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Original paper

The role of hydrology in hillslope monitoring and landslide risk mitigation

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Abstract: Relevance. Landslides constitute a major geo-hydrological hazard, and rainfall-induced subsurface processes play a critical role in slope destabilization. **The aim** of the work is to determine the condition when studying various types of landslides. Despite substantial advances in landslide research, the integration of hillslope hydrology with monitoring frameworks and early warning systems remains fragmented. This review synthesizes recent developments in landslide research, with an emphasis on hydrological triggering mechanisms and their incorporation into landslide early warning systems (LEWS). **Methods.** A structured literature review of peer-reviewed studies published between 2012 and 2022 was conducted using the Scopus database, complemented by thematic classification of experimental, numerical, and field-based investigations. **Results.** The analysis identified rainfall infiltration, pore-water pressure evolution, matric suction reduction, and groundwater fluctuations as dominant hydrological controls governing slope response. While numerous studies have focused on shallow failures under unsaturated conditions, comparatively little attention has been paid to deep-seated processes and bedrock groundwater interactions. The review further examines sensor-based and model-driven LEWS architectures, highlighting the predominance of rainfall threshold approaches and the emerging role of hydro-mechanical and machine learning frameworks. The findings underscore the necessity of integrating subsurface hydrological monitoring with geotechnical characterization to enhance the predictive reliability and operational robustness of LEWS in landslide prone regions.

Keywords: landslides, slope processes, hillslope monitoring, early warning system, rainfall-induced landslides.

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Оригинальная статья

Роль гидрологии в мониторинге склонов и снижении риска оползней

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Резюме: Актуальность работы. Оползни представляют собой серьезную геогидрологическую опасность, а подземные процессы, вызванные осадками, играют решающую роль в дестабилизации склонов. **Цель работы** – выявить состояние при изучении различных особенностей оползней. Несмотря на значительные успехи в исследовании оползней, интеграция гидрологии склонов с системами мониторинга и раннего предупреждения остается фрагментарной. В обзоре обобщены последние достижения в области исследования оползней с акцентом на гидрологические механизмы их возникновения и их включение в системы раннего предупреждения об оползнях (LEWS). **Методы.** Был проведен структурированный обзор рецензируемых исследований, опубликованных в период с 2012 по 2022 годы, с использованием базы данных Scopus, дополненный тематической классификацией экспериментальных, численных и полевых исследований. **Результаты.** Анализ выявил, что инфильтрация осадков, изменение давления поровой воды, снижение матричного всасывания и колебания уровня грунтовых вод являются доминирующими гидрологическими факторами, определяющими реакцию склонов. При этом многочисленные исследования сосредоточены на неглубоких оползнях в ненасыщенных условиях, и сравнительно мало внимания уделялось глубоким процессам и взаимодействию грунтовых вод с коренными породами. Далее рассматриваются архитектуры LEWS, основанные на датчиках и моделях, с акцентом на преобладание подходов, основанных на пороговых значениях осадков, и растущую роль гидромеханических и машинных моделей обучения. Установлена необходимость интеграции подземного гидрологического мониторинга с геотехнической характеристикой для повышения надежности прогнозирования и эксплуатационной устойчивости LEWS в регионах, подверженных оползням.

Ключевые слова: оползни, склоновые процессы, мониторинг склонов, система раннего предупреждения, оползни, вызванные осадками.

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Introduction

A landslide is the movement of a mass of rock, earth, or debris down a slope [Cruden, 1991], which is recognized globally as a major geological hazard causing fatalities and casualties [Ganapathy et al., 2010]. It is caused by various complex and diverse factors and is categorized based on the material type and movement [Hungr et

al., 2014]. Factors such as rainfall, soil type, erosion, and anthropogenic influence are recognized as landslide-triggering factors [Kervyn et al., 2015; Burdzieva et al., 2024 a, b]. Increasing tourism and the urbanization of hillside towns have increased construction and road widening in mountainous regions [Ganapathy, Hada, 2012; Klyuev, Brigida, 2025], and climate change [Andersson-Skold et al., 2013; Araujo et al., 2022; Crozier, 2010; Gassner et al., 2015; Korup et al., 2012; Wood et al., 2020; Yaitskaya et al., 2023] has directly influenced landslides, causing difficulties for people, infrastructure, and the economy, indicating that the region is associated with geo-hydrological risks [Gariano, Guzzetti, 2016]. Processes, such as slope erosion, which carves out geomorphological features forming landscapes over millions of years, create valleys and elevated hills that are inactive over the bedrock and when the external factors acting on the slopes make it vulnerable to landslides. Various researchers have studied these slopes using different approaches to identify landslide-prone slopes for developing landslide early warning systems (LEWS) for preparedness and mitigation.

External disturbances can cause disasters with high damage, and it depends on the understanding of complex subsurface processes, especially concerning landslides and hillslope hydrology [Prokesova et al., 2013]. The dynamics of rainfall infiltration, subsurface movement systems, and functioning conditions are complex and site-specific. Soil saturation, matric suction, and pore water pressure greatly influence slope stability during the infiltration process. Variations develop with the essential volume parameters of the soil by normal stress and matric suction. According to Lu and Godt [2008], few slope failures have been reported within the vadose zone that are associated with partially saturated soil conditions. This indicates that certain shallow landslides cannot be attributed to saturated conditions. Owing to the complicated lithological and hydrologic properties of unstable regions, which most of the time lead to nonlinear links between rainfall and failure [Doglioni et al., 2012]. The slope responds to rainfall distribution in the downslope portion, where the rotational slide dynamic influences the Earth's flow [Belle et al., 2018]. If there is a prolonged duration of rainfall with less intensity, it can enhance landslide stability; thus, a rainy season after a long wet period may cause more movement or failure than one after a long dry period. Even slight variations in precipitation or water stress can shift the soil's equilibrium stress condition and significantly alter the duration and magnitude of slope movement. In addition, medium- to large-scale landslides are caused by increased moisture levels and subsequent heavy rainfall [Suribabu, Sujatha, 2019]. Various researchers have proposed preliminary alert mechanisms based on sensors [Bak, 2022; Chauhan et al., 2022; Dixon et al., 2022; Guzzetti et al., 2020; Kumar, Ramesh, 2022; Liu et al., 2022; Oguz et al., 2022; Zeng et al., 2022], mostly installed on the slope surface. Based on [Baum, Godt, 2010; Bell et al., 2012; Mirus et al., 2018; Thiebes et al., 2014], the system evaluates rainfall and slope movement, and the landslide management increasingly depending on such LEWS [Landslide ..., 2005].

Evidence from these studies shows that the dynamic interplay between landslide mechanisms, hydrological dynamics, and early warning systems has yet to be fully examined. Although progress has been made in this field, greater insight into the effects of subsurface water variations on landslide initiation and progress is needed. The present study investigates the current state of global landslide research, focusing on the critical role of hillslope hydrology in landslide initiation and the effectiveness of early warning systems. The study addresses three key research questions: What are the recent trends and developments in landslide research? How do hydrological factors contribute to landslide triggering? and What is the current state and effectiveness of LEWS?

Materials and methods

Review protocol

A comprehensive literature review was conducted using the Scopus database from 2012 to 2022. This review was then expanded to include additional relevant studies identified through other research sources, ensuring a thorough and comprehensive analysis. The primary research focus and associated keywords were chosen based on an analysis of publication dates and existing studies within the relevant research area. Search terms related to landslides, hydrology, subsurface processes, early warning systems, and groundwater, along with alternative terms, were also used. The search data were exported for analysis in Biblioshiny [Aria, Cuccurullo, 2017], an R package. The articles were accessed and screened for the study based on their title, abstract, and full text.

Results

Bibliometric overview

The following analysis addresses RQ1, providing insights into the trends and patterns within global landslide research (Fig. 1). The general trend of scientific production was retrieved from the Scopus database during 2012–2022, indicating increasing interest in landslide research. The results show a nonlinear observation, indicating that publications are inconsistent over the period. The cumulative occurrence from journal sources highlights the growing trend in landslide research. The journal *Landslides* exhibits a steady increase, whereas other journals show a steady and moderate increase over production over the period, indicating the growing need for scientific publications on landslide research.

The relative scientific production (Fig. 2) from different countries worldwide depicts that China is the leading country in terms of scientific production. Many countries in Europe and North America have shown substantial production. Some countries in Asia, such as India, Japan, and South Korea, have indicated that they are emerging as significant scientific production shows the research and development in recent years. Figure 3 demonstrates the global scientific network with collaborations spanning across the continents. It shows that China has extensive thick lines connecting it to other countries, indicating active collaboration and partnerships. The dense network is highlighted among European countries. In Asia, countries such as India, Japan, and South Korea have depicted increasing collaboration.

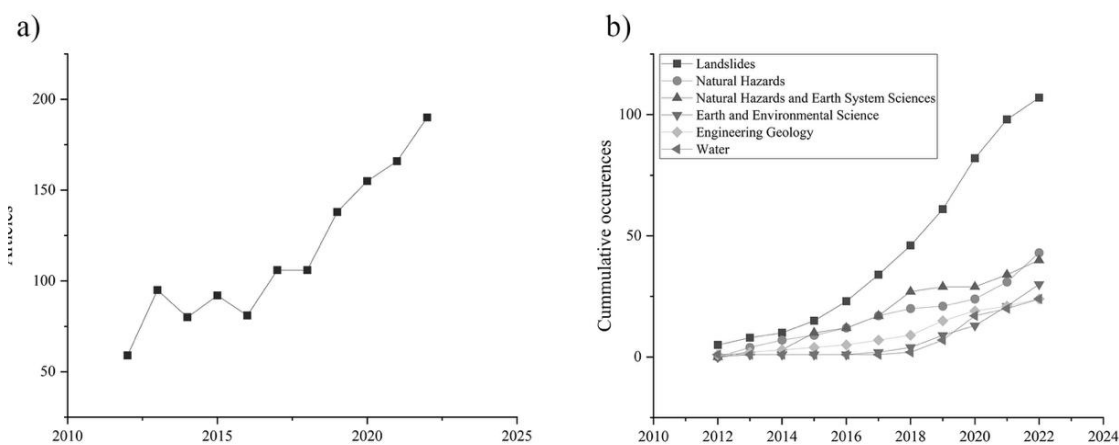


Fig. 1. (a) Annual number of publications on landslide research from 2012 to 2022. (b) Cumulative number of publications in selected journals over the same period

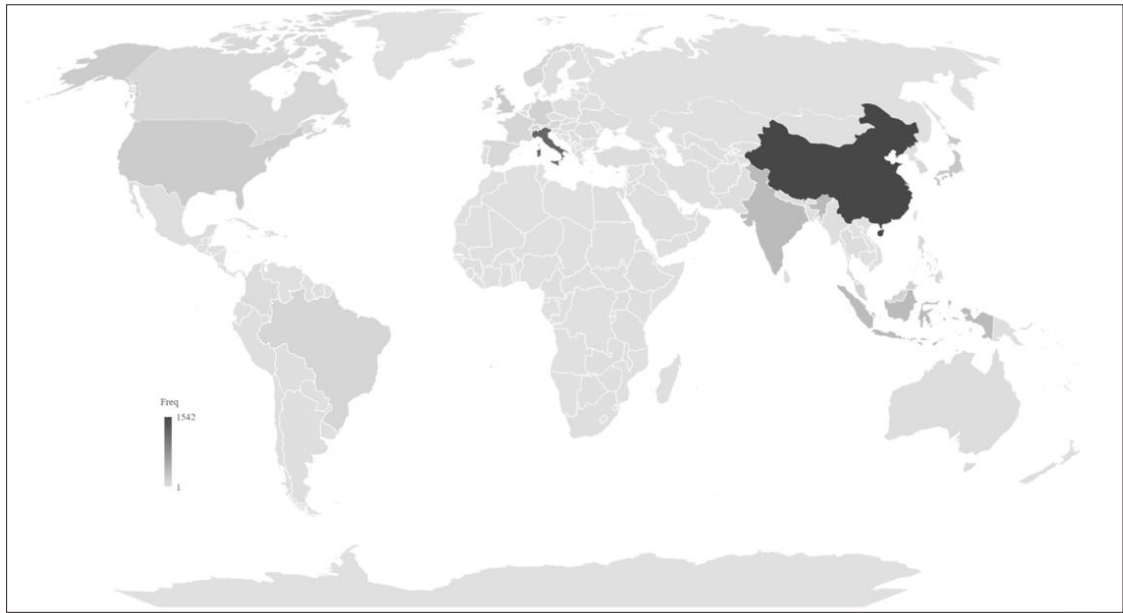


Fig. 2. The country level scientific production



Fig. 3. The country level collaboration map

Hydrological Factors and Landslide Triggering

The following analysis addresses RQ2 in Table 1. The articles connect interdisciplinary fields with landslide hydrology to understand hillslope dynamics. The review denotes that studies majorly overlook experimental physical and numerical models for understanding hydrological behavior on hillslopes. Parameters such as geotechnical properties (deformation characteristics, factor of safety, and index properties (angle of internal friction, cohesion, liquid limit, plastic limit, and relative density, matrix suction, porewater pressure, soil types and soil water interaction), hydraulic conductivity (water flux), rainfall intensity (artificial rain, seepages, and irrigations), slope inclination, slope saturation, and soil motions have been studied. Table 1 shows that experimental setups are widely used, and modelling is applied to the analysis. Studies majorly concern the slope response to water flux during wet and dry periods, as well as their characteristics behavior when the water moves towards the subsurface. Some case studies denote the deformation of slopes through field observations with or through large-scale models and laboratory tests. The stability of slopes is tested by

inputting physical, chemical, and hydromechanical properties to understand the slope's dynamic to water flux in the determination of thresholds, formulation of different slopes, and its response. These findings indicate that fluctuations in subsurface water conditions are a primary trigger of slope failures and therefore, justifying the systematic integration of hydrological monitoring within landslide early warning systems (LEWS).

Table 1

Hydrological Controls and Modeling Approaches in Rainfall-Induced Landslides

Hydrological Process	Modeling Type	Key Parameters	References	Technical Insight	Research Gap
Rainfall infiltration in unsaturated soils	FEM-based seepage deformation modeling; soil water balance models	Rainfall intensity duration; hydraulic conductivity; matric suction; pore-water pressure	Dou et al. [2021]; Yang et al. [2021]	A transient reduction in the matrix suction and a progressive increase in the pore pressure govern shallow instability.	Limited probabilistic treatment and shallow-slope dominance.
Hydro-mechanical coupling	Coupled hydro-mechanical FEM; suction stress frameworks	Effective stress; SWCC; shear strength parameters	Oh, Lu [2015]	Improved prediction of deformation timing compared with limit-equilibrium methods	High parameter sensitivity; limited large-scale validation
Groundwater fluctuation and multilayer interaction	Integrated hydrogeological modeling; field monitoring	Groundwater oscillation; permeability contrasts; perched aquifers	Kukemilks et al. [2018]; Marc et al. [2017]; Wang et al. [2020]	Subsurface flow concentration significantly alters the stability response.	Fractured bedrock flow is rarely modeled explicitly.
Preferential flow and structural discontinuities	Field and numerical case investigations	Desiccation cracks; rapid infiltration pathways	Zhang et al. [2021]	Structural discontinuities accelerate the localized pore-pressure buildup.	Long-term evolution of preferential pathways not sufficiently quantified
Rainfall pattern variability and threshold behavior	Experimental hydrological modeling	Rainfall temporal distribution; intensity–duration thresholds	Ran et al. [2019]; Kenanoglu et al. [2019]	Temporal rainfall distribution affects pore-pressure dynamics beyond cumulative totals.	Rare integration into operational warning thresholds
Deep-seated landslide hydrology	Field investigations; seasonal groundwater analysis	Delayed pore-pressure diffusion; clay–water interaction	Prokesova et al. [2013]; Sidle et al. [2019]; Bogaard, Greco [2016]	Seasonal recharge influences deep-seated slope reactivation	Limited hydro-mechanical coupling at depth

The landslide early warning systems (LEWS)

This analysis addresses RQ3 in Table 2. A review of landslide early warning systems (LEWS) highlights different approaches for landslide monitoring using sensors

(accelerometer, acoustic sensor, automated total station, crack meter, displacement sensor, echo probe, extensometer, gyroscope, inclinometer, infrasound sensor, moisture sensor, piezo vibration sensor, piezometer, potentiometer, rain gauge, strain gauge, suction sensor, tachymetry, tensiometer, tilt sensor, transducer, volumetric water content sensor, and water level indicator), ground-based radars, and remote sensing. These monitoring systems employ automated data acquisition and transmission through Internet of Things (IoT) platforms and wireless sensor networks (WSNs). The literature distribution shows that China has more studies on LEWS, emphasizing field monitoring using sensors and modeling. European countries use geotechnical monitoring with remote sensing. Countries such as India, the Philippines, and Indonesia have highlighted the design, development, and prototypes of landslide monitoring. These highlight the low cost and easy deployment of sensors and monitoring systems. These studies recommend the robustness of using artificial intelligence and machine learning techniques for automatic detection and warnings for risk reduction.

Table 2

Architectural and Methodological Approaches in Landslide Early Warning Systems (LEWS)

LEWS Architecture Type	Monitoring Basis	Parameters	References	Technical Insight	Limitation
Empirical rainfall-threshold systems	Regional rainfall monitoring	Rainfall intensity; duration; antecedent rainfall	Guzzetti et al. [2020]; Harilal et al. [2019]	Operationally scalable and straightforward to implement.	Limited subsurface representation and false-alarm sensitivity.
Subsurface hydrological monitoring	Instrumented slopes with pore-pressure sensors	Pore-water pressure; soil moisture; groundwater level	Mirus et al. [2018]	Direct Linkage Between Hydrological Response and Deformation	Higher installation and maintenance costs
Hydro-mechanical threshold integration	Stability modeling integrated with monitoring	Factor of safety; suction; deformation rate	Bell et al. [2012]	Mechanistically informed thresholds incorporating stability analysis	Model parameter uncertainty influences reliability.
Remote sensing based monitoring	Radar interferometry and displacement mapping	Surface displacement rate	Crosta et al. [2017]	High spatial coverage for complex slopes	Surface-focused; limited subsurface insight
Acoustic emission monitoring	Micro-fracturing signal detection	Acoustic emission rate; deformation precursors	Dixon et al. [2018]	Sensitive to progressive failure signals	Challenges in signal filtering and interpretation complexity
Data-driven predictive systems	Machine learning models	Multivariate hydrological and environmental inputs	Liu et al. [2022]	Captures nonlinear relationships in regional-scale prediction	Requires large training datasets and has limited interpretability

The reviewed studies indicate that effective landslide risk reduction requires a coordinated framework encompassing risk assessment, continuous monitoring, and structured

emergency response mechanisms. The modified framework (Fig. 4) for the LEWS suggests that landslide investigation starts with an understanding of the local climate, geological, and hydrological processes, followed by the identification of landslide-prone slopes and the installation of sensors. Automatic acquisition, detection, and classification with sensor values to threshold values using artificial intelligence and machine learning help to forecast landslide movements and aid in emergency responses. Modelling and experimental studies have shown that rainfall and its associated processes can induce failures. More studies have discussed the role of large and physical models on slope behavior by assuming that the bedrock is homogeneous, which neglects the role of the bedrock in landslide hydrology. The simulations are narrow towards the landslide prediction approach, showing a greater need to include multidisciplinary inputs for the models. Thus, the literature review suggests that holistic approaches for the LEWS, by understanding the response of the slope to rainfall and its subsurface processes in triggering landslides, should be delineated.

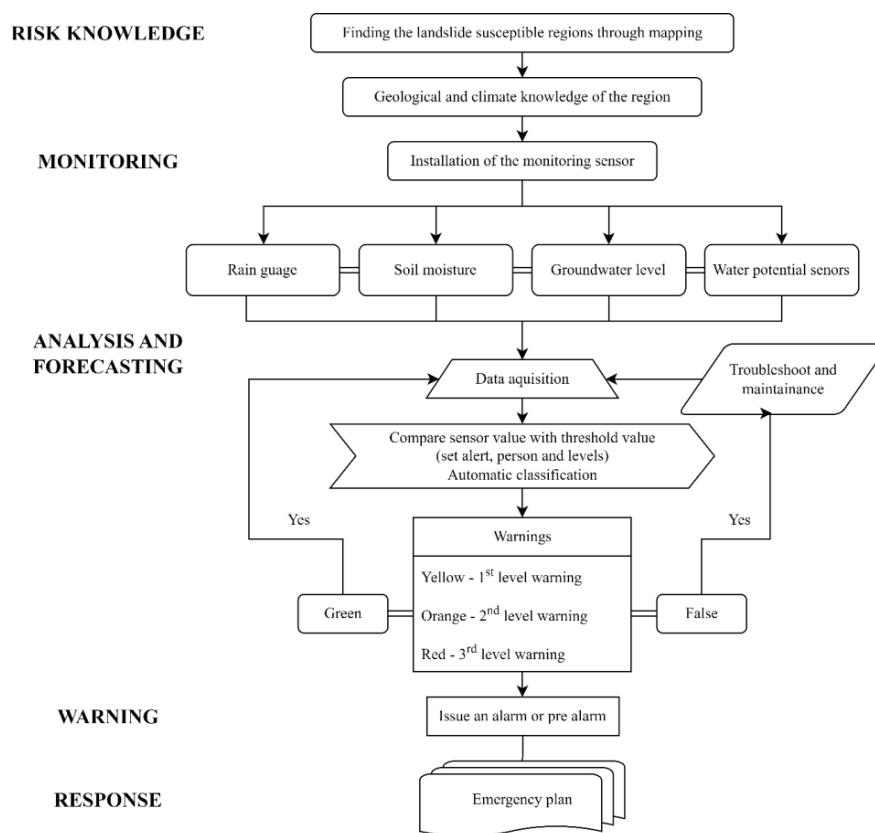


Fig. 4. Schematic representation of the landslide early warning system and its constituent components

Discussion

A comprehensive understanding of landslide mechanisms modeling mental to the effective prevention and mitigation of landslide hazards and their associated impacts on communities, infrastructure, and the environment [Nath et al., 2025]. Although landslide research has been conducted extensively, the specific focus and methodologies vary widely, reflecting the evolving nature of the field. The growing recognition of the link between climate change and landslide susceptibility has driven a surge in research activity, as evidenced by the increasing number of publications. A multidisciplinary approach is crucial for comprehensively understanding landslides and developing effective management strategies. There has been a notable increase in scientific research on landslides in developing

nations, likely driven by the growing frequency and severity of landslide-related disasters. Countries such as China, the United States, and Italy have developed distinct strategies for landslide mitigation, often supported by advanced monitoring and analytical technologies. Strengthened collaboration among researchers across regions can enhance methodological refinement and support the transfer of technical expertise.

Rainfall is a primary triggering factor of landslides [Gupta, Leong, 2019]; although rainfall and hydrology are different fields of study, there is sufficient interdisciplinary overlap, making it impossible to deny their mutual importance [Climate ..., 2005]. Complex interactions among rainfall, the physical heterogeneity of soil and bedrock, local geomorphology, vegetation, and associated biomass contribute to the complexity of subsurface hydrological processes [Sidle et al., 2019]. The specific parameters selected often depend on the research objectives and the geological and geomorphological characteristics of the study area. A variety of parameters have been considered in landslide research, with rainfall consistently identified as an inducing factor. Other factors include erosional conditions, geotechnical properties, groundwater interactions, hydraulic conductivity, hydromechanical conditions, slope saturation states, and topographical conditions. Rainfall infiltration plays an important role in slope stability. The rate of this process is influenced by the interaction between various geological formations. Thus, the formation of perched aquifers [Rahardjo et al., 2005], macropores, and cracks can enhance infiltration rates, further destabilizing slopes due to erosional activity [Idarmachev, 2025]. The combined effects of rainfall infiltration and erosional activity can trigger shallow landslides. Erosion can lead to the loss of topsoil; thus, materials can clog drainage channels and block the flow of water, making it stagnant; therefore, increasing the risk of landslides.

Geotechnical factors, such as saturation and rainfall response, on slopes are necessary to understand hydrological behavior and its impact on slope stability [Priest et al., 2011; Sun et al., 2012]. Most studies have modeling hillslope deposit covers; however, some studies have indicated the importance of groundwater and bedrock features on hillsides, such as their responses and processes in the ground. Experimental studies often rely on assumptions, such as homogeneous topsoil formation and impermeable bedrock, leading to inconsistencies between field and experimental results [Bogaard, Greco, 2016]. Variations in geological formation on hillslopes can increase infiltration, thus creating channels and groundwater interactions [Collins, Znidarcic, 2004]. Because hydrological processes are time-dependent, physical and numerical modeling approaches are widely used to analyze and simulate landslide behavior under controlled conditions [Klyuev, Brigida, 2025; Kerimov, Elzhaev, 2024]. These models can include additional factors to comprehensively understand regional characteristics, which enhances the effectiveness of LEWS.

A comprehensive understanding of hillslope hydrology is essential for the development of effective landslide early warning systems (LEWS). Adapting LEWS to site-specific needs requires a thorough understanding of local hydrological conditions. While LEWS distribution varies globally, developing countries such as India, the Philippines, and Indonesia have focused significantly on LEWS prototyping. However, many prototypes overlook the importance of subsurface monitoring and data transfer in favor of networking. Existing LEWS primarily rely on geotechnical monitoring, rainfall thresholds, slope monitoring, and surface displacement, using various sensors to measure parameters such as acoustic emission, moisture content, pore water distribution, rainfall, slope inclination, stress, and strain, and volumetric water content. The thresholds for these sensors are typically set based on historical landslide data. Although rainfall thresholds are often used, it is crucial to recognize that rainfall is not the sole trigger for landslides. Established slope monitoring utilizes geotechnical properties and slope movements by integrating water potential sensors to measure water content at various depths within hillslopes, which can

improve the efficiency of LEWS. Owing to its cost, deployment, and maintenance, it is highly expensive; therefore, it is essential to develop and deploy reliable and low-cost alternatives. Hence, we can enhance our ability to monitor slope stability and mitigate landslide risks.

Challenges, Limitations, and Future Research

The study of landslide research trends, hillslope hydrology, and its applicability to LEWS has provided valuable insights. However, important research gaps, problems, and what remains to be explored are apparent. The challenges highlighted the lack of ability of landslide experiments to replicate natural conditions, lack of understanding of deep-seated landslides with hillslope hydrology, and determining LEWS's performance remains a major challenge.

In developing countries, LEWS prioritize the use of water potential sensors and precede regional evaluations. Addressing these challenges and limitations will enable future research to advance toward a more integrated understanding of landslide processes and to develop more reliable and effective LEWS. Although it is expensive in its design and can be very expensive in LEWS, it is important to design low-cost sensors and deployment strategies. The importance in this regard lies in the prioritization of hydrological monitoring and the implementation of LEWS designs in landslide-prone regions. Despite previous research, many research gaps persist, allowing for possible innovative approaches. Future studies might better be centered on the simulation of a multilayered slope, added with groundwater fluctuations and other parameters, to improve the understanding of landslide triggering mechanisms.

Conclusion

Highlights the importance of hillslope hydrology in understanding landslide mechanisms. Identifies rainfall infiltration and subsurface interactions as key factors triggering shallow landslides. Proposes low-cost, sensor-based LEWS tailored to regional hydrological and geotechnical conditions. This highlights critical research gaps in modeling deep-seated landslides and subsurface monitoring.

This comprehensive review and bibliometric analysis evaluate the current state of knowledge regarding hydrological processes that trigger landslides and the development of early warning systems. By summarizing the data of various studies and analyzing the trends, collaborations, and frequently presented themes in publications, it contributes to understanding the research field by pointing out knowledge gaps and limitations in methodological approaches. These results can be useful in guiding future research initiatives, such as the development of low-cost early warning systems and the importance of hydrologic monitoring in landslide mitigation. Certainly, significant progress has been made in understanding landslide triggers and establishing early warning systems. However, much more needs to be learned about the complexities involved in hydrologic interactions for effective LEWS.

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