Scientific Mapping and Scientometric Evaluation of Geospatial Technologies in Landslide Research: Trends, Collaboration Networks, and Emerging Research Directions

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Abstract: Landslides remain one of the most frequent and destructive natural hazards globally, significantly influenced by climate change, rapid urbanization, deforestation, and unplanned developmental activities. In response, geospatial technologies such as Remote Sensing (RS), Geographic Information Systems (GIS), Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR), Global Navigation Satellite System (GNSS) and machine learning techniques have increasingly been applied to improve landslide prediction, monitoring, susceptibility mapping, and disaster risk reduction. This study presents a bibliometric evaluation of global research trends related to geospatial technologies in landslide studies during the period 2000–2025. A total of 14,909 publications indexed in Web of Science and Scopus were analysed using the bibliometrix package in R. The analysis identified 2,385 publication sources and an annual scientific growth rate of 14.64%, indicating the rapid expansion of research activities in the field. The study examined publication trends, citation impact, thematic evolution, keyword structure, and international collaboration patterns. The results revealed substantial growth in scientific production, particularly after 2018, driven by advances in spatial data acquisition, artificial intelligence integration, and increasing global disaster risk awareness. China, Italy, India, and the United States emerged as the leading contributors to the research domain. Keyword and thematic analyses demonstrated a clear transition from conventional geomorphological and mapping-based approaches toward advanced machine learning-driven predictive modelling and geospatial monitoring frameworks. The study further identified two major interconnected research streams: remote sensing-based monitoring and GIS-based susceptibility modelling. The findings highlight the growing global significance, interdisciplinary nature, and technological advancement of geospatial applications in landslide research and disaster management.

Keywords: Geospatial technologies, Landslide, Remote Sensing, Bibliometric analysis, GIS, Research trends.

1. Introduction

Landslides, as a recurring and devastating natural hazard, pose significant risks to human life, infrastructure, and the environment, particularly in mountainous and densely populated regions. The increasing frequency and intensity of landslides, often exacerbated by climate change and unplanned development, underscore the urgency for effective monitoring and risk management (Froude & Petley, 2018; Gariano & Guzzetti, 2016). In recent decades, geospatial technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), and Global Positioning Systems (GPS) have revolutionized landslide research by enabling accurate spatial data collection, terrain analysis, and predictive modelling. These technologies facilitate real-time monitoring and significantly improve hazard assessment and decision-making processes (van Westen et al., 2008).

Landslides are one of the most recurrent and damaging natural hazards worldwide, posing serious threats to human life, infrastructure, and the environment. Globally, the impact of landslides has increased due to a combination of natural factors and anthropogenic activities such as deforestation, unplanned urbanization, and climate change (National Research Council, 1993). Recent studies show that intensified rainfall events caused by climate change have significantly contributed to landslide occurrences, particularly in vulnerable regions like South and Southeast Asia (Dayal, 2024).

To effectively mitigate and manage landslide risks, there is a growing reliance on advanced technologies for monitoring, prediction, and decision-making. Among these, geospatial technologies including Geographic Information Systems (GIS), Remote Sensing (RS), Global Positioning Systems (GPS), and Light Detection and Ranging (LiDAR) play a vital role. These technologies enable high resolution terrain analysis, spatial modelling, and real-time monitoring, significantly enhancing our understanding of landslide dynamics (Manfré et al.,2012).

Bibliometric analysis offers a systematic and quantitative approach to examining the scholarly landscape of a given research domain. By analysing publication trends, citation patterns, authorship networks, and thematic evolution, bibliometrics provides valuable insights into the development, influence, and research directions within geospatial applications in landslide studies (Donthu et al., 2021; Moral-Muñoz et al., 2020). To the best of our knowledge, this is one of the few comprehensive bibliometric studies focusing explicitly on the intersection of geospatial technologies and landslide research. The

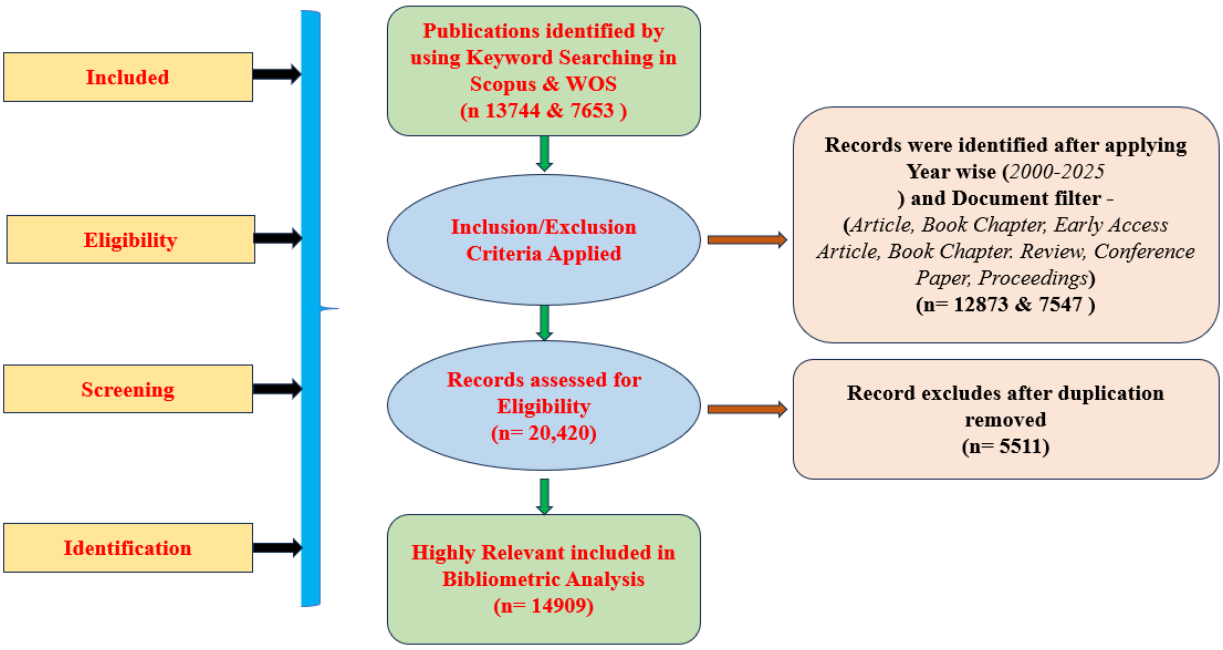


Figure 1: Methodology flow chart

findings aim to support researchers, policymakers, and practitioners by illuminating trends, identifying influential works, and suggesting potential areas for further exploration (Aria & Cuccurullo, 2017).

Over the past two decades, the integration of geospatial tools in landslide research has seen exponential growth, reflected in the increasing number of academic publications (Bui et al., 2019). However, there is limited literature that systematically analyses this growing body of research to understand its structure, trends, and knowledge gaps. Bibliometric analysis a method of applying statistical and visualization techniques to scholarly literature offers a robust framework for examining such patterns (Donthu et al., 2021). It enables researchers to assess publication trends, identify key contributors, visualize collaborative networks, and trace thematic evolutions in a given research field (Aria & Cuccurullo, 2017).

The present study aims to conduct a comprehensive bibliometric analysis of scientific publications related to the application of geospatial technologies in landslide research. This analysis is significant as it not only maps the intellectual landscape of this interdisciplinary domain but also provides valuable insights into the historical pathways of research disciplines and serves as a predictor for future directions within scholarly inquiry (Öztürk, 2023; , Xu et al., 2022).

1.1 Rationale of the study

Landslides are among the most destructive natural hazards, causing significant loss of life, infrastructure damage, and economic disruption, particularly in mountainous and vulnerable regions (Casagli et al., 2023). The increasing impacts of climate change and rapid urbanization have intensified landslide occurrences, creating a growing need for effective monitoring, prediction, and risk management strategies (Westen et al., 2008). Geospatial technologies have transformed landslide research by enabling accurate spatial analysis, terrain mapping, and predictive modelling (Ray et al., 2020). However, the rapid growth and interdisciplinary nature of this research field make it difficult to track major developments, research trends, and collaborative networks. Although numerous studies have applied geospatial tools in landslide investigations, there is still a lack of comprehensive analyses examining the overall knowledge structure and thematic evolution of the field. Therefore, this study conducts a bibliometric analysis to evaluate scientific publications, identify major research themes, leading contributors, and emerging trends, and provide insights that can support future research and interdisciplinary collaboration (Aria, 2020).

1.2 Objectives

- To analyse publication trends in the application of geospatial technologies in landslide research.
- To identify the leading institutions and countries contributing to geospatial landslide studies.
- To map institutional and international collaboration networks in the field.
- To examine thematic evolution, keyword co-occurrence, and factorial structure of geospatial landslide research.

2. Method

The bibliometric analysis of literature related to geospatial technologies in landslides, covering the period from 2000 to 2025, reveals a substantial and steadily growing body of scholarly work. Bibliometric analysis is a quantitative research method used to evaluate the structure, impact, and trends within a scientific domain through statistical and network-based approaches (Adarsh & Sulthana, 2025). A total of 14953 documents were retrieved from different sources, including journals, books, book chapters, and conference proceedings (Figure 1).

The data collection stage involves extracting relevant research articles from selected databases using well-defined search queries. The bibliometric mapping was performed using all selected keywords retrieved from the database search. The search query has been used for



Figure 2: Descriptive Analysis of the Dataset

extracting documents from Web of Science (WOS) and Scopus are listed below;

=(("Geo-spatial Technology" OR "Geospatial Technology" OR "Geospatial Technologies" OR "Geospatial Data" OR "Geospatial Analysis" OR GIS OR "Geographic Information System*" OR "Remote Sensing" OR "Satellite Imagery" OR "Earth Observation" OR "Drone Mapping" OR UAV OR LiDAR OR Geoinformatics OR Geomatics OR "Spatial Analysis") AND (Landslide OR "Landslide Susceptibility" OR "Landslide Hazard" OR "Landslide Risk" OR "Landslide Mapping" OR "Landslide Prediction" OR "Landslide Inventory"))

2.1 Data Analysis

The analysis was conducted using specialized bibliometric tools, Biblioshiny (an R-based bibliometric package) (Aria and Cuccurullo, 2017). The following techniques were applied:

- Descriptive Analysis: This involved the identification of publication trends, prominent journals, influential authors, and citation metrics.
- Co-occurrence Analysis: Keywords were analysed to visualize the thematic structure of the research field using network maps.
- Thematic Mapping: Themes were classified based on relevance and development degree using a two-dimensional analysis, categorizing topics into Basic Themes, Motor Themes, Niche Themes, and Emerging or Declining Themes.
- Collaboration Network Analysis: Country-level collaboration networks were assessed to identify leading research hubs and international partnerships.
- Thematic Evolution Analysis: Temporal changes in research focus were mapped using Sankey diagrams to trace the progression of topics over different time periods

2.2 Descriptive Analysis of the Bibliographic Dataset

The final bibliographic dataset retrieved from Web of Science (WoS) and Scopus consisted of 14,909 publications published between 2000 and 2025, representing more than two decades of research on geospatial technologies in landslide studies. The publications were distributed across 2,385 sources, including journals, conference proceedings, books, book chapters, and review publications, indicating the interdisciplinary nature of the field (Aria and Cuccurullo, 2017) (Figure 2).

2.2.1 Growth and Productivity Trends

The field showed a strong growth trend with an annual growth rate of 14.64%. This reflects the increasing application of geospatial technologies such as GIS, Remote Sensing, LiDAR, UAVs, and spatial analysis in landslide research. The average age of the documents was 7.7 years, indicating the presence of both foundational and recent studies within the dataset.

2.2.2 Impact and Citation Patterns

The dataset recorded an average of 27.95 citations per document, indicating a considerable level of scholarly impact. This suggests that research on geospatial technologies in landslide studies has gained significant academic attention across multiple disciplines.

2.2.3 Keyword Distribution and Thematic Diversity

A total of 24,792 Keywords Plus and 24,229 Author Keywords were identified in the dataset. The large number of keywords reflects the thematic diversity of the field, covering areas such as landslide susceptibility assessment, hazard mapping, spatial modelling, machine learning applications, risk analysis, and environmental monitoring.

2.2.4 Authorship Patterns and Collaboration

The dataset included contributions from 24,673 authors. While 861 publications were single-authored, most documents involved multiple authors, with an average of 4.51 co-authors per publication. This indicates a strong collaborative research culture and the interdisciplinary nature of the field. International collaboration accounted for 16.47% of the total publications, reflecting a moderate level of global scientific cooperation.

2.2.5 Document Types and Publication Characteristics

Journal articles were the dominant document type (10,467), followed by conference papers (3,258), book chapters (548), and review articles (266). The dominance of journal articles highlights the research-oriented nature of the field, while the high number of conference papers reflects ongoing technological developments and innovation in geospatial research.

3. Results and Discussion

3.1 Annual Scientific Production

The annual scientific production of publications related to geospatial technologies in landslide research exhibited a remarkable upward trend during the period from 2000 to

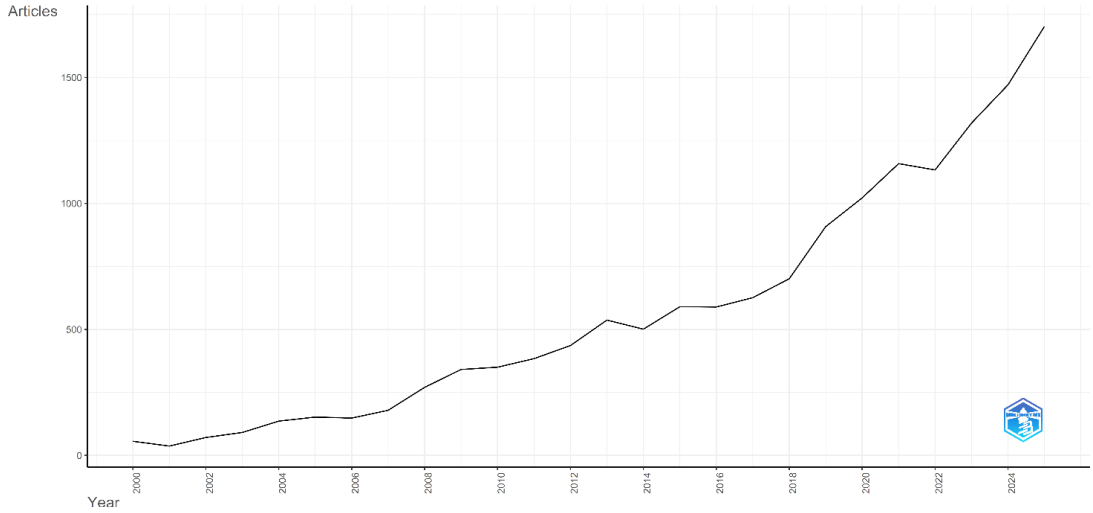


Figure 3: Annual scientific production (all figures in this paper, except Figure 3,9) has been prepared using Biblioshiny (Aria and Cuccurullo, 2017))

2025 (Fig. 3). The analysis revealed a substantial increase in the number of publications over the past two and a half decades, indicating the growing scientific importance and expanding research interest in the application of geospatial technologies for landslide studies.

In the early years of the study period, research output remained relatively limited, with only 56 publications recorded in 2000. Between 2000 and 2007, the annual publication count increased gradually, reflecting the initial adoption of Geographic Information Systems (GIS), Remote Sensing, and spatial analysis techniques in landslide investigations.

The number of publications increased from 56 articles in 2000 to 1,703 articles in 2025, indicating substantial growth in research output. Between 2000 and 2010, publication output increased gradually, rising from 56 to 350 articles per year. From 2011 onwards, the growth became more pronounced, with publications exceeding 500 articles annually after 2013.

From 2018 onwards, the field experienced an exceptionally rapid growth phase. Publications increased from 701 articles in 2018 to 908 in 2019 and surpassed 1,000 publications annually from 2020 onward. The highest annual scientific production was recorded in 2025, with 1,703 publications, demonstrating increasing global attention to the application of geospatial technologies in landslide research. The overall trend indicates continuous expansion of research activities related to geospatial technologies in landslide studies.

3.2 Life Cycle Analysis of Scientific Production

The life cycle analysis of scientific production revealed that the growth pattern of publications related to geospatial technologies in landslide research follows a logistic growth model (Aria et al., 2020). The cumulative growth curve showed an initial period of slow growth followed by a rapidly accelerating phase of scientific production (Bettencourt et al., 2009). The annual publication trend demonstrated continuous growth throughout the study period, indicating increasing research activity in the field. The logistic model identified the inflection point at approximately 2042.8, representing the stage at which the growth rate of cumulative publications is expected to reach its maximum (Figure.4).

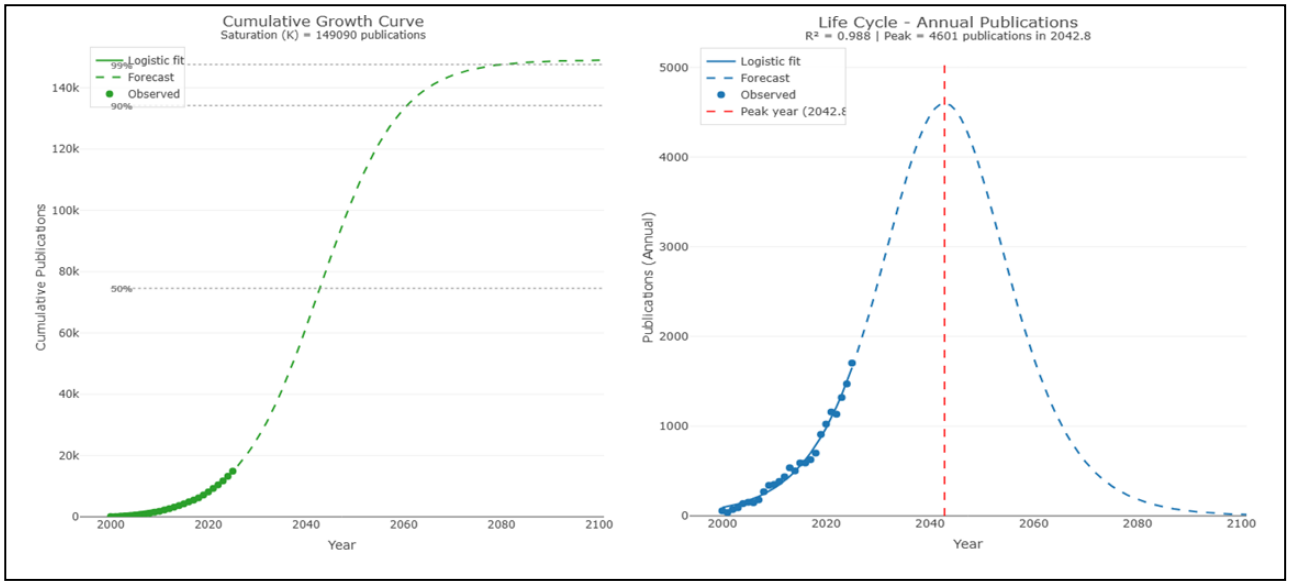


Figure 4: Life Cycle Analysis of Scientific Production

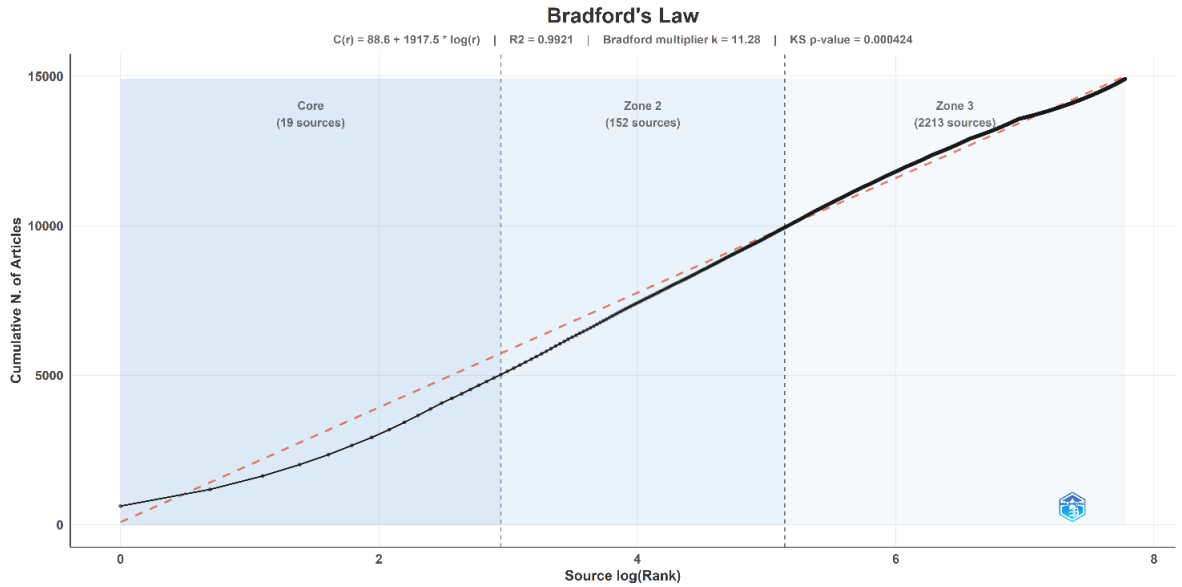


Figure 5: Core Sources Identified by Bradford's Law for Publications on Topic. The shaded region highlights the "core zone" of journals contributing the majority of publications in the dataset

The logistic model showed an excellent fit with the observed publication data, with an R^2 value of 0.988 and an RMSE value of 50.2 (Rogers, 2003). These values indicate a strong agreement between the predicted and observed publication trends (Wang, 2018). The carrying capacity (K) of the model was estimated at 149,090 publications, suggesting substantial future growth potential in the research field. The intrinsic growth rate indicated a stable and continuous increase in scientific production over time (Small & Upham, 2009). Based on the observed trends, the field is currently in an expansion phase characterized by rapidly increasing annual scientific production. The analysis suggests that research related to geospatial technologies in landslide studies continues to grow significantly and has not yet reached maturity or saturation.

3.3 Most Relevant Sources

The analysis of source productivity identified *Remote Sensing* as the most productive publication source in the field, with 626 articles, followed by *Landslides* with 557 publications and *Natural Hazards* with 447 publications. *Geomorphology* also contributed substantially with 382 articles.

Among conference-based sources, the *International Geoscience and Remote Sensing Symposium (IGARSS)* recorded 334 publications, indicating the importance of remote sensing technologies in landslide research. *Environmental Earth Sciences* published 310 articles, while the *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives* contributed 267 publications.

Other major publication sources included *Proceedings of SPIE – The International Society for Optical Engineering* with 258 articles, *IOP Conference Series: Earth and Environmental Science* with 246 articles, and *Engineering Geology* with 229 publications. The dominance of journals related to remote sensing, geomorphology, environmental science, and engineering geology indicates the interdisciplinary nature of geospatial landslide research.

3.4 Core Sources by Bradford's Law

Bradford's Law analysis revealed that the publication pattern of geospatial technologies in landslide research exhibited a highly concentrated core and a widely dispersed peripheral distribution of sources (Bradford, 1934). A small number of journals contributed a substantial proportion of the total publications, while a large number of sources published relatively fewer articles (Egghe, 1986).

The analysis identified 19 journals in the core zone (Zone 1), which collectively accounted for approximately one-third of the total publications in the dataset. Zone 2 consisted of 152 journals, while Zone 3 included 2,213 sources, indicating a progressive increase in the number of journals required to produce a similar proportion of articles (Figure 5). The empirical Bradford distribution showed a strong fit with the theoretical model, with an R^2 value of 0.9921, indicating that the model effectively explained the distribution pattern of publications across sources (Brookes,1969). However, the Kolmogorov–Smirnov test produced a p-value of 0.000424, suggesting slight deviations between the observed and theoretical distributions.

The Bradford multiplier (k) was estimated at 11.28, reflecting a substantial increase in the number of journals across successive zones. This finding indicates that although a small group of core journals dominates scientific production, relevant research is also distributed across a large number of peripheral sources. The results demonstrate that geospatial landslide research is strongly centred around a limited number of highly productive journals while simultaneously maintaining broad interdisciplinary dissemination across diverse scientific sources.

3.5 Author Productivity through Lotka's Law

Lotka's Law is one of the foundational laws of bibliometrics, first formulated by Alfred J. Lotka in 1926 (Lotka, 1926). The law describes the *frequency distribution of scientific productivity* among authors: a

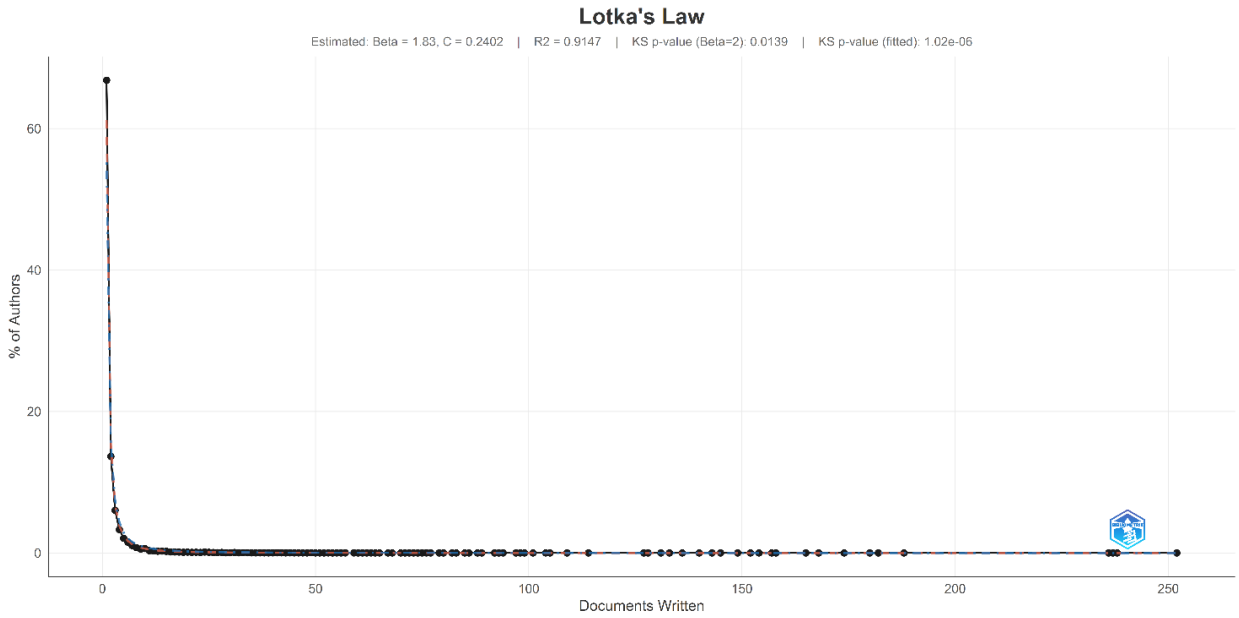


Figure 6: Author Productivity Distribution Following Lotka's Law

large proportion of authors publish only one paper, while a small proportion are highly prolific (Pao, 1985). The Lotka's Law analysis revealed that author productivity in geospatial landslide research follows a power-law distribution pattern. The fitted model showed a strong relationship with the observed data, with an R^2 value of 0.9147, indicating that the model effectively explained the distribution of author productivity within the dataset. The estimated Beta value was 1.8303, which is lower than the theoretical Lotka's Law value of 2 (Figure 6). This indicates a relatively dispersed productivity pattern, suggesting that research contributions are distributed across a broader group of authors rather than being concentrated among a few highly prolific researchers (Nicholls, 1986).

The analysis identified 24,772 authors in the dataset, of which 16,489 authors published only a single document, representing 66.56% of the total authors. In contrast, only 1,041 authors produced 10 or more publications, accounting for approximately 4.20% of the total author population. The Kolmogorov–Smirnov test for the theoretical Lotka distribution produced a p-value of 0.0139, while the fitted model showed a p-value of 1.02e−06, indicating slight deviations between the empirical data and the theoretical distribution. Nevertheless, the overall productivity trend closely followed the generalized inverse power-law pattern. The results indicate that the field consists of a large number of occasional contributors alongside a comparatively smaller group of highly productive authors, reflecting the broad and collaborative nature of geospatial landslide research.

3.6 Most Relevant Affiliations

The analysis of institutional productivity identified the Chinese Academy of Sciences as the most productive affiliation in the field, contributing 968 publications. China University of Geosciences and Chengdu University of Technology followed closely with 644 and 641 publications, respectively. Other major contributing institutions included Consiglio Nazionale delle Ricerche (CNR) with 288 publications, Chang'an University with 278 publications, and the University of Chinese Academy of Sciences, CAS with 250 publications. China Geological Survey also showed significant research output with 237 publications.

Among the leading international research organizations, Centre National de la Recherche Scientifique (CNRS) contributed 226 publications, while the Institute of Mountain Hazards and Environment, CAS produced 205 publications. The Ministry of Natural Resources of the People's Republic of China recorded 197 publications. The results indicate a strong dominance of Chinese research institutions in geospatial landslide studies, highlighting China's major contribution to scientific research related to landslide hazards, remote sensing applications, and geospatial technologies.

3.7 Corresponding Author's Countries

The corresponding author country collaboration analysis highlights considerable variations in the extent of international research cooperation in geospatial technology-based landslide studies. The collaboration pattern was assessed using Single Country Publications (SCP) and Multiple Country Publications (MCP), where the MCP ratio represents the percentage of internationally collaborated publications.

Countries such as Australia, Austria, Germany, Iran, and the United Kingdom exhibited high levels of international collaboration. Australia recorded the highest MCP ratio of 72.4%, indicating that nearly three-fourths of its publications involved international research partnerships. Austria (41.9%), Germany (41.2%), Iran (39.3%), and the United Kingdom (39.1%) also demonstrated strong global collaboration patterns, with approximately two out of every five publications being internationally co-authored (Figure 7). These findings reflect the strong integration of these countries into global scientific research networks.

Moderate levels of international collaboration were observed in countries such as the United States (20.7%),

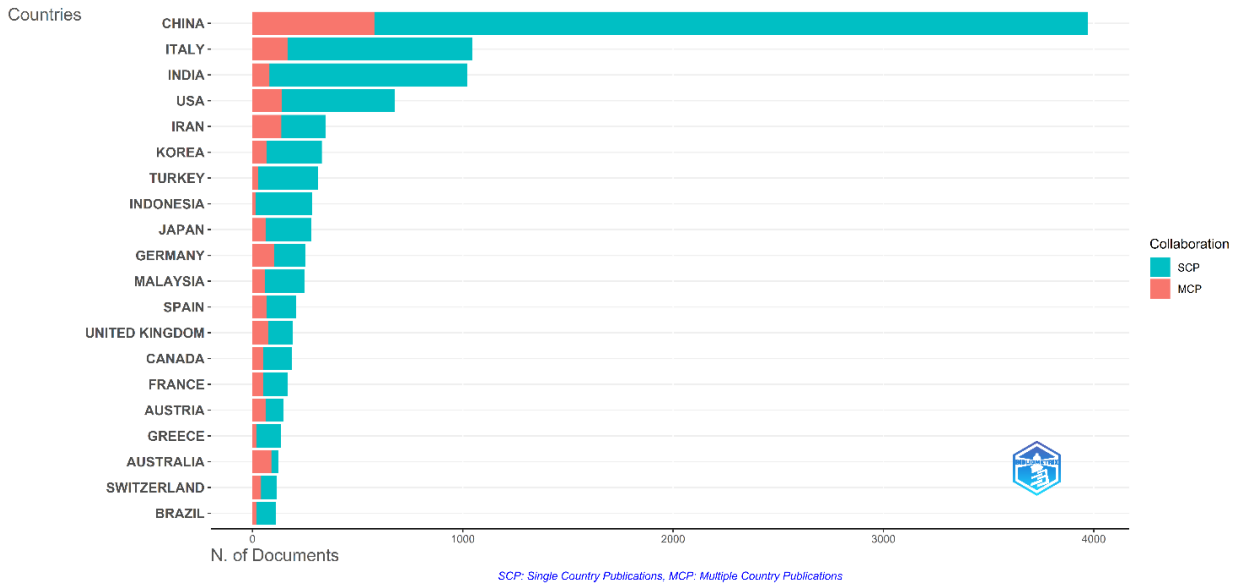


Figure 7: Corresponding Author's Countries

Japan (22.5%), South Korea (20.3%), Malaysia (23.6%), Spain (31.6%), Canada (27.1%), France (30.2%), and Switzerland (35%). These countries maintained a balanced research structure, where domestic research remained dominant while international collaborations also contributed substantially to scientific output. In contrast, countries including Indonesia, India, Turkey, and China showed relatively low MCP ratios, indicating limited international collaboration. Indonesia recorded the lowest MCP ratio at 4.9%, followed by India at 7.9%, Turkey at 9.0%, and China at 14.6%. The low proportion of internationally co-authored publications suggests a stronger reliance on domestic research networks and national scientific infrastructure in these countries.

The collaboration analysis demonstrates significant differences in international research engagement among countries. While some nations strongly depend on global scientific partnerships, others primarily focus on domestic collaborative frameworks. These variations influence knowledge exchange, technological development, and the advancement of geospatial applications in landslide research.

3.8 Countries Scientific Production

The analysis of countries' scientific production reveals the global distribution of research activities related to geospatial technologies in landslide studies. The findings indicate that research output is highly concentrated among a few countries, reflecting differences in technological advancement, research infrastructure, disaster vulnerability, and scientific investment.

China emerged as the leading contributor with 9,905 publications, accounting for the highest share of global scientific production in the field. The dominant contribution of China may be associated with its extensive landslide-prone mountainous regions, rapid technological development, and strong investment in geospatial and disaster-related research. Italy ranked second with 2,307 publications, followed by India with 2,009 publications and the United States with 1,929 publications (Figure 8).

Iran secured the fifth position with 1,004 publications, indicating its growing research engagement in geospatial hazard studies. Japan (780 publications) and South Korea (755 publications) also demonstrated substantial scientific contributions, reflecting the importance of landslide research in tectonically active and mountainous regions of East Asia. Germany contributed 599 publications, while Turkey and Spain produced 595 and 585 publications, respectively.

The results demonstrate that Asian countries dominate the scientific landscape of geospatial technology-based landslide research, particularly China, India, Iran, Japan, and South Korea. The concentration of publications in these regions can be linked to the frequent occurrence of landslide hazards, increasing urbanization in mountainous terrains, and the growing adoption of advanced geospatial technologies. European countries such as Italy, Germany, and Spain also play significant roles through sustained scientific contributions and technological research collaborations.

The country-wise scientific production analysis highlights the uneven global distribution of research activities and emphasizes the leading role of technologically advanced and hazard-prone nations in shaping the development of geospatial applications for landslide studies.

3.9 Most Cited Countries

The citation analysis revealed considerable variation in the scientific impact of countries involved in geospatial landslide research. China recorded the highest total citations (TC) with 95,224 citations, followed by Italy with 41,776 citations and the United States with 32,628 citations. India and Iran contributed 21,890 and 22,536 citations, respectively.

In terms of average article citations, the Netherlands recorded the highest value with an average of 129.1 citations per article. Iran and Malaysia also demonstrated high citation impact, with average article citations of 64.6 and 58.5, respectively. Turkey recorded an average of 58.2 citations per article, while Germany achieved 52.6 citations per article.

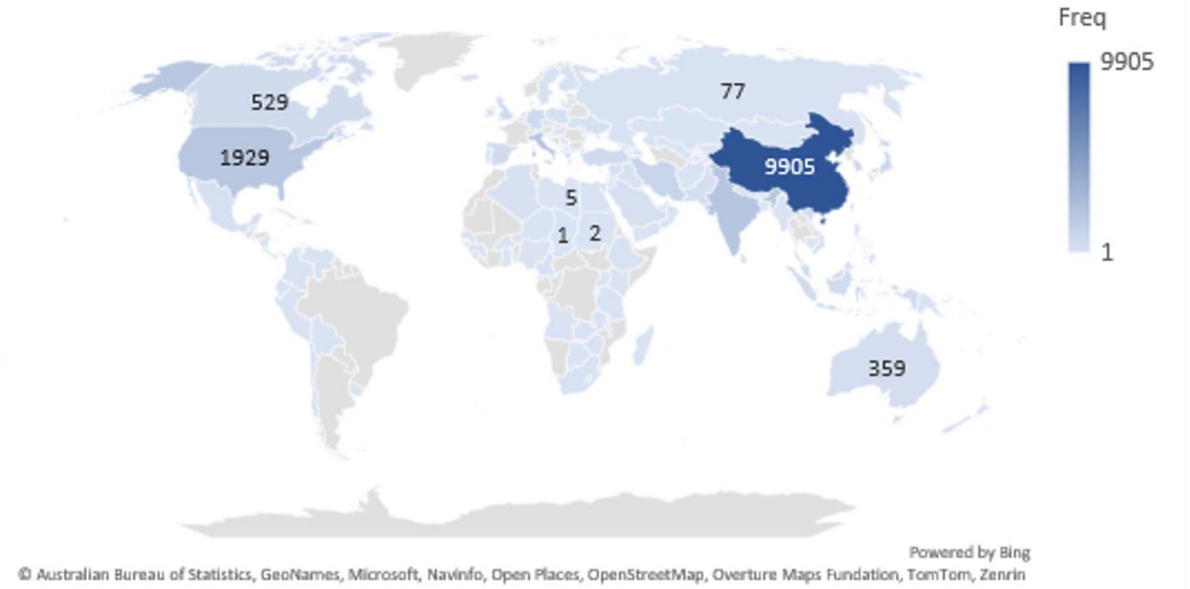


Figure 8: Countries Scientific Production of publication

The United States and South Korea recorded average article citations of 48.2 and 48.7, respectively. Italy achieved an average of 39.9 citations per article, whereas China and India recorded comparatively lower average article citations of 24 and 21.4, respectively. The findings indicate that while some countries produced a high volume of publications, others demonstrated greater citation impact in terms of average citations per article.

3.10 Most Frequent Words

The keyword occurrence analysis provides significant insights into the major research themes and conceptual structure of geospatial technology-based landslide studies. The most frequently occurring keywords reflect the dominant methodologies, analytical approaches, and thematic focus areas within the research domain.

The term "*landslide*" was the most frequent one, with 8,392 hits, highlighting the importance of this term in the field of research. For the technological terms, "*GIS*" (3,751 occurrences) and "*remote sensing*" (3,470 occurrences) were the most prominent geospatial techniques used with landslide investigations. The high frequency of these keywords reflects the wide use of *spatial analysis*, *mapping* and *remote sensing* (*satellite monitoring*) methods in *landslide* studies (Figure 9).

More than 1,734 times, the term "*landslide susceptibility*" was used, reflecting the high research focus on *landslide prone areas*. Likewise, the words "*hazard*" (1,176 times), "*hazards*" (974 times), "*susceptibility*" (940 times), "*risk assessment*" (858 times), and "*hazard assessment*" (704 times) suggest that *hazard evaluation* and *risk management* are significant research foci. They are terms that are gaining in significance for the use of *geospatial technologies* in *disaster preparedness*, as well as in *disaster mitigation planning* and *environmental risk analysis*.



Figure 9: Most Frequent Keywords

The methodological and modelling approaches also had a high representation in the keyword structure. The term "*logistic-regression*" was mentioned 1,320 times and "*frequency ratio*" 949 times. Widespread use of *statistical* and *predictive modelling techniques* for *landslide susceptibility assessment* is shown by the high frequency of these terms. Words like "*model*" (680 times) and "*prediction*" (729 times) further indicate the increasing use of *computational* and *analytical modelling solutions* in the study of *landslides*.

The use of '*geographic information systems*' (1096 times), '*satellite imagery*' (788 times) and '*mapping*' (656 times) indicates the key use of spatial technologies and earth observation data in landslide detection, monitoring and visualisation. These technologies are now indispensable tools for analysing the *terrain*, *hazard zonation* and *spatial decision-making processes*. The term '*disasters*' was used 944 times, showing a general correlation between landslide research and *disaster management studies*. Moreover, the relatively high frequency of the word "*China*" (670 times) indicates that there is significant research interest in *landslide-prone areas* in *China* and its important role in *landslide research*.

The keyword analysis shows that the research field is well focused on landslide susceptibility assessment, hazard modelling, GIS and remote sensing, predictive statistical methods, and *disaster risk management*. These results also illustrate the growing use of sophisticated *geospatial tools* and *models* in modern *landslide science*.

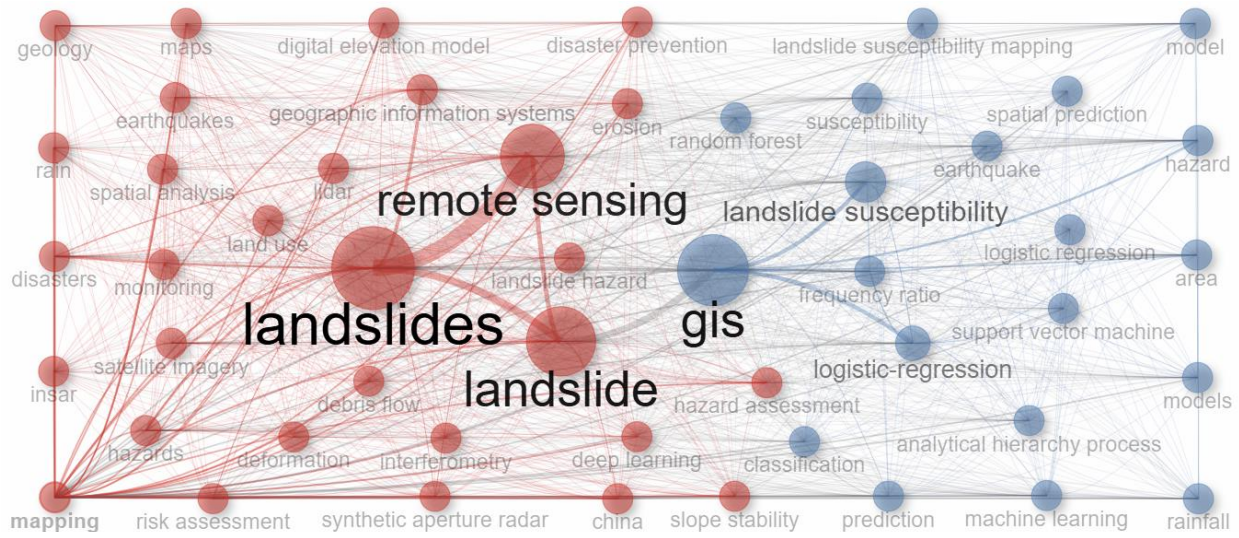


Figure 10: Co-occurrence Network of Keywords

3.11 Trend Topics

Trend analysis in bibliometrics is based on the observation that the vocabulary used in scientific publications reflects the intellectual priorities of a research community at a given point in time. By monitoring the rise and fall of specific terms across successive years, it is possible to detect shifts in research focus, the emergence of new paradigms, and the obsolescence of older topics (Aria & Cuccurullo, 2026). It identifies and visualises the temporal dynamics of key terms within a bibliometric collection (Cobo et al., 2011). By tracking the frequency of keywords (or other terms) across publication years, this tool reveals which topics are gaining momentum, which have reached maturity, and which are declining, providing a clear picture of the evolution of research interests over time (Noyons et al., 1999).

The analysis of trend topics reveals the temporal evolution of major research themes in geospatial technology-based landslide studies between 2000 and 2025. The changing prominence of keywords over time reflects the transition of the research field from fundamental geospatial data processing toward advanced artificial intelligence and machine learning applications in landslide analysis.

In the early 2000s, the research was mainly concerned with fundamental methods of *geospatial data acquisition*, *data processing* and *spatial representation*. *Satellite observatories*, *image sensors*, *digital elevation models (DEM)*, *digital data* and *information retrieval* were among the more common terms that were used during this period. These topics reflected the initial phase of *geospatial landslide research*, and focused on creating and managing *geospatial data sets* for *terrain analyses* and *mapping*. In addition, regional terms like *Central Europe*, *Asia*, *Eurasia*, *Malaysia*, *Apennines* occurred, indicating geographically oriented investigations.

Applied *geospatial analysis* and *hazard related investigations* started to attract more research effort in the mid-2000s and until around 2015. The use of terms like *geographic information systems*, *digital elevation model*, *landslides*, *hazard*, *earthquakes*, and *hazard evaluation* became increasingly prominent. A trend of increasing frequency of these keywords shows the increasing use of *GIS* and *remote sensing technologies* in *landslide susceptibility mapping*, *landslide hazard mapping*, and *landslide disaster risk analysis*. During this period, terms such as prediction and model also became more relevant, reflecting the spread of predictive modelling methods in *landslide studies*.

The advent of *artificial intelligence* and *machine learning techniques* in the late 2010s marked a significant shift in the research paradigm. Other keywords such as *machine learning*, *deep learning*, *random forest*, *learning systems*, and geospatial analysis saw significant increases and became key research themes. The growing importance of these terms signals a transition from traditional *statistical* and *spatial analysis methods* to more sophisticated, *AI-driven* and *data-intensive techniques* with a strong emphasis on *visualization*. The potential of these technologies is growing for use in landslide susceptibility assessment, hazard prediction, automated mapping, and *spatial modelling*, which are increasingly becoming the focus of these applications because of their improved analytical abilities and increased predictive power.

Another period of renewed significance for the term *remote sensing* was the recent one, especially because of combining it with *machine learning* and *deep learning techniques*. *Satellite images*, data from *Earth observation systems* and *AI-based analytical techniques* have greatly enhanced the effectiveness and precision of *landslide detection*, *monitoring*, and *hazard assessment*.

The trend topic analysis shows the evolution of research interest in the field. The evolution from basic *data management* and *geospatial mapping* with *GIS* to more complex *machine learning* and *deep learning techniques* demonstrates the advances in technology and the analytical complexity of modern *landslide studies*. The results also underscore the increasing importance of new research avenues such as *artificial intelligence*, *remote sensing*, and *predictive modelling* in *geospatial landslide research*.

3.12 Co-occurrence Network

The Co-occurrence Network is a powerful tool for mapping the conceptual structure of a research field (Callon et al.,1983). It builds a network where nodes represent terms (keywords, title words, or abstract terms) and edges connect terms that appear together in the same document. The strength of an edge reflects how frequently two terms co-occur, revealing the thematic relationships within a scientific domain (Van Eck & Waltman, 2010).

The all-keywords co-occurrence network analysis provides an overview of the intellectual structure and main thematic areas of geospatial technology-based landslide research. The network shows a clear bipartite organization with two main thematic communities, which suggests that there are two strong methodological and conceptual research strands in the discipline.

The first thematic group had *landslides* and *remote sensing* as its core theme and comprised research works related to *landslide monitoring*, *geohazard analysis*, and *observational studies*. In this cluster, the terms *LiDAR*, *synthetic aperture radar*, *interferometry*, *InSAR*, *deformation*, *satellite imagery* and *digital elevation model* were closely related and used for advanced *remote sensing technologies* for *terrain analysis* and *landslide monitoring* (Figure 10). The presence of the following phrases, *geology*, *erosion*, *land use*, *rain*, and *earthquakes*, also support the idea that emphasis is placed on understanding the physical and environmental conditions that contribute to the occurrence of *landslides*. In this research direction, keywords like *monitoring*, *disaster prevention*, *hazards*, *risk assessment*, and *hazard assessment* illustrate the emphasis on *hazard detection*, *monitoring*, and *disaster mitigation*.

The second big thematic group consisted of *GIS* and *landslide susceptibility*, with studies dealing with *predictive modelling* and *spatial susceptibility assessment* dominating. *Statistical* and *artificial intelligence*-based methods for *susceptibility modelling* are common, as evidenced by the keywords used in the paper, including *logistic regression*, *machine learning*, *random forest*, *support vector machine*, *analytical hierarchy process* and *frequency ratio*. Other terms such as *prediction*, *model*, *spatial prediction*, *classification* and *landslide susceptibility mapping*, once again highlight the increasing relevance of *data-driven predictive analysis* in *landslide research*. This cluster indicates the growing incorporation of *spatial modelling frameworks* into *GIS* and the high level of *computational techniques* into *hazard prediction* and *susceptibility assessment*.

Several bridging concepts were identified which linked the two thematic communities. *Observational monitoring studies* and *predictive susceptibility modelling approaches* were found to have common themes such as *hazard*, *hazard assessment*, *mapping*, *rainfall* and *earthquake*. The common ones show that although there are methodological differences, both thematic directions converge towards the common goal of developing understanding, evaluation and mitigation of *landslide hazards*.

The high number of keywords like *landslides*, *remote sensing*, *GIS*, and *landslide susceptibility* indicates that those are the key intellectual pillars of the research field. Their high centrality scores within the network reflect their important role in the scientific structure and methodology of *geospatial landslide studies*. The *network analysis* further highlights the increasing *methodological diversification* within the field. One thematic direction is mainly dedicated to *observation*, *monitoring*, and *geohazard analysis* through *remote sensing techniques*, while the other is dedicated to *GIS-based susceptibility modelling* and *predictive analytics*, using *machine learning* and *statistical techniques*. This thematic classification is indicative of the evolving *interdisciplinary* nature and complexity of *geospatial landslide studies*.

The *all-keywords network analysis* shows that current research on *landslides* is highly polarised around two research streams with a high level of connection: on one side, research in advanced remote sensing and monitoring technologies, and on the other side, research in GIS-based *predictive susceptibility modelling*. The results also highlight the growing use of *AI*, *machine learning*, and *high-resolution geospatial data* in today's advanced *landslide studies*.

3.13 Thematic Map

The Thematic Map (also known as the Strategic Diagram) is a two-dimensional visualization that classifies research themes according to their centrality (importance within the field) and density (internal coherence of the theme). Originally proposed by Callon et al. (1991) and further developed by Cobo et al. (2011), it provides a comprehensive snapshot of the thematic landscape of a scientific domain.

Following the framework proposed by Aria et al. (2025), publications are not assigned to a single cluster through hard partitioning. Instead, each publication receives a graded membership degree across all thematic clusters, reflecting the multi-thematic nature of scientific documents. The membership score is based on the overlap between a publication's terms and each cluster's vocabulary, weighted by the *PageRank centrality* of shared terms within the cluster. This means that a publication's affiliation with a cluster is stronger when its terms are central (high PageRank) and distinctive (low global frequency) within that cluster's semantic structure (Cobo et al., 2012).

Strategic thematic analysis was used to identify the intellectual structure and developmental nature of research themes related to *landslide studies* using *geospatial technology*. Themes were categorized by their *centrality* and *density*, which reflect the topicality and the degree of maturity of the research topics in the broad field of science. The cluster with *landslide*, *remote sensing* and *geographic information system (GIS)* was the most dominant and well-developed research theme. Such a cluster was identified as the central research area in the field, representing the high degree of linkage between *GIS* and *RS* in *landslide investigations* (Figure 11). The salient importance of these keywords in the thematic content of the text indicates that *geospatial technologies* are the core basis for conducting *landslide susceptibility assessment*, *hazard mapping*, *monitoring* and *spatial analysis*. This cluster is well connected internally and is highly relevant to modern

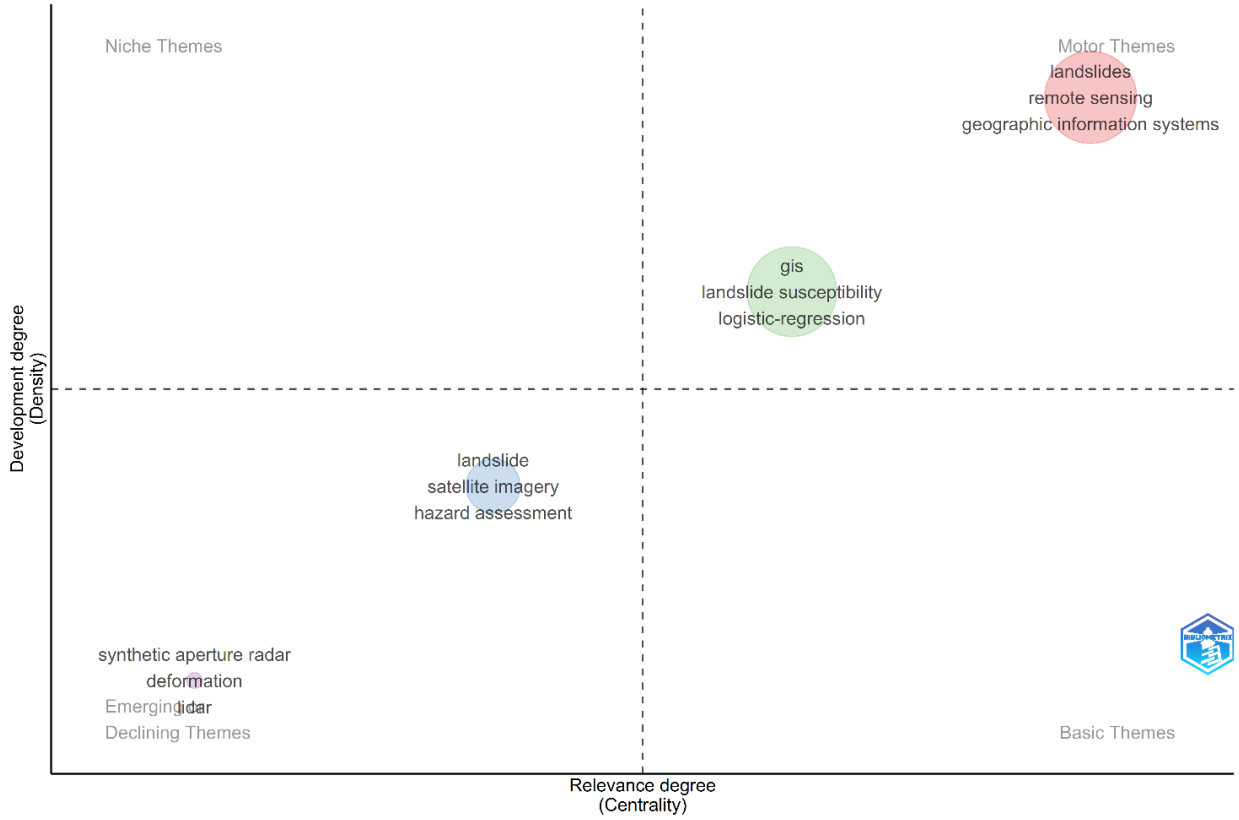


Figure 11: Strategic visualisation of the intellectual structure of research on Topic by plotting the main themes based on two key metrics: centrality and density

landslide research, suggesting that it is a catalyst for current *landslide studies*.

The other important research theme emerged from the cluster that formed around GIS, landslide susceptibility, and *logistic regression*. This theme acknowledges the widespread use of *statistical* and *spatial modelling methods* in *landslide susceptibility analysis*. A high ranking of *logistic regression* in the prominence list reflects that *logistic regression* is a widely used, efficient *predictive modelling* method in *geospatial landslide studies*. The cluster has high development scores, indicating that *susceptibility modelling* based on *GIS analytical frameworks* has reached a well-established and mature stage in the field.

The cluster of *landslide*, *satellite imagery* and *hazard assessments* was represented by a thematic area. This theme focuses on the application of satellite-based Earth observation data for landslide hazard analysis and environmental risk evaluation. This cluster shows the ongoing significance of *satellite imagery* in *terrain analysis*, *hazard zonation*, and *disaster monitoring*. This is a more specialized area of research, but is still relevant for *hazard assessment* and planning for *disaster management*.

A new research theme was found based on the cluster of *synthetic aperture radar*, *deformation*, and *LiDAR*. The presence of these *high-resolution remote sensing technologies* signifies the increasing use of *high-resolution terrain monitoring* and *deformation analysis approaches* in *landslide research*. The trend of *real-time monitoring*, *high-precision spatial analysis*, and *advanced geospatial data collection methods* is highlighted by the growing research focus on *SAR* and *LiDAR technologies*. These kinds of technologies are becoming more relevant because of their ability to enhance the precision of landslide detection and help in early warning systems.

The analysis also shows that some research areas were loosely linked with the thematic network. Themes can be very focused or new ones that are not yet well institutionalized in the research network. Themes such as these indicate the diversity and changing nature of *geospatial landslide research*. The *thematic analysis* reveals that *geospatial landslide research* is mainly focused on *GIS*, *remote sensing*, *landslide susceptibility modelling*, and hazard assessment, and that advanced technologies like InSAR and LiDAR are becoming a key future research direction. The results also show the growing *methodological sophistication* and *technological development* in the study of *landslides* through *geospatial technologies*.

3.14 Thematic Evolution

It tracks how research themes emerge, grow, merge, split, and decline over time (Callon et al.,1991). By dividing the publication timeline into consecutive time slices and performing co-occurrence analysis within each slice, this method reveals the dynamic evolution of a field's conceptual structure. The implementation in Bibliometrix adopts the integrated framework proposed by Aria et al. (2025), which reconceptualises thematic evolution as a fully network-based process where cross-sectional thematic detection, graded document affiliation, and inter-temporal linkage are jointly modelled within a coherent relational architecture (Morris & Van der Veer Martens, 2008).

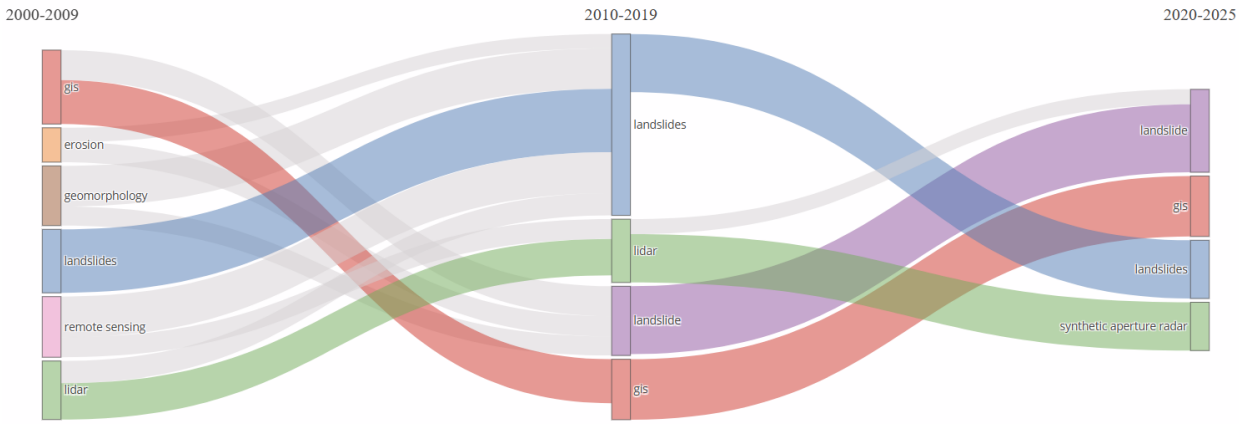


Figure 12: The thematic evolution analysis provides a longitudinal view of research themes that have evolved over time

The *evolution analysis* highlights the time transformation of research themes on *geospatial technology*-based *landslide mapping* and analysis from 2000 to 2025 (Figure 12). The development of keywords illustrates the field's evolution from basic *geomorphological* and *mapping*-based research work to the use of advanced technological tools for *monitoring*, *susceptibility prediction* and *disaster management*.

Between 2000 and 2009, *GIS, erosion, geomorphology, landslides, remotely sensed data, and LiDAR* emerged as the key research themes. This stage was predominantly the initial phase of *landslide studies*, with a focus on *landform processes* and the use of simple *geospatial techniques* for *terrain analysis* and *hazard mapping*. During this period, the incorporation of *spatial technology* in *landslide investigations* is suggested by the growing application of *remote sensing* and *GIS*. Other themes that remain relevant included *engineering geology*, *groundwater*, and *erosion*, which were clearly influenced by traditional *earth science methods* in early *landslide studies*.

During the 2010–2019 period, *landslides, remote sensing, and geographic information systems* emerged as dominant and highly developed research themes. This period is the time when *GIS* and *remote sensing technologies* emerged as the main tools used in *landslide research*. During this time period, *landslide susceptibility* and *hazard assessment* have become increasingly important, which suggests a shift towards *predictive modelling* and *risk analysis*. Also, the interest in researching advanced technologies like *synthetic aperture radar* and *LiDAR*, for example in the field of *terrain deformation analysis* and *monitoring*, rose steadily. *Deformation* has become a research theme in its own right and this only emphasizes the use of *high-tech geospatial monitoring methods* in *landslide research*.

Changes in technology and methods were clearly noticeable in the years 2020-2025. Themes like *landslides*, *remote sensing*, and *disaster generated areas* became most prominent, where it is evident that the research focus has expanded and is more *interdisciplinary*, with the inclusion of a *disaster management perspective* in addition to the *geospatial hazard analysis*. This included *synthetic aperture radar*, *InSAR*, *deformation*, and *logistic regression*, which were increasingly used in *landslide research* during this time. *Predictive analytics*, *machine learning*, and *spatial prediction modelling methods* have become more prominent in *hazard assessment* and *spatial prediction studies*, as illustrated by the growing importance of modelling *landslide susceptibility* and *logistic regression*.

The analysis also highlights the continued relevance of GIS and RS across all study periods, suggesting that they serve as the fundamental technological base of *geospatial landslide research*. Over time, the topics of geomorphology, erosion and engineering geology diminished in importance, and their concepts seem to have been absorbed into more sophisticated *geospatial* or *predictive analytical frameworks*. *Evolution analysis* shows a clear developmental trend in the research field from traditional geomorphological *mapping* to further *remote sensing*, *predictive modelling*, *susceptibility assessment* and *disaster-oriented research*.

3.15 Factorial Analysis

It applies dimensionality reduction techniques to bibliometric data, projecting high-dimensional document-term relationships onto a low-dimensional space for visualization and interpretation (Cuccurullo, et al., 2016). The primary method used is Correspondence Analysis (CA), a multivariate statistical technique particularly suited to analysing contingency tables and categorical data (Benzecri, 1973). The analysis was carried out on the combined *keyword dataset and the first two combined dimensions*, and the first two combined dimensions accounted for a significant amount of the overall variance (Greenacre, 2007), suggesting that the first two dimensions reflect the major differences in theme or content across the research field.

The first dimension is mainly concerned with whether the study is primarily at the *hazard-related* level or at the *predictive modelling* level (Figure 13). Finally, the keywords on one side of the thematic structure were linked to the other side with wide contexts of *hazards* and the traditional *geospatial applications*, and the other side was dominated by advanced *statistical* and *machine learning methods* to assess *hazards susceptibility* and to predict *hazards*. The methodologically evolving pattern of the field from traditional *hazard mapping* to *data-driven analytical modelling*.

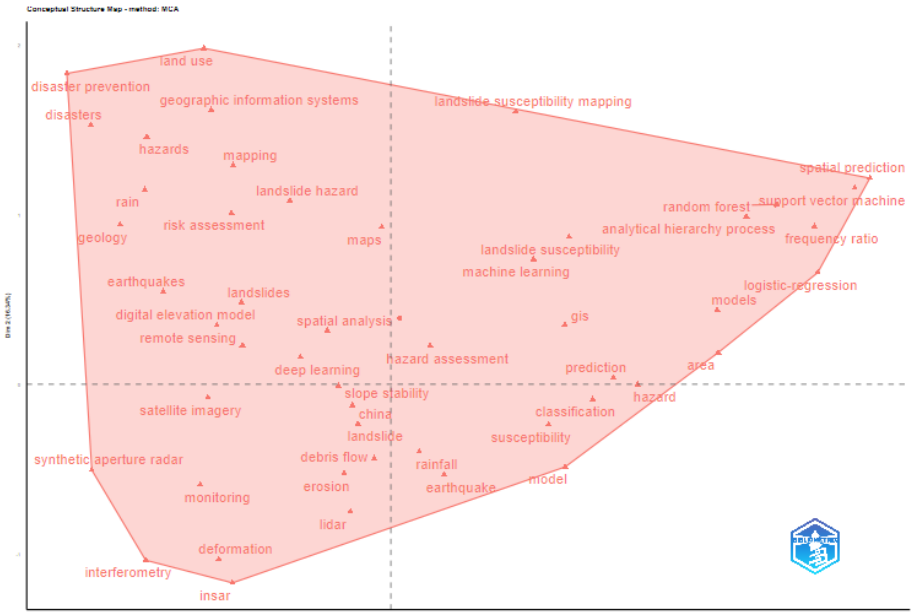


Figure 13: The factorial analysis, performed using Multiple Correspondence Analysis (MCA)

The keywords forming one of the major thematic groups in the analysis include *disaster prevention*, *geographic information systems*, *disaster*, *hazard*, *mapping*, *landslide hazard*, *geology*, *earthquake* and *landslide*. This thematic area is the basic structure of *geospatial hazard studies*, and the application of *GIS* for *disaster management* and *hazard analysis* is quite broad. These terms underscore the importance of *geospatial technologies* in understanding and controlling *natural hazards*.

Other keywords that were extremely common were related to the thematic area of *landslide susceptibility mapping*, *landslide susceptibility*, *machine learning*, *support vector machine*, *analytical hierarchy process*, *logistic regression*, *GIS*, *hazard assessment*, *classification*, and *model*. The cluster is a reflection of the increasing relevance of advanced *predictive modelling techniques* in *landslide studies*. The close link between *machine learning methods* and *susceptibility mapping* shows that *AI* and *statistical modelling methods* are gaining traction to increase *prediction accuracy* and efficiency in *hazard assessment*.

An advanced *remote sensing* and *deformation monitoring technologies* themed area. The emerging importance of *high-resolution geospatial monitoring techniques* in *landslide investigations* is evident from keywords being clustered together, such as *synthetic aperture radar*, *monitoring*, *interferometry*, *deformation*, and *LiDAR*. These technologies are increasingly employed for *terrain deformation analysis*, *surface movement detection* and real-time *hazard monitoring*. Their increasing use in the thematic organization demonstrates the technological progress of *geospatial landslide investigations*.

The analysis also revealed that a thematic area with more general conceptual words, such as landslide, earthquake, model, hazard, and classification, was present. This group supports general analytical and modelling approaches across various *hazard studies*. The use of such general terms suggests that *geospatial hazard research* is *interdisciplinary* and integrative. The *factor analysis* results show that *geospatial landslide research* has four key thematic pathways, including basic *GIS-based hazard studies*, advanced *machine learning* and *susceptibility modelling*, *remote sensing*-based *deformation monitoring*, and generic *hazard modelling approaches*. The results also demonstrate the growing *methodological maturity* of the discipline, such as the recent incorporation of *machine learning*, sophisticated *remote sensing techniques* and *predictive spatial modelling methods* in recent *landslide research*.

3.16 Collaboration Network of Countries

This analysis of the countries demonstrates their scientific networking collaboration in *landslide research* based on *geospatial technology*. The collaboration pattern shows the degree of international co-authorship and indicates key international research centres involved in the field (Aria & Cuccurullo, 2026).

The *U.S.* became one of the major hubs of international cooperation, with close ties to the *United Kingdom*, *Germany*, *France*, *Italy* and *Spain* (Figure 14). The project is a transatlantic partnership that is indicative of the tight coupling of the research systems in *North America* and *Europe* in both *landslide* and *geospatial research*. *China* also established large-scale collaborative networks with the *United States*, *Japan*, *South Korea* and other countries in *Europe*, which shows that *China* is increasingly influential in *geospatial* and *landslide research*. Likewise, *Japan*, *South Korea*, and *India* showed growth in their involvement in the global collaboration network, revealing the growing contribution of *Asian* nations to the research world.

In *Europe*, it was noted that there is a strong collaboration between *Germany*, the *United Kingdom*, *France*, *Italy* and *Spain*. These partnerships facilitate active knowledge exchange and enable methodological and technical developments in *landslide studies*. *Australia* has also established substantial international partnerships with the *U.S.*, *Europe* and *East Asian* countries, given its relatively lower level of research output.

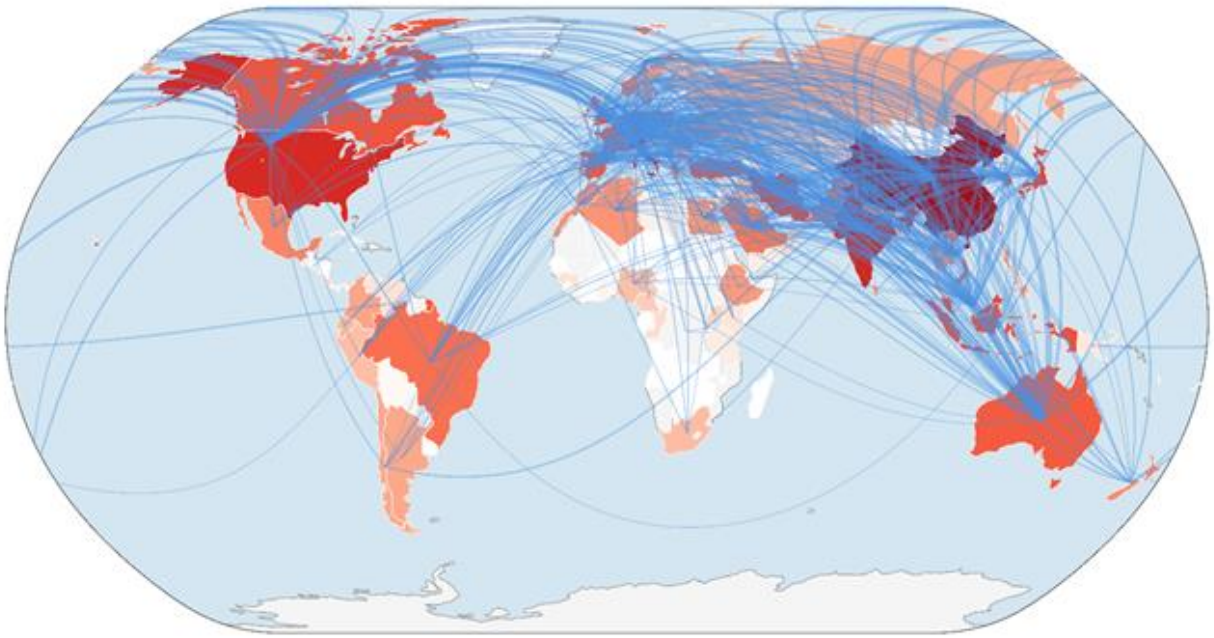


Figure 14: Collaboration Network of Countries

In *South America*, *Brazil* became the primary centre for collaborative research with close ties to the *United States* and *Europe* and *Argentina* and *Chile* continued to do international research collaborations. External scientific partnerships were evident in *Africa,* with *South Africa* primarily cooperating with *Europe* and the *United States*, indicating the significance of external partnerships in the region. The collaboration pattern again shows a *core–periphery organization* of the global scientific network with important nodes, like the *United States*, *China* and the countries of *Western Europe*, that interact with the countries with lower research activity. As a whole, it shows that *geospatial landslide research* is highly international and collaborative, fostering an exchange of knowledge and further developments of *geospatial applications* for *landslide research*.

4. Conclusion

The purpose of this study is to provide a comprehensive overview of worldwide research on geospatial technologies for landslides during the period 2000-2025 through a bibliometric approach. The results show a considerable increase in published research, which is related to the increasing significance of geospatial technologies in landslide hazard assessment, monitoring, susceptibility mapping and disaster management. The field has developed gradually from traditional geomorphological methods to new data-driven and AI-based approaches.

The top five countries identified in the country-wise analysis are both technologically advanced countries (China, Italy, India, and the United States) and landslide-prone countries that are involved in this sector. However, collaboration analysis showed that there was high international collaboration, especially between the United States, Western countries, and the emerging research hubs of Asia like China, Japan and South Korea, but there were still differences in research networking around the world.

Keyword and thematic analyses indicated that GIS, remote sensing, landslide susceptibility, hazard assessment, and logistic regression are the main pillars of the field, and technologies like machine learning, deep learning, SAR, InSAR, and LiDAR are gaining traction. These advances improve the accuracy and efficiency of landslide identification, observation, and predictive modelling.

Thematic evolution and network analysis indicated a methodological transition from simple GIS and geomorphological studies to predictive modelling, artificial intelligence, more sophisticated remote sensing, and analytical frameworks with a focus on disasters. Two key interrelated research streams have been identified: remote sensing-based monitoring and GIS-based susceptibility modelling with statistical and machine learning methods.

The study emphasizes the increasing importance of geospatial technologies in the field of landslide research and disaster risk reduction. There is a need to focus on integrating multi-source geospatial datasets, real-time monitoring systems, machine learning techniques, and international collaboration in the future to improve landslide prediction and disaster resilience. The results are useful for researchers, policymakers, disaster management institutions, and the geospatial sector.

4.1 Limitation of the Study

Due to the resources indexed by Scopus and Web of Science, other sources and grey literature may not be included in the study. It only includes publications that have been written in English, which may mean that studies from non-English-speaking areas may be missing. The data is limited to publications through 2025, and as such, some recent publications (especially after 2025) may not be indexed. Analysis is based on bibliographic metadata (author keywords and Keywords Plus) and may not necessarily reflect the detailed content of individual studies. Variations in indexing, search terms and citation methods might also impact the outcomes on themes and

collaboration. Moreover, since this study is quantitative bibliometric, it is not able to evaluate the theoretical or methodological quality of the publications included in the study.

AI Declaration

The authors declare that ChatGPT by OpenAI was used only for grammar correction and language editing during the preparation of the manuscript. The scientific content, analysis, interpretation, and conclusions of the study were developed entirely by the authors.

Authors' Contributions

AT: Conceptualization, data curation, investigation, formal analysis, validation, writing – original draft preparation, and editing. **HKPS**: Methodology, visualization, review and editing, validation, all authors read and approved the final manuscript.

Data Availability Statement

This study is based on bibliometric data retrieved from the Scopus and Web of Science databases. Due to licensing restrictions of the databases, the full datasets cannot be shared publicly; however, processed data and analytical outputs used in the study are available from the corresponding author upon reasonable request.

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