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From Local Initiatives to National Systems: Mapping the Landscape of Landslide Early Warning in Latin America

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Abstract

Rainfall-induced landslides are among the most damaging geophysical processes in Latin America, and landslide early warning systems (LEWS) have become the region's principal non-structural response. Yet how these systems are operated, financed and sustained remains largely undocumented, because regional research has concentrated on hazard analysis, susceptibility modelling and technical development rather than on deployed systems. This paper maps that operational landscape. Twenty-five warning services across ten countries (Argentina, Brazil, Chile, Colombia, Costa Rica, El Salvador, Honduras, Mexico, Nicaragua and Peru) were documented by researchers and practitioners directly involved in them, using a common template, and compared along two axes: the nine assumptions underpinning geographical LEWS, and five operational dimensions (hazard monitoring, forecasting, dissemination, governance and community engagement) rated through structured expert judgement. Three patterns emerged. First, historical records and rainfall thresholds remain the backbone of nearly every system, yet several countries now challenge the assumption that rainfall alone represents subsurface conditions, incorporating soil moisture, pore pressure, deformation and machine learning. Second, insufficient monitoring density in complex terrain is the dominant technical constraint region-wide. Third, and most consequentially, forecasting capability does not translate automatically into risk reduction. The most consolidated profiles, Brazil and Colombia, retain gaps at the municipal and land-use interface, while documented discontinuities elsewhere followed legal and ownership vacuums rather than technical failure. Sustained institutional ownership, predictable financing and locally actionable warnings, not further technological sophistication, define the region's frontier. We therefore call for greater investment in the continued monitoring of unstable hillslopes and catchments throughout the region.

1. Introduction

1.1. Landslide Early Warning Systems in Latin America overview

Across tectonically active mountain belts, from the Himalaya of India and China to the mountains of Latin America, slope failures rank among the most damaging geophysical processes, exacting recurrent human and economic tolls (Petley, 2012; Sepúlveda & Petley, 2015; Froude & Petley, 2018; Carrión-Mero et al., 2021; Gómez et al., 2023c). What turns a failure into a disaster is seldom the hazard alone: where exposed populations and fragile assets concentrate on unstable terrain, even moderate events translate into fatalities and lasting economic setbacks (Petley, 2012; Kirschbaum et al., 2015; Haque et al., 2016; Stanley & Kirschbaum, 2017; Froude & Petley, 2018; Gómez et al., 2023a, 2023c; Quesada-Román, 2023). Of the many processes capable of destabilizing a slope, rainfall is by far the most frequent trigger worldwide, as infiltrating water raises pore-water pressures and progressively erodes the shear strength that keeps a slope in equilibrium (Froude & Petley, 2018; Gómez et al., 2023a, c). Because a warming climate is making heavy and erratic rainfall increasingly common (Seneviratne et al., 2021), incorporating rainfall behaviour into risk assessment and into robust Landslide Early Warning Systems (LEWS) has become a central, and ever more pressing, strategy for safeguarding vulnerable communities (Segoni et al., 2018; Bogaard & Greco, 2018; Rosi et al., 2021).

A LEWS is a system, or a set of capacities, specifically designed to generate and disseminate timely and meaningful information on the potential occurrence of landslides, enabling exposed individuals, communities, infrastructure managers, and responsible authorities to take appropriate actions to avoid or reduce the impacts of the hazard (UNDRR, 2017). A LEWS therefore extends beyond the prediction or forecasting of landslide occurrence, integrating landslide forecast models with warning criteria, decision-making procedures, and the dissemination of advisories to support timely risk-reduction actions. From a people-centred perspective, early warning systems rest on four interrelated elements: risk knowledge, monitoring and warning services, dissemination and communication, and

response capability (Basher, 2006; UNDRR, 2017). In the landslide field, these elements have been translated into four operational activities that must remain balanced within the system: design, monitoring, forecasting, and education (Intrieri et al., 2013).

Implementing and managing LEWS has been a topic of sustained interest in the academic literature (Basher, 2006; Thiebes, 2012). LEWS have evolved from local, slope-specific monitoring setups into more complex territorial and multi-hazard frameworks, becoming a key non-structural measure for reducing risk in mountainous and urban regions worldwide (Piciullo et al., 2017; Guzzetti et al., 2020). They can be designed to predict the short-term behaviour of landslides on individual slopes, or they can operate at regional, national, and global levels, covering areas ranging from small catchments to most of the globe (UNESCO & CEPREDENAC, 2012b; Lagomarsino et al., 2013; Segoni et al., 2014; Calvello et al., 2015; Piciullo et al., 2018; Guzzetti et al., 2020; LandAware, 2022). Depending on its spatial scale and application, a LEWS may rely on rainfall or other environmental thresholds, ground-based or remote-sensing observations, physically based or statistical models, or combinations thereof, typically fed by rain-gauge networks, weather radars, and satellite precipitation products (Piciullo et al., 2018; Segoni et al., 2018; LandAware, 2022).

Global reviews highlight that many operational LEWS rely primarily on rainfall thresholds and deformation and/or displacement monitoring, but often lack full integration of soil moisture, groundwater dynamics, and high-resolution real-time forecasts, which limits spatial accuracy and lead time (Guzzetti et al., 2020; Piciullo et al., 2020). At the local scale, community-based LEWS have proven effective where simple instrumentation, clear thresholds, and participatory preparedness plans are combined with sustained institutional support and social engagement (Pecoraro et al. 2019). However, their implementation remains highly heterogeneous and uneven across regions, particularly in Latin America and the Caribbean, since long-term operation and sustainability depend strongly on stable political will, legal frameworks, and municipal budgets (UNDRR & WMO, 2023).

The development of LEWS in Latin America has been strongly shaped by major hydro-meteorological and seismic disasters, which exposed regional vulnerabilities and prompted investments in monitoring, hazard assessment, institutional capacity, and preparedness. In Central America, events such as Hurricane Mitch (1998), the 2001 El Salvador earthquakes, Hurricane Stan (2005), and Hurricane Eta/Iota (2020) were important turning points. In Nicaragua, Honduras, and El Salvador, these events drove the installation of automatic rain-gauge and radar networks, the derivation of rainfall intensity–duration thresholds, the instrumentation of individual unstable slopes, and the consolidation of institutional warning mandates. El Salvador subsequently coupled these observations with numerical weather prediction and impact-based forecasting, while Nicaragua added geophone and infrasound detection of lahars to its rainfall-based criteria. Costa Rica followed a comparable technical path from a stronger community base, combining rainfall thresholds derived from historical series with geotechnical observation and municipal emergency protocols (Japan International Cooperation Agency - JICA, 2002; Harp et al., 2002b; Tronstad et al., 2002; Baldizón et al., 2005; Guinau et al., 2005; Devoli et al., 2007a, 2007b; Devoli et al., 2009; Geocad Estudios Ambientales S.A., 2012; UNESCO & CEPREDENAC, 2012a, 2012b; Garcia-Urquia & Axelsson, 2014). These developments were accompanied by greater collaboration among government agencies, universities, communities, and international organizations, contributing to the strengthening of disaster risk governance and public preparedness (Devoli, 2008).

Across South America, a comparable instrumental basis developed around a different institutional axis. Rather than the cycles of international cooperation that followed each Central American hurricane, the dominant pattern was the creation or expansion of large national technical agencies after single catastrophic events, operating primarily at the scale of densely populated metropolitan regions. Colombia and Brazil developed comparatively advanced

operational systems integrating dense hydrometeorological monitoring, radar, susceptibility mapping, geotechnical information, and communication mechanisms, including IDEAM's BADT, SIATA, Inform@Risk, and CEMADEN (Presidência da República, 2011, 2012; Domínguez-Calle & Lozano-Báez, 2014; Calderón Ramírez & Frey, 2017; Aristizábal et al., 2022; Luiz-Silva & Oscar-Júnior, 2022; Gómez et al., 2023b; Gamperl et al., 2023a; Werthmann et al., 2024; Camarinha, 2025; UNDRR, 2025a; Gómez et al., 2026). Chile has increasingly incorporated LiDAR, InSAR, machine learning, and Weather Research and Forecasting (WRF) modelling following major disasters, while Peru and Mexico as part of North America, have expanded hydrometeorological networks, rainfall-threshold analyses, and integrated risk-management platforms in response to recurrent El Niño events, tropical cyclones, and earthquake-triggered landslides (Alcántara-Ayala, 2004, 2008; Sepúlveda et al., 2010; Lavado Casimiro et al., 2011; Alcántara-Ayala & Garnica-Peña, 2012; Morales et al., 2021; Castro-Venegas et al., 2025; Fustos-Toribio et al., 2025; Silva et al., 2025; INDECI, 2025). Argentina, in contrast, maintains a more fragmented LEWS landscape, largely associated with transportation infrastructure and rainfall-threshold alerts, although recent applications of DInSAR and satellite-based monitoring indicate growing interest in deformation-based approaches (Moreiras, 2005a, 2005b, 2009; Acosta et al., 2021; Cardozo et al., 2021; Merlín et al., 2021). Overall, the regional trajectory reflects a shift from predominantly reactive, rainfall-based, and localized initiatives toward increasingly integrated LEWS combining multi-source observations, predictive modelling, advanced monitoring technologies, and institutional and community-based risk reduction.

1.2. Rationale and objectives

Against this background, this study conducts a cross-country comparative analysis of the LEWS documented across the participating Central and South America countries to provide an integrated regional perspective of their current status, evolution, and level of development. The country-level information is systematically cross-compared to identify both common patterns and contrasting approaches in monitoring and forecasting capabilities, institutional and governance arrangements, warning dissemination, community participation, territorial coverage, and operational continuity.

The need for such a synthesis is empirical rather than rhetorical. A systematic review of the landslide early-warning literature in middle-income countries found that only 14 of 384 studies addressed the actual operational implementation of a system, with Brazil as the sole Latin American country represented (Alcántara-Ayala & Garnica-Peña, 2023b). Research effort in the region has concentrated on hazard analysis, susceptibility modelling and technical development, so that what is known about how warning systems are run, sustained, financed and discontinued remains largely undocumented. This analysis directly addresses that gap by compiling first-hand accounts of the operational arrangements of the institutions and research groups that provide or are responsible for such advice.

This comparative framework is further used to examine the technological, institutional, and social factors that enable or constrain LEWS operability, scalability, and long-term sustainability, as well as emerging opportunities for methodological and technological improvement, knowledge transfer, and regional cooperation. By synthesizing country-specific strengths, technical and institutional gaps, and priority needs, the study ultimately seeks to identify shared regional challenges and transferable lessons that can support the development of more robust, interoperable, sustainable, and people-centred LEWS across Latin America.

2. Materials and methods

2.1. Country and system inclusion criteria

The ten countries included in this review were not selected through a sampling procedure, nor were they chosen by the coordinating authors. They correspond to the national teams/researcher/practitioners that responded to an open call for collaboration circulated through the Latin American regional group of LandAware, the international network on landslide early warning systems (Calvello et al., 2020). The group was established to strengthen regional engagement and visibility and to promote collaboration among LandAware associates, researchers, institutional stakeholders and government representatives working on landslide risk reduction in Latin America. Participation was therefore self-selected, but institutionally mediated, because the call reached both academic associates and the agencies that operate warning systems, it made accessible a class of evidence, operational records, alert protocols and instrumentation inventories, that is rarely available in the peer-reviewed literature. Each responding team committed to documenting the arrangements operating on its own territory and to co-authoring the corresponding country account. The resulting set covers the two Latin American sub-regions where rainfall-induced landslides concentrate and includes both countries with consolidated national systems and countries where warning capacity is fragmentary, but it is not exhaustive. Countries with documented landslide risk and no contributing author, such as Ecuador, Bolivia, Guatemala and Panama, fall outside its scope, and the review makes no claim about the state of their warning arrangements.

Within each participating country, an arrangement was included when it met three conditions: it produces or disseminates anticipatory information about slope instability; it does so through an identifiable operating organisation; and its status could be documented by the contributing author from institutional sources, operational records, or peer-reviewed publications. Purely retrospective inventories, susceptibility maps without a warning function, and meteorological services with no landslide-specific product were excluded, except where an explicitly landslide-oriented component was identified. Arrangements addressing closely coupled processes, such as debris flows also in volcanic environments, also known with the term of, lahars, and glacial lake outburst floods, were retained when the triggering chain involves slope or channel instability, since in several countries these are the processes for which anticipatory capacity was first developed.

2.2. Comparative design and reporting protocol

The comparison developed in this paper rests on a deliberately structured design rather than on a juxtaposition of national narratives. Each country contribution was prepared by researchers or practitioners directly involved in the systems described, following a common three-part template, national context, historical evolution, and current operational scope, so that the same categories of evidence (triggering mechanisms and exposure, institutional catalysts, operating organisations, technologies, alert protocols, and territorial reach) are reported for every case. Comparability is therefore built into the reporting stage rather than imposed afterwards.

Information was compiled between November 2025 and May 2026. Each contributing team/researcher drew on institutional sources, operational records and peer-reviewed literature for its own country and returned the completed template together with the supporting references. A single harmonisation round was then carried out by the full author team to align the interpretation of the reporting categories across countries, after which every country account was returned to its contributors for confirmation. No information about a country was introduced without the endorsement of its contributing authors.

2.3. Units of analysis and classification

Two units of analysis are distinguished throughout. The individual warning system is the unit used to describe technologies, thresholds, and dissemination arrangements (Section 3.n.3), and it is the unit mapped in Figs. 1 and 2. The country is the unit used for the synthetic comparison (Table 1 and Fig. 4), understood as the aggregate of the

warning arrangements operating on its territory, since in most of the region landslide warning is not delivered by a single system but by a layered set of national, subnational, and local arrangements. Systems are further differentiated by spatial scope, following the territorial–local distinction established in the literature (Calvello, 2017; Piciullo et al., 2018; Guzzetti et al., 2020), and by development stage (operational, pre-operational, experimental, designed or discontinued), which is the attribute represented in Fig. 2.

Development stage is assigned as follows. A system is operational when it issues warnings on a routine basis under an institutional mandate, with a defined operator and dissemination protocol; pre-operational when the technical chain is complete and has been tested in real time, but routine issuance has not yet been formally mandated; experimental when instrumentation or modelling is deployed for research or demonstration without a warning-issuing function; and discontinued when a previously operating system has ceased to issue warnings, whether it was abandoned or replaced. Systems that have been handed over to an operating institution, but whose further development is suspended (discontinued) are reported under their current issuing status, with the suspension noted in the text.

2.4. Assessment against the assumptions of geographical LEWS

The systems identified in each country were assessed against the nine assumptions that underpin geographical landslide early warning systems, as discussed by Guzzetti et al. (2020). The labels A1 to A9 used in Section 4 are introduced here for ease of reference and are not part of the original formulation. For each country, an assumption was considered supported when at least one of its systems provides documented evidence consistent with it, partially supported when the corresponding capability exists but is limited in coverage, resolution, or continuity, and challenged when the evidence indicates that the assumption does not hold as formulated, typically because the system relies on variables other than rainfall or because the warning chain is interrupted before reaching protective action. The assessment refers to the evidence reported in Section 3 and is therefore bounded by the documentation available to each contributing team.

2.5. Operational dimensions for cross-country comparison

Differentiation between cases is organised along five operational dimensions derived from the people-centred early-warning framework adopted by United Nations Office for Disaster Risk Reduction (UNDRR) and World Meteorological Organization (WMO) and widely used in the landslide literature: hazard monitoring and sensing; forecasting and modelling; alert dissemination and communication; institutional framework and governance; and community engagement. These dimensions structure both the qualitative synthesis of country-level strengths, gaps, and priority needs (Table 1) and the comparative maturity assessment presented in Fig. 4.

2.6. Maturity rating procedure

Each country was rated on the five dimensions above using a five-point scale, from 1 (incipient) to 5 (consolidated), in half-point increments. The values are not the output of a formal index. They correspond to a structured expert judgement. Each country was rated by the co-authors responsible for its contribution, on the basis of the evidence compiled in Section 3 and summarised in Table 1, and the full matrix was then reviewed collectively by the author team to harmonise the interpretation of each scale point across countries.

Ratings were anchored on a common descriptive scale. A score of 1 indicates that the capability is absent or documented only as an isolated initiative; 2, that it exists in pilot or project form without institutional continuity; 3, that it operates routinely but with limited territorial coverage or resolution; 4, that it operates routinely with national or near-national coverage and an established institutional basis; and 5, that it is consolidated, institutionally

embedded, and subject to systematic updating. Half-point values were used where a country's evidence sat consistently between two anchors, typically because a capability is consolidated in part of the territory and incipient elsewhere.

This procedure was adopted for two reasons. First, the attributes being compared are documented at very different levels of detail across the region, so any arithmetic aggregation would propagate differences in reporting depth rather than differences in capability. Second, several of the dimensions, particularly institutional framework and community engagement, have no established quantitative proxy in the landslide early-warning literature. The resulting matrix should therefore be read as a comparative reading aid that summarises the qualitative assessment, not as a measurement. Differences of half a point fall within the resolution of the procedure and should not be interpreted as meaningful, whereas differences of one point or more reflect distinctions consistently identified across the country contributions. The assessment refers to capability and institutional consolidation, not to warning accuracy, which would require the standardised performance indicators proposed by Piciullo et al. (2020) and event-by-event records that most of the systems reviewed here do not publish. A criteria-based scoring protocol, in which each dimension is decomposed into observable indicators with explicit weights, is under development and will be reported separately.

2.7. Methodological limitations

Three limitations follow from this design and should be borne in mind when reading the results. First, the evidence base is expert-reported and its coverage follows the reach of the LandAware regional network rather than a stratified sample of the region. Countries where no team responded to the call are absent regardless of their landslide exposure, and within participating countries, arrangements operating outside the professional networks of the contributing authors may be under-represented; the level of detail is likewise not uniform across countries. This recruitment mechanism is simultaneously the condition that made the review possible and the limit of its coverage, and the results should be read as a documented sample of operational practice in the region, not as a census of it. Second, the review reports the status of each arrangement at the time of compilation; several of the systems described are being actively modified, and pre-operational initiatives in particular may have changed status by the time of publication. Third, the maturity assessment summarises qualitative evidence on an ordinal scale and is intended for relative comparison between countries, not as an absolute measurement of performance.

3. Current Status of LEWS: Country-by-Country Analysis

This section synthesizes the operational status, institutional architecture, and technological maturity of Landslide Early Warning Systems (LEWS) across ten Latin American countries: Argentina, Brazil, Chile, Colombia, Costa Rica, El Salvador, Honduras, Mexico, Nicaragua, and Peru. For each country, three dimensions are addressed: (i) the national context defining landslide hazard, exposure, and vulnerability; (ii) the historical evolution of monitoring and early-warning initiatives, generally catalysed by major disasters; and (iii) a structured description of the current operational LEWS, their leading organizations, technologies, alert protocols, and territorial reach. Critical reflections and forward-looking needs for each country are consolidated in a comparative table at the end of Section 4 (Table 1), which provides the basis for the regional discussion developed in Section 6.

3.1. Argentina

3.1.1. National Context Diagnosis

Argentina extends over 2.8 million km² between 20°S and 60°S, encompassing a diverse landscape that includes the Andes mountains, subtropical Yungas forests, the humid Pampa, and arid Patagonia. Climate ranges from tropical in the northern Chaco to extreme conditions in the Patagonian Ice Field, with monsoon storms in the east and Pacific-derived humidity in the west. Along the Andes, Aconcagua (6,958 m a.s.l.) is the tallest peak of the Western Hemisphere.

The confluence of diverse geography, social inequalities, and economic reliance on agriculture and infrastructure amplifies natural risks. Approximately 13% of Argentina's population, about 6 million people in 2022 (INDEC, 2022), lives in mountainous areas exposed to recurrent landslides. The Central Andes (San Juan, Mendoza) record rock avalanches linked to permafrost thaw, seismicity, and storms, while Sierras Pampeanas experience slides on fractured metamorphic rocks triggered by rainstorms and road building (Moreiras 2004; Wick et al. 2010; Merlín et al. 2021). Damaging events have also been recorded in the Yungas, including debris flows in Tartagal (Salta) in 2006 and 2009 (Moreiras and Coronato 2010). Landslides disrupt economic development by damaging roads, bridges, hydropower, and farmland, while threatening Indigenous communities in the Gran Chaco and rural populations in Andean foothills.

3.1.2. History and Evolution of Early Systems/Initiatives

Despite the high frequency of landslides in the Andean region, dedicated landslide-monitoring networks have rarely been instrumented compared with hydrological or dam-safety setups. Landslide inventories, hazard zonation, and case studies have been conducted in Andean areas (Moreiras 2005a, 2009; Moragues et al. 2019), but operational monitoring and early-warning systems remain scarce. Where they exist, alert systems are typically triggered by precipitation sensors managed by the Dirección Nacional de Vialidad (DNV), with warnings disseminated through TV, radio, and social media. Complementary approaches such as DInSAR are increasingly applied to detect active landslides in the Argentine Andes (Cardozo et al. 2021) and Precordillera (Acosta et al. 2025), and high-resolution DEMs from UAV surveys support post-disaster analysis.

An early LEWS operated for the Transandine Railway between Mendoza and Los Andes (Chile) from 1902 to 1993, using manual telegraphs at stations such as Punta de Vacas and Guido to report weather and damaging events; this communication system contributed to averting victims during the 1934 Plomo Basin glacial outburst flood. Along the same corridor, National Route 7 connecting Mendoza with Santiago handles up to 440,000 trucks per year and is repeatedly affected by snow and landslide closures (Moreiras et al. 2018). To safeguard this strategic corridor, the DNV and the Argentinean Institute of Snow, Glaciology and Environmental Sciences (IANIGLA) developed the "Sistema de Control y Manejo Vialidad Invernal de la ruta Nacional 7" (SCMVI7), funded since 2006 through a BID–DNV credit and tested in 2009; precipitation thresholds and antecedent rainfall criteria were derived from a landslide record dating to 1870 (Moreiras 2005b). SCMVI7 remains operational.

The institutional framework evolved with the Hyogo (2005–2015) and Sendai (2015–2030) frameworks. Law 27,287 of 2016 established SINAGIR (National System for Comprehensive Risk Management and Civil Protection), coordinating national, provincial, and local entities. In 2025, Decree 225/2025 created the Federal Emergency Agency (AFE) to respond to disaster situations and coordinate SINAGIR. The National Disaster Risk Reduction Plan 2025–2029 (PNRRD), under the Ministry of National Security, guides current policy and incorporates lessons from the 2018–2023 cycle. Within SINAGIR, SINAME (National Emergency Alert and Monitoring System) operates a 24/7 control room with federal security forces and civil protection personnel. The IG-GIRD geospatial platform of the Instituto Geográfico Nacional (https://riesgo.ign.gob.ar/mapa) provides online warnings for landslides, floods, earthquakes, and volcanic eruptions. Dam safety, including landslide-induced threats to natural and artificial dams, is regulated by ORSEP, created after the 1970 Frías dam failure that killed 42 people in Mendoza (ORSEP 2010).

3.1.3. Description and Current Scope of LEWS(s)

Meteorological multi-level warning system (SMN). The National Meteorological Service (Servicio Meteorológico Nacional, SMN) provides multi-temporal alerts, weekly, monthly, and real-time, through a multi-level warning system primarily focused on severe weather and flood-related hazards. These products could be adapted to support warnings for debris flows, hyper concentrated flows, and flash floods in mountainous catchments by coupling rainfall thresholds with geomorphological and land-cover information. However, in extreme Andean environments, purely hydrological remote-sensing approaches suffer from limited in-situ data, sparse rain-gauge networks, and complex topography that modulates rainfall–runoff and slope-stability dynamics.

SCMVI — Road Maintenance System (National Route 7, Mendoza). Implemented by the DNV, SCMVI ensures safety and accessibility of the Cristo Redentor International Pass through the Winter Maintenance Plan (PIMI). Components include technology to adapt trucks for clearing operations, anti-icing material spreading, avalanche monitoring in high mountains, traffic management coordinated between DNV and the National Gendarmerie, and safety operations involving Mendoza Police and local authorities (Luján and Las Heras) to manage flows exceeding 2,000 lorries per day as seasonal peaks.

SAGAZ Network. The SAGAZ Network is an early-warning system designed to assess downstream outburst-flood risk from natural dam collapses. Its architecture integrates: (a) Field-level data acquisition through lake monitoring networks, sensor nodes for rainfall, soil moisture and slope displacement, with data transmitted via the Iridium satellite constellation; (b) central processing combining ground control servers, predictive models, and external weather forecasts; and (c) a web interface (www.sagaz.org) and mobile-app dissemination accessible to the public. The system has been implemented for a GLOF in Santa Cruz province and additional glacial lakes in Chile (Rada et al. 2024). In Argentina, its deployment addresses the outburst hazard of Lago Torre, upstream of El Chaltén (Santa Cruz), where slope instability and glacial-lake hazard have been documented over the last decade (Winocur et al. 2015; Balbi et al. 2019; Schmidt et al. 2025).

Overall, Argentina's LEWS present a clear asymmetry between the developed infrastructure protecting economic corridors (particularly Route 7 and the SCMVI) and the largely absent coverage for vulnerable Andean communities. Community participation and public education have demonstrated effectiveness in reducing exposure, but the growing risks posed by climate change, intensification of storms, permafrost thaw, and glacial retreat, demand more concrete actions directed particularly at socioeconomically marginalized populations (Rodríguez et al., 2025). The integration of multi-hazard approaches within SINAGIR, the deployment of expanded monitoring networks with DInSAR and UAV technologies, and stable collaborative research funding are identified as the key strategic levers for strengthening Argentina's LEWS landscape.

3.2. Brazil

3.2.1. National Context Diagnosis

Brazil presents a pronounced geographic concentration of landslide susceptibility along the Serra do Mar and adjacent coastal massifs in the Southeast, where steep relief, intense precipitation, and high human occupation converge. Landslide risk disproportionately affects populations in environmentally fragile areas, particularly low-income urban residents in informal hillside and flood-prone settlements. The literature also indicates that hydrometeorological disasters disproportionately impact women, children, and the poor, and that Brazilian risk-management planning has historically emphasized physical susceptibility more than social vulnerability (Mendonça et al. 2023; Luiz-Silva and Oscar-Júnior 2022).

Despite favourable national Human Development Index (HDI) (0.786), vulnerability remains elevated due to uneven governance capacity, data gaps, and persistent exposure in rapidly urbanized regions (Leal Filho et al. 2018; UNDP, 2025). Historical records report 1,072 official landslide disasters between 1991 and 2019, resulting in 3,052 deaths. Notably, the January 2011 disaster in the mountainous region of Rio de Janeiro accounted for 918 fatalities, representing the deadliest landslide event recorded in Brazil.

3.2.2. History and Evolution of Early Systems/Initiatives

LEWS in Brazil are conceptualized as functional arrangements built on four interdependent pillars consistent with the UNDRR/WMO people-centred framework: risk knowledge; monitoring, analysis and forecasting; dissemination and communication; and preparedness and response (WMO, s.d.). Their governance is structured within the National Policy on Protection and Civil Defense (PNPDEC) and the National System of Protection and Civil Defense (SINPDEC), established by Law No. 12.608/2012 and organized by Decrees No. 10.593/2020 and No. 11.774/2023 (BRASIL, 2012, 2020, 2023). Accordingly, LEWS in Brazil are more appropriately characterized as functionally structured systems governed within the broader institutional framework of SINPDEC, rather than as a single, standalone warning system.

Within SINPDEC, the risk-knowledge pillar is supported by hazard and risk cartography produced by the Geological Survey of Brazil (SGB), complemented by state- and municipal-level mapping initiatives (e.g. Institute for Technological Research (IPT), and by disaster information systems such as S2iD and National Center for Monitoring and Early Warning of Natural Disasters (Cemaden) REINDESC database (Serviço Geológico do Brasil, n.d.; Bernardes et al., 2026). The monitoring–forecasting pillar is led by Cemaden, the federal technical-scientific institution created in 2011 following the disaster in the mountainous region of Rio de Janeiro State. Cemaden's operational assessments integrate meteorological, hydrological, and geodynamic data with susceptibility, exposure, and vulnerability information (BRASIL 2011; Cemaden, 2021). Federal prioritization initially encompassed 821 municipalities in 2012 and subsequently expanded to 2,095 municipalities, guiding federal risk-mapping priorities and the planned expansion of Cemaden monitoring.

3.2.3. Description and Current Scope of LEWS(s)

National Center for Monitoring and Early Warning of Natural Disasters (Cemaden). The Cemaden was created by Decree No. 7,513 of 1 July 2011 and became operational in December 2011. At the beginning of 2026, Cemaden monitored 1,133 municipalities; following an expansion in March 2026, coverage reached 1,295 municipalities, approaching the federally designed priority set of 2,095 municipalities (BRASIL, 2011; Cemaden, 2021; MCTI, 2026).

According to Cemaden's 2024 institutional inventory, its observational network comprised 2,940 automatic rain gauges, 146 hydrological stations, 115 geotechnical stations, 529 agrometeorological stations, and nine meteorological radars (Cemaden, 2024). The network has since expanded: the 2025 TCG reports 3,698 installed automatic rain gauges and 145 hydrological stations, while the RedeGeo network reached 125 geotechnical stations by December 2025 (Cemaden, 2025; Cemaden, 2026). The geotechnical stations monitor rainfall and volumetric soil moisture at multiple depths down to 3 m, with data updated every 10 minutes. Operational platforms include Risk Area Warning and Visualization System (SALVAR) for real-time geospatial monitoring and Integrated Natural Disaster Warning System (SIADEN) for warning issuance. A multidisciplinary team of specialists maintains continuous operations in Cemaden's Situation Room, providing monitoring and early warning services 24 hours a day, seven days a week.

Developed since 2019 and officially launched in 2025, the GeoRisk system (https://georisk.cemaden.gov.br/) provides landslide-risk forecasting up to 72 hours ahead, increasing event detection by 13%, improving the hit rate by

17%, and reducing false alarms by 3% relative to the previous workflow, while detecting ~ 90% of major landslide disasters with ≥ 48 h lead time (Camarinha, 2025). Interministerial Ordinance MIDR/MCTI No. 3/2026 formalized the updated SEDEC–Cemaden protocol with three early-warning levels (moderate, high, and very high), each linked to specific civil-defense actions (MIDR & MCTI, 2026). Over 10,475 landslide-related warnings issued between 2016 and 2025, hit rates were 20%, 63%, and 94% for the three levels, respectively (BRASIL, 2026a; Bernardes et al., 2026).

COR-Rio and Sistema Alerta Rio (Rio de Janeiro). The Centro de Operações e Resiliência do Rio de Janeiro (COR-Rio), established in 2010, is a multi-agency 24/7 hub integrating ~ 500 professionals from over 50 agencies (Prado et al. 2025). Within it, Sistema Alerta Rio (operational since 1996, run by Fundação Geo-Rio) operates a telemetric network transmitting rainfall, temperature, humidity, wind, and pressure every 5 minutes, complemented by weather radar and numerical models (Alerta Rio, 2026; Centro de Operações e Resiliência, 2026). A localized version of NASA's LHASA model, the LHASA Rio, developed jointly by Instituto Pereira Passos, Geo-Rio, and NASA GSFC, estimates landslide hazard at 5 m resolution using 33 rain gauges and Geo-Rio's susceptibility map (Kirschbaum and Stanley 2018; Hurwitz et al. 2020). Warnings are disseminated via SMS, the cell-broadcast system, and 164 sirens installed in 103 high-risk communities, complemented by capacity-building programs such as Rio for Disaster Risk Reduction (3RD), school-based PROMOPE/PDCE, and NUPDEC Saúde.

Santos Municipality Monitoring and Early Warning System (São Paulo State). Coordinated by the Municipal Civil Defence of Santos, intensified during the Summer Operation (December–April), and integrated with CEMADEN, CENAD, CEPDEC/SP, IPT, IPA, INMET, and INPE/CPTEC. Technologies include automatic rain gauges operated by CEMADEN (since 2014), historical municipal stations dating to the 1940s, the Salesópolis weather radar, numerical models via INMET and CPTEC, the Baixada Santista Situation Room, cell-broadcast alerts, and a siren in Vila Progresso. Operations follow the Civil Defence Preventive Plan (PPDC) developed in the 1980s by IPA and IPT, with the primary threshold of 80 mm/72 h triggering an attention state, escalating to alert and preventive evacuation under continued precipitation and slope-instability evidence. Risk management instruments include the Geotechnical Map of the Hills of Santos and São Vicente (IPT, 1980), the Mass Movement Susceptibility Map (IPT, 2013), the Municipal Risk Reduction Plan (IPT, 2024), and the Contingency Plan for Storm Surges and Flooding (2017).

The 2020 landslide disaster in Santos, and the 2024 events in Rio Grande do Sul that affected areas of previously assessed medium-to-low susceptibility (Andrades-Filho et al. 2025), highlight both the maturity and the structural limitations of Brazil's LEWS. While the PPDC demonstrated operational capability in monitoring, warning dissemination, and emergency response, the historically reactive, impact-driven model produces uneven territorial coverage and leaves municipalities with limited disaster history under-served in terms of susceptibility mapping, rainfall thresholds, and early-warning capabilities. These limitations are compounded by insufficient integration between monitoring advances and land-use regulation or sustained investment in informal settlement risk reduction. Community engagement initiatives in Santos contribute to risk awareness and preparedness but remain limited to high-risk areas already recognized. The Brazilian experience thus presents a governance architecture of considerable sophistication at the federal level, backed by Cemaden, legally anchored in SINPDEC, and increasingly automated by GeoRisk, whose full benefit depends critically on bridging the gap between national technical capacity and local governance and land-use realities.

The May 2024 mega disaster in Rio Grande do Sul state provides a critical case study for examining the operational challenges of LEWS in Brazil. The state’s complex geomorphology, characterized by elevations ranging from near sea level to approximately 1,400 m, includes the Meridional Plateau, where volcanic rock sequences from the Serra Geral Geological Group overlie aeolian sandstones of the Botucatu Formation (Rosseti et al., 2018). The steep escarpment

separating the Meridional Plateau from the Depressão Central, combined with variable rainfall regimes and increasing precipitation trends (Valente et al., 2023), contribute to the widespread occurrence of landslides in the region (Quevedo et al., 2025). Different extreme precipitation events have triggered landslides along the Meridional Plateau Escarpment, accounting for 1,211 documented occurrences between 1995 and 2017 (Gameiro et al., 2021). Although this represents a significant record, a single extreme event in 2024 resulted in 15,376 landslides across approximately 18,000 km² (Andrades-Filho et al., 2025b). The heavy rainfall that occurred between 27 April and 13 May impacted the entire state, with some municipalities recording over 600 mm (Andrades-Filho et al., 2025b). On 28 April, Cemaden issued the first alerts regarding high and very high risks of hydrogeological disasters, followed by a warning of worsening meteorological conditions sent to the Civil Defense on 30 April.

During this extreme event, 142 municipalities were directly affected by landslides, with the 10 most affected concentrating nearly 32% of the occurrences (Andrades-Filho et al., 2024). According to IBGE, (2025), 30 of these municipalities reported having no early warning system, while only 105 of the 112 municipalities with existing systems issued warnings during the event. Furthermore, 20 municipalities lacked contingency plans, and 11 had plans that were not implemented during the extreme event, partly due to insufficient personnel training and material resources (IBGE, 2025). These findings reveal gaps between the availability of warning mechanisms, institutional preparedness, and the implementation of protective measures. Veranópolis municipality, which recorded the highest number of landslides, illustrates these challenges. Despite maintaining risk area mappings since 2009, participating in the UN *Making Cities Resilient* campaign, and having a formal plan to address climate-related risks, the municipality experienced extensive landslide impacts and prolonged highway disruption. Subsequent initiatives in Veranópolis, Bento Gonçalves, and Caxias do Sul have included updates to contingency plans, community engagement, and conducting rescue simulation exercises developed after disaster recovery efforts.

The 2024 mega disaster prompted collaborative initiatives and institutional reforms to strengthen disaster risk management in Rio Grande do Sul. Immediate response efforts include real-time monitoring and mapping by a volunteer task force involving different public institutions (Possantti et al., 2024) and landslide detection to support rescue operations (Andrades et al., 2024; 2025a; 2025b). Subsequent developments included the establishment of the Plano Rio Grande and its dedicated funding mechanism (FUNRIGS) under the law No. 16.134/2024 (Rio Grande do Sul, 2024a), and the restructuring of the State Civil Protection and Defense System under Complementary Law 16.263/2024 (Rio Grande do Sul, 2024b). These institutional changes were accompanied by the implementation of cell-broadcast emergency alerts in December 2024 and the consolidation of hydrometeorological monitoring and warning activities within the State Civil Defense Monitoring Center (CMDEC) in February 2025. The regulatory framework also establishes the institutional functions of the State Center for Integrated Risk and Disaster Management (CEGIRD), conceived to integrate, monitoring, contingency planning, and interinstitutional coordination (Rio Grande do Sul, 2025). Concurrently, Cemaden expanded observational cooperation and conducted geotechnical investigations in the Serra Gaúcha to improve landslide monitoring and forecasting. Complementing these efforts, the FAPERGS-supported PREVINE Taquari-Antas research project aims to develop integrated strategies for disaster risk assessment, early warning, and emergency response in the Taquari-Antas River Basin. Its research framework encompasses three main components: (i) monitoring, modelling, forecasting, and hazard and risk mapping; (ii) community engagement through citizen science; and (iii) early warning, risk communication, and emergency response. By integrating quantitative and qualitative approaches, conventional methods, and emerging technologies, the project seeks to strengthen disaster risk management and reduce the impacts of floods, flash floods, and landslides.

The 2020 landslide disaster in Santos, and the 2024 mega disaster in Rio Grande do Sul highlight both the maturity and the structural limitations of Brazil's LEWS. While the PPDC demonstrated operational capability in monitoring,

warning dissemination, and emergency response, the historically reactive, impact-driven model produces uneven territorial coverage and leaves municipalities with limited disaster history under-served in terms of susceptibility mapping, updating and monitoring of rainfall thresholds, and early-warning capabilities. These limitations, combined with the seasonal variability of rainfall in a tropical country, are compounded by insufficient integration between monitoring advances and land-use regulation or sustained investment in informal settlement risk reduction, as well as by the need for more systematic data recording, interoperable monitoring systems, and open data sharing to support coordination and scalability across municipalities (Hader et al., 2025; Horta, 2025). Community engagement initiatives in Santos contribute to risk awareness and preparedness but remain limited to high-risk areas already recognized. The 2024 disaster in Rio Grande do Sul further exposed gaps between warning availability, municipal preparedness, and the implementation of protective measures, prompting new investments in monitoring, institutional coordination, and community-based risk reduction. Together, the experiences of Santos and Rio Grande do Sul highlight the challenges of translating Brazil’s federal early warning framework, supported by SINPDEC, Cemaden, and GeoRisk, into effective local action. Addressing these challenges requires closer integration of technical capabilities, municipal governance, community participation, and preventive land-use planning.

3.3. Chile

3.3.1. National Context Diagnosis

Chile's geographic configuration along the Pacific Ring of Fire, framed by the Andes, the Coastal Range, and the Central Valley, creates one of the most geomorphologically dynamic and hazard-prone environments globally (Silva et al. 2025). Approximately one third of the national population (~ 7 million people) lives in Santiago, while regions such as Biobío host more than 1.6 million inhabitants, often in cities expanding toward steep, unstable hillslopes (Silva et al. 2025). Unplanned urbanization and informal settlements in high-susceptibility zones amplify social vulnerability (Castro-Venegas et al. 2025).

Between 1928 and 2017, more than 1,000 fatalities were associated with mass movements, predominantly triggered by heavy rainfall and earthquakes (Castro-Venegas et al. 2025). Since 1980, geological disasters have generated losses estimated at US$32 billion (Castro-Venegas et al. 2025). Landslides recurrently disrupt critical transportation corridors such as Route 7 in Patagonia (Carretera Austral), isolate communities, and threaten tourism and mining sectors (Morales et al. 2021). Inconsistencies between scientific susceptibility mapping and Communal Regulatory Plans (PRCs) allow continued development in hazardous zones, perpetuating long-term exposure (Silva et al. 2025).

3.3.2. History and Evolution of Early Systems/Initiatives

Chile's landslide-management evolution was catalysed by major disasters: the 1960 Valdivia Earthquake (Mw 9.5), which triggered the San Pedro River landslide dams managed through "Operation Riñihue" (Araya-Cornejo et al. 2024); the 2007 Aysén Earthquake (Mw 6.2), which produced over 500 landslides and a tsunamigenic event in the fjord (Sepúlveda et al. 2010; Serey et al. 2025); and the 2017 Villa Santa Lucía mudflow that killed 22 people (Morales et al. 2021; Somos-Valenzuela et al. 2020). For most of the 20th century, governance relied on the 1965 Catastrophes Law focused on seismic response. The 2010 Maule Earthquake (Mw 8.8) exposed fatal deficiencies in tsunami warning transmission, motivating Law 21,364 of 2021 ("Ley SINAPRED") and Decree 86 (2023), which replaced ONEMI with SENAPRED and established SINAPRED as a decentralized, multi-level disaster-risk system (Silva et al. 2024, 2025).

Recent technical advances include semi-automated landslide inventories using Google Earth Engine, Landsat and Sentinel-2 (Morales et al. 2021, 2022), Sentinel-1 InSAR monitoring in Temuco, Concepción, and the Patagonian

Andes (Fustos et al. 2017, 2020a, 2020b; Gatica 2020; Vásquez-Antipán et al. 2025), 2×2m LiDAR-based susceptibility at 1:10,000 scale (Castro-Venegas et al. 2025), and machine-learning–based forecasting using the WRF model coupled to Random Forest and XGBoost (Fustos-Toribio et al. 2022, 2025). SERNAGEOMIN is the official technical authority for geological hazards, producing Technical Minutes that combine DMC meteorological forecasts with susceptibility data and supporting SENAPRED's three-tier alert structure (Green – preventive; Yellow – resource preparation; Red – imminent danger). Municipalities, mandated by Law 21,364, must establish DRM departments, integrate landslide zones into PRCs, and coordinate COGRID committees, with model practices documented in Talcahuano (Oberli et al. 2021). Evidence on the receiving end of these arrangements is also emerging: behavioural analyses of cell-broadcast evacuation alerts in Chile provide an empirical basis for evaluating how populations respond to official warnings (Elejalde et al. 2025).

Land-use regulation adds a further layer of ambiguity: the terminology used by the General Urbanism and Construction Ordinance to designate non-buildable and risk-exposed areas does not map onto the hazard categories produced by SERNAGEOMIN, which complicates the incorporation of susceptibility mapping into municipal Communal Regulatory Plans (OGUC, 1992, Art. 2.1.17).

3.3.3. Description and Current Scope of LEWS(s)

San José de Maipo (Metropolitan Region) — pilot multihazard monitoring. Located in the Andean foothills and forming part of the upper Maipo River basin (Santiago's main water supply), SERNAGEOMIN deployed pilot monitoring sites integrating infrasound sensors, meteorological stations, and seismological instrumentation with support from the Chilean Ministry of Science and the USGS. Historical events span 1908, 1936, 1957, 1982, 1986, 1987, 1991, 1993, 2004, 2005, and 2009 (Sepúlveda and Padilla 2008; Sepúlveda et al. 2015), with the 1993 Macul debris flow being particularly emblematic. Triggering is modulated by the 0°C isotherm and ENSO phase, which control rain–snow partitioning at high elevations, while glacier retreat in the Echaurren glacier alters runoff and sediment dynamics. The site is currently a pilot (not operational) and serves as a natural laboratory for multi-hazard EWS development integrating DMC, DGA, SERNAGEOMIN, and SENAPRED.

Quebrada de Ramón (Santiago, Metropolitan Region) — discontinued pilot. An instrumented monitoring pilot was deployed in this Andean foothill catchment, one of the ravines whose alluvial fans underlie the eastern districts of Santiago and was dismantled in 2021 once the research phase ended, as no institution assumed responsibility for its continued operation. The case is instructive precisely because the technical chain functioned.

Southern Chile RILEWS initiative — Rainfall-Induced Landslide EWS. A pre-operational (to the current date) framework for the southern Chilean Andes (37°S–44°S) integrating WRF mesoscale modelling at ~ 4 km resolution driven by NCEP FNL, statistically bias-corrected via the PP_M4a perfect-prognosis method using 12 local stations (Fustos-Toribio et al. 2022). Predictors include daily and accumulated rainfall (7- and 30-day windows), ERA5-Land volumetric soil moisture, and slope angle. Logistic modelling achieved AUC = 0.80; Random Forest improved validation AUC to 0.88 with balanced F1-scores. Operational lead times of 24–72 hours (experimental extension to 120 h; Yáñez-Morroni et al. 2018). Real-time tests successfully anticipated landslides in Pucón, Llacahue, and Corral with up to 72 h lead time and mean spatial offset of 76.36 m. Operational application in southern Chile began in 2025 (Fustos-Toribio et al., 2025).

Río Las Minas catchment (Punta Arenas, Magallanes). Between 1941 and 2012, at least ten major alluvial events overflowed the channel, with economic losses exceeding USD 34 million for the five most severe (Muñoz et al. 2023). Between 2019 and 2022, with FNDR funding from the Regional Government of Magallanes and SERNAGEOMIN technical execution, a multi-parameter network was deployed integrating hydrometric and

meteorological stations, a Robotic Total Station, GNSS surface-deformation measurements (Muñoz et al. 2020), UAV photogrammetry, and fixed video cameras. The system supports near-real-time correlation between hydrometeorological forcing and mass-removal processes in a basin draining directly into urbanized Punta Arenas (Oberli et al. 2021). Recommendations emphasize micro-stations for the 0°C isotherm in cold-climate basins.

Comparable threshold work in the northern Patagonian Andes has characterised the geomorphological, hydrometeorological and geological conditions under which debris flows are triggered, providing a regional reference for threshold transfer between catchments (Maragaño-Carmona et al. 2023, 2025). The Chilean experience reveals a persistent gap between innovation and institutional continuity. During the last decade, several pilot and pre-operational initiatives have demonstrated the feasibility of moving beyond reactive landslide management, particularly in southern Chile, where RILEWS (Fustos-Toribio et al., 2025) integrates numerical weather prediction, hydrometeorological information, and machine-learning models to provide regional forecasts with operationally relevant lead times. Other monitoring experiences, including Río Las Minas and instrumented pilot catchments, further demonstrate that the country possesses the scientific and technological capacity to develop LEWS. Nevertheless, the discontinuation of the Quebrada de Ramón pilot after the research phase illustrates a critical weakness: technically successful initiatives could be discontinued due several reasons such as long-term funding, maintenance, and dedicated technical personnel. Thus, the principal challenge is no longer solely to demonstrate that landslide monitoring and forecasting are technically possible, but to transform research-driven pilots into sustained operational services, preserving personnel and monitoring infrastructure and avoiding temporal gaps in observations that progressively undermine warning capability. This transition should become a strategic national investment rather than remain dependent on isolated projects. Chile's exposure to extreme hydrometeorological events, combined with steep terrain, expanding infrastructure and settlements in susceptible areas, creates substantial consequences for population safety, connectivity, tourism, mining, and regional development. The 2017 Villa Santa Lucía disaster, which caused 22 fatalities (Somos-Valenzuela et al., 2020), exemplifies the potentially catastrophic consequences of rainfall-triggered cascading processes in southern Chile. Building on the institutional framework established by SINAPRED, the next stage should therefore prioritize long-term financing, permanent technical teams, complement the current dense hydrometeorological networks, and the progressive scaling of successful southern-Chilean pilots toward interoperable regional and ultimately national LEWS.

3.4. Colombia

3.4.1. National Context Diagnosis

Colombia's equatorial position places the Andean region under the influence of the Intertropical Convergence Zone, whose meridional migration drives a bimodal rainfall regime (April–May, September–November) and, together with regional low-level jets, generates the intense convective storms that trigger most landslides (Urrea et al. 2019; Mesa et al. 2021; Vega et al. 2024). These conditions act upon high-relief terrain shaped by Nazca–Caribbean–South American plate convergence and mantled by deep tropical weathering profiles (Ojeda and Donnelly 2006), a combination that concentrates fatal landslides across the tropical Andes (Sepúlveda and Petley 2015). Consequently, 88% of Colombia's registered disasters are hydrometeorological, with mass movements accounting for 15%, second only to floods (Vega et al. 2024; World Bank 2012): the landslide inventory (SIMMA) from the Colombian Geological Service (SGC) has more than 32,000 landslides between 1900 and 2022, 92% rainfall-triggered and better explained by antecedent duration than by peak intensity (Aristizábal et al. 2022), while the 2010–2011 La Niña alone affected nearly 9% of the population and caused economic losses of about US$7.8 billion (Sepúlveda and Petley 2015; Vega et al. 2024). The expansion of monitoring networks after this episode was mandated by the 2010–2014 National Development Plan, which instructed Institute of Hydrology, Meteorology, and Environmental Studies

(IDEAM) and the SGC (previously Ingeominas) to extend monitoring and early warning networks and to update hazard maps at regional and local scales (Moreno et al. 2014).

Institutional arrangements evolved from a response-centred model to a risk-management one: the National System for Disaster Prevention and Response (SNPAD), created in 1989, first made hazard assessment a mandatory input to municipal land-use and development plans, and Law 1523 of 2012 (Congreso de la República de Colombia, 2012) replaced it with the National Disaster Risk Management System (SNGRD), which defines risk management as a social process organised around risk knowledge, risk reduction and disaster management, aligned with UNDRR guidance and the Hyogo and Sendai frameworks (Domínguez-Calle and Lozano-Báez 2014; Moreno et al. 2014; Ramón et al. 2020). Governance is anchored in Law 1523 of 2012, which establishes a three-tier structure (national, departmental, municipal) and assigns responsibilities across SGC (geological hazard), IDEAM (hydrometeorological monitoring), National Institute of Roadways (INVIAS), and National Unit for Disaster Risk Management (UNGRD). The SGC's 2015 National Landslide Hazard Map (1:100,000) classified ~ 54% of the territory as low hazard, 22% medium, 20% high, and 4% very high; cross-referencing with 2018 Census data indicates that > 83% of the population (> 40.3 million people) is exposed to high or very high landslide hazard. This can be explained from a geographic perspective, given that most of the urban centres of the largest and most populous cities were established in Colombia’s Andean region, where the highest levels of hazard and vulnerability are found. Within this structure, three national committees, risk knowledge, risk reduction and disaster management, articulate the sectoral entities that produce and apply risk information (Neira and Castillo 2018), while Law 1931 of 2018 and the 2017 National Climate Change Policy place the implementation of hydro-climatological early warning systems with departmental and municipal risk-management councils. Warning capacity has therefore been built mainly from the bottom up, and its coverage follows municipal technical and fiscal capacity rather than the distribution of hazard.

3.4.2. History and Evolution of Early Systems/Initiatives

Operational forecasting predates the current legal framework. The first warning experience dates from 1976, when the Colombian Hydrology and Meteorology Service (SCMH) ran the Sacramento rainfall–runoff model on punched cards using data relayed by radio and telephone to support relief agencies during the rainy season (Domínguez-Calle and Lozano-Báez 2014), building on commitments made from the 1960s under United Nations agreements to operate hydrometeorological networks connected to international data-exchange centres (UNGRD, 2016). IDEAM inherited and expanded the function: it issues a daily technical bulletin of hydrometeorological alerts, with special communiqués for extraordinary events, covering river levels, precipitation, landslides and fires by natural region, with forecasts based on mesoscale modelling initialised with National Oceanic and Atmospheric Administration (NOAA)'s Global Forecast System (Domínguez-Calle and Lozano-Báez 2014). Landslides entered this chain as a dedicated product, the BADT, described in Section 3.4.3. At the national level, warning functions are distributed by hazard rather than consolidated: IDEAM for hydrometeorological events, the SGC for volcanic and seismic monitoring, General Directorate of Maritime Affairs (DIMAR) for marine and tsunami warning, and the Corporación OSSO for seismic and disaster information, while regional environmental authorities (CAR) and metropolitan bodies operate their own networks (Domínguez-Calle and Lozano-Báez 2014; Ramón et al. 2020). Landslides are therefore handled by one strand of a fragmented architecture rather than by a single national operator.

Beyond these institutional platforms, several Colombian initiatives have addressed the forecasting and warning chain from complementary angles: real-time probabilistic hazard assessment coupling rainfall with quantitative risk models (Correa et al. 2020), open-source real-time monitoring of rainfall thresholds for local warning in the Colombian Andes (Marín and Marín-Sánchez 2024), and dynamic warning modelling for the national road network (Urueña Ramírez 2025). Gómez et al. (2026) propose a multilevel Random Forest framework for rainfall-induced

landslide early warning in the Colombian Andes, integrating precipitation data across spatial resolutions, national satellite estimates, departmental daily station data, and municipal hourly rainfall, to estimate occurrence probability and issue alert levels. A recent academic state-of-the-art review of the technical and operational conditions of Colombian early warning systems for landslides and floods provides the first consolidated diagnosis of their coverage and maturity (Bohorquez and Bello, 2025). Alongside these institutional and academic developments, locally deployed SAT projects have multiplied since the 2010s, with heterogeneous technologies and operating principles and no common reporting standard (Neira and Castillo 2018).

3.4.3. Description and Current Scope of LEWS(s)

BADT — National landslide alert bulletin. At the national scale, IDEAM issues the Boletín de Alertas por Pronóstico de la Amenaza por Deslizamientos de Tierra (BADT), a daily bulletin covering all natural regions of the country and classifying municipalities into high, moderate, and low alert categories. The underlying model combines the national map of general terrain susceptibility to mass movements with daily precipitation as the triggering agent, together with precipitation forecasts and additional meteorological inputs. The susceptibility layer is the 1:500,000 national zonation produced jointly with the SGC and validated in 2010. Rainfall inputs are drawn from IDEAM's national hydrometeorological network, which comprises more than 2,500 active stations, of which around 89% are conventional and only 11% are automatic with real-time transmission, a configuration that constrains the temporal resolution available to the triggering component. Bulletin numbers restart each calendar year and track the day of the year rather than cumulative output, so the sequence documents uninterrupted daily issuance within each annual cycle rather than a cumulative count since inception. Bulletins are addressed institutionally to the National Disaster Risk Management System (SNGRD) and the National Environmental System (SINA) rather than to the public directly, so their translation into protective action depends on departmental and municipal councils.

SIRE-SAB — Sistema de alerta temprana del Distrito Capital de Bogotá. The Sistema de Alerta de Bogotá (SAB) is the monitoring and warning component of the District Risk Management and Climate Change System (SDGR-CC), established by Acuerdo 546 of 2013 (Concejo de Bogotá, 2013), which replaced the former district emergency system, turned FOPAE into the District Institute for Risk Management and Climate Change (IDIGER) and created the FONDIGER fund (Arts. 1, 8 and 12; Concejo de Bogotá, 2013) and was regulated by Decretos 172 and 173 of 2014 (Alcaldía Mayor de Bogotá, 2014a, 2014b). Hosted within SIRE, IDIGER's district risk information platform (IDIGER, 2026), the SAB monitors precipitation through a telemetric rain-gauge network, reported at more than 60 stations, and an X-band dual-polarization Doppler radar, complemented by coordination with IDEAM's national forecasting service. For mass movements it departs from the municipal resolution of the national BADT, operating on a georeferenced inventory of landslide-prone sites prioritized daily in three ordinal levels and refined by POT hazard zonation. The system is operationally mature but methodologically opaque: monitoring and institutionalized response are well established and data openly published, but the algorithm translating rainfall and antecedent conditions into priority levels is not disclosed, and no performance evaluation using standard warning metrics could be located as of September 2026. Consolidating FOPAE's accelerograph and hydrometeorological networks and Sisbog-Daño (Domínguez-Calle and Lozano-Báez 2014), it is the product of two decades of incremental instrumentation rather than of a single design.

SIATA — Metropolitan EWS, Aburrá Valley. SIATA covers nine municipalities and the District of Medellín in the Aburrá Valley (~ 340 km², population > 4 million) under a science-technology contract between AMVA (public authority) and EAFIT University. As of July 2025, its network totals 1,356 sensors and devices: 327 hydrometeorological (121 rain gauges, 83 stream water-level sensors, 14 piezometers), 535 air quality devices, 115 seismic instruments (with 72 structural sensors), 29 landslide-monitoring sensors (extensometers, accelerometers, tensiometers, TDR, GNSS), 14

remote-sensing instruments including a C-band Doppler radar, 189 cameras, and 147 community-based EWS devices (69 sirens, 39 rain gauges, 39 water-level sensors). Alerts are disseminated through phone calls, WhatsApp groups, the SIATA geoportal (21 M sessions and 2.13 M new users between Nov 2023 and Dec 2024), social media (> 113,340 followers), and community sirens activated in agreement with on-the-ground community watchers. From 1996 to 2024 (incorporates previous records from the predecessor entities), SIATA generated 1,888 flood-event warnings, activated 295 sirens/call chains, and recorded 1,158 seismic events; The system had established 59 community-based EWSs, in whose covered communities the authors report no casualties (Ruiz-Carrascal et al. 2026; see also Mejía-Chavarriaga 2016 for an early assessment of the lessons learned during its consolidation).

Manizales MHEWS — Municipal multi-hazard EWS, Caldas. Manizales runs one of the longest-standing municipal landslide warning schemes in Colombia, operated within a broader multi-hazard system. Meteorological stations have been installed since 1997 to monitor rainfall as a landslide predictor, and the network now comprises 55 stations, among them 18 meteorological, 19 hydrometeorological and 17 acoustic alarm stations, together with repeaters and warning and central stations, reporting telemetrically every five minutes; data are published through the SIMAC geoportal, developed by Universidad Nacional de Colombia with Corpocaldas and the municipality. These functions were consolidated in a municipal Risk Management Monitoring Centre in 2020. Landslide alerts rest on A25, the 25-day antecedent rainfall accumulation, with a yellow threshold of 200 mm derived by Terlien (1996) from a rainfall–landslide correlation and orange and red levels (300 and 400 mm) set by the municipal Risk Management Unit on the basis of operational experience; a mean event intensity indicator (imed), calibrated with physically based TRIGRS modelling, was later added for short, high-intensity triggers. Manizales is one of the few Colombian systems whose indicators have been tested against documented events: in the storms of 19 April 2017 and 19 October 2022 the intensity indicator activated earlier than A25, covered far more of the network before the emergencies began and matched the affected neighbourhoods closely, whereas A25 responded later and did not capture the severity of the sudden-onset failures (Zambrano Nájera et al. 2024).

Other specific initiatives:

Inform@Risk — Integrated EWS in Bello Oriente informal settlement. A neighborhood-scale prototype in Bello Oriente (Comuna 3, Medellín), covering about 36.78 ha and 1,285 buildings with some 4,600 inhabitants, 49% of them in high-hazard zones (Gamperl et al. 2023a). It couples Continuous Shear Monitor and extensometer lines laid in trenches with a low-cost LoRa-based IoT network recording ground inclination, at €100–250 per node against some €5,000 for a classical chain inclinometer excluding drilling (Gamperl et al. 2021). Altogether 115 nodes, 45 with subsurface probes measuring inclination and groundwater level, and about 1 km of measurement lines were installed (Werthmann et al. 2024). Four warning levels were developed with Departamento Administrativo de Gestión del Riesgo de Desastres (DAGRD) and local civil-society organizations and are disseminated through WhatsApp groups, a solar-powered eight-speaker system and siren, and door-to-door communication, a smartphone app remaining on hold; over 40 workshops with more than 1,000 participants and some 200 coordination meetings supported the deployment, and sensor acceptance was reported as very high, only a small number having to be relocated because a landowner withheld permission or construction work intervened; no loss or tampering of monitoring equipment is reported in the project's published record (Werthmann et al. 2024; Gamperl et al. 2023a). Handover to DAGRD was completed at the end of 2022, but the process was later suspended because legal constraints on donating the equipment to the municipality remained unresolved, so the prototype was not yet a fully functioning warning system (Werthmann et al. 2024).

SAMA — Departmental Alert and Monitoring System for Antioquia. Coordinated by Departamento Administrativo de Gestión del Riesgo de Antioquia (DAGRAN) with Universidad de Antioquia, SAMA is active in at least 30

municipalities of Antioquia, focusing primarily on flash floods, inundations, and water-supply disruption. It is not primarily a landslide LEWS. Each station integrates pluviometers, meteorological stations, water-level sensors, solar-powered acoustic alarms aligned with each municipality's Disaster Risk Management Plan (PMGRD), and cameras for visual confirmation. Data flow in real time to www.dagran.antioquia.gov.co, with a dedicated geoportal (SIGRAN) for spatial visualization. SAMA is structured around a six-stage cycle in which social appropriation is constitutive (prioritization, development, installation, monitoring, alert generation, social appropriation). It facilitates participatory Community GRD Plans through four structured modules (objectives/vision, community/territorial information with "time tunnel" history, hazard/vulnerability analysis, dissemination).

SIRMED — Integrated Risk Information Platform for Medellín. Launched in October 2025 by DAGRD, SIRMED (www.medellin.gov.co/sirmed) is a publicly accessible platform (not properly a LEWS) consolidating geospatial and statistical data, technical studies, mitigation works, inspections, and normative documentation across the District. DAGRD is organized into the Subdirección de Conocimiento y Reducción del Riesgo and the Subdirección de Manejo de Desastres (Fire Corps, 123 emergency module, incident command, recovery). SIRMED's interactive geovisor displays mass movements, floods, torrential flows, mitigation works, and inspection records; advanced features include heat maps, temporal-distribution graphs, AI-based pattern analysis, and augmented reality. It does not replace SIATA's sensor network but consolidates curated historical and technical documentation, creating a closed information loop from sensor signal through technical interpretation to public communication (DAGRD 2025b).

Further local initiatives. A wider set of local schemes appears in the national literature, most oriented to floods, flash floods or agroclimatic risk rather than to landslides, and with uneven evidence of current operation. The clearest case is Mocoa (Putumayo), where a threshold-based system was designed after the March 2017 debris flow that caused 332 deaths; during the August 2018 event the rainfall–landslide threshold reached the red level about an hour before impact, more than 20,000 residents were evacuated and no fatalities were recorded, although the rainfall–discharge thresholds were not exceeded, which the evaluators read as an argument for threshold redundancy (Ramos-Cañón et al. 2023, 2026). Ibagué operates sirens, repeaters and cameras along the Combeima canyon, activated during the September 2021 flood. The participatory agroclimatic system (SAAT) of the upper Cauca basin (Popayán, Puracé and Sotará, among others) is a distinct case: it combines NOAA seasonal outlooks and IDEAM quarterly forecasts with community biological indicators and the ancestral knowledge of Indigenous and campesino organisations, so that community participation is constitutive of the system rather than an add-on. Other schemes reported since the 2010s, the acoustic system in Bucaramanga, CORPOGUAJIRA's bulletin service, the Barranquilla prototype, the participatory agroclimatic system of the upper Cauca basin and the sistemas de alerta temprana ante eventos extremos del clima (SATC) of Norte de Santander, are described only in secondary sources, with little or no published evidence of thresholds, protocols or performance (Domínguez-Calle and Lozano-Báez 2014; Ramón et al. 2020).

Colombia therefore illustrates, more clearly than any other case reviewed here, both the reach and the limits of a layered warning architecture. The country operates warning arrangements at different levels, from daily national bulletins to subsurface monitoring in a single informal settlement, and the density achieved in the Aburrá Valley has no equivalent in the region. Yet the gaps that remain are not primarily technical. The BADT resolves at the municipal scale while risk concentrates at the scale of individual slopes in dense hillside settlements; thresholds based on intensity–duration relationships are calibrated on a limited record of documented events and may miss short, high-intensity storms; and the geological heterogeneity of the Medellín Dunite constrains the transfer of site-specific instrumentation between neighbouring slopes. More consequential still are the institutional constraints, the dependence of monitoring programmes on short-duration contracts and electoral cycles, the unresolved legal framework for transferring academic equipment to municipal operators, which paused Inform@Risk after a

successful handover, and the reliability of relocation housing, which erodes the social acceptance on which community-embedded systems depend. Across the board, and except for Manizales and Mocoa, these arrangements have not been assessed against documented events using standard warning metrics, so their reliability is asserted rather than measured.

3.5. Costa Rica

3.5.1. National Context Diagnosis

Costa Rica's landslide risk is strongly conditioned by rugged topography, deeply incised river basins, and steep slopes intersecting densely populated corridors and critical infrastructure (Quesada-Román 2024). Landslides are primarily triggered by intense or prolonged rainfall and frequently occur on road cut slopes, in hillside settlements, and in headwater catchments during the rainy season (Acosta-Quesada and Quesada-Román 2025). Affected areas typically include mountainous and piedmont zones near urban centres and transportation routes (Quesada-Román 2021). At-risk populations include residents of urban and peri-urban hillside neighbourhoods, rural communities with limited resources, and populations near steep terrain and river corridors where landslides can cascade into debris flows and flooding (Arroyo-Solórzano et al. 2022). Illustrative events include the August 2002 Orosi (Cartago) rainfall-induced landslides causing at least seven deaths (IFRC 2003) and the 2010 Pico Blanco landslide in Escazú that buried 17 houses and killed 24 people (Mora and Granados 2014).

3.5.2. History and Evolution of Early Systems/Initiatives

Early-warning efforts evolved from locally organized monitoring and communication toward more formal municipal systems. Regional UNESCO (United Nations Educational, Scientific, and Cultural Organization) and CEPREDENAC (Centro de Coordinación para la Prevención de los Desastres Naturales en América Central) guidance emphasized community organization, manual rainfall observation, and coordination mechanisms as foundations of people-centred warning (UNESCO and CEPREDENAC 2012a, 2012b). A pivotal step toward formalized landslide warning occurred in Santa Ana (Cerro Tapezco) in the mid-2000s, combining hydrometeorological monitoring, slope observation, and structured local coordination (Baldizón et al. 2005); this evolved into the Tapezco–Chitaría system with explicit rainfall thresholds derived from historical precipitation and geomorphological/geotechnical information (Geocad Estudios Ambientales S.A. 2012). In Escazú, modern alerting now integrates meteorological stations, cameras, alarms, and sirens with emergency protocols and community committees (Municipalidad de Escazú 2023). Basin-scale and multi-risk initiatives have strengthened hydrometeorological warning, as documented in Sarapiquí under a national pilot integrating institutions and communities (WMO et al. 2013), and water-supply protection has adopted hybrid hydrological–statistical modelling (Benavides Juárez and Busto Zamora 2023).

3.5.3. Description and Current Scope of LEWS(s)

Tapezco–Chitaría LEWS (Santa Ana, San José). Led by CNE, the Municipalidad de Santa Ana, and Geocad Estudios Ambientales S.A. The system uses IMN precipitation records, rainfall thresholds (> 50 mm/24 h and > 100 mm monthly accumulation), geomorphological/geological information (slope, faults), geotechnical parameters (pore pressure, water table, saturation), and aerial-image interpretation. The alert logic combines empirical–statistical thresholding from historical series with hydrometeorological monitoring and ground-displacement observation and includes a community component via local coordination and dissemination protocols (Geocad Estudios Ambientales S.A. 2012).

Cerro Tapezco SAT (Río Uruca microcatchment, Santa Ana). Led by CNE and local emergency structures, using conventional manual rain gauges, slope description, and hydrometeorological monitoring combined with community

organization and institutional support (Baldizón et al. 2005).

Escazú municipal monitoring and alert system. Coordinated by the Municipalidad de Escazú with community emergency committees, the system integrates meteorological stations, cameras, alarms, sirens, and continuous 24/7 monitoring linked to emergency protocols. The 2010 Pico Blanco event (24 fatalities; 17 homes buried) anchors institutional urgency at municipal scale (Municipalidad de Escazú 2023; Mora and Granados 2014).

Other specific initiatives:

Sarapiquí basin integrated EWS. A multi-risk pilot covering districts La Virgen, Horquetas, Llanuras del Gaspar, and Cureña, led by WMO, Global Facility for Disaster Reduction and Recovery (GFDRR)–World Bank, IMN, CNE, and ICE. Technologies include 20 rain gauges (10 continuous) and automatic stations, with calibrated hydrological modelling and 24–48 h lead times. The basin's landslide context is linked to the 2009 Cinchona earthquake (Quesada-Román and Barrantes-Castillo 2016; Quesada-Román and Martínez-Rojas 2026) and subsequent sediment/flow impacts (WMO et al. 2013).

AyA infrastructure-focused systems (Jacó: Quebrada Piedra Bruja; San Ramón: Río La Paz). Operated by Instituto Costarricense de Acueductos y Alcantarillados (AyA), these systems use high-frequency (5-minute) precipitation data, DEMs, basin morphometric parameters, IDF/PDF curves, hydrographs, and statistical distributions (Weibull, Gumbel) combined with HEC-HMS hydrological modelling to define site-specific thresholds for water-supply protection (Benavides Juárez and Busto Zamora 2023). Calibration periods cover 2015–2021/2022.

Orosi community-based warning approach (Cartago, post-2002 events). Following the August 2002 rainfall-induced landslides that caused at least seven deaths (IFRC 2003), the International Federation of Red Cross and Red Crescent Societies and the Costa Rican Red Cross supported local community organization and training in Orosi, funded by the British government. Technologies relied on rainfall information, coordination with the national meteorological institution, local observation, and radio communication. The approach centred on community organization, training, and institutional coordination to support timely warning and response at local scale.

Sarapiquí cantonal emergency planning. At the cantonal level, the Comité Municipal de Emergencias (CME) Sarapiquí, CNE, and the Municipalidad have developed an institutional and community preparedness framework considering slope/susceptibility factors and operational procedures (CME Sarapiquí 2019). This complements the basin-scale pilot and represents the governance layer connecting technical warning with community response at the cantonal planning scale.

Collectively, Costa Rica's LEWS landscape demonstrates a clear trajectory from community-centred monitoring and educational approaches toward more technically sophisticated and networked systems at municipal and basin scales. However, the national landscape remains heterogeneous: LEWS capacity is often concentrated in priority municipalities, pilot basins, or critical infrastructure contexts. The primary gaps include coverage expansion to high-exposure corridors outside priority areas, technical sustainability beyond pilot funding cycles, standardization of escalation protocols across meteorological, civil-protection, and municipal actors, and adequate climate-change adaptation of the empirical rainfall thresholds that underpin all current systems.

3.6. El Salvador

3.6.1. National Context Diagnosis

El Salvador covers ~ 21,041 km² and is the most densely populated country in Central America, with ~ 6 million inhabitants (Banco Central de Reserva, 2024). Its physical environment combines steep topography, active tectonics, and widespread volcanic formations, with a central volcanic chain, northern mountainous terrain, and a Pacific coastal range. Highly weathered volcanic soils and steep slopes promote instability, particularly during the rainy season (May–October). Landslide exposure is amplified by high population density and urban expansion onto unstable hillsides, with low-income housing often lacking adequate slope stabilization. Major rainfall- and earthquake-triggered events include Hurricane Mitch (1998) and the 2001 earthquakes; lahars have historically caused some of the highest fatality counts in the country, including those at San Salvador Volcano (1982) and San Vicente Volcano (2009). The 2001 earthquakes also produced the Las Colinas flow slide, one of the most damaging single slope failures recorded in the country (Crosta et al. 2005).

3.6.2. History and Evolution of Early Systems/Initiatives

The first landslide EWS in El Salvador was established through a 2002–2003 cooperation between the National Service of Territorial Studies (SNET) and the Norwegian Geotechnical Institute (NGI), under the project "Protective Measures to Reduce Landslide Risk in El Salvador" funded by the Norwegian Ministry of Foreign Affairs. Two dedicated rain gauges were installed at San Vicente Volcano and San Ignacio (Chalatenango), with custom software triggering email alerts when thresholds were exceeded (Tronstad et al. 2002). Another pilot lahar early warning system in the northern flank of San Vicente Volcano, including sensors, digital telemetry, and automated sirens, was developed under a project funded through an Inter-American Development Bank loan to the Government of El Salvador, implemented by the Ministry of Agriculture and Livestock with the French firm GIPEA, and handed over to the Municipality of Guadalupe as the end user in 2002 (GIPEA, 2002). By the time a lahar triggered by a storm associated with the combination of Tropical Depression 96E and Hurricane Ida struck the area on the night of 7–8 November 2009, the system was no longer operational (UNESCO & CEPREDENAC, 2012b). A national LEWS began operating in 2005, initially activated only during extreme events. In 2007, SNET was integrated into the Ministry of Environment and Natural Resources (MARN). A major shift followed the November 2009 San Vicente lahars (triggered by Hurricane Ida), which caused 24 fatalities in Verapaz, and Tropical Depression 12E in October 2011. SNET was reorganized into the Environmental Observatory, now called Observatory of Hazards and Natural Resources, integrated into MARN, with additional rain gauges and eight X-band radars; meteorology, hydrology, and landslide units merged into the Integrated Hazards Monitoring Centre.

3.6.3. Description and Current Scope of LEWS(s)

El Salvador Landslide Early Warning System (national). Technical operations are managed by the Observatory of Hazards and Natural Resources (MARN); alert issuance is the responsibility of the General Directorate of Civil Protection, which falls under the Ministry of Governance. Technologies include 106 automatic rain gauges (hourly transmission) and 7 X-band radars; numerical weather prediction uses the WRF model (Skamarock et al. 2019). During the rainy season a daily forecast is issued (~ 10 a.m.) based on a heuristic model, a modified Mora–Vahrson approach (Mora and Vahrson 1994), a soil moisture–rainfall model developed for the Central America Flash Flood Guidance System (CAFFGS; Posner and Georgakakos 2015), or a combination of these. An Impact-Based Forecast (WMO 2015) is the final product, with probability of occurrence derived from analysis and magnitude assessed from experience, recent landslide reports, and meteorological information. Updates are issued depending on severity or forecast changes; near-real-time monitoring with hourly rainfall updates supports additional alerts. Forecasted landslide impacts are displayed on a web platform together with meteorological and hydrological impacts, and an infographic synthesizes expected impacts. Bulletins are distributed via email to Civil Protection, the Observatory's webpage, social media, and instant messaging applications and radio. The system operates at national scale and

has supported evacuations in critical areas, notably during Tropical Storm Agatha (2010) when residents near the 1982 San Salvador lahar zone (300–500 fatalities) were evacuated voluntarily under high meteorological uncertainty.

The system is maintained by MARN, with operational costs covered by the Observatory's budget. Communication with the General Directorate of Civil Protection is well established, and an ongoing project seeks to further strengthen that protocol. Multi-hazard integration has improved with the creation of the Integrated Hazard Monitoring Centre, though further work is required regarding cascading hazards. Efforts to strengthen community involvement through education initiatives targeting vulnerable communities and public outreach continue, alongside the challenge of reaching populations without internet access and combating misinformation, both identified as persistent operational concerns. Strengthening the system would benefit from increased regional cooperation and technology transfer, particularly with other Central American early-warning initiatives and international research institutions.

3.7. Honduras

3.7.1. National Context Diagnosis

Honduras is among the most landslide-prone countries in Central America, with ~ 80% mountainous terrain (SERNA 1997; Quesada-Roman et al. 2024)) and prominent slopes in the eastern (Olancho), central (Francisco Morazán, including Tegucigalpa), and western (Intibucá, Lempira, Santa Bárbara) sectors.

Tropical storms and hurricanes from the Atlantic during the rainy season (May–October) drive recurrent landsliding (Garcia-Urquia and Axelsson 2014). Hurricane Mitch (1998), the worst Central American disaster of the last century (Alcántara-Ayala 2009), triggered thousands of landslides (Harp et al. 2002b); Hurricanes Eta and Iota (November 2020) caused widespread landslides in western and central sectors (El Heraldo 2020; BID 2021). Approximately 63% of Honduras's 10.6 million inhabitants live in poverty (INE 2025), driving informal settlement on unstable hillsides in cities such as Tegucigalpa (Garcia-Urquia and Axelsson 2014). Urban landslides such as the destruction of La Soto neighbourhood on El Berrinche hill in 1998, which triggered a landslide dam and massive upstream flooding (Harp et al. 2002), illustrate the high physical and social vulnerability. Long-term analyses of disaster occurrence in the country confirm that this accumulation of risk is neither recent nor episodic (Quesada-Román et al. 2024).

3.7.2. History and Evolution of Early Systems/Initiatives

The Permanent Commission of Contingencies (COPECO) was established in 1990 to coordinate public and private entities for emergencies. Hurricane Mitch (October 1998) exposed severe deficiencies and motivated international support: the USGS (United States Geological Survey) developed a landslide hazard map for Tegucigalpa (Harp et al. 2002a), and JICA (Japan International Cooperation Agency) proposed a master plan for hazard mapping, slope stability, and risk-reduction planning (JICA 2002), implementing the installation of piezometers, extensometers, and inclinometers, as well as the construction of catchment wells, and counterweight berms in several landslide sites in Tegucigalpa (El-Heraldo 2013). Subsequent research developed press-based landslide databases (Garcia-Urquia and Axelsson 2014), rainfall thresholds (Garcia-Urquia 2016; Garcia-Urquia and Axelsson 2015), susceptibility maps integrating remote sensing and data mining (Garcia-Urquia and Yamagishi 2017; Braun et al. 2018), colluvium-based susceptibility refinements (Suárez and Domínguez-Cuesta 2021), and logistic-regression-based susceptibility integrating 12 morphometric predictors (Ruiz-Álvarez et al. 2025). Methodologies for estimating average annual loss have also been proposed despite data scarcity (Suárez and Domínguez-Cuesta 2024). A national inventory and characterisation of Honduran early warning systems, prepared under the same regional programme that produced

the Central American guidance discussed above, provides the baseline against which these advances can be read (UNESCO and CEPREDENAC 2012c).

3.7.3. Description and Current Scope of LEWS(s)

In 2014, COPECO created CENAOS (National Centre for Atmospheric, Oceanographic and Seismic Studies) under the SINAGER (National Risk Management System) Law, equipped with meteorological, pluviometric, hydrological, seismic, wave-monitoring, and electrical-storm observatories, plus real-time visualization software. COPECO works closely with municipal CODEMs (Municipal Emergency Committee) in emergency handling.

SIMET-AMDC (Central District). Available at https://simet.amdc.hn/, the SIMET (Measurement and Telemetry System) of the AMDC (Municipal Government of the Central District) is the best-structured LEWS in the country. It is led by AMDC with support from USAID (United States Agency for International Development), the Resiliencia Urbana project from the GIZ (German Agency for International Cooperation), the GOAL NGO, and the SICA (Central American Integration System), among others. The platform displays real-time data on rainfall, river levels, humidity, temperature, atmospheric pressure, air quality, and wind. Forecast maps are available for floods, landslides, river levels, fires, and evacuation routes, along with alert bulletins for different hazards. Warnings are disseminated via the webpage and AMDC social media; emergencies are coordinated with CODEM, COPECO, and community leaders. AMDC also monitors specific landslide areas with piezometers, extensometers, and inclinometers donated by JICA (e.g., El Berrinche, El Reparto, El Bambú, and La Guillén landslides). The 2022 La Guillén landslide illustrates the value of monitoring: instrumentation enabled timely warnings (JICA 2026), ~ 150 families were evacuated before slow-movement destroyed at least 70 households (El-Heraldo 2022), though the relocation plan was insufficient and many families returned for affordability reasons (El-Heraldo 2026).

Beyond Tegucigalpa, monitoring infrastructure remains sparse across Honduras's mountainous regions. While meteorological forecasting and social media coordination substantially improved preparedness for Hurricanes Eta and Iota (2020) relative to Hurricane Mitch (1998), the physical vulnerability of cities, exemplified by Tegucigalpa, and weak urban-expansion policy enforcement continue to drive landslide risk accumulation in informal settlements (El Heraldo 2023). Several instruments installed in landslide-prone communities have been vandalized or stolen, underscoring the need for community ownership and education, an area where community-led climate risk management in Lenca Indigenous communities offers a documented national reference (Bautista-Soto and Alvarado-Peña 2024). The positive model of academia–government–JICA collaboration at the National Autonomous University of Honduras, AMDC, and COPECO provides a replicable framework for strengthening LEWS beyond the capital, particularly through integration of susceptibility studies with temporal and spatial landslide analysis and vulnerability assessments that current research has not yet achieved.

3.8. Mexico

3.8.1. National Context Diagnosis

Mexico's predominantly mountainous geography, the Sierra Madre Occidental and Oriental, the Trans-Mexican Volcanic Belt, and widespread volcanic and tectonically active terrains, combines with intense seasonal rainfall, tropical cyclones, and seismic activity to make landslides one of the country's most recurrent natural hazards (Alcántara-Ayala 2004, 2008). Impacts concentrate in the Sierra Norte de Puebla, the highlands of Veracruz, Hidalgo, Chiapas, Oaxaca, Guerrero, Michoacán, and the Mexico City Metropolitan Area, where rainfall-induced shallow and deep-seated landslides, debris flows, and slope failures recur, often triggered by prolonged precipitation associated with hurricanes or compound events. Long-term inventories in Teziutlán show strong spatial persistence over more

than seven decades Murillo-García & Alcántara-Ayala 2017), and Alcántara-Ayala (2004) demonstrated that triggering conditions vary significantly between neighbouring municipalities even within similar geological settings. Rural and Indigenous communities are disproportionately affected (Alcántara-Ayala et al. 2018), with informal urban expansion further amplifying exposure.

3.8.2. History and Evolution of Early Systems/Initiatives

The initial warning relied largely on local observations, community experience, and emergency response (Alcántara-Ayala & Garnica-Peña 2012). The 19 September 1985 Mexico City earthquake led to the creation of the National Civil Protection System and CENAPRED. From the early 2000s, CENAPRED promoted structured studies on slope instability, rainfall thresholds, and susceptibility mapping (Mendoza & Domínguez 2006). The Institute of Geography (UNAM), designated as an ICL World Centre of Excellence, consolidated work on landslide inventories, post-event analysis, slope monitoring, and community-based warning, particularly in the Sierra Norte de Puebla (Alcántara-Ayala et al. 2021). The October 1999 disasters in Puebla, Veracruz, and Hidalgo were a turning point: subsequent practice combined slope instrumentation with communication-oriented measures, with Alcántara-Ayala & Garnica-Peña (2012) cautioning against equating early warning with instrumentation alone. From the 2010s, multi-risk perspectives emerged, recognizing interactions among landslides, floods, and tropical cyclones (Alcántara-Ayala & Oliver-Smith 2019).

3.8.3. Description and Current Scope of LEWS(s)

Mexico has developed a national landslide-specific alerting framework through CENAPRED's Sistema de Alertamiento Temprano por Inestabilidad de Laderas (SIAT-Laderas), complemented by regional, municipal, research-based, and community initiatives. Although SIAT-Laderas provides a national framework for anticipating conditions conducive to slope instability, CENAPRED still describes it as under development and testing, and it should therefore be distinguished from a fully consolidated end-to-end operational LEWS.

National and regional monitoring frameworks. CENAPRED's SIAT-Laderas integrates the National Landslide Susceptibility Map with observed rainfall from the National Meteorological Service and short-range precipitation forecasts to identify municipalities where conditions may favour slope instability and to generate technical alerting products for Civil Protection authorities. Rainfall thresholds and accumulated precipitation from historical analyses provide an important scientific basis for this framework (González Huesca & Domínguez Morales 2021). The scientific basis includes event, antecedent, and cumulative rainfall coefficients validated through Sierra Norte de Puebla case studies (Alcántara-Ayala 2004). In the Sierra Madre Oriental (Nuevo León), probabilistic "interim zones" rather than deterministic thresholds were tested (Sanchez-Castillo et al. 2017; see also Salinas-Jasso et al. 2020 for rainfall thresholds derived for shallow landslides in the same range). Complementary risk-information platforms include the Risk Atlas of Mexico City, which integrates susceptibility, exposure, and social vulnerability within a GIS environment to support preparedness and land-use planning, particularly in the western and southwestern sectors (Novelo-Casanova et al. 2022).

National susceptibility mapping and municipal applications. The Atlas Nacional de Riesgos hosts the national landslide susceptibility map (Álvarez et al. 2021). CENAPRED guidance combines susceptibility classes with short-window rainfall fields and georeferenced housing data to prioritize attention and relocation (Zaragoza Álvarez et al. 2021). This national susceptibility information also provides a fundamental input to SIAT-Laderas, where it is combined with observed and forecast rainfall to identify potentially affected municipalities. Applications in marginalized municipalities of Chiapas and Oaxaca demonstrated operational use of rainfall-based logic during

2020 events associated with Tropical Storms Amanda (Pacific, May 2020) and Cristóbal (Atlantic, June 2020) (González Huesca & Domínguez Morales 2021).

Site-based monitoring and pilot systems. Technologies include conventional rain gauges, radar, satellite precipitation estimates, geotechnical instrumentation, and geospatial platforms; UAVs and high-resolution DTMs have been applied in pilot areas (Garnica-Peña & Alcántara-Ayala 2021). In Tijuana, a pilot combined geotechnical characterization with IoT-based sensors measuring volumetric water content and suction; field observations identified rapid suction loss as a consistent precursor, with alerts issued via a central dashboard. Challenges include maintenance, intermittent transmission, power outages, and weather-related sensor failures (Ambika et al. 2025). Such site-based initiatives complement the national rainfall- and susceptibility-based approach by directly monitoring subsurface and slope conditions that precipitation alone cannot capture.

Sierra Norte de Puebla — Teziutlán site. The Casa CENAPRED monitoring site at La Aurora was the first sustained national effort to instrument an inhabited unstable slope with combined geotechnical and hydrometeorological sensors. Although not a fully automated warning system, it generated key insights into rainfall–slope response, soil moisture, and the institutional demands of long-term monitoring (Alcántara-Ayala & Garnica-Peña 2012). Subsequent initiatives integrated landslide inventories, threshold analysis, participatory mapping, and community workshops; school-centred participatory approaches improved preparedness (Hernández-Moreno and Alcántara-Ayala 2017; Ruiz-Cortés and Alcántara-Ayala 2020). Recent damaging rainfall events have continued to illustrate the high exposure of rural and Indigenous communities and the importance of linking hazard information with locally meaningful communication and capacity to act (World Weather Attribution 2025).

Coverage across Mexico's landslide-warning arrangements remains uneven despite the emergence of a national SIAT-Laderas framework. National-scale susceptibility information, rainfall observations, and meteorological forecasts can now be combined to identify areas requiring attention, but landslide-specific ground monitoring, locally calibrated thresholds, and end-to-end warning and response capacities remain concentrated in selected municipalities and pilot sites. Populations affected by poverty, remoteness, language barriers, and limited digital access may therefore remain less well served. Technical products are communicated through Civil Protection channels, while decisions concerning local alerts, preparedness measures, and evacuation depend substantially on state and municipal authorities. Evidence from Teziutlán shows that warning effectiveness can be strengthened when monitoring and mapping are accompanied by structured knowledge transfer and community ownership; television was the most common information source, but radio was the most trusted, and initiatives perceived as externally driven lacked community legitimacy (Alcántara-Ayala & Moreno 2016). These experiences illustrate that effective landslide warning depends not only on forecasting capability, but also on institutional coordination, trusted communication, and the capacity to translate technical information into locally actionable measures (Alcántara-Ayala & Garnica-Peña 2023a). Looking forward, strengthening LEWS in Mexico requires consolidating SIAT-Laderas as an end-to-end system, expanding locally calibrated and dynamic thresholds, integrating multi-parameter and multi-hazard monitoring, strengthening municipal capacities and community participation, and promoting sustained coordination and learning across national, state, municipal, and community levels (Alcántara-Ayala 2025).

3.9. Nicaragua

3.9.1. National Context Diagnosis

Nicaragua is largely flat (63%), with 37% mountainous and volcanic terrain reaching 2,107 m.a.s.l. Five physiographic units (Interior Highlands, Atlantic Coastal Plain, Pacific Coastal Plain, Nicaraguan Depression, and Pacific Volcanic Chain) differ in geology, climate, and landslide susceptibility. The tropical climate produces annual rainfall of 800–

5,000 mm, and landslides are commonly triggered by intense rainfall driven by the ITCZ, ENSO, cyclones, and tropical depressions from May to October (Devoli et al. 2007a). Rural communities at the foot of volcanoes and across the Interior Highlands face the highest exposure. Shallow slides are most frequent, followed by rockfalls, debris flows (volcanic and non-volcanic), rotational slides, complex landslides, and translational slides. Hurricane Mitch (October 1998) caused catastrophic damage, including the Casita Volcano landslide that killed more than 2,000 people (Scott et al. 2005; Devoli et al. 2009). Concepción volcano debris flows occurred between 2002 and 2006 (Álvarez et al. 2012), and Hurricanes Eta and Iota (November 2020) triggered multiple landslides, notably in the Peñas Blancas Massif (La Dalia, Matagalpa).

3.9.2. History and Evolution of Early Systems/Initiatives

The Instituto Nicaragüense de Estudios Territoriales (INETER) (created in 1981) collects meteorological, hydrological, seismic, volcanic, and geological data. It provides scientific monitoring, forecasts and issues alerts for weather and natural hazards like drought, flood, landslides, volcanic eruptions earthquakes, and tsunami. Before 1998, landslides were not a formal study area. Hurricane Mitch and the Casita landslide disaster motivated the creation of INETER's first Landslide Unit (1999) within the Department of Geophysics, which became the Department of Geology in 2002. Law 337 (2000) created SINAPRED (Sistema Nacional para la Prevención, Mitigación y Atención a Desastres, www.sinapred.gob.ni) as the primary disaster-management and civil protection institution (Devoli et al. 2007b). SINAPRED is an inter-institutional network made up of government ministry, public security forces and community organizations and core institutional members are Civil Defense, INETER, Ministry of Health, Municipalities and local committees.). International cooperation during 1999–2006 supported training and field studies (Devoli et al. 2007b). More recently, in 2020 the landslides triggered by the intense rainfall and high soil moisture of Hurricane Eta in the northern and Central area and of Hurricane Iota, that affected two weeks later the same areas, required the activation of the municipal alert protocols by SINAPRED and the evacuation of 71,145 people (over nearly 2 million exposed). Before the arrival of the hurricanes INETER assisted with the early national forecasting and warning. Lessons learned drove finalization of the national landslide database, post-event mapping, and initiation of data-automation processes for warning preparation and dissemination (SINAPRED 2020).

Local LEWS at volcanoes for lahars evolved from a community-based oral system at San Cristóbal (designed January–April 2000 by INETER with the support of Swiss specialists, Civil Defense, and Chinandega municipality; Devoli 2000), then to instrument-based systems using rain gauges and existing geophones at closest seismic stations and extended at four volcanoes San Cristóbal, Casita, Mombacho, and Concepción. Between 2000 and 2002 the first version of local LEWS was designed by INETER with the support of Norwegian specialists. The system included the installation of rain gauges at the four volcanoes, definition of rainfall thresholds (of 60 mm/h) and alarm software (Sandersen 2002; Tronstad 2001; Høydal and Sandersen 2003). The system incorporated later also the use of geophones, since it was observed that lahars occurred during the design period, left clear seismic signals (Álvarez et al., 2012). This system was pre-operational since 2002. It was tested at Concepción in October 2002 (Álvarez et al. 2012) and activated on multiple occasions between 2002 and 2008, and again in 2014. The rain gauges suffered different technical problems and were dismissed in 2008 but replaced more recently by new ones. A monitoring system for the Dipilto deep-seated rotational earth slide was designed combininga meteorological station, seismic station, and extensometers. The system (now dismissed) was at experimental stage between 2004–2006 but never detected movements.

The first national warning was issued by INETER in October 2000 during Hurricane Keith, combining rainfall forecasts with the first preliminary landslide inventory, created after Hurricane Mitch and the July 2000 Apoyo earthquake. About 20% of the forecasted hot spots experienced landslides. Some years later, in 2008, the first

version of the national LEWS designed with the support of the German cooperation under the project "Mitigación de Georiesgos en Centroamérica", used GOES/NESDIS satellite data with 15-minute updates and intensity–duration thresholds (Strauch 2012). It was pre-operational from 2008 until 2020. The design has been replaced by a newer version and now incorporated into the new national LEWS.

3.9.3. Description and Current Scope of LEWS(s)

Local LEWS – Volcanoes (INETER). Uses geophones at seismic stations and infrasound sensors to detect lahar signals in real time (http://geofisica-ew1.ineter.gob.ni/sismogramas/welcome.html). Weather forecasts and real-time rainfall data at closest and recently re-installed rain gauges are also used. The system counts also with lahar hazard maps. Geologists and/or seismologists follow weather forecasts and monitor daily seismic records and issue alarms by radio to SINAPRED if a lahar signal is detected. Coverage is local, focused on communities near main lahar trajectories at San Cristóbal and Concepción volcanoes. This local LEWS is an evolution of the local system described in Chap. 3.9.2. The system is fully operational since 2020.

National LEWS (INETER). The actual national LEWS was first systematically activated in November 2020 during the back-to-back Eta and Iota Category-4 hurricanes. The system integrates precipitation data from the national weather service with 160 automatic hydrometeorological station and landslide locations from the national database. The system is a new version of the national system created in 2008 and uses the same principle, based on continuous rainfall monitoring and downloading precipitation estimates for each hydrometeorological station. Instead of using NESDIS/NOAA data, the system uses Nicaraguan meteorological forecasts. The method uses the same Rainfall Intensity-Duration threshold but updated at three levels. A list is compiled showing those hydrometeorological stations that report accumulations greater than 60 mm/h, 80 mm/h or 100 mm/h. Using these stations, a geospatial intersection operation is performed to interpolate and extract the critical landslide sites close to the stations that meet the above criteria. For each identified critical site, a buffer of at least 2 km is calculated to determine all nearby human settlements that could be affected by a potential landslide. Under critical conditions, the geologist also analyses a separate soil moisture map, which is not yet integrated into the system. During Hurricanes Eta and Iota, a specialist geologist monitored conditions continuously: a national susceptibility map identifying critical sites was sent to SINAPRED before landfall, with reports issued every eight hours.

Regarding the overall state of Nicaragua's LEWS, the country has an updated national landslide database, a landslide susceptibility map, operational national and local LEWS, and multi-risk maps for approximately 50% of Nicaraguan municipalities. Warning dissemination benefits from good INETER–SINAPRED communication. Key needs include integrating soil-moisture data, refining regional and seasonal thresholds, distinguishing short-duration from long-duration rainfall, and expanding monitoring networks in high-risk areas while accounting for instrument hazards (vandalism, seismic damage, acid rain, corrosion) that are particularly relevant in volcanic regions. Automating warning generation, establishing dedicated forecasting teams, and building an interdisciplinary exchange between geologists, meteorologists, hydrologists, and seismologists for integrated multi-hazard monitoring remain central priorities for system improvement.

3.10. Peru

3.10.1. National Context Diagnosis

Peru's complex physiography is dominated by the Andes, which strongly influence climate, hydrology, and geomorphology and generate steep topography and highly dynamic hydrological processes contributing to landslides and debris flows (Bookhagen and Strecker 2008). The country is divided into Pacific, Atlantic (Amazon),

and Titicaca basins. The Pacific basin has only ~ 2% of the national freshwater yet concentrates more than 50% of the population (Rau et al. 2018; ANA 2012). Hydroclimate is controlled by the South American Monsoon System, ITCZ migration, and ocean–atmosphere interactions, with intense austral-summer (November–March) precipitation on eastern Andean slopes (Lavado Casimiro et al. 2011). Rainfall-triggered landslides and debris flows (locally huaicos) frequently affect Pacific catchments with rapid runoff and sediment conveyance to populated areas, particularly during El Niño episodes (1982–1983, 1997–1998, 2017) and the 2023 Yaku event (INDECI 2025). Urban expansion along alluvial fans and dry riverbeds in Lima, and proximity of rural and Indigenous Andean communities to unstable slopes, amplify vulnerability.

3.10.2. History and Evolution of Early Systems/Initiatives

Major El Niño events catalysed monitoring and warning initiatives, with the 2015–2016 preparation building capacity that proved critical during the 2017 Coastal El Niño. SENAMHI developed monitoring products at national, regional, and local scales; IGP implemented camera networks and geophysical instrumentation in volcanic and mountainous regions; ANA implemented local monitoring through pluviometric stations and critical-point identification (INDECI 2025). A major milestone was the creation of SILVIA (Sistema de Monitoreo de Movimientos en Masa Potenciales Generados por Lluvias Intensas), initially developed as a research and operational prototype within SENAMHI (Millán 2020; Millán et al. 2021; Millán-Arancibia and Lavado-Casimiro 2023). SILVIA fed the national "Aviso de Activación de Quebradas" issued by SENAMHI since 2020 under Ministerial Resolution N°049-2020-PCM. After 2017, the Reconstruction Authority with Changes (ARCC), later the National Infrastructure Authority (ANIN), developed integrated watershed-scale interventions in pilot basins such as Ica and Piura.

3.10.3. Description and Current Scope of LEWS(s)

SILVIA — Monitoring System for Rainfall-Induced Landslides (SENAMHI). National monitoring system identifying areas where rainfall conditions may trigger debris flows and landslides. It integrates SENAMHI's PISCO-based operational gridded precipitation products, historical-event rainfall thresholds, and susceptibility maps within a web platform (https://www.senamhi.gob.pe/?p=monitoreo-silvia). Hazard levels are categorized by rainfall intensity and terrain susceptibility, with sub-basin resolution at Pfafstetter Hydrological Unit Code level 12.

Aviso ante posible activación de quebradas (SENAMHI). National warning service issuing 24-hour debris-flow alerts (https://www.senamhi.gob.pe/?&p=aviso-activacion-quebrada). Combines rainfall monitoring with short-term precipitation forecasts and SILVIA-derived thresholds. Warnings are disseminated through official platforms and emergency operation centres, and in some cases through the national emergency messaging system (SISMATE).

ISAAC — Lima regional rainfall monitoring (SENAMHI). The regional system focused on the Lima region, integrating hourly rainfall observations from rain gauges with locally derived thresholds. Communication occurs through online platforms and direct WhatsApp coordination with local authorities and communities.

Other specific initiatives:

SAMAQ — Local Rainfall Monitoring (ANA). Local monitoring system based on pluviometric stations integrated into a web platform (https://snirh.ana.gob.pe/VisorPorCuenca/?IdVar=106), focused on rainfall accumulation in critical basins to support local risk monitoring through coordination with civil-protection agencies.

Lahar and Debris Flow Monitoring (IGP). Camera-based monitoring systems and instrumentation in selected catchments and volcanic environments (https://grd.igp.gob.pe/lahares-huaicos/), with real-time visualization on the IGP web platform and sharing with national and regional emergency operation centers. During the 2023 Yaku event,

SILVIA and the "Aviso de Activación de Quebradas" supported identification of susceptible catchments and tracking of hazardous conditions in real time. Local siren-coupled rainfall stations have shown that poorly calibrated thresholds may generate false alarms, eroding public confidence and underscoring the need for locally calibrated thresholds combined with complementary observations and modelling.

Despite these advances, several structural challenges persist. The primary technical limitation is the insufficient station density to capture the high spatial variability of Andean precipitation driven by strong orographic effects; many mountainous catchments with high landslide susceptibility in remote Andean regions remain poorly instrumented (Lavado Casimiro et al. 2011). Institutional coordination remains fragmented: SENAMHI, ANA, IGP, INDECI, and regional emergency operation centres operate largely separate platforms, limiting integration into a coherent national landslide warning framework. Social dimensions are equally critical, building public trust in warnings and improving preparedness in peri-urban and rural mountain communities remain pending tasks, exacerbated by the limited access to early-warning information faced by many vulnerable populations. Looking ahead, integrating higher-resolution hydrometeorological models, open interoperable platforms, community-based preparedness, and climate-projection-informed threshold revision represent the central strategic priorities (Millán-Arancibia and Lavado-Casimiro 2023; INDECI 2025).

Across the ten countries reviewed in this section, a set of structural patterns emerges that is relevant for the regional synthesis in Section 4. First, the evolution from reactive to anticipatory LEWS has been driven almost universally by catastrophic events acting as institutional catalysts, Hurricane Mitch in Central America, the 2011 Serra do Mar disaster in Brazil, the 1987 Villatina catastrophe in Colombia, the 2010 Maule Earthquake in Chile, underscoring the continued reactive architecture of regional risk governance even where technical progress has been substantial. Second, a persistent and widening gap exists between the sophistication of national-scale warning tools and Institutions (BADT in Colombia, SILVIA in Peru, Cemaden in Brazil, the El Salvador national LEWS) and the spatial and temporal resolution required for actionable community-level warnings, particularly in densely inhabited informal hillside settlements. Third, the effectiveness of LEWS depends critically on social components, community participation, communication trust, community-authored preparedness plans, and socially embedded sensor networks, that require years of continuous investment and cannot be retrofitted onto technical systems after deployment. Fourth, long-term sustainability depends on stable institutional ownership, legal clarity for academic-to-public-sector technology transfer, predictable multi-year funding, and alignment with climate finance mechanisms. These cross-cutting lessons form the analytical foundation for the regional comparison and recommendations developed in Sections 4 to 6.

4. Cross-Comparison and Regional Analysis

To further characterize the regional status of LEWS, the systems identified in each country were assessed against the nine assumptions proposed by Guzzetti et al. (2020). These assumptions underpin geographical landslide early warning systems; the labels A1 to A9 used throughout this section are introduced for ease of reference and are not part of the original formulation. The criteria used to classify each assumption as supported, partially supported or challenged are given in Section 2.4:

- A1, landslides can be predicted in space and time;
- A2, the past provides a basis for predicting future landslide behaviour;
- A3, rainfall is a primary landslide trigger;
- A4, rainfall provides a suitable proxy for groundwater conditions leading to slope instability;

- A5, rainfall thresholds reliably describe slope response;
- A6, rainfall can be measured and forecast at the spatial and temporal resolution required for prediction;
- A7, sufficient time exists to issue warnings before impacts occur;
- A8, forecasts can be translated into useful advisories;
- A9, advisories enable actions that reduce landslide risk.

The assessment below considers how the characteristics of the LEWS identified in each country support, partially support, or challenge these assumptions. This approach is particularly useful because it evaluates LEWS not only according to their forecasting technology, but also according to their capacity to connect observations and prediction with warning and risk-reduction actions.

In Argentina, the LEWS landscape remains relatively fragmented and includes systems with different purposes. The SMN multi-level warning system is primarily focused on severe weather and flood hazards and could support landslide warnings by coupling rainfall thresholds with geomorphological information; consequently, it provides only partial support for A1 and A3–A6. The SCMVI7 on National Route 7 combines historical information, precipitation monitoring, avalanche and road conditions, and traffic management, providing stronger evidence for A2 and A8–A9, although it is not a landslide-specific forecasting system. The SAGAZ Network represents a multi-sensor approach, integrating rainfall, soil moisture, slope displacement and predictive models, thereby challenging the conventional rainfall-centred assumptions A3–A5 while strengthening A4 and A6 through direct environmental observations. Overall, sparse in-situ observations and complex Andean topography remain important constraints on A6.

Brazil presents some of the most mature operational examples in the region. CEMADEN/GeoRisk combines rainfall, susceptibility and risk information and produces automated forecasts up to 72 h ahead, with warning levels explicitly linked to civil-defense actions; this provides strong evidence for A1, A6, A7 and A8–A9. Alerta Rio further strengthens these assumptions through high-frequency rain gauges, radar, numerical models and the LHASA Rio model, which provides high-resolution landslide hazard estimates and is connected to SMS, cell-broadcast, sirens and community preparedness programs. The Santos system similarly combines historical and real-time rainfall observations, radar and numerical forecasts with civil-defense actions. These systems therefore demonstrate a relatively complete warning chain, although their continued reliance on historical rainfall–landslide relationships means that A2 and particularly A5 remain subject to threshold updating under changing climatic conditions.

Chile shows a clear transition toward multi-parameter and model-based forecasting. RILEWS combines daily and antecedent rainfall, soil moisture and slope angle with WRF forecasts and machine-learning models, achieving 24–72 h lead times and successfully anticipating landslides during real-time tests; it therefore provides strong evidence for A1, A4, A6 and A7 while moving beyond the conventional threshold formulation of A5. The Río Las Minas system integrates meteorological and hydrometric observations with GNSS deformation, robotic total stations, UAV photogrammetry and cameras, shifting the focus from rainfall forcing toward direct observation of slope and channel response and consequently challenging A3–A5. San José de Maipo similarly integrates meteorological, seismic and infrasound observations and considers the effects of the 0°C isotherm, ENSO and glacier dynamics, demonstrating that landslide triggering mechanisms may extend beyond rainfall alone. However, its pilot status limits the evidence for A7–A9.

Colombia combines a mature national forecasting system with highly developed local initiatives. IDEAM's BADT uses rainfall observations from more than 2,500 stations and meteorological forecasts to produce daily municipal-scale alerts, strongly supporting A2, A3 and A6, although its spatial resolution limits the application of A1 and A9 at neighbourhood scale. SAB, SIATA and Manizales MHEWS complement this national framework through dense

monitoring, site-specific observations, public platforms and community warning plans, strengthening A7–A9. Inform@Risk represents a different approach, using IoT monitoring of subsurface and surface conditions rather than relying exclusively on rainfall; it therefore challenges A3–A5 while supporting A1 and A4 through direct monitoring of slope conditions. The main constraints are site-specific geological heterogeneity, limited historical events for threshold calibration, institutional continuity and the translation of national information into localized action.

Costa Rica's systems emphasize local monitoring and community preparedness. Tapezco–Chitaría combines historical rainfall thresholds with geological, geomorphological and geotechnical information, including pore pressure, water table and saturation, providing relatively strong support for A2–A5. Escazú integrates meteorological stations, cameras, alarms, sirens and emergency protocols, strengthening A8–A9 even though evidence for validated predictive relationships is more limited. The Sarapiquí basin-scale initiative uses dense rainfall monitoring and hydrological modelling, supporting A4 and A6 while extending warning lead time. Nevertheless, the heterogeneous distribution of systems, concentration in priority municipalities and infrastructure contexts, and reliance on empirical thresholds requiring continuous validation indicate that A1, A5 and A6 remain spatially and operationally uneven.

El Salvador has developed a comparatively comprehensive national system, integrating 106 automatic rain gauges, eight X-band radars, WRF forecasts, Mora–Vahrson modelling and CAFFGS soil-moisture estimates within an impact-based forecasting framework. This provides strong support for A1, A3, A4 and A6 and indicates an explicit move beyond rainfall alone toward representation of antecedent hydrological conditions. However, aging radar infrastructure, the absence of operational radar-based rainfall forecasting and the need to update thresholds for different environments constrain A5 and A6. Limited human resources, misinformation and incomplete access to the internet also affect A8–A9.

Honduras has a more geographically concentrated but operationally relevant system. SIMET-AMDC combines real-time environmental monitoring, landslide forecasting and warning dissemination, complemented by JICA instrumentation at selected landslides. The successful evacuation associated with the 2022 La Guillén event provides direct evidence for A7–A9, while the use of monitoring and historical information supports A1–A3. Nevertheless, the predominance of susceptibility studies, limited integrated risk analysis, equipment vandalism and difficulties with relocation restrict the broader fulfilment of A4–A6 and the translation of warnings into sustained risk reduction.

Mexico presents a heterogeneous, multi-scale warning landscape rather than a single national landslide-specific LEWS. CENAPRED, UNAM and local initiatives combine susceptibility mapping, rainfall thresholds, long-term monitoring and participatory approaches, supporting A2, A3 and A8–A9. The Tijuana pilot is particularly relevant to A4 because suction sensors directly characterize soil-water conditions, thereby challenging the assumption that rainfall alone is an adequate proxy for subsurface hydrological conditions. Conversely, the limited transferability of locally calibrated thresholds constrains A5, while maintenance, power and communication problems constrain A6–A8.

Nicaragua combines a national landslide database, susceptibility and hazard mapping with operational national and local LEWS, mainly specialized on lahar warning at San Cristóbal and Concepción volcanoes. These initiatives provide evidence for A2 and A8–A9 through historical information, hazard mapping and coordinated SINAPRED–INETER warning procedures. However, the rainfall thresholds in operational use derive from the original local design of 2000–2002 and from the national design of 2008, and soil-moisture information is analysed separately rather than integrated into the warning chain, so A4–A5 remain incompletely addressed, while network expansion and

equipment vulnerability constrain A6. The volcano LEWS, fully operational since 2020, complements rather than replaces rainfall criteria: weather forecasts and real-time data from the re-installed rain gauges guide monitoring, and the alarm is issued when geophones or infrasound sensors detect a lahar signal (Section 3.9.3). The arrangement therefore combines forecasting with detection within a single chain, compensating for thresholds calibrated on a limited record while preserving the lead time available to the communities located along the main lahar trajectories. It is the clearest regional example of threshold redundancy obtained through an independent physical observable rather than through a second rainfall criterion.

Peru's SILVIA and “Aviso de Activación de Quebradas” provide national-scale rainfall-based monitoring, complemented by ISAAC in Lima and other local monitoring initiatives. These systems strongly reflect the classical Guzzetti framework, particularly A2–A3 and A5, through the use of historical rainfall thresholds and precipitation observations. However, insufficient station density across strong Andean orographic gradients constrains A6, while poorly calibrated thresholds can generate false alarms, affecting A5 and potentially reducing trust in A8–A9. Institutional fragmentation among SENAMHI, ANA, IGP and INDECI further limits the integration of forecasts into coordinated action.

This review identifies higher-resolution hydrometeorological networks, interoperable platforms, community preparedness and climate-informed thresholds as priorities for strengthening the system. Overall, the comparison shows that the nine Guzzetti et al. (2020) assumptions are unevenly satisfied across Latin America. A2 and A3 remain fundamental to most systems, as historical information and rainfall continue to constitute the principal basis for landslide forecasting. However, A4 and A5 are increasingly challenged by evidence that rainfall alone does not adequately represent subsurface hydrological conditions or slope response, leading several systems to incorporate soil moisture, pore pressure, deformation, seismic signals, hydrological models and machine-learning approaches. A6 remains a major regional constraint because of uneven monitoring density, complex terrain and limitations in rainfall forecasting. Finally, A7–A9 reveal that technical forecasting capacity does not necessarily translate into effective risk reduction: the most mature systems are those that connect prediction with timely warning, institutional coordination, communication and concrete preparedness or evacuation actions. Thus, the regional trajectory is not simply toward more sophisticated forecasting, but toward LEWS that progressively integrate the physical, technological and social dimensions required for an effective warning system.

To better illustrate the discussion, Fig. 1 provides a spatial overview of the LEWS identified and analysed in Latin America, highlighting the diversity of their geographic coverage and stages of development. The distribution of the systems across the ten participating countries illustrates the uneven development of landslide early warning capacity across the region, with systems ranging from experimental and pre-operational initiatives to established operational frameworks. The spatial distribution of fatal landslides from the NASA Global Landslide Catalog (Kirschbaum et al., 2010) provides a complementary representation of the regional landslide context, allowing the location of LEWS to be considered in relation to areas with documented landslide occurrence. The location of major triggering disasters further illustrates the role of significant events in the emergence and development of LEWS across the region.

Figure 2 synthesizes the main characteristics of the LEWS identified in Latin America, providing a comparative basis for assessing differences in their spatial coverage, development status, technological approaches, and degree of integration. The systems are characterized according to their geographic scale, operational maturity, rainfall data sources, forecasting methods, and incorporation of the four components of the UNDRR/WMO early-warning framework. This comparison highlights the heterogeneity of LEWS across the region, particularly in terms of their technological sophistication and integration of monitoring, forecasting, warning communication, and preparedness

and response. The characterization follows the conceptual approach proposed by Guzzetti et al. (2020), providing the basis for the subsequent cross-country assessment of LEWS development and operational characteristics.

The development of LEWS in Latin America has not followed a continuous or uniform trajectory. Rather, it reflects a sequence of institutional responses to specific disasters, combined with the gradual adoption of international disaster risk reduction frameworks. Figure 3 summarises part of this trajectory for the systems identified in this review, placing the operational lifespan of each initiative against the events and policy milestones that shaped it. Three patterns are apparent. First, the earliest systems (Santos PPDC, Alerta Rio, CENAPRED) preceded any regional framework and emerged from municipal or national civil protection mandates rather than from landslide-specific concerns. Second, a marked expansion occurs in Central America after Hurricane Mitch (1998) and the 2001 El Salvador earthquake, and in South America after the 2011 Serra do Mar disaster, indicating that catastrophic events remain the dominant trigger for institutional investment. Third, the systems established after 2015 are concentrated in the experimental and pre-operational stages, which suggests that the most recent wave of initiatives has yet to consolidate into sustained operation. The persistence of most bars up to the present also indicates that discontinuation is rare once a system becomes operational, the Nicaraguan national LEWS being the main exception, where the original INETER platform was replaced rather than abandoned.

The assumption-based assessment and the system-level inventory presented above describe what each system does; neither indicates what each country still lacks. Table 1 therefore consolidates the critical reflections closing each country subsection into a single comparative frame, organised along four columns: key strengths, technical gaps, institutional and social gaps, and priority needs. Every entry condenses evidence reported by the contributing authors in the corresponding subsection of Section 3, so the table is a structured summary of the country contributions rather than an additional layer of analysis.

Read across rows, Table 1 shows that similar technical constraints recur under markedly different institutional arrangements: sparse rain-gauge networks in complex terrain, thresholds calibrated on short or incomplete historical records, and limited transferability of locally derived criteria appear in countries whose governance capacity ranges from consolidated federal architectures to largely municipal responsibility. Read down columns, it shows that the priority needs identified independently by ten national teams converge on a small number of shared themes: continuous threshold updating under non-stationary rainfall, interoperability between institutional platforms, predictable multi-year financing, and the translation of national-scale products into locally actionable warnings. This convergence, obtained without coordination between country contributions beyond the common reporting template, is itself a result: it suggests that the constraints on landslide early warning in the region are structural rather than country-specific.

Table 1
Consolidated comparative synthesis of country-level critical reflection sections.

Country	Key strengths	Technical gaps	Institutional / social gaps	Priority needs
Argentina	SCMVI7 operational since 2009 on Route 7; SINAGIR/AFE national framework; SINAME 24/7 monitoring; SAGAZ for GLOF.	Sparse rain-gauge networks; limited landslide-specific instrumentation; reliance on meteorological proxies in Andean environments.	Funding and resource constraints; uneven coverage across vast territory; need for multi-hazard integration under SINAGIR.	Expanded coverage, community participation in marginalized Andean populations, collaborative research and financing.
Brazil	Federal to municipal specialized institutions. Cemaden monitors 1,295 municipalities; GeoRisk with 72h lead time; Alerta Rio with cell broadcast and 164 sirens; Santos PPDC since 1980s.	Reactive impact-based prioritization underserves low-history areas; rainfall thresholds based on historical records may not capture non-stationary risk (Rio Grande do Sul – 2024).	Effective municipal–state–federal coordination but uneven integration with land-use control; informal settlements expand faster than risk reduction.	Shift to anticipatory, susceptibility-oriented frameworks; continuous threshold updating considering rainfall seasonality; interoperable platforms; stable funding; recording, monitoring and making inventory data publicly available.
Chile	Law 21,364 SINAPRED decentralization; RILEWS pre-operational (2025) with AUC 0.88; LiDAR 1:10,000 susceptibility; InSAR monitoring in urban areas; Talcahuano community model.	Quebrada de Ramón pilot dismantled (2021) due to ownership gap; 0°C isotherm monitoring still incipient; mismatch between scientific mapping and PRC zones.	Partial decentralization; municipalities lack capacity to update PRCs; OGUC Art. 2.1.17 terminology gaps; over-centralization risk.	Stable ownership of pilots; harmonized regulatory terminology; integrated bias-corrected meteorological+impact-based forecasting.
Colombia	BADT continuously operational at national scale; SIATA 1,356 sensors; SIRMED public platform with AI/AR; Inform@Risk IoT prototype; SAMA 30 + municipalities with community plans.	BADT spatial resolution insufficient for neighbourhood scale; Medellín Dunite heterogeneity requires site-specific monitoring; limited historical events for threshold calibration; intensity–duration thresholds miss short events.	Dependence on short-duration contracts and electoral cycles; Inform@Risk on hold due to legal constraints on equipment donation; absence of dignified relocation housing erodes social acceptance.	Resolve legal frameworks before equipment installation; site-specific subsurface characterization; multilevel LWM integration into SAMA/SIRMED; redundancy with community visual monitoring.
Costa Rica	Progression from UNESCO–CEPREDENAC community guidance to Tapezco–Chitaría	Heterogeneous national landscape; concentration of LEWS in priority	Risk of fragmentation between hazard-specific and multi-hazard warning streams;	Risk-based prioritization for coverage expansion; standardized escalation protocols;

Country	Key strengths	Technical gaps	Institutional / social gaps	Priority needs
	and Escazú municipal systems; Sarapiquí basin-scale pilot; AyA infrastructure-focused thresholds.	municipalities and infrastructure contexts; reliance on empirical thresholds requiring continuous validation.	sustainability beyond pilot funding.	people-centered design and climate-adaptive thresholds.
El Salvador	National coverage; Integrated Hazard Monitoring Centre; 106 automatic rain gauges + 8 X-band radars; WRF + Mora–Vahrson and CAFFGS soil-moisture model; impact-based forecasting.	Radar systems near the end of operational life; rainfall thresholds need updating for new events and different environments; no operational rainfall forecasting from radar yet; no soil-moisture sensors.	Limited human resources for research; misinformation challenges; coverage of populations without internet access.	Network expansion in volcanic areas; soil-moisture sensors; updated thresholds; strengthened community education and regional cooperation.
Honduras	Post-Mitch institutional strengthening (COPECO, CENAOS); JICA monitoring at Tegucigalpa landslides (El Berrinche, La Guillén); SIMET-AMDC integrating multiple hazards; La Guillén 2022 evacuation success.	Most studies focus on susceptibility; lack of integrated risk analysis with vulnerability and exposure; few multi-hazard integrated studies despite shared rainfall origin.	Weak implementation of urban-expansion policies; vandalism of monitoring equipment; difficult relocation (La Guillén); limited access to technical reports.	Nationwide network expansion; multi-hazard approach; community training; updated rainfall thresholds for changing climate; academia–government collaboration.
Mexico	SIAT-Laderas (CENAPRED) provides a national landslide-specific alerting framework at a pre-operational stage, integrating national susceptibility mapping with observed and forecast rainfall; complemented by multi-scale initiatives, including long-term monitoring in Sierra Norte de Puebla (Casa CENAPRED), the Tijuana multi-parameter pilot, and participatory child- and school-centred mapping in Teziutlán.	Locally calibrated thresholds non-transferable; multi-parameter monitoring remains largely pilot-based (Tijuana suction sensors); persistent maintenance, transmission, and power challenges.	Fragmented mandates across national/state/municipal levels; warning effectiveness limited by trust in messengers; rural/Indigenous communities underserved.	Locally calibrated dynamic thresholds; expansion and consolidation of multi-parameter monitoring; stronger integration between national alerting and local response capacities; standardized minimum components following CENAPRED guidance for highly marginalized municipalities (Chiapas, Oaxaca).
Nicaragua	Updated national landslide database, susceptibility map, operational national	Need to integrate soil-moisture data; refine regional/seasonal	Need automation of warning preparation; consolidation of dedicated forecasting	Multi-hazard integrated system; interdisciplinary exchange; focus

Country	Key strengths	Technical gaps	Institutional / social gaps	Priority needs
	and local LEWS; lahar hazard maps and multi-risk maps for ~ 50% of municipalities; volcano lahar LEWS at San Cristóbal/Concepción; SINAPRED–INETER coordination.	rainfall thresholds; expand networks with care for vandalism, seismic damage, acid rain, corrosion.	teams; minimum core of landslide specialists.	monitoring on hot-spot areas; resettlement from highest-risk zones; regional cooperation in Central America.
Peru	SILVIA national monitoring; "Aviso de Activación de Quebradas" under Ministerial Resolution N°049-2020-PCM; ISAAC regional monitoring in Lima; SAMAQ (ANA); IGP camera networks at volcanic catchments.	Insufficient station density in Andean orographic gradients; siren systems with poorly calibrated thresholds generate false alarms; institutional data fragmentation.	Multiple institutions (SENAMHI, ANA, IGP, INDECI) operate separate platforms; building public trust and avoiding inequities in remote/vulnerable communities.	Higher-resolution hydromet networks and models; interoperable platforms; community-based preparedness; climate-projection integration into thresholds; regional knowledge exchange.

Table 1 records differences in kind. To compare countries in degree, the same body of evidence was rated along the five operational dimensions introduced in Section 2.5, using the five-point scale and the anchored rating procedure described in Section 2.6. Figure 4 presents the resulting matrix. As set out there, the values correspond to a structured expert judgement rather than to a formal index and are intended for relative comparison between countries. Differences of half a point fall within the resolution of the procedure, whereas differences of one point or more reflect distinctions consistently identified across the country contributions.

Read together, Table 1 and Fig. 4 show that the two most consolidated profiles in the region, Brazil and Colombia, are not the ones with the fewest gaps, but the ones whose gaps have shifted from the technical to the institutional and territorial domains. The interpretation of this pattern, and of the asymmetries it reveals, is developed in Section 6.

5. Further developments, improvements and continuity over time of LEWSs in Latin America

Beyond the operational aspects of LEWSs already discussed, their long-term relevance in Latin America depends on continued technological and methodological innovation, the region's capacity to sustain these systems institutionally and financially, and the extent to which international experience can be adapted to local conditions.

Landslide inventories are the foundation of the models used for LEWS but compiling them through traditional field surveys and manual photointerpretation remains labour-intensive and constrained by cloud cover in tropical regions. Optical missions such as Sentinel-2 and Landsat-8/9 have enabled semi-automatic inventory workflows through Object-Based Image Analysis and machine learning (Amatya et al., 2021), while Synthetic Aperture Radar (SAR) overcomes atmospheric limitations: Sentinel-1's C-band sensors support cloud-based backscatter and coherence analysis for rapid landslide density mapping (Handwerger et al., 2022), and the recent NASA-ISRO (NISAR) mission will add L-band and S-band radar with substantially greater canopy penetration, improving InSAR-based detection of slow precursory deformation under the dense forest cover typical of mountainous Latin America (Lisano et al., 2023).

Beyond inventory mapping, satellite-derived rainfall products offer a complementary avenue for improving the rainfall thresholds that underpin most operational LEWSs, particularly in regions where ground-based rain gauge networks are sparse. In a comparative study of 197 landslides in India, satellite rainfall products (GPM IMERG and SM2RAIN-ASCAT) outperformed interpolated rain-gauge data in predicting triggering rainfall conditions, owing to their finer spatial and temporal resolution, suggesting these products may offer similar value in other data-scarce, landslide-prone regions such as Latin America (Brunetti et al., 2021).

Machine learning is also being explored to predict landslide occurrence from rainfall, topographic, and soil variables (Horta, 2025). In the southern Andes of Chile, Random Forest and XGBoost models optimized through genetic-algorithm feature selection have been used to predict rainfall-induced landslides, though such a system has not yet been implemented operationally in the region (Labbé et al., 2026). In South Korea, a similar Random Forest approach, selected through automated machine learning, has been proposed to generate daily, high-resolution landslide susceptibility maps updated with short-term rainfall forecasts (Lee et al., 2025).

A further step in the evolution of LEWSs in Latin America is the incorporation of impact-based forecasting approaches (World Meteorological Organization, 2015). Traditional warning systems generally focus on the probability of landslide occurrence, whereas impact-based systems combine the likelihood of failure with information on exposure and vulnerability, such as population, buildings, roads, critical infrastructure, and essential services. By integrating rainfall forecasts with susceptibility maps and dynamic exposure datasets, operational agencies can prioritize areas where landslides are expected to produce the greatest social and economic consequences rather than simply the highest hazard levels. Although impact-based forecasting is already implemented by several agencies in Latin America, most explicitly by MARN in El Salvador (Section 3.6.3), significant room for improvement remains in both its technical capabilities and communication strategy.

Participatory approaches represent a particularly promising opportunity for Latin America, especially in informal settlements where technical monitoring networks are sparse and risk is concentrated among the most vulnerable populations. The Inform@Risk project in Bello Oriente, Medellín (Colombia) (Gamperl et al. 2021, 2023a), illustrates this potential: a site-specific, participatory LEWS was co-developed with the local community through risk-analysis workshops, neighbourhood walking tours with technical professionals, and community involvement in the installation and maintenance of low-cost sensor networks. Mobile applications and low-cost reporting mechanisms can further extend this model, supporting rapid inventory updating, validation of warning outputs, and the strengthening of risk communication and public trust.

The comparison between two of the cases reviewed here gives this argument an empirical edge that is rarely available. In Bello Oriente (Medellín-Colombia), where the monitoring network was co-designed with residents through workshops, neighbourhood walks and community participation in installation and maintenance, acceptance of the instrumentation was reported as very high and no loss or tampering of equipment appears in the project's published record (Gamperl et al., 2023a; Werthmann et al., 2024). In Honduras, by contrast, several instruments installed in landslide-prone communities were vandalised or stolen, and Nicaragua likewise lists vandalism among the constraints on expanding its monitoring network. The three cases differ in many respects and the comparison is not controlled, but they point to the same practical conclusion: in settlements where residents have no stake in the equipment, physical survival of the instrumentation becomes a recurrent operating cost, whereas co-production converts the network into a community asset. Since instrument loss is one of the few failure modes that no amount of sensor redundancy can offset, participatory design should be understood as a condition of technical viability in these contexts, and not only as a desirable feature of risk communication. The limits of that protection are equally

instructive: whatever social appropriation achieved for the network's physical security, it did not prevent the system from being suspended once the legal transfer of the equipment to the municipality stalled.

Despite technological progress, long-term sustainability remains a major challenge for LEWSs in the region. A 2012 assessment by UNESCO and CEPREDENAC found that landslide early warning systems in Central America, many established in the aftermath of Hurricane Mitch (1998), tend to lose operational continuity once external funding ends, as implementing NGOs and cooperation agencies withdraw after the initial project phase without long-term technical or institutional follow-up (UNESCO & CEPREDENAC, 2012b).

This pattern is illustrated by cases such as the Guadalupe lahar warning system in El Salvador, discussed earlier in this article, where a technically sound pilot system ceased to function before the 2009 San Vicente disaster, not for lack of technology, but for lack of sustained institutional follow-up after the initial project ended.

The gap between research output and documented operational continuity is reflected more broadly in the regional literature: a systematic review of LEWS publications in upper-middle-income countries found that only 14 of 384 studies (3.6%) addressed the actual operational implementation of a system, nearly all concentrated in China and Brazil, with no other Latin American country represented (Alcántara-Ayala & Garnica-Peña, 2023b). While this predominantly reflects where researchers have concentrated their efforts, largely on hazard analysis, modelling, and technical development rather than on documenting deployed systems, it also indicates how little is systematically known about the long-term operational status of LEWSs in the region, a gap that likely obscures cases such as Guadalupe from the broader scientific record. These findings underscore that technological capability alone does not guarantee continuity: without sustained institutional oversight and domestic financing mechanisms, even well-designed systems risk becoming inactive once the initial project cycle ends.

International experiences provide valuable lessons for Latin America. Italy offers an example of multi-level governance, where regional warning systems operate within a national civil protection framework and are supported by extensive historical landslide databases (Rossi et al., 2012, 2018). Japan offers a complementary example centred on the standardization and communication side of a national warning architecture. Since 2005, the Japan Meteorological Agency has operated a nationwide early-warning system for debris flows and slope failures that applies a statistically calibrated threshold model at 5-km grid resolution across the country, disseminating warnings to the public directly through TV, radio, and the Internet (Osanai et al., 2010). While Japan's dense radar and rain-gauge network is not readily replicable in most of Latin America, the underlying principle, a centrally standardized, grid-based threshold model coupled with direct multichannel public communication, is transferable regardless of the underlying data source, and offers a governance model for how rainfall-derived hazard information can be translated into consistent, nationwide public alerts. In the United States, the National Landslide Preparedness Act (Public Law 116–323) established a long-term national framework for landslide risk reduction. The associated National Strategy for Landslide Loss Reduction (Godt et al., 2022) emphasizes the development of publicly accessible landslide databases, interagency coordination, support for early warning systems, effective communication and preparedness, and the transition of scientific advances into operational applications. These principles provide a useful reference framework for strengthening LEWSs in Latin America.

The three cases above share a condition that most of Latin America does not meet, dense observational networks sustained by high-income public budgets. Indonesia offers a closer analogue. Facing widespread landslide exposure with limited instrumentation, a national standard for landslide early warning was developed around the operational limitations of local communities rather than around sensor density, specifying minimum requirements for detection, prediction, interpretation and response, and coupling low-cost monitoring devices with the technical and socio-

economic assessment that enables communities to operate and maintain them independently (Fathani et al., 2016). The experience is also instructive in its difficulties, since stolen and poorly maintained equipment has been reported as a persistent constraint on reliability, the same failure mode identified in Honduras and anticipated in Nicaragua. What transfers from this case is therefore not a technology but a design principle: that in data-scarce settings the standard should be written from the capabilities of the operating community upwards, and that maintenance and social appropriation belong inside the specification rather than outside it. This design principle is not specific to Asia. The regional assessment of technology for disaster risk reduction in the Americas and the Caribbean reaches the same conclusion from the opposite direction, observing that tools built on the data, assumptions and infrastructure of industrialized settings transfer poorly, and that countries in the region frequently acquire off-the-shelf solutions rather than shaping technologies around their own operational constraints (UNDRR, 2025b).

These lessons acquire urgency within the current policy frame. The Early Warnings for All initiative, launched by the United Nations Secretary-General in 2022 and structured through an Executive Action Plan for 2023–2027 co-led by WMO and UNDRR, commits the international system to universal early-warning coverage by the end of 2027, organised around four pillars, risk knowledge, detection and forecasting, dissemination and communication, and preparedness to respond, that coincide with the framework used throughout this review and with Target G of the Sendai Framework (UNDRR, 2015; WMO, 2022). Two features of its regional roll-out are relevant to the findings presented here. First, national implementation has so far concentrated on small island developing states and least developed countries, and in the Americas the six countries designated for priority implementation, Antigua and Barbuda, Barbados, Ecuador, Guatemala, Guyana and Haiti, are not those with the most developed landslide warning arrangements (WMO, 2024); several of the systems documented in this review therefore operate outside the initiative's national planning cycles, and the operational experience they hold is at risk of remaining outside them. Second, the initiative is framed around hydrometeorological, climatological and related environmental hazards, whereas landslides are geological processes with hydrometeorological triggers. Their inclusion in national multi-hazard roadmaps is consequently not automatic and depends on whether geological surveys are brought to the table alongside meteorological services and civil-protection agencies, an arrangement that the regional experience reviewed here shows to be the exception rather than the rule.

Taken together, these opportunities and constraints suggest that the next generation of LEWSs in Latin America will depend less on isolated technological breakthroughs and more on the region's ability to institutionalize, finance, and sustain the integration of remote sensing, participatory knowledge, and international best practice into coherent national frameworks.

6. Discussion, Main Challenges, and Outstanding Issues

Despite differences in scale and resources, LEWS across Latin America converge on a common conceptual architecture built around the four canonical components of risk knowledge, monitoring, forecasting, and warning dissemination (Guzzetti et al., 2020; Piciullo et al., 2018). Most operational and pilot systems in the region remain fundamentally rainfall-threshold based, reflecting the same reliance on empirical intensity–duration or cumulative-rainfall relationships that characterizes territorial LEWS worldwide (Segoni et al., 2018; Piciullo et al., 2017). A second commonality is institutional embedding within civil-protection or civil-defense frameworks rather than purely scientific initiatives, which links forecasting outputs to codified emergency-response protocols in countries as different as Brazil, Colombia, and El Salvador (Calvello, 2017). Finally, nearly every national system has emerged from, or been substantially reshaped by, multi-stakeholder collaboration among universities, meteorological and geological agencies, civil-protection authorities, and international cooperation bodies, a pattern consistent with the broader shift toward networked, multi-hazard governance documented for the region and globally (Calvello et al.,

2020; United Nations Office for Disaster Risk Reduction & World Meteorological Organization, 2023). This convergence is reinforced by a shared and intensifying exposure: the region remains the second most disaster-prone in the world, and recent regional assessments confirm that hydro-meteorological events, including landslides, are rising in frequency and severity across virtually all the countries reviewed here (United Nations Office for Disaster Risk Reduction, 2024; Trancoso et al., 2025).

Beneath this shared architecture, the region displays marked heterogeneity in technological sophistication, spatial coverage, and institutional maturity. Brazil and Colombia operate comparatively advanced, densely instrumented systems capable of automated, multi-day-ahead forecasting linked directly to civil-defense action thresholds, whereas several Central American and Andean countries still depend on sparser rain-gauge networks and locally calibrated, non-transferable thresholds (Alcántara-Ayala & Garnica-Peña, 2023b; Gómez et al., 2023b). Governance models also diverge: some countries operate under explicit national legal mandates for landslide warning (e.g., Peru's Ministerial Resolution N°049-2020-PCM), while others rely on decentralized municipal responsibility with uneven technical capacity, as in Chile's post-2021 decentralization framework (Ley N° 21.364, 2021; Silva et al., 2024). This institutional unevenness is not merely a matter of degree: comparative reviews of disaster-related public policy show that Latin American countries have followed markedly different historical trajectories in formalizing civil-protection and early-warning legislation, producing systems that remain structurally difficult to compare or interoperate even where the same hazard is at stake (Kuhn et al., 2022). Countries outside the scope of this review illustrate the lower end of the regional spectrum: the response to the 2023 Alausí disaster in Ecuador was documented mainly through post-event geotechnical and geophysical investigation (Macías et al., 2024), and no operational landslide warning arrangement for the affected area is reported in that literature. Technological trajectories differ as well, with Chile and Colombia increasingly incorporating InSAR, LiDAR, IoT, and machine-learning approaches, in contrast to countries where community-based, low-technology monitoring remains the dominant model. These asymmetries in station density, funding continuity, and institutional maturity translate directly into unequal lead times, spatial resolution, and reliability of warnings across the region.

This asymmetry points toward concrete opportunities for south–south cooperation. Regional and international networks such as LandAware already provide a platform through which countries with mature systems could formalize technical exchange, joint training, and shared threshold-validation protocols with less-resourced neighbours (Calvello et al., 2020). This review is itself an instance of that mechanism at work: the country accounts assembled here were made available through the network's regional group, which suggests that the same channel could support the sustained documentation of operational practice that the region currently lacks. Participatory, low-cost models such as the Inform@Risk approach piloted in informal settlements in Medellín demonstrate a transferable template, combining low-cost sensor networks, community co-monitoring, and local capacity building, that could be adapted to comparable urban-periphery contexts throughout the region (Gamperl et al., 2023a; Werthmann et al., 2024). A closely related contribution is the development of data-driven cost-estimation frameworks for LEWS instrumentation, which allow decision-makers to identify priority monitoring sites and balance financial constraints against population coverage; such tools, piloted in Medellín, are directly transferable to other data- and resource-scarce cities in the region (Sapena et al., 2023). Open-access satellite products (e.g., Sentinel-1/2, GPM-IMERG) offer a further cost-effective way for data-scarce countries to partially compensate for sparse ground networks without requiring the capital investment of dense in-situ infrastructure (Amatya et al., 2021; Handwerger et al., 2022; Brunetti et al., 2021). Regional financing and investment mechanisms, as recently outlined for the Americas and the Caribbean, could formalize this transfer of knowledge and infrastructure by channelling resources toward countries with the least-developed systems (United Nations Office for Disaster Risk Reduction, 2024). Finally, adapting elements of internationally documented frameworks, such as the multi-level governance

structure of Italy's national system or the interagency coordination emphasized in the U.S. National Strategy for Landslide Loss Reduction, could help countries with emerging LEWS design institutional architectures suited to their own administrative and legal contexts (Rossi et al., 2018; Godt et al., 2022).

Formal intergovernmental channels already exist alongside these scientific networks. Within the Andean Community (CAN), CAPRADE has compiled and exchanged experiences on early-warning implementation across Bolivia, Colombia, Ecuador and Peru, with the explicit aims of identifying institutional and financial gaps, strengthening technical capacity through knowledge exchange, and supporting the transition toward multi-hazard arrangements (Moreira Carrasco, 2021). The persistence of the same constraints identified in this review, long-term financing for maintenance and upgrading, coordination between technical institutions and local authorities, and integration with climate-change adaptation, suggests that the obstacle is not the absence of a cooperation mechanism but the difficulty of converting one into sustained national commitments.

What transfers in such models, however, is the process rather than the hardware. The evidence assembled here suggests that co-production has a measurable operational return. The instrumentation co-designed and co-maintained with residents in Bello Oriente drew high reported acceptance and no documented losses, while equipment installed without comparable engagement in Honduran hillside communities was vandalised or stolen, and Nicaragua identifies the same risk as a constraint on expanding its network (Section 5). Since instrument loss is a failure mode that sensor redundancy cannot offset, the months of workshops and coordination meetings that precede installation are not an accessory to the technical design but part of its cost structure, a consideration that the cost-estimation frameworks now being developed for LEWS instrumentation could usefully internalise (Sapena et al., 2023). This also delimits what participation can achieve. Social appropriation appears to have shielded the Bello Oriente network from its physical risks; it did not shield it from an administrative vacuum, and the system was suspended once the legal transfer of equipment to the municipality stalled. Community engagement and institutional ownership are complementary conditions, and neither substitutes for the other.

The review is also silent on private operators. Every arrangement documented here is public or academic, yet mining, hydropower and road concessions run internal monitoring in several of the countries reviewed, and the articulation of that monitoring with the national warning chain falls outside the reporting template used here.

These opportunities are not equally within reach and distinguishing them matters for anyone deciding where to start. Three can be pursued immediately with resources that already exist. Structured technical exchange and shared threshold-validation protocols through regional networks, the use of open-access satellite products to compensate partially for sparse ground observation, and the adoption of cost-estimation tools to prioritise monitoring sites under fixed budgets. A second group requires project-scale funding and sustained institutional commitment rather than new policy, extending participatory, low-cost monitoring to informal settlements, and moving from hazard-based to impact-based warning. The remaining constraints, densifying observational networks across Andean and Central American terrain, resolving the legal frameworks that govern the transfer of research equipment to public operators, enforcing land-use restrictions in susceptible terrain, and providing dignified relocation for populations advised leaving, are not technical problems and cannot be solved by cooperation among researchers. They require political decision and predictable multi-year financing. The uncomfortable implication is that the measures most readily available are not the ones that currently bind: the region can improve its forecasting faster than it can improve what happens after a warning is issued.

Regardless of technological maturity, LEWS operators across Latin America face a common set of structural pressures. Climate change is increasingly destabilizing the historical rainfall–landslide relationships on which most

thresholds are calibrated, raising uncertainty about the continued validity of empirically derived warning criteria and demanding more frequent threshold updating (Rosi et al., 2021; Segoni et al., 2018; Luiz-Silva & Oscar-Júnior, 2022). This uncertainty is compounded by unplanned urban expansion, which is now recognized globally as interacting with climate change to amplify landslide risk far faster than mitigation and early-warning capacity can adapt (Ozturk et al., 2022). In the Andes specifically, weak land-use governance and permissive urban policy continue to channel population growth into landslide-susceptible terrain, a dynamic documented from Ecuador's urban peripheries to informal settlements in Medellín and reflected in the scale of recent disasters (Puente-Sotomayor et al., 2021; Werthmann et al., 2024; Macías et al., 2024). Layered onto both pressures is the persistent challenge of translating technical forecasts into effective public action: content analysis of the external communication of Brazilian civil-protection agencies found that publications associated with the response phase predominate over those oriented to risk and prevention, indicating that the reactive orientation identified in the region's institutional architecture extends to how these agencies communicate with the public (Beling Loose et al., 2023). Addressing this gap requires sustained investment in risk communication and education, particularly for children, rural communities, and other historically underserved groups, as demonstrated by school-based disaster-education initiatives in Argentina and Rio de Janeiro that have shown measurable gains in risk awareness and preparedness when embedded in formal education systems (Rodríguez et al., 2025; Mendonça et al., 2025). Together, these findings suggest that closing the region's early-warning gap depends as much on culturally grounded communication and education strategies as on further technical or instrumental development (Pecoraro et al., 2019; Piciullo et al., 2020).

7. Conclusions

The cross-country assessment confirms that landslide early warning systems (LEWS) in Latin America have advanced considerably, but their maturity remains markedly uneven across countries and operational dimensions. Within the comparative framework applied in this study, Brazil and Colombia emerge with the most broadly developed LEWS profiles, combining relatively consolidated monitoring, forecasting, institutional, and communication capacities, while Chile also shows comparatively strong technological and institutional development. El Salvador and Peru have established important national-scale monitoring and warning arrangements but still face limitations related to observational coverage, integration, and local implementation. Colombia, Costa Rica and Mexico stand out for participatory and community-oriented experiences despite more heterogeneous technical and territorial coverage. In contrast, Argentina, Honduras, and Nicaragua show more pronounced gaps in landslide-specific monitoring, forecasting capacity, territorial coverage, or operational consolidation, although relevant national and local initiatives are already in place.

A central finding is that LEWS maturity cannot be explained by technological capability alone. Brazil and Colombia demonstrate that advanced monitoring and forecasting can coexist with gaps in municipal implementation, land-use integration, long-term financing, or local-scale warning resolution. Conversely, experiences in Costa Rica and Mexico show that community participation, trusted communication, and preparedness can strengthen warning effectiveness even where technological infrastructure is less extensive. Across the region, therefore, the most persistent weaknesses concern the connection between national technical capacity and locally actionable warning, long-term institutional ownership, stable financing, and equitable coverage of remote and socially vulnerable populations.

As the assessment of assumptions A3 to A5 in Section 4 showed, a key conceptual shift is under way in landslide early warning: the recognition that rainfall alone does not adequately represent the hydrological processes governing slope instability. While rainfall intensity and accumulation remain fundamental predictors, increasing attention has been given to antecedent wetness, soil moisture, infiltration, and the capacity of soils to absorb and transmit water, a reformulation of the threshold concept in hydro-meteorological rather than strictly meteorological terms (Bogaard &

Greco, 2018). This shift reflects the understanding that similar rainfall inputs can produce substantially different slope responses depending on pre-event moisture conditions, soil properties, permeability, and drainage. Consequently, emerging LEWS increasingly combine rainfall observations with soil-moisture estimates, hydrological models, pore-pressure measurements, and other indicators of subsurface conditions. This transition from rainfall-centred prediction toward process-informed, multi-parameter approaches is one of the clearest directions of development identified in this review, and it is particularly consequential under changing climatic conditions, when historical rainfall thresholds alone may no longer characterise, landslide triggering conditions.

Future improvements should prioritize impact-based and climate-adaptive forecasting, interoperable monitoring platforms, denser observations in poorly instrumented mountainous areas, and stronger integration of rainfall, soil moisture, deformation, susceptibility, exposure, and vulnerability information. Remote sensing, satellite rainfall products, SAR/InSAR, low-cost sensors, and machine-learning approaches offer clear opportunities, particularly in data-scarce areas, but the regional experience shows that these advances will only become effective LEWS if they are operationally validated and incorporated into sustained institutional workflows.

Overall, the principal lesson for risk managers and public agencies is that investments should extend beyond monitoring technology to include institutional coordination, maintenance, long-term financing, communication, preparedness, and community participation. For the scientific community, the priority is to move beyond model development toward operational validation, transferability, performance assessment, and integration with decision-making. The future of LEWS in Latin America will therefore depend less on isolated technological advances than on the capacity to transform existing national and local experiences into sustained, interoperable, scalable, and people-centred warning systems adapted to the environmental and socioeconomic diversity of the region.

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Ethics and Consent to Participate declarations

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Author Contribution

JV, ITLGH, DG, MER and EGU conceptualized the study, designed the methodology, performed the formal analysis, wrote the original draft and acquired the funding. JV, ITLGH, MER and EGU curated the data, and JV prepared the figures. JV, ITLGH and DG administered the project. All authors (JV, ITLGH, DG, MER, EGU, AQR, IAA, IFT, CMA, CG, PIC, PH, RPQ and SM) participated in the investigation, validated the results, and critically reviewed and edited the manuscript. All authors read and approved the manuscript and agree to be accountable for all aspects of the work.

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Data Availability:

The data used in this study will be made available by the authors upon request.

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Figures

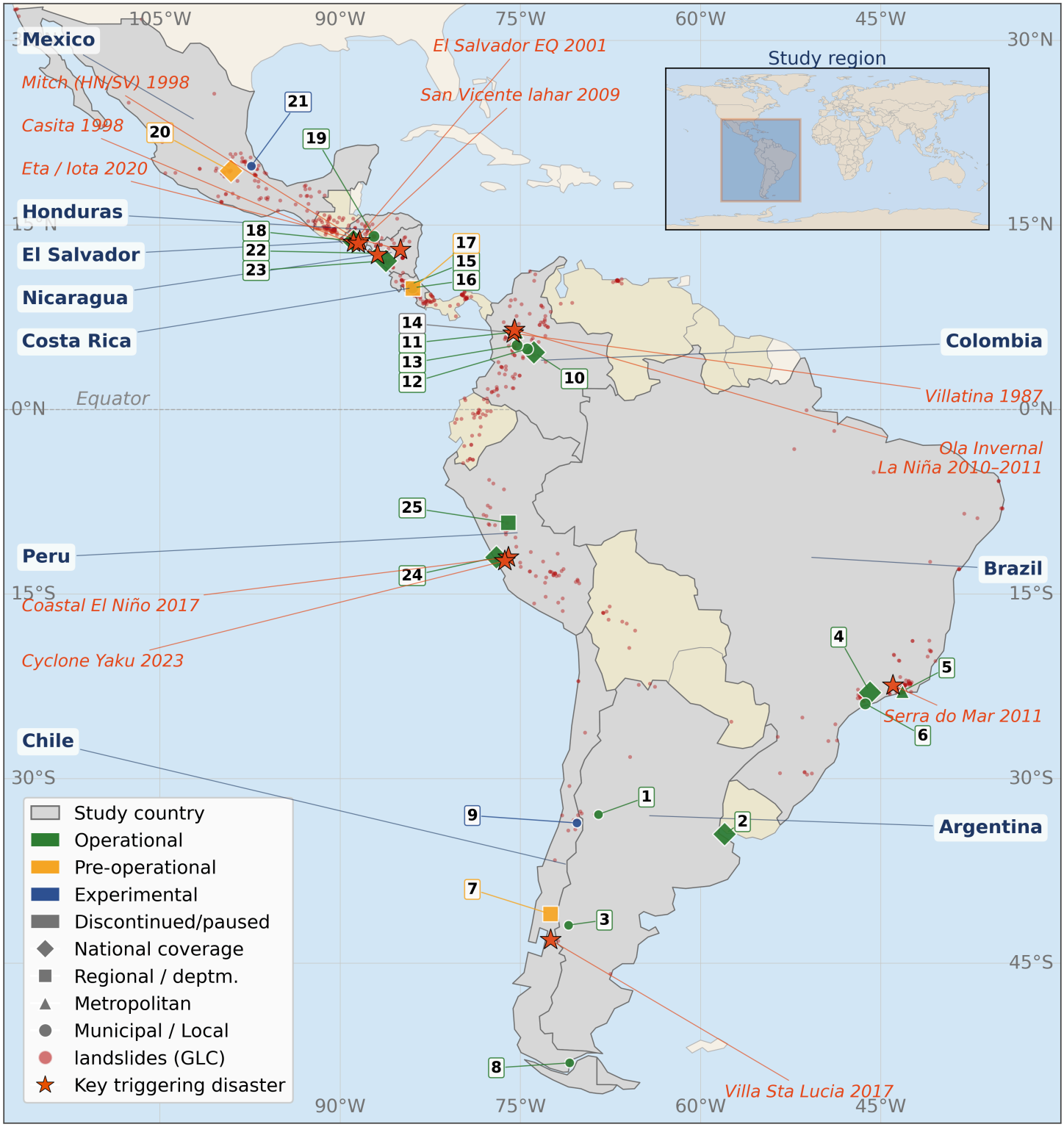


Figure 1

Landslide Early Warning Systems (LEWS) analysed in Latin America. Red dots represent landslides from the NASA Global Landslide Catalog (GLC) (Kirschbaum et al., 2010), indicating the areas with the highest incidence of landslides. Stars represent key triggering disasters that contributed to LEWS emergence. Numbered labels identify the individual systems and correspond to the identifiers listed in Fig. 2.

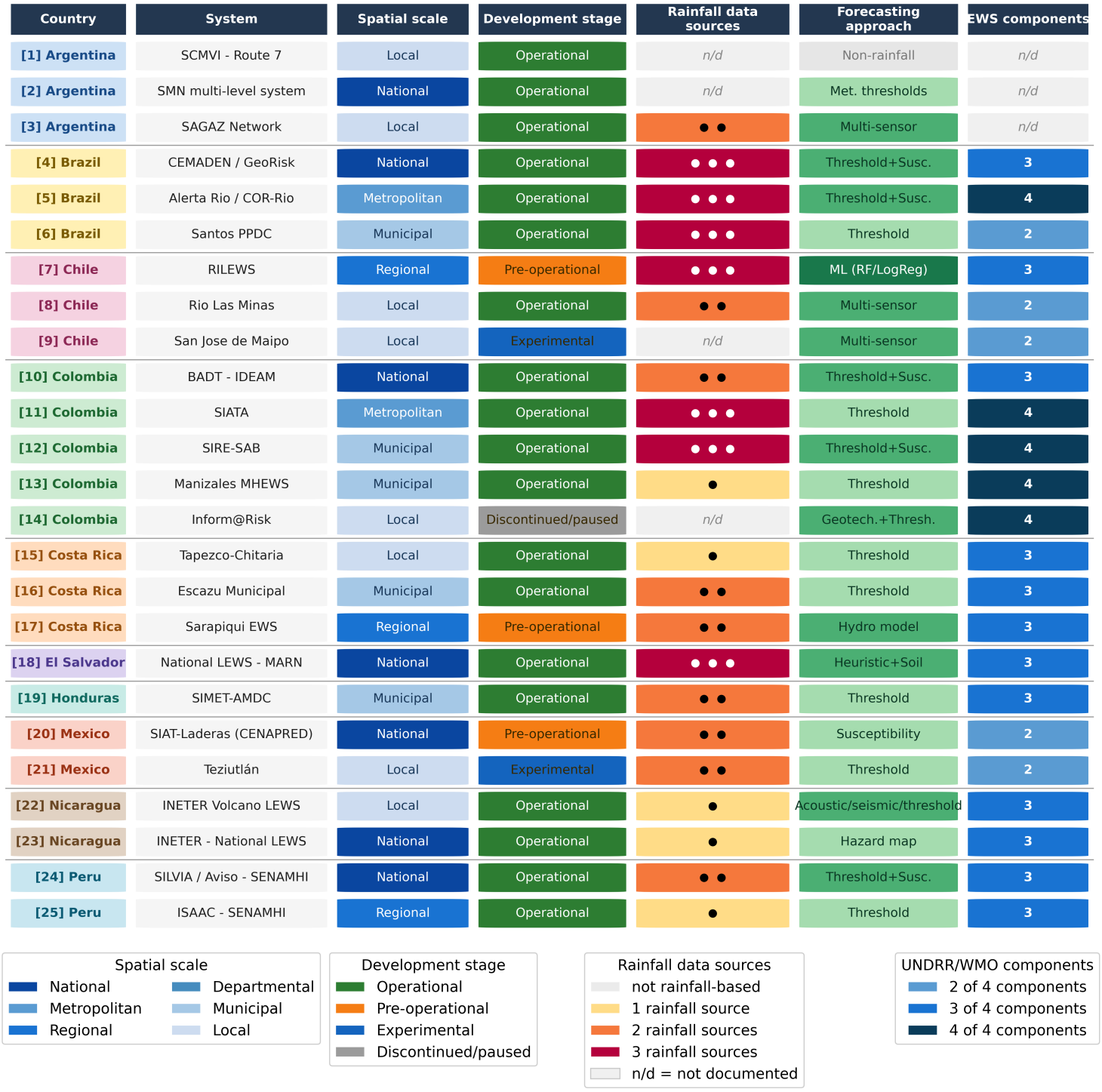


Figure 2

List of Landslide Early Warning Systems (LEWS) identified in Latin America according to spatial scale, development stage, rainfall data sources, forecasting approach, and integration of the four UNDRR/WMO early-warning components: risk knowledge, monitoring and forecasting, warning dissemination and communication, and preparedness and response. Rainfall data sources are categorized according to the number and type of sources used, and forecasting approaches include meteorological or rainfall thresholds, hydrological models, susceptibility-based approaches, geotechnical and multi-sensor approaches, and machine-learning methods. The EWS component score indicates the number of UNDRR/WMO components incorporated by each system. Systems are numbered 1 to 25; these identifiers correspond to the numbered labels in Fig. 1.

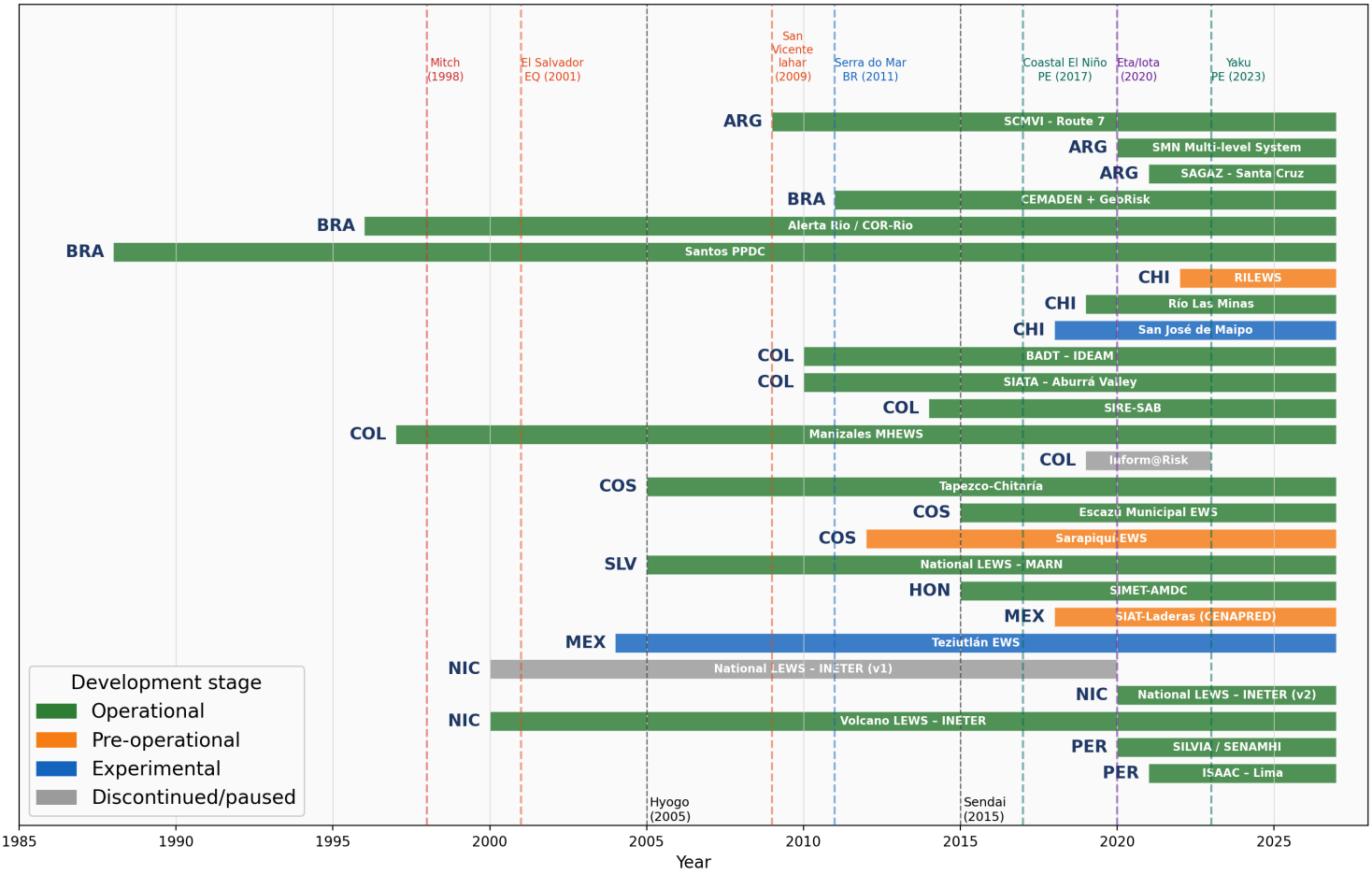


Figure 3

Temporal evolution of Landslide Early Warning Systems (LEWS) and related warning initiatives identified in Latin America, showing the period of development and current operational status of systems across the study countries. Horizontal bars represent the period from system establishment or implementation to the most recent year documented in this review, with colours indicating the development stage: operational, pre-operational, experimental, or discontinued. Vertical dashed lines indicate major disasters or events that influenced the development of landslide risk monitoring and early-warning initiatives in the region, including Hurricane Mitch (1998), the 2001 El Salvador earthquake, the 2011 Serra do Mar disaster in Brazil, the 2017 Coastal El Niño in Peru, the 2020 Iota and Eta events in Central America, and the 2023 Yaku event in Peru. Black dotted lines mark UN frameworks. The figure illustrates the emergence and progression of LEWS in each country.

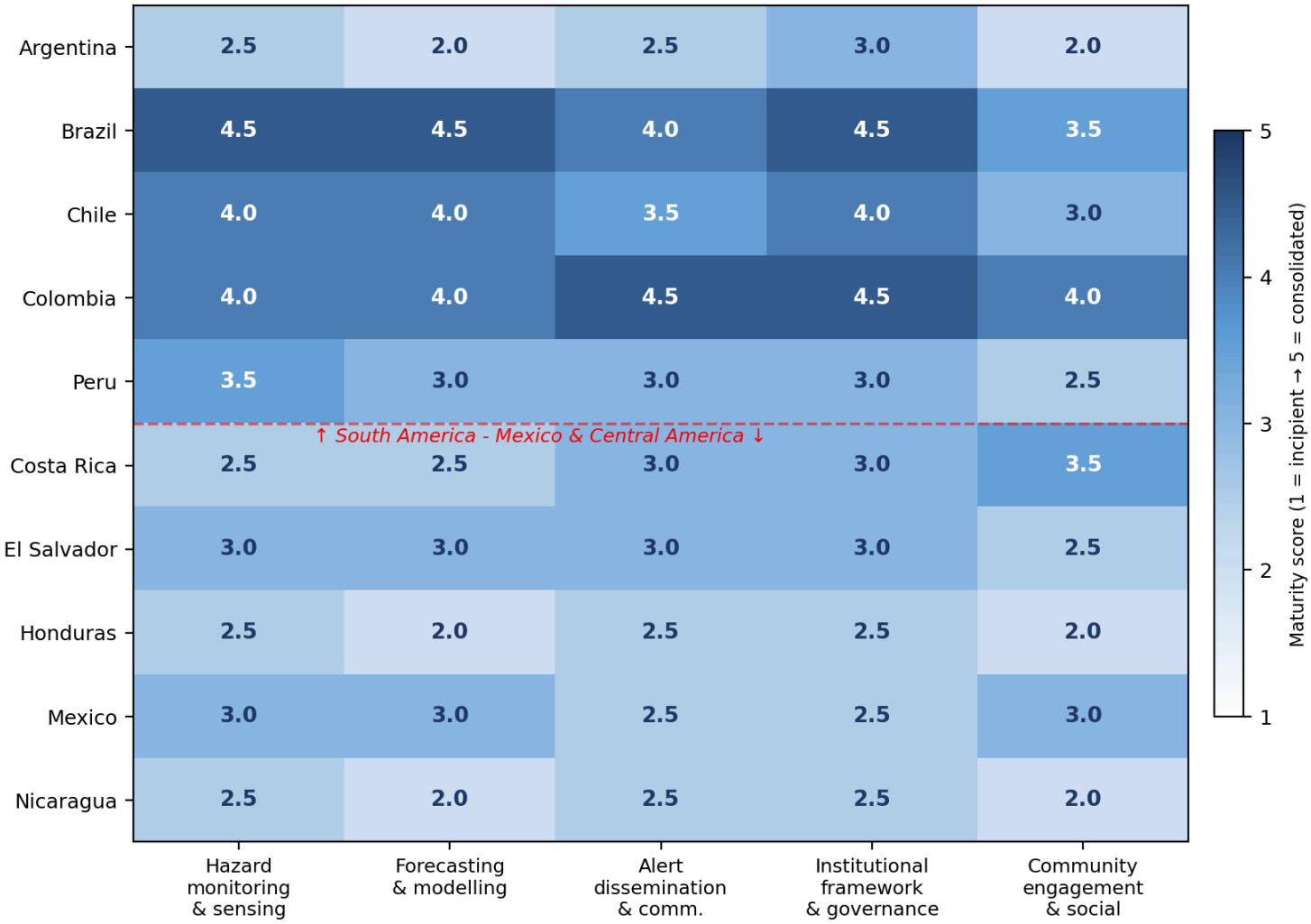


Figure 4

Comparative LEWS maturity heatmap across ten considered Latin American countries in five operational dimensions.