

Visualization Analysis of Research Literature on Early Warning of Geo-Hazards Based on Meteorological Factors in the Past 20 Years

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Received: July 3, 2025, Accepted: October 30, 2025

Abstract: The complex geo-environment of China, characterized by extreme rainfall, earthquakes, floods, and expanding engineering activities, has led to increasing geo-hazard risks. Since 2003, China has pursued meteorological factor-based geo-hazard early warning, achieving notable societal and economic benefits. With the rise of bibliometric and visualization tools such as CiteSpace, research trends and knowledge structures in this domain can now be systematically examined. This study analyzes 1,040 Chinese papers (CNKI) and 856 international papers (SCI-Expanded) published over the past two decades. Through bibliometrics, co-word analysis, clustering, and hotspot detection, the research identifies major themes, evolutionary trends, and future hotspots in meteorological factor-based geo-hazard early warning.

Keywords: Geo-hazards, Early warning, Bibliometrics, Visual analysis, Cite space.

Introduction

China encompasses vast and geologically diverse terrain, including mountain belts, plateaus, and active fault systems. Across these landscapes, extreme rainfall, earthquakes, floods, snowmelt, and other climatic triggers interact with complex geological settings to generate frequent geo-hazards. Landslides, debris flows, collapses, and hazard chains are widespread and often catastrophic. Simultaneously, rapid urbanization and the construction of megaprojects transport corridors, hydropower stations, and new towns have exposure and vulnerability.

Against this backdrop, Chinese authorities initiated a national geo-hazard early warning program in 2003, jointly operated by the land and resources sector and the China Meteorological Administration. Over the past two decades, this system has evolved from basic rainfall-triggered alerts to more refined, data-driven, and model-supported early warning practices. The initiative has substantially reduced casualties, safeguarded engineering works, and generated considerable socio-economic benefits. While scientific understanding of geo-hazards is expanding, bibliometric studies that synthesize knowledge specifically on meteorological factor-based geo-hazard early warning remain limited. As research continues to

grow, especially with interdisciplinary integration of meteorology, geology, remote sensing, and machine learning, a systematic evaluation of progress and emerging trends is increasingly necessary.

CiteSpace and similar visualization tools based on bibliometrics have become powerful means to reveal disciplinary evolution, research hotspots, and intellectual structures. Although some scholars have applied these tools to geological disaster research, focused analyses on meteorological triggers are scarce. This study fills that gap by analyzing 1,040 papers from CNKI and 856 papers from SCI-Expanded databases published over the last 20 years.

Data and methods

The study utilized two major literature sources: CNKI (China National Knowledge Infrastructure): 1,040 Chinese-language papers and SCI-Expanded (Web of Science): 856 international papers. Bibliometric indicators combined with CiteSpace visualization were applied to investigate keyword co-occurrence and research themes, cluster analysis and evolutionary timelines and research hotspot and burst detection. This approach enabled a systematic assessment of how research on meteorological factor-based geo-hazard early warning has evolved and what frontline techniques and topics dominate the field.

Research themes and keyword

Keyword frequency and co-occurrence networks help identify core research topics (Figure 1 and 2). Results from both Chinese and international datasets reveal strong consistency in research directions. Five thematic clusters dominate the field, and they are geo-hazards (general geological disaster mechanisms), debris flows, landslides, early warning and forecasting technologies and critical rainfall and thresholds. Among these, research on rainfall thresholds holds a central position. Establishing empirical or physically based rainfall thresholds provides the foundation for operational early warning systems in mountainous areas. Co-word analysis reveals structural relationships among concepts. Strong linkages appear among rainfall, slope

instability, numerical modeling, monitoring, and warning systems, illustrating an increasingly interdisciplinary approach. The network also highlights meteorological factors, rainfall intensity, cumulative precipitation, and antecedent moisture, as dominant trigger terms.

Cluster analysis and evolutionary trends

Cluster analysis groups keywords into conceptually related themes. Both Chinese and international literature show a high number of studies on warning models and threshold determination, strong focus on different geo-hazard types under varying meteorological conditions and increasing sophistication in identifying hazard formation mechanisms. This indicates that research is shifting from broad operational approaches to refined, mechanism-based analysis.

Early stage (2003–2010): Operational focus

Initial work centered on practical early warning techniques for landslides and debris flows. Efforts emphasized defining rainfall standards, developing hazard maps, and implementing community-based early warnings.

Transitional stage (2010–2016): Integration of monitoring and modeling

Advances occurred in real-time monitoring, GIS-based models, remote sensing applications and statistical rainfall threshold methods. Researchers began linking atmospheric processes with slope response. International studies show rapid adoption of new technologies such as Electrical resistivity for subsurface moisture profiling, Remote sensing and InSAR for deformation detection, Machine learning for threshold optimization and hazard prediction and IoT-enabled early warning systems.

These approaches are reshaping the scientific direction of meteorology-based geo-hazard early warning and promoting the development of quantitative, dynamic, and intelligent models.

Research hotspots and frontier trends

Keyword burst analysis identifies research topics that have gained rapid attention. Consistent hotspots across Chinese and international literature include rainfall-related criteria and thresholds, real-time monitoring, debris flow prediction and landslide rainfall triggering mechanisms. The continued prominence of rainfall threshold research indicates its foundational role and future importance. Newer hotspots reflect interdisciplinary integration, and trends align with global advances in disaster science and climate resilience.

1. Machine learning and data-driven prediction
2. Multi-source remote sensing fusion

3. Slope hydrological modeling
4. Hazard chain forecasting under extreme climate events

Conclusions

This bibliometric study presents the research progress, thematic evolution, and emerging trends in meteorological factor-based geo-hazard early warning over the past two decades. Key conclusions include:

- Rainfall threshold research continues to dominate and will remain a core future direction.
- International research is increasingly integrating advanced technologies such as machine learning, remote sensing, and IoT-based systems.
- Refinement and mechanism-based models are becoming crucial for improving early warning accuracy.
- Both Chinese and global research communities are converging toward data-driven, multidisciplinary, and dynamic early warning approaches.

This work provides a valuable knowledge framework for future studies and supports the development of resilient and grounded early warning systems.

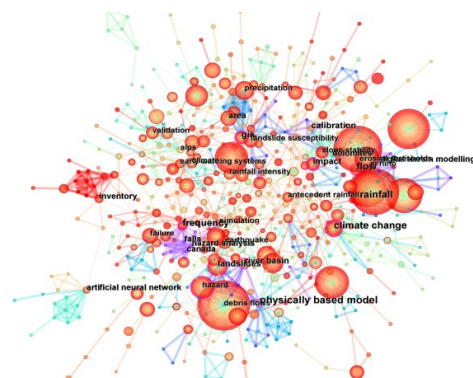


Figure 1, Co-occurrence network of keywords in 6 SCI-Expend databases on early warning of geo-hazards based on meteorological factors.

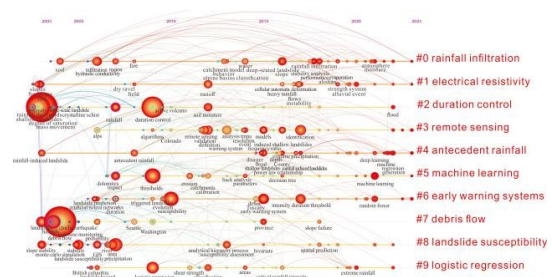


Figure 2, Co-occurrence network of keywords in SCI-Expend database on early warning of geo-hazards based on meteorological factors.

Acknowledgement

This work was supported by the special project of China's key research and development program (2023YFC3007205).