes in drainage ~~pattern change~~patterns, groundwater infiltration, and ~~so on~~others. If ~~any~~ a slope ~~has more than one~~contains multiple groundwater ~~table~~ tables at ~~multiple~~ different depths, its stability may become more complex, and such conditions are not uncommon ~~it makes the slope more critical in terms of slope instability, and this is not very unusual~~ (Tang et al., 2020). If the soil becomes saturated, ~~it increases~~both pore water pressure and the overall weight of the soil increase.~~, and~~ This can further ~~decreases the~~reduce shear strength, ~~making a~~creating favourable ~~condition~~ conditions for ground movement and potentially leading to slope failure (Wu et al., 2021). In this case, a piezometer is a ~~powerful~~ useful tool ~~to~~ for measuring~~e~~ the pore water pressure, ~~and~~ while an inclinometer is used ~~for detecting~~to detect ground movement. Therefore, integrating ~~the~~ piezometers and inclinometers into the ~~LEWS~~ system can improve its reliability~~makes the system more reliable~~. However, ~~the maintenance cost of~~ these sensors can also involve high maintenance costs and generally provide measurements only at specific locations~~is so high as well, and they can only provide data about a specific point~~. Therefore, even a system covering a relatively small area may require multiple sensors to monitor pore water pressure and ground movement at different locations across the slopes. ~~So, if any LEWS is operational for even a small place, it requires a number of these sensors to get data on pore water pressure and ground movement from different points of the slopes covering the whole area.~~ Thus, integrating ~~the~~ piezometers and inclinometers into the LEWS ~~is~~ may not be cost-effective for providing EW ~~to~~ across a wider region, but may be more suitable for monitoring specific slopes or locations ~~rather effective for a specific point~~ (Sapena et al., 2023). The predominance of non-operational local sensor-based systems in this review reinforces the distinction between technical monitoring capability and sustained operational implementation.~~Again, developing a costly LEWS for a specific point is not feasible for a landslide-affected community, as the whole community cannot benefit from the system (Sapena et al., 2023).~~

Artificial intelligence (AI) and machine learning (ML) were less commonly used, appearing in five out of 45 systems. Among these five systems, two were Local (both forecasting-focused and non-operational), and three were Regional. Only one of these three Regional systems was operational. No National system used AI/ML. However, this pattern does not indicate that the use of AI/ML reduces the performance of LEWS. AI/ML can be used extensively to fill data gaps, especially by integrating satellite remote sensing data (Pfeiffer et al., 2024). This makes AI an important tool for data-

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

[2] Inclinometer is used to monitor and measure the displacement of the ground and deformation of the slope. It is usually used for detecting soil or rock movement.

[3] Pore water pressure is the pressure exerted by the water (groundwater) within the porous medium (pore) of soil and rock. Elevated pore water pressure increases the chance of landslides occurring.

sparse regions where conventional ground-based observations are limited or unevenly distributed. It can also support pattern recognition, data integration, and susceptibility mapping. Thus, AI may improve the scalability of LEWS when implemented carefully. ~~AI is used in one or more steps of developing 17 of 61 LEWS (Fig. 9). Among these 17 LEWS, only a single LEWS is operational (Patton et al., 2023). It is proven that AI is a fantastic tool to solve complex problems (Jarrahi, 2018). It is extensively used in filling data gaps, especially by integrating satellite remote sensing (Pfeiffer et al., 2024).~~ However, ~~there are some drawbacks to using AI. It~~AI models generally ~~requires~~ require large volumes ~~a huge amount~~ of high-quality data ~~to train the model~~for training. In ~~the case of a~~ data-sparse region~~s~~, ~~fulfilling~~ meeting this requirement is a major challenge. For instance, satellite-based detection is often hindered during the monsoon season due to cloud cover (Salam et al., 2024). Moreover, many AI models tend to overlook social and community dimensions, such as local knowledge, cultural contexts, and communication preferences, which are critical for effective early warning and community response. Although various categories of open-access global datasets are available for model training,~~There are open-access global-level different categories of datasets available that can be used for training. However,~~ every landslide setting is unique, and the characteristics of the triggering factors (e.g., vegetation, land use pattern~~s~~, soil composition, hydrology, slope, and ~~so on~~others) ~~of each~~vary between landslide-~~affected~~ prone area~~s are distinctive~~. Therefore, using ~~these~~ globally available datasets to train ~~the~~ an AI model and applying the resulting model to ~~extract data for~~ another region ~~can be~~may ~~oversimplified~~oversimplify local conditions, leading to inaccurate warnings (Patton et al., 2023; Pfeiffer et al., 2024). Thus, AI should be considered a complementary component of a hybrid LEWS, combined with expert interpretation, field validation, and institutional decision-making. Operational use also requires interpretable model outputs, transparent validation, clear communication of uncertainty, and human oversight. Poorly interpretable predictions may make it difficult for warning authorities to justify decisions, communicate uncertainty, and establish accountability (Pfeiffer et al., 2024).~~Second, apart from data generation, even using AI in further steps like landslide susceptibility mapping, generating an early prediction of slope failure, and so on, can produce a huge distrust. Because several AI (e.g., artificial neural networks – ANN), especially deep-learning (DL) techniques, run as a 'black box' as these techniques produce a quick result without providing any transparent and underlying logic in internal decision-making (Wolchowski et al., 2022). In most cases, it is impossible to customise the contribution of the influencing factors of landslides by using AI to produce the results. Although these results can be statistically significant and excellent, they may not be reliable practically due to the complex nature of the landslide disasters, due to the dynamic human intervention, changes in weather patterns, and social vulnerability aspects. Because of these reasons, using AI directly in developing an effective and near-reliable LEWS is very challenging.~~

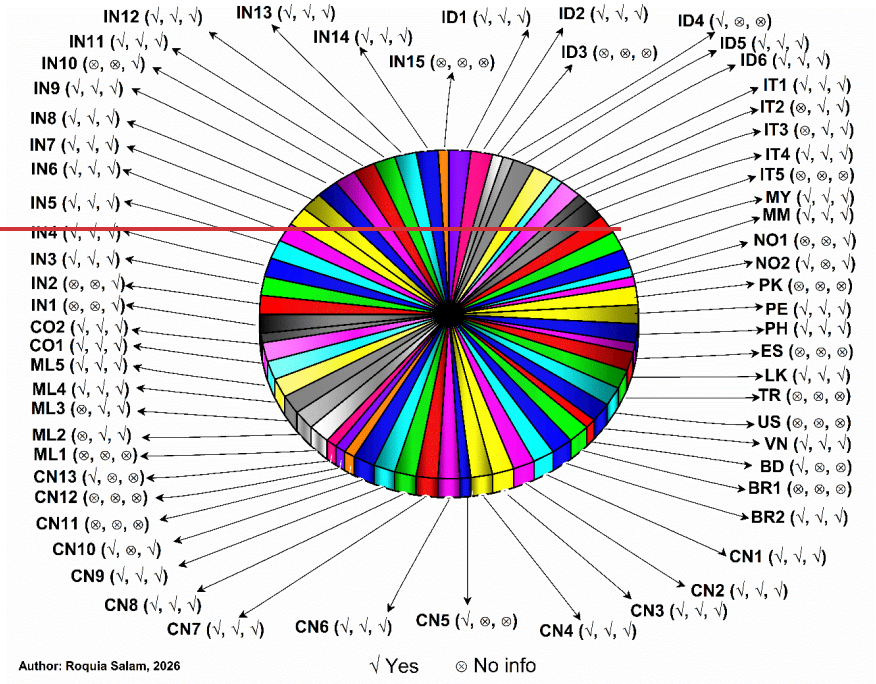



**Figure 9**: Countries used, respectively (in brackets from left to right), API, IoT, and other sensors for creating LEWS.

Fig. 9 depicts, respectively (in brackets from left to right), applicationApplication programming interface(s) (API), were used in eight of the 45 systems, two of which were forecasting-focused and non-operational. Of these eight systems, five (62.5%) were operational, compared with 22 of the 37 systems without API integration (59.5%), of which 21 were LEWS (Table 1, Appendix II). This indicates that API use is not, by itself, a useful proxy for operational maturity. Spatially, the eight API-enabled systems comprised two Local, four Regional, and two National systems; one Local, two Regional, and both National systems were operational (Table 1). internet of things (IoT), and other sensors (apart from inclinometer and piezometer) for creating LEWS. Out of 61 LEWS, the API for integrating different categories of data is used in 42 LEWS. Among these 42 LEWS, nine are operational (Figs. 7 and 9). In some cases, an API is used to merge integrate data generated from otherby external systems (Ofoeda et al., 2019). For instance, to develop a LEWS system dedicated to rainfall-induced landslides, forecasted rainfall data is are required to calculate estimate the potential accumulated rainfall for the nextover the following day or days(s) (Ahmed et al., 2018; Ahmed et al., 2020). This helps to understand determine whether rainfall is likely to exceed crossing the threshold and to issue an EW for potential upcoming landslide

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Normal, Centered

Formatted: Font color: Text 1

events. Some dedicated institutions forecast rainfall at ~~(~~hourly or~~,~~ daily intervals~~)~~ using advanced statistical modelling. This forecast~~ed~~ rainfall ~~is~~ can then be integrated into the system ~~usually used~~ through an API ~~into the LEWS~~, potentially improving the timeliness and reliability of~~which significantly improves the~~ warnings (Krøgli et al., 2018).

IoT technology[4] ~~is~~ was used in seven~~42~~ ~~LEWS~~systems (one forecasting-focused and non-operational), ~~and seven~~ of which two ~~of them~~ (both LEWS) ~~are~~ were operational ~~(Fig. 9)~~. Among these seven, six were Local (one operational), and one was Regional (operational)~~Similarly, apart from the piezometer and inclinometer, other sensors like the accelerometer, rain gauge, crack meter, tiltmeter, and so on are used in 47 LEWS, and nine of them are operational. Among these seven and nine operational LEWS that use, respectively, IoT and other sensors, seven are in common~~. IoT has a direct role in enabling automated, real-time data transmission from dense, site-specific sensor networks. ~~There is a linear relationship between IoT and data transmission from these sensors.~~ It provides an efficient means of~~is a very convenient way to~~ immediately transmitting sensor measurements to the system through wireless communication, thereby enabling real-time monitoring ~~transfer the data measured by the sensors to the LEWS system using wireless communication like IoT, making this monitoring real-time~~ (Liu et al., 2022). Remote sensing technology was used in 17 systems (six of which were forecasting-focused, with one of these being operational); eight (47.1%) of the 17 systems were operational. However, among the remaining 28 systems (22 LEWS and six forecasting-focused) that did not use remote sensing, 19 were operational. Remote sensing is frequently adopted in research-oriented or recently developed systems, while its main operational advantages include broader spatial coverage and support for data-sparse areas (Pfeiffer et al., 2024). In the reviewed sample, all three National systems using remote sensing were operational, compared with four of eight Regional systems and one of six Local systems, indicating that the institutional context in which Earth observation is integrated remains important.

No single technology was found to consistently predict operational status in this cross-tabulation analysis. Several apparent associations were also influenced by spatial scale and the distinction between LEWS and forecasting-focused systems. Operational maturity therefore appears to be more closely associated with institutional responsibility, routine maintenance, authority to issue warnings, and established communication and response arrangements than with any individual technology. These patterns are descriptive and should not be interpreted as evidence of causal relationships.

~~From the above-mentioned analysis, it is clear that the precise landslides detection, observation, monitoring, analysis, and forecasting are compromised due to data~~

Formatted: Font color: Text 1

[4] IoT technology ~~in a LEWS~~ refers to the network of interconnected sensors and devices (e.g., piezometer, inclinometer, rain gauge) that transmit real-time data through a wireless communication system over the internet to the cloud or central server. It enables algorithms on the server to analyse the real-time data and generate a timely alert.

~~scarcity. In this case, EO data and AI can mitigate this issue by filling the data gap using advanced statistical and hydrometeorological modelling to enhance observation, monitoring, and forecasting capabilities. However, these models should be scientifically sound and reliable, and to ensure this, capable human resources are needed. Besides, AI-generated data needs to be verified on the ground to ensure the quality of the data. The UN has initiated~~Initiatives such as the Global Basic Observing System (GBON) can help address observation ~~to close this gap~~gaps in LDCs and SIDs and thereby ~~to~~ support EW4All initiatives (UN, 2023). Another important aspect of ~~pillar~~ Pillar 2 is to facilitate data exchange among countries, thereby increasing the scalability of the LEWS (UN, 2023; UNDRR and WMO, 2025). An essential element of Pillar 2 is to reduce the compound effects of landslides, which requires collaboration across ~~emphasising the need to collaborate with~~ multiple disciplines. Monitoring architectures need to be scientifically sound, routinely maintained, validated against local conditions, supported by capable personnel, and connected to reliable institutional decision pathways (Krøgli et al., 2018; Sapena et al., 2023). By incorporating these ~~points~~elements, it ~~will~~ may be easier to develop an actionable and targeted LEWS. However, ~~above all,~~ funding ~~is the most~~remains a critical factor in implementing these measures~~executing the aforementioned tasks~~, and securing adequate financial resources is ~~it is~~ a major challenge, especially for ~~the least developed~~LDCs and other developing countries (UNDRR and WMO, 2025). This challenge should be more prominently addressed, with a focus on ~~promoting~~ improving access to international climate finance. Mechanisms under the Paris Agreement, particularly the Fund for Responding to Loss and Damage ~~fund~~, and other UN climate frameworks offer ~~critical~~ important opportunities for vulnerable countries to secure the necessary resources to build and sustain effective EWS. Prioritising LEWS within these funding channels ~~is essential to~~could help protect lives and livelihoods in high-risk areas.

### ~~4~~3.3 Pillar 3: Warning dissemination and communication, and Pillar 4: Preparedness and response capability

Formatted: Font: 11 pt, Font color: Text 1

Formatted: Font: 11 pt

Formatted: Font: 11 pt, Font color: Text 1

Formatted: Font: 11 pt

Formatted: Font: 11 pt, Font color: Text 1

Formatted: Font: Not Bold, Font color: Text 1

Formatted: Normal, Justified

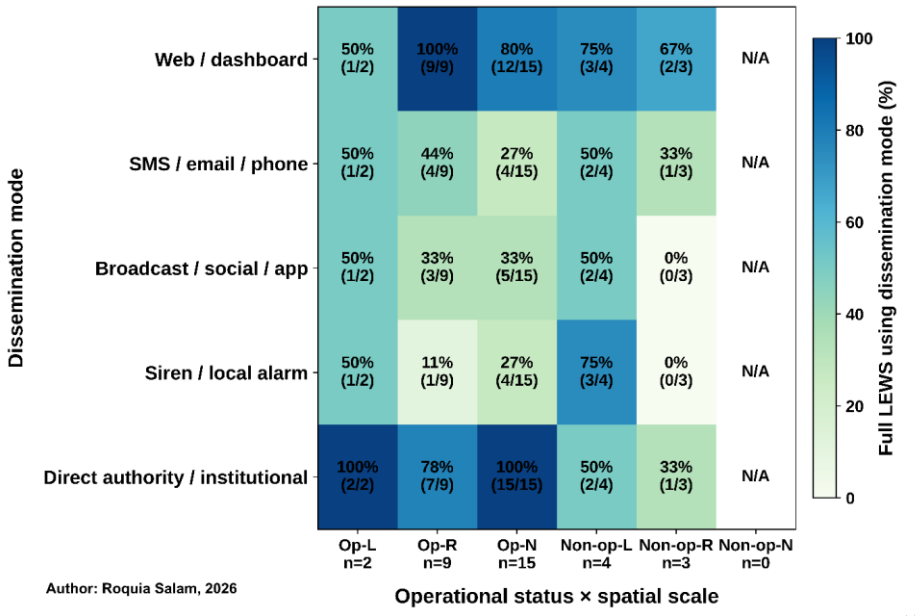



**Figure 9:** Modes of disseminating warnings generated by the forecasting system to the last mile (Op-L: Operational – Local; Op-R: Operational – Regional; Op-N: Operational - National; Non-op-L: Non-operational - Local; Non-op-R: Non-operational - Regional; and Non-op-N: Non-operational – National).

A reporting gap was identified in Pillar 3 regarding how warnings were disseminated and communicated to the last mile,[5] and in Pillar 4 regarding how preparedness and response capabilities were strengthened, particularly in academic publications. Academic publications documented Pillar 3 evidence for approximately 22 of the 45 systems and Pillar 4 evidence for 15 of the 45 systems; supplementation with official sources was therefore essential (Appendix I). ~~The referenced publications lack sufficient details on how warnings are disseminated and communicated (Pillar 3) to the last mile[6]. In addition, discussions on preparedness and response capabilities (Pillar 4) are missing from most articles. Only a handful of papers (five in total) address one or more of the following steps: warning dissemination, communication, preparedness, and response planning (Krøgli et al., 2018; Ahmed et al., 2020; Kumar and Ramesh, 2022; Patton et al., 2023; Werthmann et al., 2024).~~ However, even among these publications, the extent of discussion of Pillar 3 and Pillar 4 was very

[5] The last mile refers to the final step of disseminating the alert directly to the people who are at risk. It ensures that understandable and actionable alert information reaches the right individuals.

~~[6] The last mile refers to the final step of disseminating the alert directly to the people who are at risk. It ensures that understandable and actionable alert information reaches the right individuals.~~

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

limited. Academic publications often describe thresholds, monitoring, and forecasting methods in greater technical detail than they describe who is authorised to issue a warning, how alerts move through institutional and community channels, or how preparedness and response are activated. To supplement information on these two pillars, information was gathered from official websites, blogs, and relevant documents. However, information on Pillars 3 and 4 could not be identified for all 45 systems. The missing information may be available from other sources that were not captured in this review. Even after consulting the supplementary sources, 33 systems were classified as LEWS. In this section, only these 33 LEWS were considered for further analysis. ~~However, even among these few, most focus primarily on the frameworks they propose. Perhaps, these information might avaiable in other sources which were not concisered for this study.~~Fig. 9 depicts the modes used by the 33 LEWS to disseminate generated warnings to the last mile, according to their operational status and spatial scale. Among these 33 LEWS, 26 were operational (two Local, nine Regional, and 15 National), and seven were non-operational (four Local and three Regional).

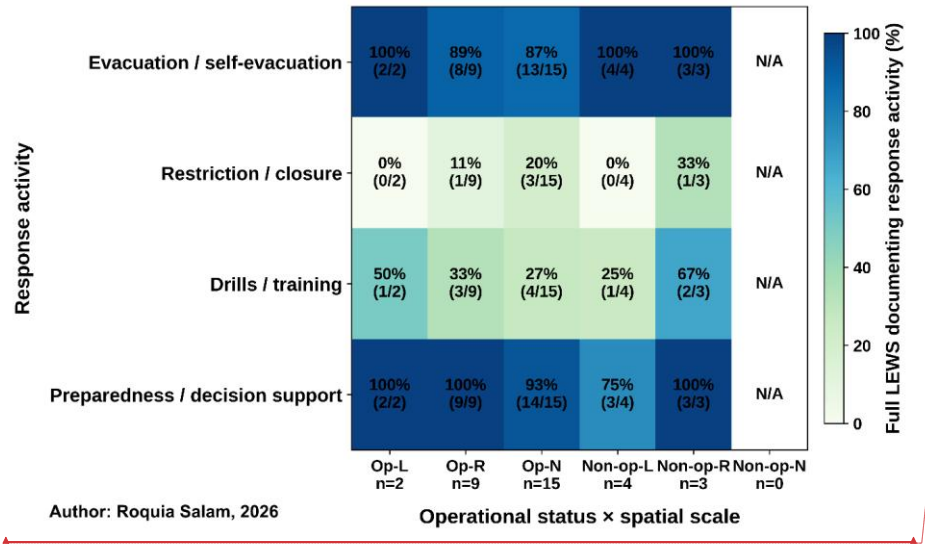



**Figure 10:** Preparedness and response activities across the 33 LEWS (Op-L: Operational – Local; Op-R: Operational – Regional; Op-N: Operational - National; Non-op-L: Non-operational - Local; Non-op-R: Non-operational - Regional; and Non-op-N: Non-operational – National).

The heatmap shows that dissemination through responsible authorities or institutions stood out as the most consistent pathway in operational LEWS (two Local, seven Regional, and 15 National). The second prominent mode of warning dissemination in operational LEWS was web-based platforms/dashboards (one Local, nine Regional, and 12 National). Direct public-facing modes of warning dissemination, such as SMS,

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

email, phone calls, broadcasting, social media, apps, sirens, and local alarms, were reported less consistently. The proposed non-operational LEWS also documented these as intended dissemination modes for future warning dissemination. This pattern suggests that institutional dissemination was the most consistently documented pathway, whereas the use of direct public-facing channels varied among systems. More detailed discussions ~~on~~ of warning dissemination and communication can be found in the reviews by Guzzetti et al. (2020) and Piciullo et al. (2018). In these studies, the authors draw not only on their academic research but also on their ~~own~~ field experience and information obtained through direct communication ~~personal contacts~~ with the relevant authorities.

Fig. 10 shows the preparedness and response activities documented for 33 LEWS. In both operational (two Local, eight Regional, and 13 National) and non-operational LEWS (four Local and three Regional), evacuation/self-evacuation was identified as the most frequently documented response activity. Preparedness/decision support mechanisms were also consistently reported in both operational LEWS (two Local, nine Regional, and 14 National) and non-operational LEWS (three Local and three Regional). Other documented preparedness and response activities included drills, training, restrictions, and closures. The frequencies shown in Figs. 8 and 9 represent practices documented in the searched sources and should not be interpreted as estimates of their prevalence or effectiveness in operational LEWS worldwide.

From the above analyses, it can be stated that operational systems were more consistently represented within the LEWS sample; National systems were found to be more frequently operational, followed by Regional systems; and Local LEWS showed greater variation. However, this pattern may partly reflect the small Local sample size and gaps in reporting. ~~It has been observed from the referenced publications that LEWS are generally limited to issuing forecast alerts, which are typically made available on official websites. The decision on whether to disseminate these warnings to the last mile rests with the relevant authorities. More detailed discussions on warning dissemination and communication can be found in the reviews by Guzzetti et al. (2020) and Piciullo et al. (2018). In these studies, the authors draw not only on their academic research but also on their own field experience and information obtained through personal contacts with the relevant authorities.~~

Therefore, it remains difficult to gain a comprehensive understanding of any country's LEWS solely from ~~selected~~ academic publications. To capture the full picture, deeper engagement with national systems, through direct communication with stakeholders, field visits, or other means, is often necessary. This ~~points to~~highlights a significant gap ~~in~~ between the literature and operational practice, as the available academic sources provide only partial insights into how LEWS actually operate ~~on the ground~~in practice. Moreover, in academic publications, the terms 'early warning system' and 'forecasting system' should be used appropriately, as a forecasting system alone should not be considered equivalent to an early warning system.

## 4.4 Additional LEWS from the review papers

A few pieces of related information on the additional LEWS are mainly gathered from two peer reviewed published articles by Guzzetti et al. (2020) and Piciullo et al. (2018). Available information on the characteristics of the LEWS discussed in the review papers includes their stages, status, the type of landslides they focused on, the use of rainfall thresholds, and sustainability mapping (Table 2). Information on all these LEWS is not available in the existing academic databases, according to the authors (Guzzetti et al., 2020, and Piciullo et al., 2018). The authors collected information about those LEWS from several sources, including academic databases, websites, and personal contacts. So, these are discussed separately from the previous sections because the information is directly gathered from the two above-mentioned publications. The information presented in this section is related to the previous sections in the sense that similar information was extracted from the 61 referenced publications. This information is useful to understand the basic characteristics of rainfall induced LEWS.

**Table 2**: Overview of the characteristics of the LEWS discussed in previous review articles.

| ID | Country | Stages | Status | Focused landslide types | Used rainfall threshold | Integrated susceptibility map |
|---|---|---|---|---|---|---|
| 1 | Taiwan | Operational | National | Debris flow | Yes | No info |
| 2 | Italy | Design | National | No info | Yes | Yes |
| 3 | Norway | Operational | National | Debris flow, and shallow landslides | Yes | Yes |
| 4 | Central America and the Caribbean | Dismissed | National | No info | Yes | Yes |
| 5 | Indonesia | Operational | National | No info | Yes | No info |
| 6 | Scotland, UK | Design | National | Shallow landslides | Yes | No info |
| 7 | Malaysia | Operational | National | Debris flows, and shallow landslides | Yes | No info |
| 8 | Japan | Operational | National | No info | Yes | No info |
| 9 | Appalachians, USA | Operational | No info | Shallow landslides | Yes | No info |
| 10 | Hong Kong, China | Operational | Regional | Cut slopes, rock slopes, fill slopes, and retaining walls | Yes | No info |
| 11 | San Francisco Bay area, USA | Dismissed | Regional | Debris flow | Yes | No info |
| 12 | Western Oregon, USA | Operational | Regional | Debris flow | Yes | No info |
| 13 | Seattle, USA | Dismissed | Regional | Debris flow and shallow landslides | Yes | No info |
| 14 | Southern California, USA | Operational | Regional | Debris flow | Yes | No info |
| 15 | North Vancouver, Canada | Dismissed | Regional | Debris flow | Yes | No info |
| 16 | Rio de Janeiro, Brazil | Operational | Regional | Debris flow | Yes | No info |
| 17 | Combeima Valley, Colombia | Experimental | Regional | Debris flow | Yes | No info |
| 18 | Java, Indonesia | Pre-operational | Regional | No info | No info | Yes |
| 19 | Chittagong Metropolitan Area, Bangladesh | Operational | Regional | Shallow landslides | Yes | Yes |

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

| ID | Country | Stages | Status | Focused landslide types | Used rainfall threshold | Integrated susceptibility map |
|---|---|---|---|---|---|---|
| 20 | Southern Taiwan | Design | Regional | No info | Yes | Yes |
| 21 | Emilia-Romagna, Italy | Operational | Regional | Shallow landslides | Yes | Yes |
| 22 | Piedmont, Italy | Operational | Regional | Debris flow and shallow landslides | Yes | Yes |
| 23 | Umbria, Italy | Operational | Regional | No info | Yes | No info |
| 24 | Tuscany, Italy | Operational | Regional | No info | Yes | No info |
| 25 | Liguria, Italy | Design | Regional | No info | Yes | Yes |
| 26 | Sardinia, Italy | Design | Regional | No info | Yes | Yes |
| 27 | Apulia, Italy | Design | Regional | No info | Yes | Yes |
| 28 | Sicily, Italy | Operational | Regional | Shallow landslides | Yes | No info |
| 29 | Zhejiang Province, China | Operational | Regional | No info | Yes | Yes |
| 30 | Hubei Province, China | Operational | Regional | No info | Yes | No info |

All the LEWS were developed to issue warnings for rainfall-induced landslides. In total, eight and 21 LEWS are national and regional categories, respectively. However, it is not clear what type (national, regional, or individual) of LEWS is operational in Appalachians, USA. Practically, four LEWS found in Central America and the Caribbean; North Vancouver, Canada; San Francisco Bay Area, USA; and Seattle, USA are already dismissed. Six LEWS were only designed (four from Italy, one from Scotland, and Taiwan). One LEWS was found in the experimental stage from Combeima Valley, Colombia, and one was found in the pre-operational stage from Java, Indonesia.

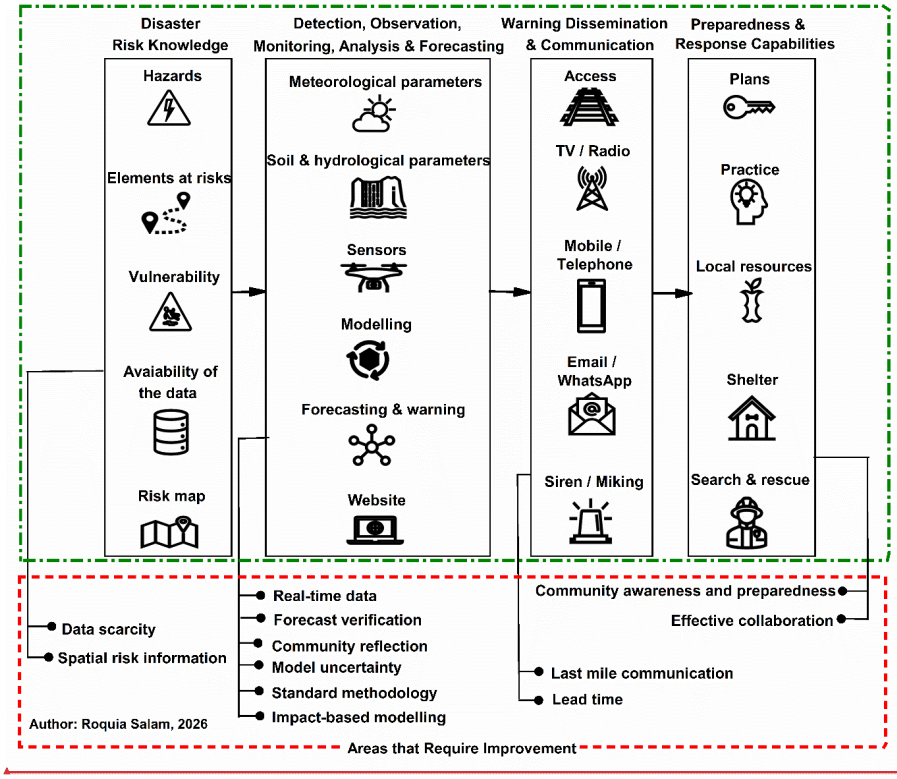
Among these 30 LEWS, the one still operational in Hong Kong, China, is the first known LEWS in the world and has been operational since 1977 (Guzzetti et al., 2020). It is the most successful LEWS in history. Since its initial operation, it has gone through several improvements. Unlike other areas, landslides in Hong Kong are not purely natural, as the slopes of this region are human-made, and due to rainfall, these human-made slopes often fail.

Out of these 30 LEWS, 18 (12 are regional, from five in Italy, two in the USA, three in China, one from Bangladesh, and one from Brazil; five are national from Japan, Taiwan, Malaysia, Indonesia, and Norway) are found as operational by Guzzetti et al. (2020) and Piciullo et al. (2018). Mostly, these operational LEWS (12 LEWS out of 18) focus on two types of landslides: debris flow and shallow landslides, which are analogous to the findings of the systematic review of this study. However, it is not clear what type of landslides are focused on by the six other operational LEWS. In all these 18 LEWS, one or more rainfall thresholds are integrated, indicating the significance of local thresholds in issuing an effective warning. The landslide susceptibility map is integrated into five LEWS out of 18. Among all these 30, no LEWS incorporated a risk map.

### 34.45. Gaps in the referenced 61 LEWS in the lens of the EW4All framework

Formatted: Font color: Text 1

While considerable contextual variation exists, the reviewed ~~literature~~ systems ~~suggests~~ suggest that a typical LEWS warning value chain comprises four interrelated pillars: landslide risk knowledge; risk monitoring, detection, forecasting, evaluation, and warning formulation; warning dissemination through appropriate communication channels; and the uptake of warnings to support preparedness and early action. These pillars are functionally interconnected, as each stage provides the basis for the next. Weaknesses in any one pillar can reduce the effectiveness of subsequent stages and ultimately compromise the performance of the system as a whole. The gap analysis of Pillar 1 and Pillar 2 is based on all 45 systems. However, the analyses of gaps in Pillar 3 and Pillar 4 are based on the 33 LEWS. This section highlights the key gaps that concern both operational implementation and the available evidence for assessing such implementation (Fig. 11). It should not be interpreted as a complete inventory of deficiencies in LEWS practice worldwide.~~Accordingly, a LEWS can be considered successful only when all four pillars operate in a coordinated manner, enabling warnings to be generated, communicated, understood, and translated into timely and appropriate action. Although the 61 reviewed publications do not provide comprehensive coverage of all four pillars of a LEWS, they do reveal important strengths and weaknesses in existing systems when considered against the EW4All framework. However, the analysis in this section is confined to Pillars 1 and 2, since these pillars were reported more consistently and in greater comparable detail across the reviewed cases. Accordingly, 11 priority areas for improvement were identified within these two pillars. Fig. 10 illustrates these key areas requiring further attention in relation to Pillars 1 and 2.~~

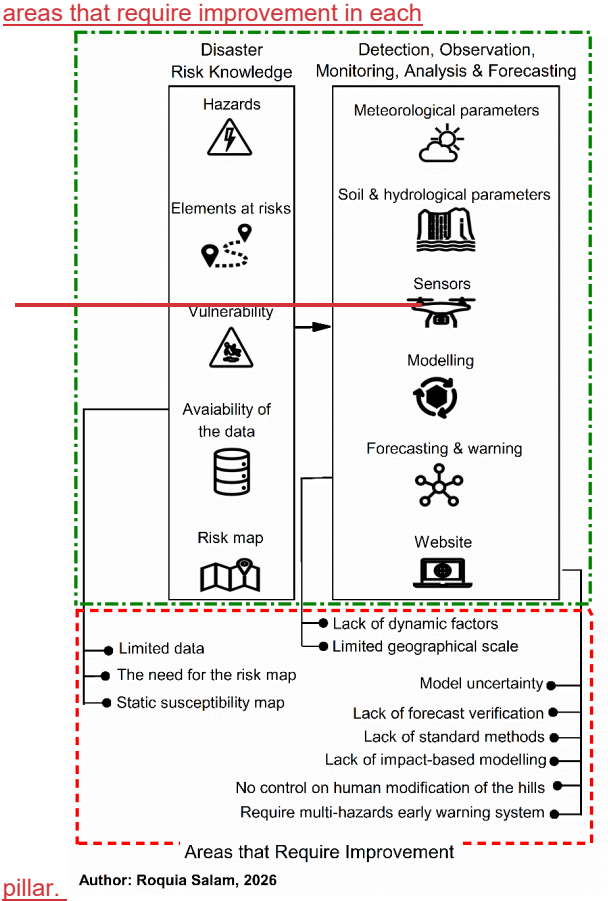



1083

**Formatted:** Font: (Default) Arial, Font color: Text 1

**Formatted:** Font color: Text 1

**Figure 11**: Elements of the four Pillars of LEWS based on UN-defined EW4All, and areas that require improvement in each




pillar.

~~**Figure 10**: Elements of Pillars 1 and 2 for LEWS based on UN-defined EW4All, and areas that require improvement in each pillar identified from the referenced publications.~~

**43.54.1 Pillar 1: Incomplete and insufficiently dynamic risk and impact knowledge~~Gaps under Pillar 1~~**

**~~4.5~~3.4.1.1 Data scarcity ~~Limited data~~**

Data scarcity is one of the most critical challenges~~problems~~. It is often~~quite~~ difficult and, in some cases,~~sometimes~~ impossible to obtain essential ~~collect basic~~ data ~~like~~ such as landslide inventories from many landslide-prone areas (Patton et al., 2023; Liu et al., 2024). Many countries still face serious challenges in landslide observation

Formatted: Left

Formatted: Normal, Left, Line spacing: Multiple 1.15 li

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Justified

Formatted: Font: Not Bold

Formatted: Normal

Formatted: Font color: Text 1

because of shortages of ground-based and space-based data, particularly in parts of the Global South, Africa, western Latin America, and the Pacific (UN, 2023). This data scarcity is a major constraint on the development of LEWS in these countries. ~~Based on the types of landslides, the categories of inventories are different. Therefore, it is important to prepare the database of the different categories of inventories separately and make sure inventories of one category are not mixed with another type. Because each category has varying types of risks. Consequently, mixing multiple categories of inventories for analysis does not properly represent the risk; rather, it simplifies the risk, which is a major issue still in many areas. Each landslide inventory category gives an idea of where landslides can happen and how they would impact an area. Therefore, having landslide inventories in hand indicates that the analyst knows which areas are more and less prone to landslides.~~

~~However, except for some developed countries like Italy, Hong Kong (in China), Norway, and so on, it is still a major limitation. Apart from the inventories, to better understand the pattern and risk of landslides in an area, several datasets (e.g., hydrological, meteorological, geological, lithological, and so on) are required to analyse. However, all these datasets are not available everywhere (because of several reasons like lack of adequate resources, funds, and others) (Ponziani et al., 2020; Ponziani et al., 2023; Palau et al., 2023). Although some dedicated institutions provide simulated data. However, these are not as accurate as the station data. The same happens to the gridded data. Therefore, without analysing the gridded or simulated data with station data to explore the most suitable one (among many simulated or gridded data), the perception of landslide risk for an area is not highly accurate. Low temporal and spatial resolution of the satellite data is further impacting the accuracy of the LEWS (Dai et al., 2020; Fang et al., 2023).~~ Data limitations ~~is~~ are a major concern because landslide forecasting and warning require the integration of information across a range of institutions and specialist disciplines, including meteorology, hydrology, geology, engineering, and communication. In this context, 'limited data' is not simply a matter of insufficient observations within a single domain; rather, it reflects a broader, cross-sectoral challenge ~~concerning~~ related to the routine collection, integration, and sharing of critical parameters relevant to LEWS. This issue is therefore closely connected to governance, especially ~~with regard~~in relation to institutional coordination, data-sharing agreements, and the mechanisms through which information is exchanged ~~between~~ among relevant actors. Therefore, it is essential to establish interoperable inventories, documented quality-control procedures, and sustained arrangements among relevant institutions for data sharing. Such data scarcity can directly hamper the implementation of EW4All by weakening risk knowledge, monitoring and forecasting capability, and the evidence base required for timely and reliable early warning.

~~**Figure 10**: Elements of Pillars 1 and 2 for LEWS based on UN-defined EW4All, and areas that require improvement in each pillar identified from the referenced publications.~~

### 3.4.1.2 Spatial risk information~~4.5.1.2 The need for the risk map~~

A risk map is a vital element of a LEWS, yet it was largely absent from the reviewed systems. ~~Because it~~It usually integrates data on all ~~the~~ components of risk, ~~like~~ such as hazard, vulnerability, and exposure. However, these components do not necessarily contribute equally to the overall level of risk. ~~Even, each component does not have the same impact on the risk level.~~ Exposure is often a major contributor to overall risk~~the most dominant component in the risk level~~. Therefore, it is essential to ~~provide~~ assign appropriate weights or ~~the right~~ importance to ~~the~~ each component~~s~~ when developing~~in creating~~ a risk map. ~~From the existing literature review, it is explored that a risk map is missing in the referenced LEWS (Ahmed et al., 2020; Andrade et al., 2023; Konagai et al., 2023). However, a susceptibility map is used to categorise the risk zones. Most~~ Susceptibility maps are sometimes incorrectly interpreted as risk maps, and this distinction should be clearly addressed. ~~people confuse susceptibility with risk maps due to a lack of disciplinary background training. This is not an adequate method. Several factors of landslides are used here altogether to create a susceptibility map without providing relevant importance to each component. Even elements of all these components are not included. For instance, some elements of hazard and vulnerability components may be considered to create the susceptibility map, where any element of exposure is not included. In some cases, this map is created without any element of exposure and is used as a risk map, which is a very big misconception.~~ A susceptibility map should not be considered equivalent to ~~can never be~~ a risk map.

#### ~~4.5.1.3 Static susceptibility map~~

In some LEWS, a susceptibility map is integrated into the system. However, ~~it is found that this~~ these susceptibility map~~s is~~ are often static rather than dynamically updated ~~not dynamic~~ (Rossi et al., 2018; Ahmed et al., 2020). This is a limitation because conditions in many landslide-prone areas change continuously. ~~However, most of the landslide-prone areas are continuously changing. It means that because of hill~~Hill cutting, slope alteration, deforestation, urbanisation, demographic changes, and other factors~~, the~~ can alter both ~~at-risk areas~~susceptibility and exposure over ~~are changing~~ time. Consequently~~Therefore~~, the associated risk levels ~~of these areas are~~may also change~~ing~~, creating a need for regularly ~~which requires an~~ updated susceptibility ~~map~~maps. Such updating could be undertaken ~~This change can be done~~ automatically or semi-automatically at appropriate intervals~~after a reasonable time gap~~. The limited availability of up-to-date spatial risk information can hinder the implementation of EW4All by weakening risk knowledge and reducing the capacity to identify and prioritise populations and locations most at risk.

Formatted: Justified

Formatted: Font color: Text 1

Formatted: Font color: Text 1

~~If there is an impact-based warning, the local community can plan better to minimise their risks.However, it is observed that the susceptibility map, which was used initially to develop the system, did not change later. This reflects that the warning generated from the old susceptibility map is not the same as they claim.~~

### ~~4~~3.~~54~~.2 Pillar 2: Monitoring continuity, validation, and scalability~~Gaps under Pillar 2~~

#### ~~4.5.2.1 Lack of dynamic factors~~

#### 3.4.2.1 Real-time data

Some landslide-related variables, including rainfall, groundwater conditions and ground deformation, vary over time and therefore require continuous or near-real-time observation (Krøgli et al., 2018; Sapena et al., 2023). ~~factors of landslides are regularly changing, such as rainfall, pore water pressure, ground movement, land use, and others.~~ Several barriers (e.g., limited funding and~~lack of funds,~~ maintenance requirements~~issues~~) can constrain the continuous collection of ~~exist to getting~~ data ~~dynamically from~~ (Sapena et al., 2023) ~~the~~ from rain gauge~~s station~~, piezometers, and inclinometers. The cross-tabular analysis of the 45 systems indicates that technical monitoring is relatively common; however, it does not always ensure operational use, especially for Local and forecasting-focused systems. A major concern is how to integrate and sustain all required real-time data so that a system remains functional and operationally capable. These include instruments, communications, power supplies, data services, calibration, maintenance, and trained personnel. ~~Most of the LEWS lack most of these data (Rossi et al., 2018; Ahmed et al., 2020; Patton et al., 2023; Ponziani et al., 2023), and a few have one or more dynamic factors integrated into the system. Therefore, there is a limitation in the monitoring, observing, and analysing stage. Integrating these dynamic data into the system helps it issue an effective warning.~~

Formatted: Font color: Text 1

#### ~~4.5.2.2 Limited geographical scale~~

~~There are very few developed countries where the entire landslide-prone area is covered under one or more LEWS. It is identified that, except for the area where there is a single landslide site and a local LEWS is present, most of the landslide-prone countries have the limitation of covering the whole landslide-prone area under LEWS (Ahmed et al., 2020; Ju et al., 2020; Andrade et al., 2023; Singha et al., 2024). For instance, the whole Chittagong Hill District (CHD) situated in the southeastern part of Bangladesh has five districts, and each district is affected by varying degrees of landslides. However, this area has an LEWS covering a small part of a single district, which is a small portion of the whole landslide-affected area. There might be a higher cost of operating several LEWS to cover the entire affected area. Then, a single LEWS can be operated to cover the entire affected area, which would be cost-effective and cover the whole area. Therefore, securing enough funding is another challenge (especially for LDCs and SIDS) to ensure LEWS in all areas affected by landslides.~~ ~~Beyond~~Beyond financial constraints, institutional factors can also affect implementation and long-term sustainability, including institutional capacity, technical

Formatted: Font color: Text 1

expertise, resource availability, and cooperation among relevant stakeholders (Piciullo et al., 2018; Sapena et al., 2023). From an operational perspective, the choice of monitoring strategy influences system design, maintenance requirements, transferability, and operational scalability (Segoni et al., 2018; Sapena et al., 2023).~~institutional barriers also hinder progress. For instance, limitations in capacity, expertise, or infrastructure within national agencies can significantly affect the development, operation, and sustainability of effective warning systems.~~

### 3.4.2.2 Forecast verification

Forecast verification is an essential component~~part~~ of LEWS, because it provides an objective basis for assessing forecasting skill, identifying false and missed alarms, and refining warning criteria (Piciullo et al., 2017; Guzzetti et al., 2020).~~.~~ Forecast verification may be constrained by the lack of adequate data. The absence~~lack~~ of forecast verification may ~~indicates~~ indicate weaknesses in the system development and validation~~that the system was not developed by following a precise~~ process, thereby reducing confidence in its~~decreasing~~ reliability. Moreover, forecast verification requires~~demands~~ substantial funding and human resources, which are often unavailable. Limited availability ~~The absence~~ of these resources can constrain systematic forecast verification and, consequently, undermine confidence in~~suggests gaps in the development process, ultimately undermining~~ system reliability.~~4.5.2.3 Absence of the community reflection~~

Formatted: Font: Bold

### 3.4.2.3 Community reflection

The local community ~~of the~~in a landslide-prone area plays a central role in LEWS development and should be given high priority throughout the process (Thapa and Adhikari, 2019; Lempert et al., 2023; Gamperl et al., 2023)~~is very important. They should have given the highest priority while developing a LEWS~~. LEWS are primarily dedicated to ensuring ~~their~~ community safety and reducing potential loss and damage~~security~~. However, the review found ~~it is explored~~ that community engagement ~~is~~ was infrequently documented in the reviewed ~~absent in most~~ systems, particularly Forecasting-focused systems~~LEWS~~, which may limit their effectiveness in achieving their intended purpose~~is one of the major reasons for the failure of the purpose of the system~~. It is essential to consult local communities regarding the ~~with them about what~~ resources available and unavailable ~~are present and absent~~ in their area, as this can help tailor the system to local needs and conditions (Lempert et al., 2023; Gamperl et al., 2023; Werthmann et al., 2024)~~which helps to customise the system accordingly~~. Local communities are also an important source of information on how warnings should be communicated and which communication channels are most appropriate and accessible to them.~~Besides, they are the only reliable source who can provide the information on how they need the warning, and which medium is suitable for them to receive the warning .~~ These may include ~~It can be~~ email, SMS, radio or television ~~/TV~~ announcements, megaphone miking, and other locally appropriate channels~~s~~. Even a technically robust LEWS may be ineffective if warning information is not communicated to local communities in a timely and accessible manner. Local people cannot take appropriate action if warnings do not reach them through suitable communication channels (Lempert et al., 2023; Werthmann et al., 2024). Limited community engagement can hinder the implementation of EW4All by weakening its people-centred approach, particularly by reducing the accessibility, trust, local relevance, and effective use of warnings for timely preparedness and response.~~A very good LEWS can fail if it cannot disseminate information to the locals effectively. Because the locals cannot respond to the warning if the warning is not disseminated to them via the correct medium.~~

### ~~3.4.2.44.5.2.4 Model uncertainty~~

### Model uncertainty

Model uncertainty ~~is~~ remains a major challenge~~gap~~ in LEWS (Segoni et al., 2018; Patton et al., 2023). ~~It means that there are some internal limitations and possible inaccuracies within the modelling (Ponziani et al., 2020; Zhang et al., 2024a). For instance, to reduce the data gap, AI is extensively used. However, the product created by AI is not reliable in many cases (Li et al., 2024). There are always some errors. In many cases, the LEWS do not incorporate this uncertainty into the system, making it less reliable. Besides, if a model is customised for an area with specific characteristics, and then used for another area, that is completely different in temporal and spatial extent, leading to model uncertainty. Because of this model uncertainty, a LEWS can produce a very simplified warning that may not reflect the ground truth.~~ To address

Formatted: Font: Bold
Formatted: Font: Bold
Formatted: Font color: Text 1
Formatted: Heading 5, Line spacing: single
Formatted: Font color: Text 1

these this issuees, generating multiple scenarios based on varying input conditions and conducting a sensitivity analysis can help identify how changes in key parameters affect model outputs. In the case of AI/ML use, these approaches should be supported by local validation, transferability assessment, interpretable outputs, uncertainty communication, and human oversight. Thus, AI should be considered a complementary component of a hybrid LEWS, combined with expert interpretation, field validation, and institutional decision-making (Pfeiffer et al., 2024).

### 3.4.2.54.5.2.5 Lack of standard methods

### Standardised methodology

So far, there is no known universally standardised methodology for developing LEWSforecasting systems. For instance, there are several monitoring approachesmethods, such as remote sensing, community-based monitoring, and ground-based monitoring. These Thus, data are collected using different methods by different users, reflecting inconsistenciesy in the instrumentation and data collection protocols of data collection (Piciullo et al., 2017; Liu et al., 2024). This can reduce data quality and, in some cases, makeleads to the degradation of the quality of the data and even makes it sometimes difficult to integrate into the system. Another example is the rainfall threshold, which is a very potentkey element of any rainfall-induced LEWS. However, in all LEWS,rainfall thresholds are not used in all LEWS. In some LEWS, dynamic rainfall data is are used directly. These methodological differences may contribute to All these can increased the false alarm rates. Nevertheless, existing contributions, including the performance and evaluation frameworks discussed by Calvello (2017) and Guzzetti et al. (2020), provide a useful foundation for threshold validation, warning-level evaluation, and operational performance assessment. However, it is unclear from the EW4All framework how a standardised methodology could be applied globally when landslide characteristics vary considerably between locations.to ensure a standard method applicable to the whole world when the characteristics of each landslide are different.

### 3.4.2.6 Impact-based modelling

A key gap in existing LEWS is the limited use of impact-based modelling (Guzzetti et al., 2020). Impact-based modelling should link the likelihood of forecast landslide occurrence with the exposure and vulnerability of people, infrastructure, and public services. If impact-based warnings are available, local communities can make more informed preparedness decisions and take appropriate actions to reduce their risks. The limited use of impact-based modelling can constrain the implementation of EW4All by weakening the connection between forecast hazards and their likely consequences for exposed and vulnerable populations, thereby limiting informed and timely preparedness and response actions.

## 3.4.3 Pillar 3: Last mile communication, and lead time

### 3.4.3.1 Last mile communication

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Academic publications often describe thresholds, monitoring, and forecasting methods in greater technical detail than they describe who is authorised to issue a warning, how alerts move through institutional and community channels, or how preparedness and response are activated. Fig. 9 shows that dissemination through responsible authorities or institutions and web-based platforms/dashboards were the most consistently documented modes of warning dissemination. Direct public-facing modes of warning dissemination, such as SMS, email, phone calls, broadcasting, social media, apps, sirens, and local alarms, were reported less consistently. However, the availability of warning channels alone is insufficient (Thapa and Adhikari, 2019; Werthmann et al., 2024). The warning should reach the appropriate community in the relevant location and specify the potential hazard, timing, impacts, uncertainty, and recommended actions in locally understandable formats (UNDRR and WMO, 2025). Communication planning should consider the multiple languages used within local communities, differences in literacy, disability, trust, connectivity, and the possibility that one or more dissemination channels may fail (UNDRR and WMO, 2025; Werthmann et al., 2024). For instance, in remote and mountainous areas, mobile and internet connectivity, as well as road access, may be severely disrupted during the monsoon season. Similarly, warnings delivered through megaphones or sirens may not reach all vulnerable locations. Under the EW4All warning dissemination and communication pillar, effective LEWS require redundant and locally appropriate communication pathways so that warnings can reach exposed populations despite differences in connectivity, literacy, language, disability, and access to communication technologies. The comparatively limited reporting of SMS, email, phone calls, broadcasting, social media, apps, sirens, and local alarms therefore highlights a documentation and implementation gap in last-mile communication that demands greater attention. Therefore, locally appropriate, manageable, and adaptable communication techniques should be adopted. These requirements strengthen the people-centred function of Pillar 3 without assuming that limited reporting is equivalent to the absence of operational practice.

#### 3.4.3.2 Lead time

The time interval between warning dissemination to the community and the anticipated occurrence of a hazardous event is operationally important because it determines whether appropriate protective actions can be completed (Tupper and Fearnley, 2023; Werthmann et al., 2024). A technically adequate forecast can still provide limited benefit if responsibilities are unclear or if evacuation destinations, transport arrangements, support for people requiring assistance, and decision protocols cannot be activated within the available lead time (Tupper and Fearnley, 2023; Werthmann et al., 2024; UNDRR and WMO, 2025).

### 3.4.4 Pillar 4: Preparedness and response

#### 3.4.4.1 Community awareness and preparedness

Fig. 10 shows the preparedness and response activities documented for 33 LEWS. Evacuation or self-evacuation and preparedness or decision-support mechanisms

**Formatted:** Font: Bold, Font color: Text 1

**Formatted:** Font color: Text 1

were the most frequently documented activities, while drills, training, restrictions, and closures were reported less consistently across operational-status and spatial-scale groups. However, these frequencies do not provide sufficient information to assess how effective these activities were for local communities. Evacuation or self-evacuation and preparedness or decision-support mechanisms may not always lead to effective community responses. Local people may not take proactive measures even after receiving an EW because of limited awareness or preparedness (Piciullo et al., 2018). In some cases, they may also be uncertain about the actions required to protect themselves from danger. Others may understand the warning and the recommended actions but still choose not to respond, for example because of risk perception, previous experience, trust, or other social and cultural factors.

Under the EW4All preparedness-to-respond pillar, drills and training are essential for translating landslide warnings into timely and appropriate protective actions by testing response procedures, clarifying institutional and community responsibilities, and improving public understanding of how to respond when an alert is issued. Similarly, restrictions and closures can reduce exposure by limiting access to hazardous areas during periods of elevated landslide risk; therefore, their comparatively limited reporting across the reviewed LEWS indicates that these practical warning-to-action mechanisms require greater attention to strengthen the overall effectiveness of LEWS. Therefore, greater emphasis should be placed on strengthening community awareness and preparedness through locally appropriate activities, such as mock drills, workshops, street theatre, booklets, posters, and other forms of communication delivered in local languages.

#### 3.4.4.2 Effective collaboration

In many cases, local resources, such as emergency managers, volunteers, and community actors, are available but are not effectively mobilised when needed. This can delay preparedness and response actions and increase the severity of disaster impacts. Such shortcomings often reflect weak coordination and collaboration among relevant actors. Effective coordination and collaboration with locally available resources can help reduce loss and damage, yet these arrangements may remain underutilised even where advanced warning systems are in place. Preparedness depends on prior participation, credible and understandable warnings, feasible protective options, inclusive planning, regular exercises, and feedback after warning events (Tupper and Fearnley, 2023; Werthmann et al., 2024).

**Formatted:** Font: Bold, Font color: Text 1

**Formatted:** Font color: Text 1

**Formatted:** Font: Bold, Font color: Text 1

**Formatted:** Font color: Text 1

Overall, the analysis of 45 systems does not indicate that the principal weakness of rainfall-induced LEWS lies in one technology or one pillar. Rather, it indicates an uneven transition from risk and forecasting information to authorised communication and feasible early action. Several gaps remain and require collaborative improvement, particularly in relation to Pillars 3 and 4. Researchers are making substantial contributions to Pillars 1 and 2. Forecast issuance (Pillar 2) provides the basis for warning dissemination and communication (Pillar 3). One of the most important components of an LEWS is the preparedness and response capacity of the community (Pillar 4). A LEWS is more likely to be effective when Pillars 3 and 4 function adequately and are well integrated with the preceding pillars. A LEWS may still be ineffective despite a sophisticated Pillar 2 and an effective Pillar 3 if adequate preparedness and response mechanisms are lacking, as information generated through the preceding pillars does not automatically translate into protective action. Many activities are implemented in isolation and are fragmented across different locations and organisations, making it difficult to unlock the full potential and overall effectiveness of LEWS. As LEWS comprises multiple interconnected pillars, each of which needs to function effectively, collaboration across multiple partners, institutions, and sectors is essential. Such collaboration remains limited in several areas and therefore needs to be strengthened.

**Formatted:** Font: 12 pt, Font color: Text 1

**Formatted:** Justified, Line spacing: Multiple 1.15 li

**Formatted:** Font color: Text 1

**Formatted:** Line spacing: Multiple 1.16 li

~~**4.5.2.6 Lack of impact-based modelling**~~

~~A key gap in the existing LEWS is impact-based modelling (Guzzetti et al., 2020). Very few LEWS can be able to perform this task like the one in Hong Kong, China. Although the LEWS in Hong Kong is very impactful, in many areas in China, there is no operational LEWS where it is required. To date, most of the existing LEWS are just informing the community about upcoming hazards instead of informing them about the impact of the hazards. It means the LEWS should be developed to inform the local community about the impacts on the specific structures and livelihoods. If there is an impact-based warning, the local community can plan better to minimise their risks.~~

**Formatted:** Font color: Text 1

~~**4.5.2.7 Lack of forecast verification**~~

~~Still, a lot of LEWS do not perform verification, which limits their applicability (Guzzetti et al., 2020; Gamperl et al., 2021). It can occur due to several factors. One of the main factors is the lack of historical data. If there is a lack of enough historical records, it is not possible to perform the verification. Data limitation is a big challenge in many areas. Second, it can happen if there are multiple significant underlying factors of past occurrences, like rainfall, earthquakes, human modification, and others.~~

**Formatted:** Font color: Text 1

~~Third, the spatial and temporal information of past events can vary widely, and thus, make it difficult to perform forecast verification.~~

#### ~~4.5.2.8 No control on the human modification of the hills~~

~~To date, there is no single landslide-prone area where human modification of the hills can be controlled, not even in Hong Kong and Italy. Every day, there are small or huge modifications (e.g., toe cutting, slope cutting, and so on) of hills happening. Even if there is a very advanced LEWS, it cannot perform 100% accurately, because of this human modification (Hidayat et al., 2019; Thomas et al., 2023). Because if there is any modification on any slope, the risk level of this slope is changed instantly. Therefore, to get an accurate warning, there is a need to integrate this new risk data (through susceptibility or risk map) into the system immediately, which is not yet possible. Because it is a huge task to update it daily. It is only possible if there is a dynamic susceptibility or risk map in the system.~~

#### ~~4.5.2.9 Require a multi-hazard early warning system~~

~~Although it is complex to develop a multi-hazard EWS, it is very much required because of the cascading or simultaneous nature of the hazards. However, it is explored that only a few (2-3) LEWS are focusing on multi-hazards like landslides and floods (Krøgli et al., 2018; Guzzetti et al., 2020; Prakasam et al., 2021). However, the rest of the LEWS are not MHEWS. MHEWS is essential to reduce the overall risks and losses. For instance, before hitting a rainfall-induced landslide, there is a high probability of the occurrence of flash floods. A cyclone can result in landslides. Therefore, if a LEWS is only focusing on landslides but the area is affected by multiple hazards, the community may be impacted by the first hazard or another simultaneous hazard. This instantly reduces the capacity of the community to respond to the next hazard. Consequently, an MHEWS can solve this problem.~~

## 4~~.6~~ Feasibility of implementing EW4All for LEWS

The EW4All framework is very comprehensive. It clearly calls for action across several areas and places a strong emphasis on protecting people and improving human well-being. ~~urges action on several fronts and, for the first time in history, focuses so strongly on the betterment of humans.~~ However, it also presents several feasibility concerns ~~has a number of issues~~ beyond the broader~~general~~ challenges and gaps ~~that were~~ discussed in the ~~earlier~~ previous section. Some of the feasibility concerns are outlined briefly here.

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: 14 pt

Formatted: Font color: Text 1

## 4.1 Financing and sustained implementation capacity

~~First, it~~It calls for the implementation of MHEWS worldwide. Funding is a major challenge in this regard, especially for SIDS and LDCs. At present, the UN is providing direct financial support ~~-~~to only 30 selected countries in the initial phase of ~~under~~ this framework, which appears insufficient relative to the global scale of implementation required~~is far from adequate~~.~~-~~ The latest UN global assessment report found that LDCs and SIDS still face inadequate funding for implementing the EW4All framework at the national level (UNDRR and WMO, 2025). Therefore, h~~H~~ow ~~the rest of~~all ~~the~~ countries will secure the ~~necessary~~ sustained ~~resources~~ funding necessary to implement and maintain~~ensure~~ EW4All ~~is~~ remains ~~not clearly specified in the current mandate~~a significant concern. This creates a significant feasibility concern, since securing adequate and sustained funding is challenging and represents an essential prerequisite for initiating and maintaining ~~not an easy task, and is in fact the essential first step for initiating any~~ such a programme. This concern is particularly important given the scale and ambition required to achieve universal coverage within a relatively short implementation period (Tupper and Fearnley, 2023).

## 4.2 Global consistency and local adaptation

~~Second, t~~The framework appears to promote ~~seems to emphasise the application of similar~~ common standards, or methods, or ~~models~~ approaches across different contexts~~everywhere~~. This is ~~problematic~~challenging, as lithology, physiography, geology, climatology, land use, rainfall patterns, and other characteristics differ considerably across the globe. Given these variations, it may not be feasible ~~is not viable~~ to apply a single approach to~~ developing~~ LEWS development in all locations~~everywhere~~. Recent research similarly emphasises that standardisation in MHEWS must retain sufficient flexibility to account for variations in scale, hazards, populations, and local needs (Rokhideh et al., 2025).

~~Third, while the framework highlights inclusivity, which is indeed vital, it does not provide clear guidelines on how to achieve it in practice. Experience shows that even in regions or countries with a relatively strong number of landslide forecasting systems, warning dissemination and response often fail due to extreme weather, difficult geography, or other barriers. Since "safety first" is a fundamental principle for all emergency workers, they cannot be expected to risk their lives in the immediate aftermath of a disaster. Responders often need to wait until conditions become less hostile before they can assist affected people. As these situations are largely shaped by nature, ensuring complete inclusivity is practically impossible.~~

## 4.3 Global forecasting products and local calibration

~~Fourth, ~~A related concern is how to balance globally standardised forecasting tools with the local calibration required for operational LEWS.~~the framework calls for the use of a standard forecasting model.~~ In ~~reality, reliable landslide forecasting systems~~

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

~~require the definition of local thresholds and proper calibration, which does not align with the idea of~~ practice, reliable landslide forecasting systems require locally or regionally appropriate thresholds and proper calibration (Piciullo et al., 2017; Nocentini et al., 2024), which may not align with a uniform global model. Relying on a ~~standard~~ uniform model risks producing overly general outputs that are less useful at the local level. ~~Moreover, the framework does not explain how such a standard model implementation could actually be achieved.~~This limitation is recognised in the latest global assessment report, which notes that detailed local prediction cannot be achieved using global meteorological products alone (UNDRR and WMO, 2025).

## 4.4 Last mile communication

~~Fifth, L~~last ~~-~~mile communication presents another significant challenge, particularly in areas with high linguistic diversity. Populations at risk may include people in remote locations, those without reliable telecommunications, people with disabilities, transient populations, and speakers of different languages, meaning that no single communication channel is likely to reach all groups effectively (UNDRR and WMO, 2025).

## 4.5 Inclusivity in operational implementation

While the framework highlights inclusivity, which is indeed vital, it does not provide clear guidelines on how to achieve it in practice. Experience shows that even in regions or countries with a large number of landslide forecasting systems, warning dissemination and response often fail due to extreme weather, difficult geography, or other barriers. Since “safety first” is a fundamental principle for emergency workers, they cannot be expected to place themselves at unacceptable risk in the immediate aftermath of a disaster. Responders may need to wait until conditions become sufficiently safe before they can assist affected people. As these situations are often shaped by hazard conditions and local physical constraints, ensuring complete inclusivity in practice remains difficult. The 2025 global assessment acknowledges that the implementation of inclusive approaches often lags behind policy commitments and that MHEWS may fail to reach or adequately meet the needs of diverse and marginalised groups (UNDRR and WMO, 2025).

## 4.6 Feasibility of universal coverage by 2027

~~TSixth, t~~he framework aims to achieve universal MHEWS coverage by the end of 2027. It is unclear how this target will be met, given that ~~it is already midway through~~ 2026 is already well advanced and many of the designated countries still face serious resource and capacity constraints. While the UN is providing some support, the countries outside the current support pool face even greater uncertainty. For them, implementing this framework within the stated timeframe may be particularly challenging. ~~seems unrealistic.~~The same assessment concluded that, despite tangible progress at the halfway stage of EW4All, considerable work was still required to

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

achieve universal coverage, particularly because many LDCs and SIDS lacked sufficient financial resources for implementation (UNDRR and WMO, 2025).

Other feasibility issues may also constrain the effective implementation ~~hinder the success~~ of EW4All (Rokhideh et al., 2025). Therefore, a more detailed and region-specific framework under the broader EW4All framework may be ~~is~~ needed, one that accounts for contextual realities rather than relying solely on a broad global model.

## 5 Conclusion

The analysis of 45 systems indicates that significant progress has been made towards the operationalisation of LEWS. ~~By examining 61 LEWS, it is found that significant progress has been made to make the LEWS operational. Both advancements and gaps are identified through the lens of the EW4All framework. Some gaps can be improved with experts' collaborative efforts. Currently, more landslide-affected areas are covered under LEWS than before.~~ Operational LEWS can support ~~This indicates that LEWS are no longer a dream for the affected people, which enhances~~ community~~people's~~ preparedness, response, and risk mitigation capabilities, thereby contributing to an ~~ultimately reducing the~~ overall reduction in disaster risk~~risks~~. However, progress remains fragmented and uneven.

The analysis of 45 systems shows that 27 were classified as operational, indicating substantial operational implementation within the reviewed systems, although this implementation remains uneven across spatial scales and system types. Local systems showed particularly limited operational maturity. The findings reflected not only technical challenges but also wider implementation barriers, including limited funding, maintenance requirements, weak institutional coordination, unclear warning mandates, and insufficient communication and response protocols.

One of the main findings is that the current academic literature is concentrated on Pillars 1 and 2, whereas Pillars 3 and 4 remain underreported in academic publications. This indicates a structural imbalance between technical LEWS development and the people-centred operational requirements of EW4All. It also highlights a gap between academic publications and operational reality. Many studies describe forecasting methods in detail; however, they provide limited information on institutional responsibility, warning dissemination, community preparedness, and response planning. This affects the robustness of global comparisons, as differences between systems may partly reflect differences in reporting practices rather than differences in actual operational performance. ~~Several activities have been undertaken for developing LEWS in different areas over the past few years; however, they lack proper coordination and collaboration. These activities are often fragmented into several places, making the development of LEWS quite difficult. Institutional barrier is another issue that hinders the successful implementation of a LEWS.~~

While EW4All provides an important global framework, its feasibility for LEWS is constrained~~limited~~ by insufficient funding, the promotion of standardised ~~push for standard~~ models that may not adequately account for~~neglect~~ local thresholds, and

Formatted: Font color: Text 1

persistent challenges related to~~in~~ inclusivity and last-mile communication. Future LEWS development should prioritise operational governance, risk- and impact-based information, last-mile communication, preparedness, and scalable approaches that remain responsive to local landslide conditions. Unless region-specific approaches are prioritised and adequate~~enough~~ resources are secured, establishing effective LEWS globally~~everywhere~~ by 2027 will remain ~~unrealistic~~difficult. A LEWS is more likely to be effective when Pillars 3 and 4 function adequately and are well integrated with the preceding pillars.

## Code and data availability

The data used for creating the graphs related to the trends and patterns of disasters in the world can be found in the following GitHub repository: https://github.com/RoquiaSalam/Natural-disasters.

## Declaration of ~~generative AI and~~ AI-assisted technologies ~~in the writing process~~

The main text of this work was originally written by the authors. ChatGPT ~~and Copilot were~~was used ~~selectively on a very few paragraphs~~ to improve sentence ~~clarity~~ structure and readability, including punctuation, spelling, and ~~correct~~ grammatical checks~~errors~~, while ensuring that the original ideas and meaning remained unchanged. After using these tools, the authors carefully reviewed and edited the content as needed.

## Author contributions

Roquia Salam, Bayes Ahmed, and Peter Sammonds conceptualised the research. Roquia Salam and Bayes Ahmed ~~-~~designed the methodology. Roquia Salam collected the resources, carried out the analysis, and wrote the associated interpretation. Bayes Ahmed and Peter Sammonds supervised and reviewed the manuscript. Roquia Salam prepared the final manuscript with contributions from all co-authors.

## Competing interests

One of the co-authors is a member of the editorial board of the Natural Hazards and Earth System Sciences (NHESS) journal.

## Disclaimer

Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.

Formatted: Font color: Text 1

Formatted: Font: Not Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Not Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: Not Bold, Font color: Text 1

Formatted: Font: Not Bold, Font color: Text 1

Formatted: Font: Not Bold, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Justified

**Acknowledgements**

This work is part of the PhD thesis of Roquia Salam, and she is grateful to the University College London (UCL) for fully funding her PhD study by awarding the UCL Research Excellence Scholarship (RES).

## References

Ahmed, B., Mahamud, R., Alam, S. M. R. A., Arif, M. T. A., and Bhuiyan, M. S. H.: Designing Standard Operating Procedures for a Landslide Early Warning System for Cox's Bazar, Bangladesh, in: Progress in Landslide Research and Technology, Volume 4 Issue 2, 2025, 345–364, Springer, 2026.

Ahmed, B., Rahman, M. S., Islam, R., Sammonds, P., Zhou, C., Uddin, K., and Al-Hussaini, T. M.: Developing a dynamic Web-GIS based landslide early warning system for the Chittagong Metropolitan Area, Bangladesh, ISPRS International Journal of Geo-Information, 7, 485, 2018.

Ahmed, B., Rahman, M. S., Sammonds, P., Islam, R., and Uddin, K.: Application of geospatial technologies in developing a dynamic landslide early warning system in a humanitarian context: the Rohingya refugee crisis in Cox's Bazar, Bangladesh, Geomatics, Natural Hazards and Risk, 11, 446-468, 2020.

Alcántara-Ayala, I.: Landslides in a changing world, Landslides, 1-15, 2025.

Andrade, M. R. M. D., Bortolozo, C. A., Carvalho, A. R., Egas, H. M., Garcia, K., Metodiev, D., ... and Scofield, G.: The SNAKE System: CEMADEN's Landslide Early Warning System (LEWS) Mechanism, International Journal of Geosciences, 14, 1146-1159, 2023.

ARPA Piemonte.: Scenario di innesco frane, Agenzia Regionale per la Protezione Ambientale del Piemonte (ARPA Piemonte), https://www.arpa.piemonte.it/rischi_naturali/snippets_arpa/frane/ (Accessed on 16 September 2026), 2026.

Azarafza, M., Azarafza, M., Akgün, H., Atkinson, P. M., and Derakhshani, R.: Deep learning-based landslide susceptibility mapping, Scientific Reports, 11, 24112, 2021.

Barthélemy, S., Bernardie, S., and Grandjean, G.: Assessing rainfall threshold for shallow landslides triggering: a case study in the Alpes Maritimes region, France, Natural Hazards, 1-27, 2024.

Calvello, M., D'Orsi, R. N., Piciullo, L., Paes, N. M., Magalhaes, M. A., Coelho, R., and Lacerda, W. A.: The community-based alert and alarm system for rainfall induced landslides in Rio de Janeiro, Brazil, in: Engineering Geology for Society and Territory – Volume 2: Landslide Processes, 653–657, Springer International Publishing, 2015b.

Calvello, M., D'Orsi, R. N., Piciullo, L., Paes, N., Magalhaes, M., and Lacerda, W. A.: The Rio de Janeiro early warning system for rainfall-induced landslides: Analysis of performance for the years 2010–2013, International Journal of Disaster Risk Reduction, 12, 3–15, 2015a.

Calvello, M.: Early warning strategies to cope with landslide risk, Rivista italiana di geotecnica, 2, 63-91, 2017.

Formatted: Font color: Text 1

Chaturvedi, P., Srivastava, S., and Kaur, P. B.: Landslide Early Warning System Development Using Statistical Analysis of Sensors' Data at Tangni Landslide, Uttarakhand, India, in: Proceedings of Sixth International Conference on Soft Computing for Problem Solving, 259–270, Springer, 2017.

DMR.: Daily Landslide-Susceptibility Areas from AP Model, Department of Mineral Resources (DMR), Thailand, https://data.dmr.go.th/dataset/daily-susceptibility-data-from-ap-model (Accessed on 16 September 2026), 2026.

Farina, P., Catani, F., Rosi, A., Setiawan, I., Junaidi, A., Afrizal, K., and Wijayanto, A.: Development of an early warning system for shallow landslide hazard in the Grasberg area, Indonesia, in: Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, 1425–1438, Australian Centre for Geomechanics, Perth, 2020.

Froude, M. J. and Petley, D. N.: Global fatal landslide occurrence from 2004 to 2016, Natural Hazards and Earth System Sciences, 18, 2161-2181, 2018.

Fustos-Toribio, I., Manque-Roa, N., Vásquez Antipan, D., Hermosilla Sotomayor, M., and Letelier Gonzalez, V.: Rainfall-induced landslide early warning system based on corrected mesoscale numerical models: an application for the southern Andes, Natural Hazards and Earth System Sciences, 22, 2169–2183, 2022.

Gamperl, M., Singer, J., and Thuro, K.: Internet of things geosensor network for cost-effective landslide early warning systems, Sensors, 21, 2609, 2021.

Gamperl, M., Singer, J., Garcia-Londoño, C., Seiler, L., Castañeda, J., Cerón-Hernandez, D., and Thuro, K.: Recommendations for Landslide Early Warning Systems in Informal Settlements Based on a Case Study in Medellín, Colombia, Land, 12, 1451, 2023.

Gian, Q. A., Tran, D.-T., Nguyen, D. C., Nhu, V. H., and Bui, D. T.: Design and implementation of site-specific rainfall-induced landslide early warning and monitoring system: a case study at Nam Dan landslide (Vietnam), Geomatics, Natural Hazards and Risk, 8, 1978–1996, 2017.

GSI.: Landslide Hazard, Bhusanket, Geological Survey of India (GSI), https://bhusanket.gsi.gov.in/LanslideHazard.html (Accessed on 16 September 2026), 2026.

Guo, Z., Yin, K., Gui, L., Liu, Q., Huang, F., and Wang, T.: Regional rainfall warning system for landslides with creep deformation in three gorges using a statistical black box model, Scientific Reports, 9, 8962, 2019.

Guterres, A.: United Nations Secretary-General's message on World Meteorological Day, United Nations, https://www.un.org/sg/en/content/sg/statement/2022-03-23/secretary-generals-message-world-meteorological-day (Accessed on 16 September 2026), 2022.

Guzzetti, F., Gariano, S. L., Peruccacci, S., Brunetti, M. T., Marchesini, I., Rossi, M., and Melillo, M.: Geographical landslide early warning systems, Earth-Science Reviews, 200, 102973, 2020.

Guzzetti, F.: Invited perspectives: Landslide populations–can they be predicted?, Natural Hazards and Earth System Sciences, 21, 1467-1471, 2021.

Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Haque, U., Da Silva, P. F., Devoli, G., Pilz, J., Zhao, B., Khaloua, A., ... and Glass, G. E.: The human cost of global warming: Deadly landslides and their triggers (1995–2014), Science of the Total Environment, 682, 673-684, 2019.

Harilal, G. T., Madhu, D., Ramesh, M. V., and Pullarkatt, D.: Towards establishing rainfall thresholds for a real-time landslide early warning system in Sikkim, India, Landslides, 16, 2395-2408, 2019.

Hidayat, R., Sutanto, S. J., Hidayah, A., Ridwan, B., and Mulyana, A.: Development of a landslide early warning system in Indonesia, Geosciences, 9, 451, 2019.

IDEAM.: Boletín de Alertas por Pronóstico de la Amenaza por Deslizamientos de Tierra (BADT), Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), IDEAM BADT bulletin archive, https://www.ideam.gov.co/sala-de-prensa/boletines/Bolet%C3%ADn-de-Alertas-por-Pron%C3%B3stico-de-la-Amenaza-por-Deslizamientos-de-Tierra-%28BADT%29 (Accessed on 16 September 2026), 2026.

INDECI.: 634 distritos de la sierra centro y sur en riesgo por precipitaciones, Instituto Nacional de Defensa Civil (INDECI), Nota de Prensa N.° 096-2026, Official INDECI notice, https://www.gob.pe/institucion/indeci/noticias/1366054-865-distritos-de-la-sierra-en-riesgo-por-precipitaciones (Accessed on 16 September 2026), 2026.

INGEMMET.: Ingemmet identifica 185 zonas críticas por peligros geológicos ante lluvias, Instituto Geológico, Minero y Metalúrgico (INGEMMET), https://www.gob.pe/institucion/ingemmet/noticias/1355346-ingemmet-identifica-185-zonas-criticas-por-peligros-geologicos-ante-lluvias (Accessed on 16 September 2026), 2026.

JMA.: Information at a glance: Real-time Landslide Risk Map and Weather Warnings/Advisories, Japan Meteorological Agency (JMA), https://www.jma.go.jp/jma/en/quickinfo/quickinfo.html (Accessed on 16 September 2026), 2026.

JMG.: Sistem Amaran Bencana Geologi, Jabatan Mineral dan Geosains Malaysia (JMG), https://ews.jmg.gov.my/ (Accessed on 16 September 2026), 2026.

Ju, N., Huang, J., He, C., Van Asch, T. W. J., Huang, R., Fan, X., ... and Wang, J.: Landslide early warning, case studies from Southwest China, Engineering Geology, 279, 105917, 2020.

Ju, N.-P., Huang, J., Huang, R.-Q., He, C.-Y., and Li, Y.-R.: A Real-time Monitoring and Early Warning System for Landslides in Southwest China, Journal of Mountain Science, 12, 1219–1228, 2015.

Kebaili, M. O., Foughali, K., Fathallah, K., Frihida, A., Ezzeddine, T., and Claramunt, C.: Landsliding Early Warning Prototype Using MongoDB and Web of Things Technologies, Procedia Computer Science, 98, 578–583, 2016.

KFS.: Landslide Information System – Landslide Prediction Information, Korea Forest Service (KFS), Korea Forest Service Landslide Information System, https://sansatai.forest.go.kr/mhms_pub/mhms/main/mainPage.do (Accessed on 16 September 2026), 2026.

Formatted: Font color: Text 1

Field Code Changed

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Khan, M. Y., Shafique, M., Turab, S. A., and Ahmad, N.: Characterization of an unstable slope using geophysical, UAV, and geological techniques: Karakoram Himalaya, Northern Pakistan, Frontiers in Earth Science, 9, 668011, 2021.

Konagai, K., Karunawardena, A., Bandara, K. N., Sassa, K., Onishi, R., Uzuoka, R., ... and Ariyarathna, I.: Early warning system against rainfall-induced landslide in Sri Lanka, in: Progress in Landslide Research and Technology, Volume 1 Issue 1, 2022, 217-235, Cham: Springer International Publishing, 2023.

Kong, V. W. W., Kwan, J. S. H., and Pun, W. K.: Hong Kong's landslip warning system—40 years of progress, Landslides, 17, 1453–1463, 2020.

Krøgli, I. K., Devoli, G., Colleuille, H., Boje, S., Sund, M., and Engen, I. K.: The Norwegian forecasting and warning service for rainfall-and snowmelt-induced landslides, Natural Hazards and Earth System Sciences, 18, 1427-1450, 2018.

Kumar, N. and Ramesh, M. V.: Accurate iot based slope instability sensing system for landslide detection, IEEE Sensors Journal, 22, 17151-17161, 2022.

Lay, T.: Why giant earthquakes keep catching us out, Nature, 483, 149-150, 2012.

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., ... and Zommers, Z.: Climate change 2023: synthesis report, Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change, The Australian National University, 2023.

Lee, R., White, C. J., Adnan, M. S. G., Douglas, J., Mahecha, M. D., O'Loughlin, F. E., ... and Zscheischler, J.: Reclassifying historical disasters: From single to multi-hazards, Science of the Total Environment, 912, 169120, 2024.

Lempert, R. J., Busch, L., Brown, R., Patton, A., Turner, S., Schmidt, J., and Young, T.: Community-Level, Participatory Co-Design for Landslide Warning with Implications for Climate Services, Sustainability, 15, 4294, 2023.

Lin, W., Palau, R. M., Hürlimann, M., Yin, K., and Li, Y.: A Regional-Scale Early Warning System for Rainfall-Induced Shallow Landslides Based on the Outputs of a Physically Based Model: Application to Cili County, China, Water, 18, 168, 2026.

Liu, L., Deng, J., and Tang, Y.: A dynamic management and integration framework for models in landslide early warning system, ISPRS International Journal of Geo-Information, 12, 198, 2023a.

Liu, S., Du, J., Yin, K., Zhou, C., Huang, C., Jiang, J., and Yu, J.: Regional early warning model for rainfall induced landslide based on slope unit in Chongqing, China, Engineering Geology, 333, 107464, 2024.

Liu, Y., Hazarika, H., Kanaya, H., Takiguchi, O., Murai, M., Hidayat, M. N., and Kochi, Y.: Design and Deployment of an IoT-based Landslide Early Warning System, in: 2022 International Conference and Utility Exhibition on Energy, Environment and Climate Change (ICUE), 1-7, IEEE, 2022.

Liu, Y., Hazarika, H., Murai, M., and Kochi, Y.: An IoT-based sustainable early warning system for rainfall induced landslides, in: Smart Geotechnics for Smart Societies, 1141–1144, CRC Press, 2023b.

MGB-V.: Landslide Warning Bulletin No. 1 for Tropical Storm “Ada”, Mines and Geosciences Bureau Regional Office V (MGB-V), Department of Environment and Natural Resources, https://region5.mgb.gov.ph/ (Accessed on 16 September 2026), 2026.

Miraballes, M. N. L.: Establishing Landslide Early Warning System Using Rainfall Thresholds in the Province of Albay, Philippines, Mines and Geosciences Bureau Region V (MGB-V), Official MGB technical document (Accessed on 16 September 2026), 2021.

Mondal, A. U., Liu, X., and Li, B.: Development and Deployment of IoT-Based Early Warning System for Rainfall-Induced Landslides Using Surface and Subsurface Sensors and Its Application, Applied Sciences, 16, 5738, 2026.

Murgia, E., Galli, A., Rinaldi, A., Agostino, I., Peca, M., Morgia, M., and Innocca, F.: SANF-RFI: An operational early warning system for rainfall-induced landslides along the Italian railway network, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, OnlineFirst, 2026.

Naidu, S., Sajinkumar, K. S., Oommen, T., Anuja, V. J., Samuel, R. A., and Muraleedharan, C.: Early warning system for shallow landslides using rainfall threshold and slope stability analysis, Geoscience Frontiers, 9, 1871-1882, 2018.

NDMA.: Disasters Early Warning 2 (DEW 2), National Disaster Management Authority (NDMA), Pakistan, NDMA Disaster Early Warning 2, https://ndma.gov.pk/ (Accessed on 16 September 2026), 2026.

Niyibizi, J. P. and Valentino, R.: A Comprehensive Landslide Early Warning System for Rwanda: Integrating Predictive Modeling, Environmental Parameters, and Community Engagement, International Journal of Applied and Advanced Scientific Research, 10, 48–60, 2025.

Nocentini, N., Medici, C., Barbadori, F., Gatto, A., Franceschini, R., Del Soldato, M., Rosi, A., and Segoni, S.: Optimization of rainfall thresholds for landslide early warning through false alarm reduction and a multi-source validation, Landslides, 21, 557–571, 2024.

NWS.: Flash Flood Warning – Forsyth Burn Scar, National Weather Service (NWS), Salt Lake City, UT, NWS Flash Flood Warning (Accessed on 16 September 2026), 2026.

Ofoeda, J., Boateng, R., and Effah, J.: Application programming interface (API) research: A review of the past to inform the future, International Journal of Enterprise Information Systems (IJEIS), 15, 76-95, 2019.

Ozturk, U., Bozzolan, E., Holcombe, E. A., Shukla, R., Pianosi, F., and Wagener, T.: How climate change and unplanned urban sprawl bring more landslides, Nature, 608, 262-265, 2022.

Park, J.-Y., Lee, S.-R., Lee, D.-H., and Choi, G.-M.: A study of the combination of risk analysis with a citywide landslide early warning system, WIT Transactions on Engineering Sciences, 121, 21–31, 2018.

Patton, A. I., Luna, L. V., Roering, J. J., Jacobs, A., Korup, O., and Mirus, B. B.: Landslide initiation thresholds in data-sparse regions: application to landslide early

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

warning criteria in Sitka, Alaska, USA, Natural Hazards and Earth System Sciences, 23, 3261-3284, 2023.

Pecoraro, G., Calvello, M., and Piciullo, L.: Monitoring strategies for local landslide early warning systems, Landslides, 16, 213–231, 2019.

Perera, D., Seidou, O., Agnihotri, J., Rasmy, M., Smakhtin, V., Coulibaly, P., and Mehmood, H.: Flood early warning systems: a review of benefits, challenges and prospects, UNU-INWEH, Hamilton, 2019.

Petley, D. N.: On the impact of urban landslides, Geological Society, London, Engineering Geology Special Publications, 22, 83–99, DOI: https://doi.org/10.1144/egsp22.6, 2009.

Pfeiffer, S., Dewi, M., Dall, K., Reichstein, M., Usamah, M., Werners, S. E., Shekhar, H., and Hagenlocher, M.: Strengthening equitable, impact-based early warning through artificial intelligence: four key perspectives, PreventionWeb, https://www.preventionweb.net/drr-community-voices/strengthening-equitable-impact-based-early-warning-through-artificial (Accessed on 16 September 2026), 2024.

Piciullo, L., Calvello, M., and Cepeda, J. M.: Territorial early warning systems for rainfall-induced landslides, Earth-Science Reviews, 179, 228-247, 2018.

Piciullo, L., Dahl, M. P., Devoli, G., Colleuille, H., and Calvello, M.: Adapting the EDuMaP method to test the performance of the Norwegian early warning system for weather-induced landslides, Natural Hazards and Earth System Sciences, 17, 817-831, 2017.

Ponziani, F., Ciuffi, P., Bayer, B., Berni, N., Franceschini, S., and Simoni, A.: Regional-scale InSAR investigation and landslide early warning thresholds in Umbria, Italy, Engineering Geology, 327, 107352, 2023.

Prakasam, C., Aravinth, R., Kanwar, V. S., and Nagarajan, B.: Design and Development of Real-time landslide early warning system through low cost soil and rainfall sensors, Materials Today: Proceedings, 45, 5649-5654, 2021.

RCP.: Multi-Hazard Emergency (Lifesaving) Relocation Protocol for the Rohingya Refugee Response in Bangladesh, Rohingya Coordination Platform (RCP), Cox's Bazar, Bangladesh, Multi-Hazard Emergency (Lifesaving) Relocation Protocol, 2026.

Rokhideh, M., Fearnley, C., and Budimir, M.: Multi-Hazard Early Warning Systems in the Sendai Framework for Disaster Risk Reduction: Achievements, Gaps, and Future Directions, International Journal of Disaster Risk Science, 16, 103–116, 2025.

Rossi, M., Marchesini, I., Tonelli, G., Peruccacci, S., Brunetti, M. T., Luciani, S., ... and Guzzetti, F.: TXT-tool 2.039-1.1 Italian national early warning system, Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tools: Volume 1: Fundamentals, Mapping and Monitoring, 341-349, 2018.

Salam, R., Pla, F., Ahmed, B., and Painho, M.: A Convolutional Neural Network-based approach for automatically detecting rainfall-induced shallow landslides in a data-sparse context, Natural Hazards Research, 2024.

**Formatted:** Font: (Default) Arial, Font color: Text 1

Sapena, M., Gamperl, M., Kühnl, M., Garcia-Londoño, C., Singer, J., and Taubenböck, H.: Cost estimation for the monitoring instrumentation of landslide early warning systems, Natural Hazards and Earth System Sciences, 23, 3913-3930, 2023.

Satyaningsih, R., Jetten, V., Ettema, J., Sopaheluwakan, A., Lombardo, L., and Nuryanto, D. E.: Dynamic rainfall thresholds for landslide early warning in Progo Catchment, Java, Indonesia, Natural Hazards, 119, 2133-2158, 2023.

Segoni, S., Battistini, A., Rossi, G., Rosi, A., Lagomarsino, D., Catani, F., Moretti, S., and Casagli, N.: Technical Note: An operational landslide early warning system at regional scale based on space–time-variable rainfall thresholds, Natural Hazards and Earth System Sciences, 15, 853–861, 2015.

Segoni, S., Piciullo, L., and Gariano, S. L.: Preface: Landslide early warning systems: monitoring systems, rainfall thresholds, warning models, performance evaluation and risk perception, Natural Hazards and Earth System Sciences, 18, 3179-3186, 2018.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., Zhou, B. and Allan, R.: Weather and Climate Extreme Events in a Changing Climate, in: Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1513–1766, doi: 10.1017/9781009157896.013, 2021.

Singh, A., Dhiman, N., Niraj, K. C., and Shukla, D. P.: Ensembled transfer learning approach for error reduction in landslide susceptibility mapping of the data scare region, Scientific Reports, 14, 29060, 2024.

Tang, D., Jiang, Z., Yuan, T., and Li, Y.: Stability analysis of soil slope subjected to perched water condition, KSCE Journal of Civil Engineering, 24, 2581-2590, 2020.

Thapa, P. S. and Adhikari, B. R.: Development of community-based landslide early warning system in the earthquake-affected areas of Nepal Himalaya, Journal of Mountain Science, 16, 2701–2713, 2019.

Tupper, A. C. and Fearnley, C. J.: Disaster early-warning systems can succeed—but collective action is needed, Nature, 623, 478–482, 2023.

UN.: Early Warnings for All. The UN Global Early Warning Initiative for the Implementation of Climate Adaptation. Executive Action Plan 2023-2027, United Nations (UN), https://library.wmo.int/records/item/58209-early-warnings-for-all (Accessed on 16 September 2026), 2023.

UNDRR and WMO.: Global status of multi-hazard early warning systems: Target G report 2022, United Nations Office for Disaster Risk Reduction (UNDRR), World Meteorological Organization (WMO), https://www.undrr.org/publication/global-status-multi-hazard-early-warning-systems-2022 (Accessed on 16 September 2026), 2022.

UNDRR and WMO.: Global Status of Multi-Hazard Early Warning Systems 2025, United Nations Office for Disaster Risk Reduction (UNDRR) and World Meteorological

**Formatted:** Font: (Default) Arial, Font color: Text 1

**Formatted:** Font: (Default) Arial, Font color: Text 1

Organization (WMO), https://www.undrr.org/reports/global-status-mhews-2025 (Accessed on 16 September 2026), 2025.

UNDRR.: The disaster risk reduction (DRR) glossary, United Nations Office for Disaster Risk Reduction (UNDRR), https://www.undrr.org/drr-glossary/terminology (Accessed on 16 September 2026), 2017.

UNISDR.: 2009 UNISDR Terminology on Disaster Risk Reduction, United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction (Accessed on 16 September 2026), 2009.

UNISDR.: Global Survey of Early Warning Systems, https://www.undrr.org/publication/global-survey-early-warning-systems (Accessed on 16 September 2026), 2006.

UNISDR.: Hyogo Framework for Action 2005–2015: Building the resilience of nations and communities to disasters, United Nations International Strategy for Disaster Reduction (UNISDR), https://www.undrr.org/publication/hyogo-framework-action-2005-2015-building-resilience-nations-and-communities-disasters (Accessed on 16 September 2026), 2005.

UNISDR.: Sendai Framework for Disaster Risk Reduction 2015–2030, United Nations, United Nations International Strategy for Disaster Reduction (UNISDR), https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030 (Accessed on 16 September 2026), 2015.

UNISDR.: Yokohama strategy and plan of action for a safer world: Guidelines for natural disaster prevention, preparedness and mitigation, United Nations International Strategy for Disaster Reduction (UNISDR), https://www.undrr.org/publication/yokohama-strategy-and-plan-action-safer-world-guidelines-natural-disaster-prevention (Accessed on 16 September 2026), 1994.

USGS.: Postfire Debris-Flow Hazard Maps, Landslide Hazards Program, U.S. Geological Survey (USGS), https://www.usgs.gov/programs/landslide-hazards/science/postfire-debris-flow-hazard-maps (Accessed on 16 September 2026), 2026.

Varnes, D. J.: Slope movement types and processes, Special report, 176, e33, 1978.

Werthmann, C., Sapena, M., Kühnl, M., Singer, J., Garcia, C., Breuninger, T., ... and Taubenböck, H.: Insights into the development of a landslide early warning system prototype in an informal settlement: the case of Bello Oriente in Medellín, Colombia, Natural Hazards and Earth System Sciences, 24, 1843-1870, 2024.

WHO.: Landslides, World Health Organization (WHO), https://www.who.int/health-topics/landslides (Accessed on 16 September 2026), 2025.

Wieczorek, G. F. and Snyder, J. B.: Monitoring slope movements, in Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 245–271, doi: 10.1130/2009.monitoring(11), 2009.

Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font: (Default) Arial, Font color: Text 1

Wu, D., Wang, Y., Zhang, F., and Qiu, Y.: Influences of Pore-Water Pressure on Slope Stability considering Strength Nonlinearity, Advances in Civil Engineering, 2021, 8823899, 2021.

Ya'acob, N., Tajudin, N., and Azize, A. M.: Rainfall–landslide early warning system (RLEWS) using TRMM precipitation estimates, Indonesian Journal of Electrical Engineering and Computer Science, 13, 1259–1266, 2019.

Yang, Z., Shao, W., Qiao, J., Huang, D., Tian, H., Lei, X., and Uchimura, T.: A Multi-Source Early Warning System of MEMS Based Wireless Monitoring for Rainfall-Induced Landslides, Applied Sciences, 7, 1234, 2017.

Yin, H.-Y., Lee, C.-Y., and Jan, C.-D.: A Web-Based Decision Support System for Debris Flow Disaster Management in Taiwan, in: Engineering Geology for Society and Territory – Volume 3, 109–113, Springer, 2015.

~~Abbate, A., Papini, M., and Longoni, L.: Analysis of meteorological parameters triggering rainfall-induced landslide: a review of 70 years in Valtellina, Natural Hazards and Earth System Sciences, 21, 2041-2058, 2021.~~

~~Ahmed, B.: The root causes of landslide vulnerability in Bangladesh, Landslides, 18, 1707-1720, 2021.~~

~~Ahmed, B., Rahman, M. S., Islam, R., Sammonds, P., Zhou, C., Uddin, K., and Al-Hussaini, T. M.: Developing a dynamic Web-GIS based landslide early warning system for the Chittagong Metropolitan Area, Bangladesh, ISPRS International Journal of Geo-Information, 7, 485, 2018.~~

~~Ahmed, B., Rahman, M. S., Sammonds, P., Islam, R., and Uddin, K.: Application of geospatial technologies in developing a dynamic landslide early warning system in a humanitarian context: the Rohingya refugee crisis in Cox's Bazar, Bangladesh, Geomatics, Natural Hazards and Risk, 11, 446-468, 2020.~~

~~Alcántara-Ayala, I.: Landslides in a changing world, Landslides, 1-15, 2025.~~

~~Amelia, A., Arief, A., Lubis, A. M. P., Sundawa, B. V., and Rusdi, M.: Design of Early Landslide Warning System Caused By Rainfall Influence, in: 2018 International Conference on Applied Science and Technology (iCAST), 477-480, IEEE, 2018.~~

~~Amune, A., Patil, S., Ushir, D., and Nangare, A.: IOT Based Smart LandSlide Detection System (S-LDS), in: 2023 International Conference on Emerging Smart Computing and Informatics (ESCI), 1-6, IEEE, 2023.~~

~~Andrade, M. R. M. D., Bortolozo, C. A., Carvalho, A. R., Egas, H. M., Garcia, K., Metodiev, D., ... and Scofield, G.: The SNAKE System: CEMADEN's Landslide Early Warning System (LEWS) Mechanism, International Journal of Geosciences, 14, 1146-1159, 2023.~~

~~Azarafza, M., Azarafza, M., Akgün, H., Atkinson, P. M., and Derakhshani, R.: Deep learning-based landslide susceptibility mapping, Scientific Reports, 11, 24112, 2021.~~

~~Barthélemy, S., Bernardie, S., and Grandjean, G.: Assessing rainfall threshold for shallow landslides triggering: a case study in the Alpes Maritimes region, France, Natural Hazards, 1-27, 2024.~~

Binu, K. E., Anoopkumar, L. T., Sunil, M., Jose, M., and Preetha, K. G.: Dynamic Landslide Prediction, Monitoring, and Early Warning with Explainable AI: A Comprehensive Approach, in: 2024 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC), 960-965, IEEE, 2024.

Calvello, M.: Early warning strategies to cope with landslide risk, Rivista italiana di geotecnica, 2, 63-91, 2017.

Cao, Y. M., Guo, W., Wu, Y. M., Li, L. P., Zhang, Y. X., and Lan, H. X.: An hourly shallow landslide warning model developed by combining automatic landslide spatial susceptibility and temporal rainfall threshold predictions, Journal of Mountain Science, 19, 3370-3387, 2022.

Chinamuttevi, V. S., Prasad, K. D. V., Gowda, D., Begum, A. Y., Tanguturi, R. C., and Ahmed, B.: Implementation of an Early Warning System using Internet of Things and Rainfall Threshold, in: 2022 6th International Conference on Electronics, Communication and Aerospace Technology, 491-496, IEEE, 2022.

Collini, E., Palesi, L. I., Nesi, P., Pantaleo, G., Nocentini, N., and Rosi, A.: Predicting and understanding landslide events with explainable AI, IEEE Access, 10, 31175-31189, 2022.

Curipaco, D. S. C., Jerónimo, P. L. G., Diaz, A. T., Campomanes, G. P., Quijano, S. A. C., Mohamed, M. M. H., and Guerreros, D. C.: Coupling of an Automatic Landslide Warning System for Retaining Walls for Road Infrastructure Protection, in: 2023 9th International Conference on Mechatronics and Robotics Engineering (ICMRE), 158-162, IEEE, 2023.

Dai, K., Li, Z., Xu, Q., Bürgmann, R., Milledge, D. G., Tomas, R., ... and Liu, J.: Entering the era of earth observation based landslide warning systems: A novel and exciting framework, IEEE Geoscience and Remote Sensing Magazine, 8, 136-153, 2020.

Du, Y., Ning, L., Chicas, S. D., and Xie, M.: A new early warning Criterion for assessing landslide risk, Natural Hazards, 116, 537-549, 2023.

Fang, Z., Tanyas, H., Gorum, T., Dahal, A., Wang, Y., and Lombardo, L.: Speech recognition in landslide predictive modelling: A case for a next generation early warning system, Environmental Modelling & Software, 170, 105833, 2023.

Fatimah, P., Irawan, B., and Setianingsih, C.: Design of landslide early warning system using fuzzy method based on android, in: 2020 12th International Conference on Information Technology and Electrical Engineering (ICITEE), 350-355, IEEE, 2020.

Froude, M. J. and Petley, D. N.: Global fatal landslide occurrence from 2004 to 2016, Natural Hazards and Earth System Sciences, 18, 2161-2181, 2018.

Gamperl, M., Singer, J., and Thuro, K.: Internet of things geosensor network for cost-effective landslide early warning systems, Sensors, 21, 2609, 2021.

GSI.: Landslide Hazard, Bhusanket, Geological Survey of India (GSI), https://bhusanket.gsi.gov.in/LanslideHazard.html (Accessed on 31 March 2026), 2024.

Guo, Z., Yin, K., Gui, L., Liu, Q., Huang, F., and Wang, T.: Regional rainfall warning system for landslides with creep deformation in three gorges using a statistical black box model, Scientific Reports, 9, 8962, 2019.

Gupta, K. and Satyam, N.: Integrating real time sensor data for improved hydrogeotechnical modelling in landslide early warning in Western Himalaya, Engineering Geology, 338, 107630, 2024.

Guterres, A.: United Nations Secretary-General's message on World Meteorological Day, United Nations, https://www.un.org/sg/en/content/sg/statement/2022-03-23/secretary-generals-message-world-meteorological-day (Accessed on 31 March 2026), 2022.

Guzzetti, F.: Invited perspectives: Landslide populations–can they be predicted?, Natural Hazards and Earth System Sciences, 21, 1467-1471, 2021.

Guzzetti, F., Gariano, S. L., Peruccacci, S., Brunetti, M. T., Marchesini, I., Rossi, M., and Melillo, M.: Geographical landslide early warning systems, Earth Science Reviews, 200, 102973, 2020.

Guzzetti, F., Melillo, M., Calvello, M., Pecoraro, G., and Mondini, A. C.: Independent demonstration of a deep learning system for rainfall-induced landslide forecasting in Italy, Landslides, 1-8, 2024.

Haque, U., Da Silva, P. F., Devoli, G., Pilz, J., Zhao, B., Khaloua, A., ... and Glass, G. E.: The human cost of global warming: Deadly landslides and their triggers (1995–2014), Science of the Total Environment, 682, 673-684, 2019.

Harilal, G. T., Madhu, D., Ramesh, M. V., and Pullarkatt, D.: Towards establishing rainfall thresholds for a real-time landslide early warning system in Sikkim, India, Landslides, 16, 2395-2408, 2019.

Hidayat, R., Sutanto, S. J., Hidayah, A., Ridwan, B., and Mulyana, A.: Development of a landslide early warning system in Indonesia, Geosciences, 9, 451, 2019.

ISO.: ISO Online Browsing Platform (OBP), International Organization for Standardization (ISO), https://www.iso.org/obp/ui/ (Accessed on 31 March 2026), n.d.

Jarah, N. B., Alasadi, A. H. H., and Hashim, K. M.: Earthquake prediction technique: A comparative study, IAES Int. J. Artif. Intell.(IJ-AI), 2252, 1027, 2023.

Jarrahi, M. H.: Artificial intelligence and the future of work: Human-AI symbiosis in organizational decision making, Business Horizons, 61, 577-586, 2018.

Joshi, A., Grover, J., Kanungo, D. P., and Panigrahi, R. K.: Edge assisted reliable landslide early warning system, in: 2019 IEEE 16th India Council International Conference (INDICON), 1-4, IEEE, 2019.

Joshi, A., Kanungo, D. P., and Panigrahi, R. K.: Fault tolerant edge for landslide early warning system, in: 2022 IEEE 19th India Council International Conference (INDICON), 1-7, IEEE, 2022.

Joshi, A., Kanungo, D. P., and Panigrahi, R. K.: Development of landslide forecasting system using deep learning, in: 2023 IEEE Applied Sensing Conference (APSCON), 1-3, IEEE, 2023.

Ju, N., Huang, J., He, C., Van Asch, T. W. J., Huang, R., Fan, X., ... and Wang, J.: Landslide early warning, case studies from Southwest China, Engineering Geology, 279, 105917, 2020.

Khan, M. Y., Shafique, M., Turab, S. A., and Ahmad, N.: Characterization of an unstable slope using geophysical, UAV, and geological techniques: Karakoram Himalaya, Northern Pakistan, Frontiers in Earth Science, 9, 668011, 2021.

Konagai, K., Karunawardena, A., Bandara, K. N., Sassa, K., Onishi, R., Uzuoka, R., ... and Ariyarathna, I.: Early warning system against rainfall-induced landslide in Sri Lanka, in: Progress in Landslide Research and Technology, Volume 1 Issue 1, 2022, 217-235, Cham: Springer International Publishing, 2023.

Krøgli, I. K., Devoli, G., Colleuille, H., Boje, S., Sund, M., and Engen, I. K.: The Norwegian forecasting and warning service for rainfall and snowmelt induced landslides, Natural Hazards and Earth System Sciences, 18, 1427-1450, 2018.

Kumar, D., Mahapatro, A. K., and Singh, S. K.: A Potential Landslide Early Warning System Based on Threshold Velocity of 1 mm/min, in: 2023 IEEE International Conference on Recent Advances in Systems Science and Engineering (RASSE), 1-6, IEEE, 2023.

Kumar, N. and Ramesh, M. V.: Accurate iot based slope instability sensing system for landslide detection, IEEE Sensors Journal, 22, 17151-17161, 2022.

Kumar, S., Panigrahi, R. K., and Kanungo, D. P.: Development of IoE Edge AI Architecture For Landslide Early Warning System, in: 2024 IEEE Applied Sensing Conference (APSCON), 1-4, IEEE, 2024.

Lay, T.: Why giant earthquakes keep catching us out, Nature, 483, 149-150, 2012.

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., ... and Zommers, Z.: Climate change 2023: synthesis report, Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change, The Australian National University, 2023.

Lee, R., White, C. J., Adnan, M. S. G., Douglas, J., Mahecha, M. D., O'Loughlin, F. E., ... and Zscheischler, J.: Reclassifying historical disasters: From single to multi-hazards, Science of the Total Environment, 912, 169120, 2024.

Li, M., Zhu, M., Hec, Y., He, Z., Wang, N., Zheng, Z., and Zhou, G.: Warning of rainfall-induced landslide in Bazhou District, in: IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium, 6879-6882, IEEE, 2020.

Li, Y., Fu, B., Yin, Y., Hu, X., Wang, W., Wang, W., ... and Long, G.: Review on the Artificial Intelligence-based methods in Landslide Detection and Susceptibility Assessment: Current Progress and Future Directions, Intelligent Geoengineering, 2024.

Li, Y., Huang, J., Jiang, S. H., Huang, F., and Chang, Z.: A web-based GPS system for displacement monitoring and failure mechanism analysis of reservoir landslide, Scientific Reports, 7, 17171, 2017.

Liu, L., Deng, J., and Tang, Y.: A dynamic management and integration framework for models in landslide early warning system, ISPRS International Journal of Geo-Information, 12, 198, 2023.

Liu, Q., Jian, W., and Nie, W.: Rainstorm-induced landslides early warning system in mountainous cities based on groundwater level change fast prediction, Sustainable Cities and Society, 69, 102817, 2021.

Liu, S., Du, J., Yin, K., Zhou, C., Huang, C., Jiang, J., and Yu, J.: Regional early warning model for rainfall induced landslide based on slope unit in Chongqing, China, Engineering Geology, 333, 107464, 2024.

Liu, Y., Hazarika, H., Kanaya, H., Takiguchi, O., Murai, M., Hidayat, M. N., and Kochi, Y.: Design and Deployment of an IoT based Landslide Early Warning System, in: 2022 International Conference and Utility Exhibition on Energy, Environment and Climate Change (ICUE), 1-7, IEEE, 2022.

Naidu, S., Sajinkumar, K. S., Oommen, T., Anuja, V. J., Samuel, R. A., and Muraleedharan, C.: Early warning system for shallow landslides using rainfall threshold and slope stability analysis, Geoscience Frontiers, 9, 1871-1882, 2018.

Nguyen, V. T., Nguyen, Q. A., and Nguyen, N. K.: Method for monitoring and forecasting landslide phenomenon based on machine learning, MethodsX, 102797, 2024.

Nong, M. A. H. B. M., Berahan, N. B., Raya, L., and Alkawaz, M. H.: Solar Powered Landslide Detection Using Global System Mobile (GSM) Communication, in: 2023 IEEE 14th Control and System Graduate Research Colloquium (ICSGRC), 139-143, IEEE, 2023.

Ofoeda, J., Boateng, R., and Effah, J.: Application programming interface (API) research: A review of the past to inform the future, International Journal of Enterprise Information Systems (IJEIS), 15, 76-95, 2019.

Ozturk, U., Bozzolan, E., Holcombe, E. A., Shukla, R., Pianosi, F., and Wagener, T.: How climate change and unplanned urban sprawl bring more landslides, Nature, 608, 262-265, 2022.

Palau, R. M., Berenguer, M., Hürlimann, M., and Sempere-Torres, D.: Implementation of hydrometeorological thresholds for regional landslide warning in Catalonia (NE Spain), Landslides, 20, 2039-2054, 2023.

Patton, A. I., Luna, L. V., Roering, J. J., Jacobs, A., Korup, O., and Mirus, B. B.: Landslide initiation thresholds in data-sparse regions: application to landslide early warning criteria in Sitka, Alaska, USA, Natural Hazards and Earth System Sciences, 23, 3261-3284, 2023.

Perera, D., Seidou, O., Agnihotri, J., Rasmy, M., Smakhtin, V., Coulibaly, P., and Mehmood, H.: Flood early warning systems: a review of benefits, challenges and prospects, UNU-INWEH, Hamilton, 2019.

Petley, D. N.: On the impact of urban landslides, Geological Society, London, Engineering Geology Special Publications, 22, 83-99, DOI: https://doi.org/10.1144/egsp22.6, 2009.

Pfeiffer, S., Dewi, M., Dall, K., Reichstein, M., Usamah, M., Werners, S. E., Shekhar, H., and Hagenlocher, M.: Strengthening equitable, impact-based early warning through artificial intelligence: four key perspectives, PreventionWeb,

https://www.preventionweb.net/drr-community-voices/strengthening-equitable-impact-based-early-warning-through-artificial (Accessed on 31 March 2026), 2024.

Piciullo, L., Calvello, M., and Cepeda, J. M.: Territorial early warning systems for rainfall-induced landslides, Earth Science Reviews, 179, 228-247, 2018.

Piciullo, L., Dahl, M. P., Devoli, G., Colleuille, H., and Calvello, M.: Adapting the EDuMaP method to test the performance of the Norwegian early warning system for weather induced landslides, Natural Hazards and Earth System Sciences, 17, 817-831, 2017.

Ponziani, F., Ciuffi, P., Bayer, B., Berni, N., Franceschini, S., and Simoni, A.: Regional-scale InSAR investigation and landslide early warning thresholds in Umbria, Italy, Engineering Geology, 327, 107352, 2023.

Ponziani, M., Pogliotti, P., Stevenin, H., and Ratto, S. M.: Debris-flow Indicator for an early warning system in the Aosta valley region, Natural Hazards, 104, 1819-1839, 2020.

Prakasam, C., Aravinth, R., Kanwar, V. S., and Nagarajan, B.: Design and Development of Real time landslide early warning system through low cost soil and rainfall sensors, Materials Today: Proceedings, 45, 5649-5654, 2021.

Renuga, D., S., Arulmozhivarman, P., and Venkatesh, C.: ANN based rainfall prediction—a tool for developing a landslide early warning system, in: Advancing Culture of Living with Landslides: Volume 3 Advances in Landslide Technology, 175-182, Springer International Publishing, 2017.

Rossi, M., Marchesini, I., Tonelli, G., Peruccacci, S., Brunetti, M. T., Luciani, S., ... and Guzzetti, F.: TXT-tool 2.039-1.1 Italian national early warning system, Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tools: Volume 1: Fundamentals, Mapping and Monitoring, 341-349, 2018.

Salam, R., Pla, F., Ahmed, B., and Painho, M.: A Convolutional Neural Network-based approach for automatically detecting rainfall-induced shallow landslides in a data-sparse context, Natural Hazards Research, 2024.

Sapena, M., Gamperl, M., Kühnl, M., Garcia-Londoño, C., Singer, J., and Taubenböck, H.: Cost estimation for the monitoring instrumentation of landslide early warning systems, Natural Hazards and Earth System Sciences, 23, 3913-3930, 2023.

Satyaningsih, R., Jetten, V., Ettema, J., Sopaheluwakan, A., Lombardo, L., and Nuryanto, D. E.: Dynamic rainfall thresholds for landslide early warning in Progo Catchment, Java, Indonesia, Natural Hazards, 119, 2133-2158, 2023.

Segoni, S., Piciullo, L., and Gariano, S. L.: Preface: Landslide early warning systems: monitoring systems, rainfall thresholds, warning models, performance evaluation and risk perception, Natural Hazards and Earth System Sciences, 18, 3179-3186, 2018.

Sejera, M. M., Ballado, A. H., Fernando, B. N. H., Montemayor, M. F. I. A., and Niebres, A. V. D.: Mobile App Based Early Warning System for Landslides Using Land Monitoring through GSM, in: 2020 IEEE Region 10 Symposium (TENSYMP), 90-93, IEEE, 2020.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-

Serrano, S. M., Wehner, M., Zhou, B. and Allan, R.: Weather and Climate Extreme Events in a Changing Climate, in: Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1513–1766, doi: 10.1017/9781009157896.013, 2021.

Sigiro, M. M. T., Manalu, I. P., Wowiling, G. I., Silalahi, S. M., Sinambela, E. S., and Simatupang, F.: Improving Road Safety in Landslide Prone Areas: Real-time LoRa-Based Landslide Detection and Warning System, in: 2023 29th International Conference on Telecommunications (ICT), 1-5, IEEE, 2023.

Singh, A., Dhiman, N., Niraj, K. C., and Shukla, D. P.: Ensembled transfer learning approach for error reduction in landslide susceptibility mapping of the data scare region, Scientific Reports, 14, 29060, 2024.

Singha, S., Rath, J., Ghosh, S., Nanda, S., and Ranjan, P.: Sensor Driven Landslide Detection System for the South Eastern Region of India, in: 2024 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), 1-6, IEEE, 2024.

Sofwan, A. and Azka, T. H.: Early Warning System of Landslide Disaster using Generalized Neural Network Algorithm, in: 2019 6th International Conference on Information Technology, Computer and Electrical Engineering (ICITACEE), 1-4, IEEE, 2019.

Sousa, I. A., Bortolozo, C. A., Mendes, T. S. G., de Andrade, M. R. M., Neto, G. D., Metodiev, D., ... and Mendes, R. M.: Development of a soil moisture forecasting method for a landslide early warning system (LEWS): Pilot cases in coastal regions of Brazil, Journal of South American Earth Sciences, 131, 104631, 2023.

Tang, D., Jiang, Z., Yuan, T., and Li, Y.: Stability analysis of soil slope subjected to perched water condition, KSCE Journal of Civil Engineering, 24, 2581-2590, 2020.

Thein, T. L. L., Sein, M. M., Murata, K. T., and Tungpimolrut, K.: Real-time monitoring and early warning system for landslide preventing in myanmar, in: 2020 IEEE 9th global conference on consumer electronics (GCCE), 303-304, IEEE, 2020.

Thomas, J., Gupta, M., and Prusty, G.: Assessing global parameters of slope stability model using Earth data observations for forecasting rainfall-induced shallow landslides, Journal of Applied Geophysics, 212, 104994, 2023.

UN.: Early Warnings for All. The UN Global Early Warning Initiative for the Implementation of Climate Adaptation. Executive Action Plan 2023-2027, United Nations (UN), https://library.wmo.int/records/item/58209-early-warnings-for-all (Accessed on 31 March 2026), 2023.

UNDRR and WMO.: Global status of multi hazard early warning systems: Target G report 2022, United Nations Office for Disaster Risk Reduction (UNDRR), World Meteorological Organization (WMO), https://www.undrr.org/publication/global-status-multi-hazard-early-warning-systems-2022 (Accessed on 31 March 2026), 2022.

UNDRR.: The disaster risk reduction (DRR) glossary, United Nations Office for Disaster Risk Reduction (UNDRR), https://www.undrr.org/drr-glossary/terminology (Accessed on 31 March 2026), 2017.

UNISDR.: Yokohama strategy and plan of action for a safer world: Guidelines for natural disaster prevention, preparedness and mitigation, United Nations International Strategy for Disaster Reduction (UNISDR), https://www.undrr.org/publication/yokohama-strategy-and-plan-action-safer-world-guidelines-natural-disaster-prevention (Accessed on 31 March 2026), 1994.

UNISDR.: Hyogo Framework for Action 2005-2015: Building the resilience of nations and communities to disasters, United Nations International Strategy for Disaster Reduction (UNISDR), https://www.undrr.org/publication/hyogo-framework-action-2005-2015-building-resilience-nations-and-communities-disasters (Accessed on 31 March 2026), 2005.

UNISDR.: Global Survey of Early Warning Systems, https://www.undrr.org/publication/global-survey-early-warning-systems (Accessed on 31 March 2026), 2006.

UNISDR.: Sendai Framework for Disaster Risk Reduction 2015-2030, United Nations, United Nations International Strategy for Disaster Reduction (UNISDR), https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030 (Accessed on 31 March 2026), 2015.

USGS.: Early warning system, United States Geological Survey (USGS), https://www.usgs.gov/programs/landslide-hazards/science/early-warning-system (Accessed on 31 March 2026), 2018.

Varnes, D. J.: Slope movement types and processes, Special report, 176, e33, 1978.

Wang, D.: Prototype Design of Landslide Forecast System Based on Axure, in: 2020 3rd International Conference on Advanced Electronic Materials, Computers and Software Engineering (AEMCSE), 1-4, IEEE, 2020.

Wardana, D. P. T., Ramdani, F., and Pradana, F.: Real Time Landslide Monitoring System Based on 3D WebGIS and Embedded System, in: 2018 4th International Symposium on Geoinformatics (ISyG), 1-7, IEEE, 2018.

Welchowski, T., Maloney, K. O., Mitchell, R., and Schmid, M.: Techniques to Improve Ecological Interpretability of Black-Box Machine Learning Models: Case Study on Biological Health of Streams in the United States with Gradient Boosted Trees, Journal of Agricultural, Biological and Environmental Statistics, 27, 175-197, 2022.

Werthmann, C., Sapena, M., Kühnl, M., Singer, J., Garcia, C., Breuninger, T., ... and Taubenböck, H.: Insights into the development of a landslide early warning system prototype in an informal settlement: the case of Bello Oriente in Medellín, Colombia, Natural Hazards and Earth System Sciences, 24, 1843-1870, 2024.

WHO.: Landslides, World Health Organization (WHO), https://www.who.int/health-topics/landslides (Accessed on 31 March 2026), 2025.

Wieczorek, G. F. and Snyder, J. B.: Monitoring slope movements, in Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 245-271, doi: 10.1130/2009.monitoring(11), 2009.

Wu, D., Wang, Y., Zhang, F., and Qiu, Y.: Influences of Pore-Water Pressure on Slope Stability considering Strength Nonlinearity, Advances in Civil Engineering, 2021, 8823899, 2021.

Wu, Y., Niu, R., Wang, Y., and Chen, T.: A fast deploying monitoring and real-time early warning system for the Baige Landslide in Tibet, China, Sensors, 20, 6619, 2020.

Xu, Q., Peng, D., Zhang, S., Zhu, X., He, C., Qi, X., ... and Ju, N.: Successful implementations of a real-time and intelligent early warning system for loess landslides on the Heifangtai terrace, China, Engineering Geology, 278, 105817, 2020.

Yang, X., Jia, M., Wang, J., Yang, X., Wu, P., and Ji, B.: An integrated space-air-ground monitoring and early warning system of landslide disaster, in: 2021 7th International Conference on Hydraulic and Civil Engineering & Smart Water Conservancy and Intelligent Disaster Reduction Forum (ICHCE & SWIDR), 846-851, IEEE, 2021.

Zhang, J., Tang, H., Li, C., Gong, W., Zhou, B., and Zhang, Y.: Deformation stage division and early warning of landslides based on the statistical characteristics of landslide kinematic features, Landslides, 21, 717-735, 2024b.

Formatted: Indent: Left: 0 cm

~~Zhang, J., Tang, H., Tan, Q., Mao, M., Zhou, B., and Zhang, Y.: A generalized early warning criterion for the landslide risk assessment: deformation probability index (DPI), Acta Geotechnica, 1-21, 2024a.~~

~~Zhang, J., Tang, H., Zhou, B., Wen, T., and Zhang, S.: A new early warning criterion for landslides movement assessment: Deformation Standardized Anomaly Index, Bulletin of Engineering Geology and the Environment, 83, 205, 2024.~~

~~Zhang, S., Jiang, T., Pei, X., Huang, R., Xu, Q., Xie, Y., ... and Zhi, L.: A new forecasting method for failure time of creep landslide based on nonlinear creep behavior and new pre-warning criterion, Frontiers in Earth Science, 10, 1018432, 2022.~~Appendix I: Rainfall-induced LEWS records reviewed (2015–2026), including locality, areal coverage, system scale, system type (LEWS vs. forecasting-focused), operational evidence, evidence strength, the evidence basis for each EW4All pillar, source type, and reference.

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bangladesh | Chittagong Metropolitan Area (CMA) | City / metropolitan-area-wide | Regional | LEWS | A dynamic public Web-GIS EWS was developed, but the paper presents it as a proposed research system rather than a confirmed, routinely operational system managed by an authorised institution. | High: non-operational stage explicit | Paper itself | Paper itself | Paper itself | Journal article | Ahmed et al., 2018 |
| Bangladesh | Cox's Bazar District, especially Rohingya refugee camps in Ukhia and Teknaf | District-wide / multiple subdistricts and camps | Regional | LEWS | A live web-based landslide early warning system operates in Cox's Bazar District and is institutionally linked to the Bangladesh Meteorological Department's official Landslide Warning portal, through which the FAO-supported system is provided as a landslide warning service. | High: direct operational evidence | Paper itself | Paper itself + Official website | Paper itself + Official document | Journal article, public document, official website | Ahmed et al., 2020; Ahmed et al., 2026; RCP, 2026 |
| Brazil | CEMADEN-monitored high-risk municipalities; examples include Blumenau, Petrópolis, Nova Friburgo and Florianópolis | National/high-risk municipalities | National | LEWS | SNAKE is deployed in the CEMADEN Situation Room and is presented as an operational system for monitoring and issuing alerts in high-risk municipalities. | High: direct operational evidence | Paper itself | Paper itself + Official website | Paper itself | Journal article, official website | Andrade et al., 2023 |
| Brazil | Rio de Janeiro municipality, including 103 informal communities | Municipality-wide / multi-community warning network | Regional | LEWS | Alerta-Rio is a municipality-operated, citywide landslide early warning system, and the paper evaluates its operational performance. A2C2 was | High: direct operational evidence | Paper itself | Paper itself + Official website 1 + Official website 2 | Official website 1+ Official website 2+ Official Blog | Book chapter, Journal article, | Calvello et al., 2015a; Calvello et al., 2015b |



Formatted: Indent: Left: 0 cm
Formatted: Centered
Formatted Table
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Justified
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Justified
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Justified
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Justified
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1
Formatted: Font color: Text 1
Formatted: Font: (Default) Arial, 8 pt, Font color: Text 1

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | deployed and is reported to be currently in use across 103 informal communities in Rio de Janeiro. | | | | | official website | |
| Chile | Southern Andes / northern Patagonia in southern Chile | Broad subnational mountainous region | Regional | Forecasting focused | The paper explicitly describes the system as pre-operational and states that an operational-scale RILEWS has not yet been established in the southern Andes. | High: non-operational stage explicit | Paper itself | No explicit information | No explicit information | Journal article | Fustos-Toribio et al., 2022 |
| China | Cili County, Hunan Province | County-wide / regional warning area | Regional | Forecasting focused | The LEWS was implemented and retrospectively tested using 2020 data and is described as adaptable for future operational implementation. | High: non-operational stage explicit | Paper itself | No explicit information | No explicit information | Journal article | Lin et al., 2026 |
| China | Huaihua City, Hunan Province case study / operational host LEWS | City / municipality-wide operational host system | Regional | Forecasting focused | The paper describes an operational LEWS in Huaihua City with GIS, monitoring-data processing, warning mechanisms, and SMS-based warning-information release. However, the study primarily focuses on the experimental integration and testing of a model-management framework within this host system, while routine adoption, operational responsibility, or warning authority by a recognised institution is not demonstrated. | Moderate: non-operational stage inferred | Paper itself | Paper itself | No explicit information | Journal article | Liu et al., 2023a |
| China | Landslide-prone slope in the Wenchuan earthquake region | Single instrumented slope / site | Local | Forecasting focused | The multi-source system was established and tested on an actual slope, and warning criteria were proposed; however, routine operational use for warning purposes was not demonstrated. | Moderate: non-operational stage inferred | Paper itself | No explicit information | No explicit information | Journal technical note | Yang et al., 2017 |
| China | Southwest China; site-specific deployments including Longjingwan | Multiple site-specific slope and catchment deployments | Local | LEWS | The SKLGP site-specific LEWS was progressively developed and applied across multiple landslide and debris-flow sites in Southwest China. | Moderate: non-operational stage inferred | Paper itself | Paper itself | Paper itself | Journal article | Ju et al., 2015; Ju et al., 2020 |

**Formatted:** Centered
**Formatted Table**
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

| Country | | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | landslide, Kaiyang County, Guizhou Province; Xingyi rockslide, Guizhou Province; Baige debris slide at the Tibet–Sichuan border; and Zoumaling catchment, Qingping, Sichuan Province | | | | Ju et al. (2015) document a real-time monitoring and computer-aided warning application at Longjingwan, while Ju et al. (2020) report subsequent real-time applications and successful warning cases at Baige, Xingyi,and Zoumaling. However, the publications do not clearly demonstrate routine institutional adoption, operational responsibility, or formal warning authority by a governmental or other recognised operational institution. | | | | | | |
| China | | Xinyu City, Jiangxi Province | Single instrumented slope / site within Xinyu City | Local | LEWS | The IoT-based real-time monitoring and early warning system was deployed on a landslide-prone residential slope and successfully detected and recorded a rainfall-induced slope failure in July 2021. The system includes automated notifications to experts and registered users, together with a proposed formal warning and emergency-response workflow involving local government. However, routine institutional adoption, operational responsibility, or formal warning authority by a recognised operational institution is not demonstrated. | Moderate: non-operational stage inferred | Paper itself | Paper itself | Paper itself | Journal article | Mondal et al., 2026 |
| Colombia | | Bello Oriente informal settlement, Medellín | Single settlement / community | Local | LEWS | The Inform@Risk LEWS project was still under implementation and testing at the time of publication; its classification as a Full LEWS refers to the documented design of the complete warning | High: non-operational stage explicit | Paper itself | Paper itself | Paper itself | Journal article | Gamperl et al., 2021; Gamperl et al., 2023; and Werthmann et al., 2024 |

**Formatted:** Centered

**Formatted Table**

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | chain rather than to confirmed operational maturity. | | | | | | |
| Colombia | Nationwide Colombia; municipal alert classification | National / municipal alert coverage | National | LEWS | The official IDEAM page states that the BADT is produced daily and that current bulletins are publicly archived up to September 2026. | High: direct operational evidence | Official website | Official website | Official website 1 + Official website 2 | Official government operational bulletin / portal | IDEAM, 2026 |
| Hong Kong, China | Hong Kong territory | Territory-wide | Regional | LEWS | The Hong Kong Landslip Warning System is implemented jointly by the GEO and HKO and has been operational since 1977. | High: direct operational evidence | Paper itself | Official website | Official website | Journal technical note, official website | Kong et al., 2020 |
| India | Amboori, Kerala | Single landslide / local slope area | Local | Forecasting focused | The study develops rainfall and slope-stability thresholds, together with an EWS methodology; however, it does not document an operational warning service in routine use. | Moderate: non-operational stage inferred | Paper itself | No explicit information | No explicit information | Journal research article | Naidu et al., 2018 |
| India | Chandmari, Sikkim, North Eastern Himalayas | Single instrumented slope/site | Local | LEWS | The IoT LEWS was installed in Chandmari, Sikkim, in 2019 and is reported to have remained operational since then. | High: direct operational evidence | Paper itself | Official website | Official website | Journal article, official website | Kumar and Ramesh, 2022 |
| India | Himachal Pradesh Himalayan region; pilot field site | Pilot field site / local slope | Local | Forecasting focused | A pilot EWS was installed for sensor and data-quality assessment; however, the paper states that further calibration and deployment are required, indicating that the system is not yet operational. | High: non-operational stage explicit | Paper itself | No explicit information | No explicit information | Conference proceedings article | Prakasam et al., 2021 |
| India | Operational bulletins for Darjeeling and Kalimpong (West Bengal) and The Nilgiris (Tamil Nadu); experimental expansion to other landslide-prone districts | National programme / selected operational districts across multiple states | National | LEWS | The Geological Survey of India (GSI) explicitly states that the system is operational and that public landslide forecast bulletins are routinely issued for Darjeeling, Kalimpong, and the Nilgiris. | High: direct operational evidence | Official website | Official website | Official website | Official government operational portal / bulletin | GSI, 2026 |

**Formatted:** Centered

**Formatted Table**

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1

**Formatted:** Justified

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| India | Tangni landslide, Chamoli District, Uttarakhand | Single landslide/site | Local | Forecasting focused | A near-real-time instrumentation setup was installed, and sensor-based warning thresholds were developed; however, the study does not demonstrate routine prospective warning issuance or the existence of an established operational warning service. | Moderate: non-operational stage inferred | Paper itself | No explicit information | No explicit information | Conference proceedings paper | Chaturvedi et al., 2017 |
| Indonesia | Grasberg mining area and surrounding valleys, Papua | Mine-site / local valley area | Local | Forecasting focused | The work develops thresholds and an EWS to support an operational risk chain, but presents the system as a basis for establishing routine, continuous alarm services rather than demonstrating mature operational use. | Moderate: non-operational stage inferred | Paper itself | No explicit information | No explicit information | Conference proceedings paper | Farina et al., 2020 |
| Indonesia | National application; demonstrated for Pacitan (East Java) and Brebes (Central Java) | National application / national programme | National | Forecasting focused | The Indonesian LEWS is explicitly stated to have been operational since the end of 2017 and to have issued warnings twice weekly. | High: direct operational evidence | Paper itself | Paper itself | No explicit information | Journal article | Hidayat et al., 2019 |
| Italy | Emilia-Romagna Region | Region-wide / Emilia-Romagna | Regional | LEWS | SIGMA operates in Emilia-Romagna, and the paper describes its operational use over two decades. | High: direct operational evidence | Paper itself | Paper itself + Official website | Official website | Journal technical note, official website | Segoni et al., 2018 |
| Italy | Italian railway network; operational case on Marradi–Faenza line | National sectoral railway network | National | LEWS | SANF-RFI is explicitly presented as an operational national-scale landslide early warning and decision-support system for the Italian railway network. | High: direct operational evidence | Paper itself | Paper itself + Website | Paper itself + Website | Journal article, official website | Murgia et al., 2026 |
| Italy | Nationwide Italy | National | National | LEWS | SANF is implemented for the Italian Civil Protection system, with routine outputs and reports provided to the relevant Civil Protection authorities. | High: direct operational evidence | Paper itself | Paper itself + Official website | Paper itself + Official website | Book chapter, official website | Rossi et al., 2018 |
| Italy | Piemonte Region | Region-wide / Piemonte | Regional | LEWS | Official ARPA/Regione Piemonte pages describe the regional system as operational for civil protection purposes and provide current landslide- | High: direct operational evidence | Official website | Official website | Official website | Official regional government operational warning portal | ARPA Piemonte, 2026 |

**Formatted:** Centered
**Formatted Table**
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Not Highlight
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | trigger scenarios and daily warning products. | | | | | | |
| Italy | Tuscany Region | Region-wide / Tuscany | Regional | LEWS | The Tuscany EWS is explicitly described as operational, implemented through WebGIS, and managed by the Tuscany Civil Protection Authority. | High: direct operational evidence | Paper itself | Paper itself + Official website | Official website | Journal technical note, official website | Segoni et al., 2015 |
| Italy | Umbria Region | Region-wide / Umbria | Regional | LEWS | The Umbria Civil Protection LEWS is operational and issues daily bulletins, while the study is conducted within this established operational system. | High: direct operational evidence | Paper itself | Official website | Official website | Journal article, official website | Ponziani et al., 2023 |
| Japan | Fukuoka/Kyushu University laboratory-scale sandy slope tests | Pilot instrumented site / local slope | Local | LEWS | The EWS was experimentally validated on representative sandy slopes and is presented as suitable for future operational implementation rather than as an established operational warning service. | Moderate: non-operational stage inferred | Paper itself | Paper itself | Paper itself | Conference proceedings paper / book chapter | Liu et al., 2022; Liu et al., 2023b |
| Japan | Nationwide Japan | National | National | LEWS | JMA publishes current national landslide warning and advisory information, together with a live Real-time Risk Map that provides explicit protective actions corresponding to different alert levels. | High: direct operational evidence | Official website | Official website | Official website | Official government operational portal / warning service | JMA, 2026 |
| Malaysia | Multiple monitored critical slopes and landslide hotspots across Malaysia | National programme / selected critical slopes and hotspots nationwide | National | LEWS | Official JMG sources state that real-time landslide early warning services and GeoSlide analytics are operational, and that the government is expanding the installed EWS network. | High: direct operational evidence | Official website | Official website | Official website | Official government operational portal / programme | JMG, 2026 |
| Malaysia | Ulu Kelang, Selangor | Subregional catchment / urban area | Regional | Forecasting focused | A real-time web-based RLEWS was developed and updated daily, but routine operational adoption, use, or formal responsibility by a recognised authority was not demonstrated. | Moderate: non-operational stage inferred | Paper itself | Paper itself | No explicit information | Journal article | Yaacob et al., 2019 |

**Formatted:** Centered
**Formatted Table**
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nepal | Sundrawati village / Mehele landslide, Kalinchowk Rural Municipality, Dolakha District | Single village/landslide site | Local | LEWS | The community LEWS was installed in Sundrawati/Mehele, linked to local authorities and evacuation procedures, with documented application within the local community. | High: direct operational evidence | Paper itself | Paper itself | Paper itself | Journal article | Thapa and Adhikari, 2019 |
| Norway | Nationwide Norway warning regions | National | National | LEWS | Norway's national Landslide Forecasting and Warning Service was officially launched in 2013 and provides routine daily assessments and warnings. | High: direct operational evidence | Paper itself | Paper itself + Official website | Paper itself + Official website | Journal article, official website | Krøgli et al., 2018; Piciullo et al., 2017 |
| Pakistan | Mountainous northern Pakistan, particularly Khyber Pakhtunkhwa, Gilgit-Baltistan and Azad Jammu & Kashmir | National programme / mountainous high-risk regions | National | LEWS | NDMA's 2026 DEW-2 explicitly includes a Landslide Early Warning Overview, and current NDMA portals provide dated landslide advisories and hazard projections for 2026. | High: direct operational evidence | Official website | Official website | Official website | Official national government early-warning assessment / advisory programme | NDMA, Pakistan, 2026 |
| Peru | Nationwide Peru; forecast-triggered critical zones and district-level mass-movement risk scenarios | National / forecast-triggered district and critical-zone coverage | National | LEWS | INGEMMET identified 185 critical zones based on a SENAMHI forecast for February 2026 and transmitted the resulting report to COEN and the relevant authorities; INDECI subsequently issued district-level landslide and huaico risk information and response guidance in March 2026, also based on a SENAMHI forecast. | High: direct operational evidence | Official website | Official website | Official website | Official national multi-agency government operational alert / risk-scenario service | INGEMMET, 2026; INDECI, 2026 |
| Philippines | Albay Province, Bicol Region | Province-wide / Albay warning landscapes | Regional | LEWS | The official MGB technical document states that the thresholds are currently used to issue warning bulletins for Albay, and government bulletins from 2025 and 2026 demonstrate operational warning issuance and associated response actions. | High: direct operational evidence | Official website | Official website | Official website | Official government operational warning bulletin / technical programme | Miraballes, 2021; MGB-V, 2026 |

Formatted ...
Formatted Table ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rwanda | 15 high-risk districts in northwestern, western and southern Rwanda; pilot in Ngororero | Multi-district subnational coverage | Regional | LEWS | The EWS was implemented as a pilot web-based platform; however, the paper does not clearly demonstrate established, routine institutional warning operations beyond the pilot stage. | Moderate: non-operational stage inferred | Paper itself | Paper itself | Paper itself | Journal article | Niyibizi and Valentino, 2025 |
| South Korea | Busan; case study at a debris-flow-vulnerable mountain site | City / municipality-wide | Regional | LEWS | The Busan LEWS was implemented within the local government framework but was explicitly described as undergoing trial operation at the time of publication. | High: non-operational stage explicit | Paper itself | Paper itself | Paper itself | Conference proceedings paper | Park et al., 2018 |
| South Korea | Nationwide Republic of Korea | National | National | LEWS | The official Korea Forest Service portal provides current landslide forecasts, prediction information, crisis warnings, risk maps, and shelter information. | High: direct operational evidence | Official website | Official website | Official website | Official government operational portal / warning service | Korea Forest Service (KFS), 2026 |
| Sri Lanka | National landslide-prone districts | National / landslide-prone districts | National | LEWS | The NBRO Regional Landslide Early Warning System has operated since 2007, using predefined rainfall thresholds and three warning levels (watch, alert, and evacuation) for rainfall-induced landslide warnings. | High: direct operational evidence | Paper itself | Paper itself + Official website | Paper itself + Official website | Book chapter, official website | Konagai et al., 2023 |
| Taiwan | Nationwide Taiwan debris-flow-prone torrents | National | National | LEWS | The Taiwan SWCB DDMI system has an explicit operational process for real-time warning generation, dissemination, and evacuation support. | High: direct operational evidence | Paper itself | Official website | Official website | Book chapter, official website | Yin et al., 2015 |
| Thailand | Nationwide landslide-prone areas and community warning networks | National warning surveillance with community implementation | National | LEWS | DMR's official dataset states that the AP-Model supports landslide surveillance and warning across Thailand, while supporting government materials document operational community-based warning networks. | High: direct operational evidence | Official website | Official website | Official website | Official government operational data / programme | DMR, 2026 |

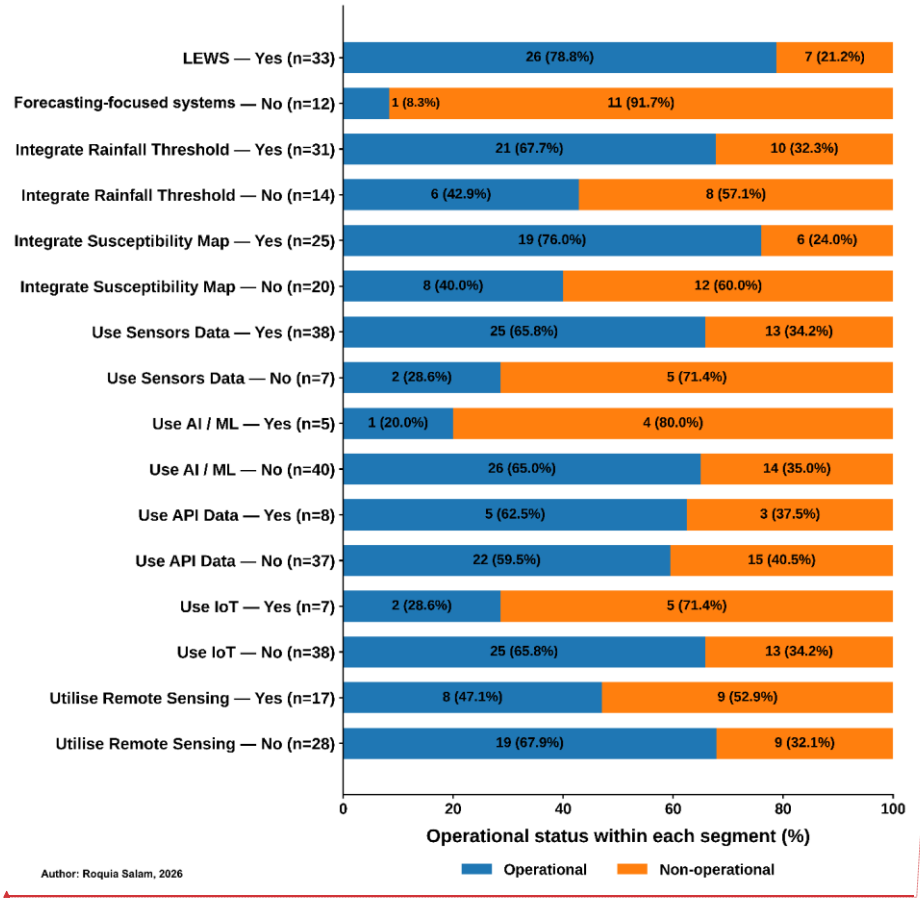
**Formatted:** Centered
**Formatted Table**
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified

| Country | Locality | Areal coverage | System scale | Type of the system | Operational evidence | Evidence strength | P1 and P2 assignment source | P3 assignment source | P4 assignment source | Source type | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tunisia | Metline, northern Tunisia | Single site / local prototype | Local | Forecasting focused | The paper explicitly presents a landslide early warning system prototype. | High: non-operational stage explicit | Paper itself | No explicit information | No explicit information | Conference proceedings paper | Kebaili et al., 2016 |
| United States | Recently burned watersheds and burn scars across the western United States | Federal national programme / selected burn scars across multiple states | National | LEWS | USGS explicitly states that postfire hazard assessments and rainfall thresholds support early warning, while the NWS issued multiple Flash Flood Warnings in 2026 that explicitly forecast or reported observed debris flows in burn-scar areas. | High: direct operational evidence | Official website | Official website 1 + Official website 2 | Official website 1 + Official website 2 | Official federal government operational hazard assessment / warning service | USGS, 2026; NWS, 2026 |
| United States | Sitka, Alaska | City / community-wide warning area | Regional | LEWS | The Sitka Landslide Risk Dashboard is an active, community-facing service that provides current and forecast rainfall-induced landslide risk levels, together with associated preparedness actions. It is a non-governmental risk-information dashboard and does not independently issue push notifications or formal warnings. | High: direct operational evidence | Paper itself | Paper itself+ Official website | Paper itself + Official website | Journal article, official website | Patton et al., 2023; Lempert et al., 2023 |
| Vietnam | Nam Dan landslide, Xin Man District, Ha Giang Province | Single landslide / site | Local | Forecasting focused | The EWMRIL system was implemented and experimentally validated at a case-study site, but the warning workflow is presented as proposed and experimental rather than as a documented routine operational service. | Moderate: non-operational stage inferred | Paper itself | Paper itself | No explicit information | Journal article | Gian et al., 2017 |

**Note:** The hyperlinks were active at the time the article was processed.

**Formatted:** Centered
**Formatted Table**
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Font: (Default) Arial, 8 pt, Font color: Text 1
**Formatted:** Justified
**Formatted:** Font: 8 pt, Bold
**Formatted:** Font: 8 pt

Appendix II: Operational status by key characteristics across the 45 unique systems.




Formatted: Centered

Formatted: Font: (Default) Arial, Font color: Text 1

Formatted: Left