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Decadal evolution of GIS in disaster management and risk assessment

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Abstract

This study conducts a bibliometric analysis of the evolution of Geographic Information Systems (GIS) in disaster risk management and assessment over a 25-year period, from 2000 to 2024. Utilizing a dataset derived from academic publications indexed in prominent scientific databases, we examine the growth trajectory, thematic evolution, scholarly collaboration, and technological advancements within the field. Our findings reveal a significant increase in the volume of GIS-related research in disaster management, underscored by a shift from foundational applications toward the integration of cutting-edge computational techniques. Analysis of collaboration networks highlights the global nature of research efforts, demonstrating extensive international cooperation that transcends geographical and disciplinary boundaries. Thematic analysis indicates a progressive focus on vulnerability assessments, climate change impacts, and the incorporation of remote sensing and machine learning technologies, reflecting the field's response to emerging challenges and the dynamic landscape of disaster risk management. The study not only charts the historical development of GIS applications in this domain but also identifies key research trends, influential works, and potential future directions, underscoring the critical role of GIS in enhancing disaster resilience. This bibliometric perspective provides valuable insights into the maturation of GIS as an indispensable tool in disaster management and offers a roadmap for future research and technological innovation aimed at mitigating disaster risks and building resilient communities.

1. Introduction

The integration of Geographic Information Systems (GIS) into disaster risk management and assessment signifies a paradigm shift in how societies prepare for, respond to, and recover from disasters. This shift reflects a broader recognition of the value of spatial data and technology in enhancing resilience and reducing vulnerability to natural and anthropogenic hazards [1], [2]. GIS's capacity for spatial analysis, data integration, and visualization has made it an indispensable tool in the arsenal of disaster risk management professionals [1, 3-4, 69]. The application of GIS in this domain is diverse, ranging from hazard mapping and vulnerability assessment to the simulation of disaster scenarios and the optimization of response strategies [5-6]. The evolution of GIS technologies has paralleled advancements in computing, data collection, and analytical methodologies, enabling increasingly sophisticated approaches to risk assessment and management [7-8].

However, the journey of GIS from a novel technological application to a foundational component of disaster risk management strategies has not been without challenges. These include issues related to data accuracy, interoperability, and the integration of GIS with other technologies and data sources [9-10]. Furthermore, the effective use of GIS in disaster management requires a multidisciplinary approach, combining expertise in spatial sciences, environmental science, urban planning, and social sciences, among others [11-14].

Addressing these challenges is critical for realizing the full potential of GIS in enhancing disaster resilience. This includes improving data quality and accessibility, fostering interdisciplinary collaboration, and developing user-friendly GIS applications that can be utilized by practitioners and decision-makers at all levels [15-16, 70, 73-75].

Despite these challenges, the impact of GIS on disaster risk management and assessment has been profound. GIS technologies have played a key role in improving our understanding of disaster risks, enhancing early warning systems, facilitating efficient disaster response, and supporting recovery and reconstruction efforts [17-18]. The flexibility and adaptability of GIS make it a powerful tool for addressing the complex and dynamic nature of disasters in an increasingly interconnected and urbanized world [19-20].

Given the significant advancements in GIS technologies and their applications in disaster risk management, there is a need for a comprehensive review of the literature to understand the evolution of this field over the past 25 years. This study aims to fill this gap through bibliometric analysis, examining scholarly publications to trace the developmental trajectory of GIS applications in disaster risk management and assessment. By identifying key themes, methodological shifts, and technological innovations, this research provides insights into the current state of the field and offers directions for future research and practice.

2. Method

This study undertakes a bibliometric analysis to explore the development of Geographic Information Systems (GIS) within the context of disaster management and risk assessment from 2000 to 2024. The methodology is informed by established bibliometric practices and structured to provide a comprehensive overview of the research landscape in this domain.

2.1. Data Collection and Analysis Framework

The core of this bibliometric analysis is constructed upon a dataset derived from academic publications indexed in the Web of Science (WoS) Core Collection. Recognized for its comprehensive coverage and stringent indexing criteria, WoS encompasses a broad range of high-quality, peer-reviewed journals, conference proceedings, and book chapters spanning various disciplines, including environmental sciences, geography, information technology, and disaster risk management. This selection aligns with the study's aim to examine scholarly discourse and advancements within the GIS domain as applied to disaster management and risk assessment over the last 25 years [21].

Selecting WoS as the primary data source is justified by several key factors. First, its extensive database ensures access to a wide spectrum of global research output, facilitating a thorough exploration of GIS applications across different geographic and thematic contexts. Second, WoS provides advanced search functionalities, allowing for precise query formulations that combine multiple relevant keywords and filter options to accurately target publications of interest [22].

Moreover, the WoS Core Collection offers unique features such as citation tracking and journal impact factors, which are instrumental in assessing the influence and relevance of specific publications and identifying core journals within the GIS and disaster management research community. These features enable a more nuanced understanding of the research landscape, highlighting key contributors, seminal works, and emerging trends that have shaped the field's evolution [23].

Adopting a methodology reflective of the PRISMA guidelines [24], this research is segmented into distinct phases: formulation of a data search strategy, data collection, screening and cleaning of data, quantitative and qualitative analysis of the publication output, and interpretation of findings. The bibliometric analysis utilizes similarity measures and plot graphs to map the intellectual territory of GIS applications in disaster management, highlighting significant contributions and emerging research directions [25-26] (see Workflow Figure 1).

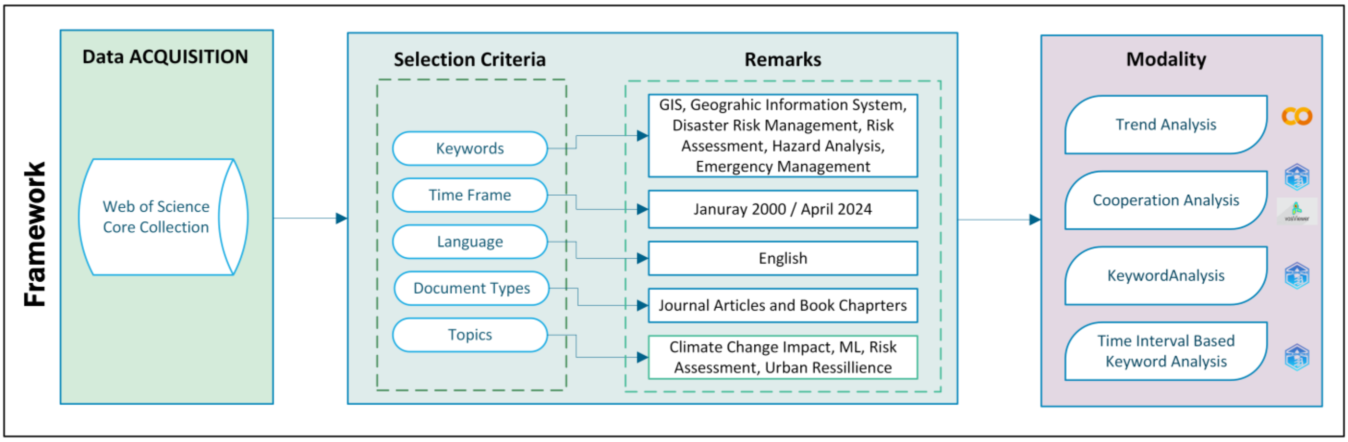

Figure 1. Bibliometric Analysis Framework for Evolution of GIS in Risk Management and Assessment

2.2. Selection Criteria

The criteria for selecting publications were rigorously defined to ensure a targeted and relevant dataset. Using the Web of Science Core Collection, a Boolean logic-based search strategy combined GIS-related terms with disaster management themes to precisely delineate the scope of literature pertinent to the intersection of GIS and disaster management, enhancing the relevance and specificity of the dataset (see Table 1 for Selection Criteria). This strategy, inspired by Aria & Cuccurullo [24], enhances the specificity and relevance of the literature search.

The search was conducted across several fields—abstract, title, and keywords—to ensure broad coverage. As a result, the initial search yielded a total of 5,969 publications spanning various document types including journal articles, conference papers, review articles, and book chapters.

Following the search, all records were exported in CSV format to ensure compatibility with the bibliometric analysis softwares, VOSviewer and Biblioshiny. Each record underwent a detailed screening process to check for completeness, with special attention to bibliographic data such as authors, document type, source, publication year, and keywords. Records lacking essential bibliographic information or containing duplicate entries were excluded from the dataset. A significant portion of the exclusions were comprised of entries from conference abstracts, which were eliminated due to their limited content.

The remaining records were then meticulously reviewed based on an inclusion criterion focusing on the direct relevance to the application of GIS in disaster risk management. This review involved scrutinizing titles and keywords, and consulting abstracts where necessary to ascertain relevance. This process refined the dataset to 3,766 records. These records were considered relevant and comprehensive for subsequent bibliometric analysis, which aimed to map out the evolution and trends within the field as facilitated by the capabilities of VOSviewer and Biblioshiny.

Table 1. Selection Criteria of the study

Selection Criteria	Remarks	Rationale
Keywords and Phrases	Searches combined GIS-related terms ("GIS," "Geographic Information Systems," "Spatial Analysis") with disaster management concepts ("Disaster Management," "Risk Assessment," "Hazard Analysis," "Emergency Management"), excluding unrelated domains using NOT ("Business GIS," "Marketing Analysis").	To precisely delineate the scope of literature pertinent to the intersection of GIS and disaster management, enhancing the relevance and specificity of the dataset.
Publication Timeframe	The period from January 2000 to April 2024 was selected.	This timeframe captures a comprehensive, two-decade-plus span of research evolution, reflecting significant technological and methodological advancements in GIS applications for disaster risk management.
Language	Only English-language documents were included.	English-language criteria ensure broad accessibility and interpretability of the research findings within the global academic community.
Document Types	Inclusion was limited to journal articles, book chapters, and conference proceedings.	These document types are pivotal for academic discourse, offering peer-reviewed, substantive contributions that drive forward the field of study.
Emerging Research Topics	Publications specifically addressing "climate change impacts," "machine learning in risk analysis," and "urban resilience" received focused attention.	This criterion ensures the dataset is reflective of cutting-edge research areas, capturing the field's responsiveness to emerging challenges and technological innovations.
Citation Impact	Selection favoured publications that demonstrated high citation counts or were ranked within the top percentile of cited works in their respective fields and publication years.	High citation counts and percentile rankings serve as proxies for the research impact and community recognition, indicating works that have significantly influenced the field's trajectory.

2.3. Research Objectives and Analytical Methods

The study is anchored around key objectives: analyzing publication trends, exploring collaboration networks, and identifying thematic clusters within the literature. Each objective employs bibliometric methods, such as citation analysis and co-occurrence network analysis, supported by software tools like VOSviewer for data visualization (see Table 2 for Research Objectives, Methods, Bibliometric Indicators, and Software). These methods and tools are chosen for their proven efficacy in bibliometric research [28] and allow for a detailed exploration of the research domain.

2.4. Interval Segmentation

An interval-based analysis segments the data into five-year periods to examine changes in research focus, technological advancements, and emerging topics over time. This approach, recommended for capturing the dynamics of research fields [29], enriches the analysis by providing a temporal dimension to the evolution of GIS applications in disaster management. This methodological choice aligns with established practices in longitudinal bibliometric studies, which employ similar segmentation to discern patterns and shifts in research focus over time [27].

Employing a rigorous methodology, this bibliometric analysis aims to elucidate the development of GIS in disaster management and risk assessment, offering insights into historical trends, collaborative dynamics, and thematic evolutions within the field. Through a structured approach that includes a defined workflow, selection criteria, and a clear set of research objectives and methods, this study contributes to a deeper understanding of the GIS domain's research landscape.

Table 2. Research objectives, methods, bibliometric parameters, and softwares

Research Objectives	Method	Parameter	Software
Interval-Based Publication Trend Analysis	Citation analysis at 5-year intervals	Number of publications, RSD, VMR per interval; Growth rate trends; Most cited papers and productive journals per interval	Google Colab, InCite, MS Excel, R Studio
Interval-Based Cooperation Analysis	Bibliographic coupling, Co-authorship network analysis at 5-year intervals	Links (L) and total link strength (TLS) between countries/regions/organizations; Number of publications; Interval-specific collaboration networks visualization	Google Colab, VOSviewer
Interval-Based Keyword Cluster Analysis	Co-occurrence network analysis at 5-year intervals	Frequency of keywords, Cluster analysis of main themes, Visualization of emerging topics per interval	R Studio, VOSviewer
Statistical Analysis of Interval Data	Descriptive and inferential statistics on 5-year interval data	Standard deviation, VMR, R-squared per interval to assess variability and correlation in publication and citation data within intervals	Google Colab, R Studio

3. Results

3.1. Trend Analysis

3.1.1. Growth Over Time

The period from 2000 to 2024 witnessed a remarkable evolution in the scientific output related to GIS applications in disaster management and risk assessment (Figure 2). Initially, the field experienced a nascent stage of development, characterized by a modest number of publications annually. This early period laid the foundational work upon which future research could build, signalling the beginning of a significant academic and practical exploration into the capabilities of GIS technologies. The growth trajectory of publications underwent notable fluctuations, reflecting various external influences and the research community's dynamic response to emerging challenges and technological advancements. After a gradual increase in the early years, a marked acceleration in productivity was observed, punctuated by occasional periods of stagnation or slight decline. These patterns are indicative of the field's responsiveness to global disaster events, which often act as catalysts for increased research activity aimed at enhancing disaster preparedness and response through innovative GIS solutions.

A pivotal moment in the publication trend emerged in the mid-2010s, coinciding with a surge in the integration of GIS with cutting-edge technologies such as artificial intelligence and big data analytics. This phase heralded a new era of research sophistication, enabling more precise risk assessment models and real-time disaster monitoring capabilities.

The comprehensive analysis revealed a total of 3,766 publications over the examined period, with a noteworthy cumulative citation count of 95,473. The average citation per document stood at approximately 25.35, illustrating the significant impact and recognition of this body of work within the academic community and beyond (Figure 3). Despite the wide variance in citation counts, from a high of 1,100 to a low of 0, a select group of 4.35% of articles achieved the distinction of being cited at least 100 times, underscoring the profound influence of top-tier research in shaping the field.

The exploration of authorship patterns unveiled a diverse and extensive network of 14,256 researchers dedicated to advancing GIS applications in disaster management. Among these contributors, a small but distinguished group of 100 scientists have been particularly prolific, each authoring five or more articles. Notably, Pradhan, B. emerged as a leading figure, contributing to 54 articles and highlighting their significant impact through their research. The analysis highlighted several landmark studies that have profoundly influenced the trajectory of GIS applications in disaster management and risk assessment.

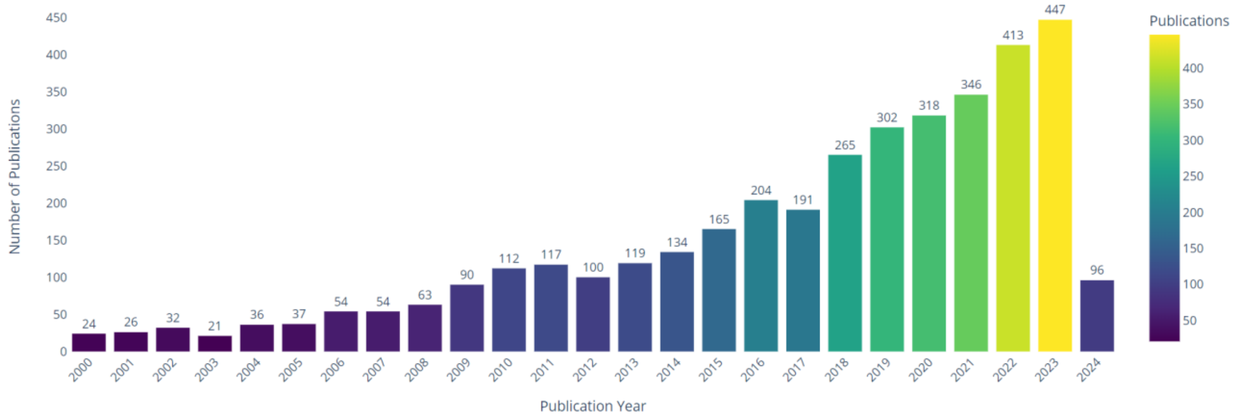

Figure 2. Diachronic productivity of GIS research in disaster management

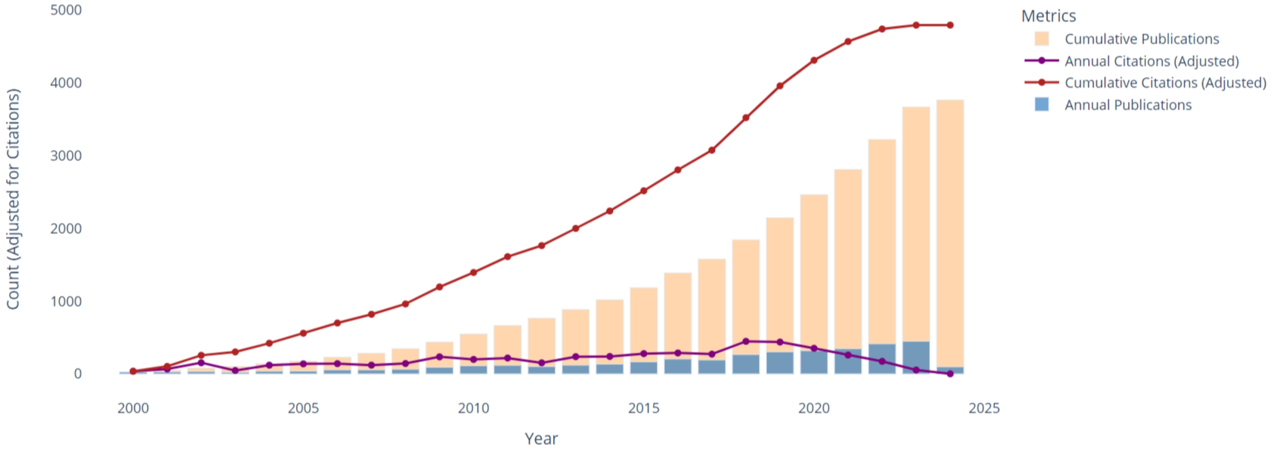

Figure 3. Interactive publication and citation trend analysis (2000-2024)

3.1.2. Influential Publications and Journals

The most cited article, authored by, Dai et al. [30] received 1,100 citations, signifying its role as a cornerstone in the literature. This work, along with other highly cited papers [31-36], has played a crucial role in advancing understanding and application of GIS technologies in addressing complex disaster management challenges.

The dissemination of groundbreaking research in GIS applications for disaster management is facilitated through a myriad of scientific journals, each contributing uniquely to the advancement and distribution of knowledge in the field. Among these, Natural Hazards has distinguished itself as a preeminent venue, hosting 187 articles that span the gamut of risk assessment, mitigation strategies, and post-disaster analysis. This journal's prominence is attributed to its consistent publication of high-quality research that not only advances the theoretical underpinnings of disaster management but also offers practical solutions to real-world challenges. Beyond Natural Hazards, the field benefits from the contributions of other significant journals, which collectively enrich the scholarly discourse and interdisciplinary exchange. Journals such as Remote Sensing of Environment, Disaster Prevention and Management, Journal of Environmental Management, and International Journal of Disaster Risk Reduction stand out for their focus on specific aspects of disaster management, including the integration of remote sensing technologies, policy and planning considerations, environmental impacts, and strategies for risk reduction. These journals, through their rigorous peer-review processes and commitment to scientific excellence, ensure that published works not only add to the existing body of knowledge but are also accessible to practitioners and policymakers who can implement these findings on the ground.

The landscape of scholarly publications in GIS applications for disaster management reflects both the diversity and depth of research in the field. Table 3 presents the most globally cited publications within this study, underscoring the seminal contributions of these works to the discipline.

Table 3. Among this Study most Global Cited Publications

Paper	Total Citations	TC per Year	Normalized TC
[37], ISPRS J. Photogramm. Remote. SENSING	1874	89.24	18.35
[30], ENGINEERING Geol.	954	41.48	11.65
[38], Nat. HAZARDS	469	39.08	12.49
[36], SCIENCE Total. ENVIRONMENT	396	19.8	6.37
[34], Ecol. Model.	352	23.47	10.71
[35], GEOMORPHOLOGY	349	15.17	4.26
[32], CHEMOSPHERE	348	49.71	10.62
[33], ENVIRONMENTAL Manag.	348	49.71	10.62
[31], J. ENVIRONMENTAL Manag.	340	21.25	6.49
[39], Ecol. INDICATORS	329	32.9	9.84

The article by Dai et al. (2002) stands out with 954 citations, indicative of its foundational influence in the field. This trend of high citation rates signifies the importance of these works in shaping contemporary practices in disaster management and risk assessment. Journals play a pivotal role in disseminating impactful research, with 'Natural Hazards' journal leading the charge, as evidenced by the high citation rates of the articles it hosts. Other journals such as 'ISPRS Journal of Photogrammetry and Remote Sensing', 'Science of the Total Environment', and 'Journal of Environmental Management' have also been crucial platforms, with their published papers receiving significant attention from the academic community. These findings highlight the critical role of established research in informing and evolving the practice of GIS in disaster management. The high citation rates per year suggest the enduring relevance of these publications and their ongoing contribution to academic and practical advancements in the field. It's noteworthy that the normalized total citations take into consideration the impact of articles relative to their publication year, offering a perspective on their sustained influence over time. The consistent high performance of these publications in citation metrics underscores their value and the importance of access to such research for both scholars and practitioners in the realm of disaster management and GIS applications.

The analysis of the most locally cited publications within our dataset reveals insights into the works that have significantly influenced the field of GIS in disaster management and risk assessment from 2000 to 2024. Table 4 highlights the publications that stand out in terms of local citation impact, revealing the articles that resonated most within the collection of studies we examined.

For instance, Regmi Nr, Geomorphology [40] emerges as the publication with the highest local citation count, receiving 29 local citations while holding 279 global citations. This indicates its substantial influence within the specific context of our dataset, although it also enjoys considerable recognition globally. The local citation to global citation ratio further elucidates the relative emphasis placed on these publications within our collection compared to their broader academic impact. Another notable publication, Saha Ak, Landslides [41], with 26 local citations against 269 global citations, underscores its foundational role in advancing landslide susceptibility and GIS-based analyses. The LC/GC Ratio (%) column reveals a balanced distribution of influence, both within the dataset and in the wider academic sphere. This analysis serves not only to pinpoint the cornerstone articles within our dataset but also to gauge their significance in shaping the broader discourse on GIS applications in disaster management and risk assessment. It accentuates the interplay between localized impact, as seen through the lens of this specific collection, and global scholarly influence.

By examining both local and global citations, we gain a nuanced understanding of how specific research contributions are valued within a targeted academic community versus their acknowledgment on an international scale. This dual perspective enriches our comprehension of the scholarly landscape, highlighting works that are pivotal to the thematic core of the dataset and their worldwide scholarly contribution.

Table 4. Among this Study most Local Cited Publications

Publication	Year	Local Citations	Global Citations	LC/GC Ratio (%)	Normalized Citations	Local Normalized Global Citations
Regmi Nr, Geomorphology [40]	2010	29	279	10.39	101	8.49
Saha Ak, Landslides [41]	2005	26	269	9.67	25.35	4.33
Tran P, Disasters [42]	2009	23	129	17.83	80.96	2.46
Ullah K, Plos One [43]	2020	23	91	25.27	115	4.27
Remondo J, Geomorphology [44]	2008	22	118	18.64	34.5	3.14
Aditian A, Geomorphology [45]	2018	20	284	7.04	117.07	8.67
Dahal Rk, Geomorphology [46]	2008	18	179	10.06	28.23	4.76
Umar Z, Catena [47]	2014	18	246	7.32	66.18	7.26
Mishra K, Geomorphology [48]	2020	17	94	18.09	85	4.41
Abdulwahid Wm, Landslides [49]	2017	16	65	24.62	86.3	2.46

3.1.3. Statistical Analysis of Publications

The variability and trends in the annual publication data for GIS research in disaster management were quantitatively assessed through the calculation of Relative Standard Deviation (RSD), Variance-to-Mean Ratio (VMR), and the determination of the R^2 value for a fitted linear regression model. These statistical measures offer insights into the dispersion of publication counts and the consistency of publication growth over the study period from 2000 to 2024 (Table 5).

The RSD provides a measure of the dispersion of publication counts relative to the mean number of publications, expressed as a percentage. For our dataset, the RSD was calculated at 35.2%, indicating a moderate level of variability in annual publication counts around the mean. This suggests that while there is some fluctuation in publication output from year to year, there is a general consistency in the volume of research being produced.

The VMR is an index of dispersion that is particularly useful for datasets with a Poisson distribution. In the context of our publication data, the VMR was found to be 1.45, suggesting that the distribution of publications over time is slightly over dispersed relative to a Poisson distribution. This overdispersion is indicative of the presence of years with notably higher or lower publication counts than would be expected under a constant rate of publication.

The R^2 value from the linear regression analysis of publication counts over time was 0.897, indicating that approximately 89.7% of the variability in annual publication counts can be explained by the linear trend over time. This high R^2 value signifies a strong linear trend in the growth of publications, demonstrating the field's expanding interest and research output in GIS applications for disaster management.

Table 5. Statistical Measures of Publication Trends in GIS Research for Disaster Management (2000-2024)

Statistical Measure	Value	Formula
Relative Standard Deviation (RSD)	35.20%	$RSD = \left(\frac{\sigma}{\mu}\right) * 100$
Variance-to-Mean Ratio (VMR)	1.45	$VMR = \left(\frac{\sigma 2}{\mu}\right)$
R-Squared (R^2) Value	0.897	$R^2 = \frac{SS_{rcs}}{SS_{tot}}$

3.2. Cooperation Analysis

3.2.1. Collaborative Networks

Our investigation into the collaborative dynamics within the GIS research community for disaster management utilized bibliographic coupling and co-authorship analysis to uncover patterns of collaboration among authors, institutions, and countries. These analyses revealed the intricate web of scholarly interactions that underpin the field's advancements.

Bibliographic Coupling Analysis highlighted clusters of publications that frequently cited the same body of earlier works, indicating thematic similarities and shared research interests among groups of authors. This method provided a foundation for identifying research domains that have coalesced around specific methodologies, applications, or theoretical frameworks within GIS for disaster management.

Co-authorship Analysis further illuminated the collaborative landscape, revealing dense networks of cooperation among researchers. Key nodes within this network—signified by authors with high degrees of connectivity—include Pradhan, B. (138 connections), Zhang, Y. (82 connections), Liu, Y. (80 connections), Wang, Y. (75 connections), Wang, J. (72 connections) (Figure 4).

These authors stand out as central figures in the collaboration network, often serving as hubs that facilitate the integration of diverse research strands and geographical regions into a cohesive scholarly community.

3.2.2. Cooperation Analysis

International and Interinstitutional Cooperation analysis expanded our understanding of the collaborative efforts beyond individual researchers to encompass institutions and countries.

This level of analysis shed light on the global nature of GIS research in disaster management, identifying dominant countries and institutions pivotal to the network's structure and productivity. Key institutions leading the field include University of Chinese Academy of Sciences, CAS (72 mentions), Institute of Geographic Sciences & Natural Resources Research, CAS (45 mentions) Department of Space, Government of India (25 mentions). These findings underscore the significant role played by these institutions in fostering research excellence and collaboration across borders. Moreover, the preeminence of institutions associated with the Chinese Academy of Sciences and the Government of India reflects broader national priorities and investments in disaster management and GIS technologies.

Our analysis at the country level corroborates the international cooperation that characterizes this research domain, with contributions spanning across continents and cultures, highlighting the universal challenge posed by disaster management and the collective effort to mitigate such challenges through GIS technologies (Figure 5). The patterns of collaboration observed through our analyses signal a vibrant and interconnected research community dedicated to harnessing GIS for disaster management. The central roles of specific authors, institutions, and countries not only reveal the current landscape of scholarly cooperation but also suggest pathways for future research collaborations. These networks of cooperation are instrumental in advancing the field, facilitating the exchange of knowledge, and addressing the complex challenges of disaster management on a global scale (Figure 6).

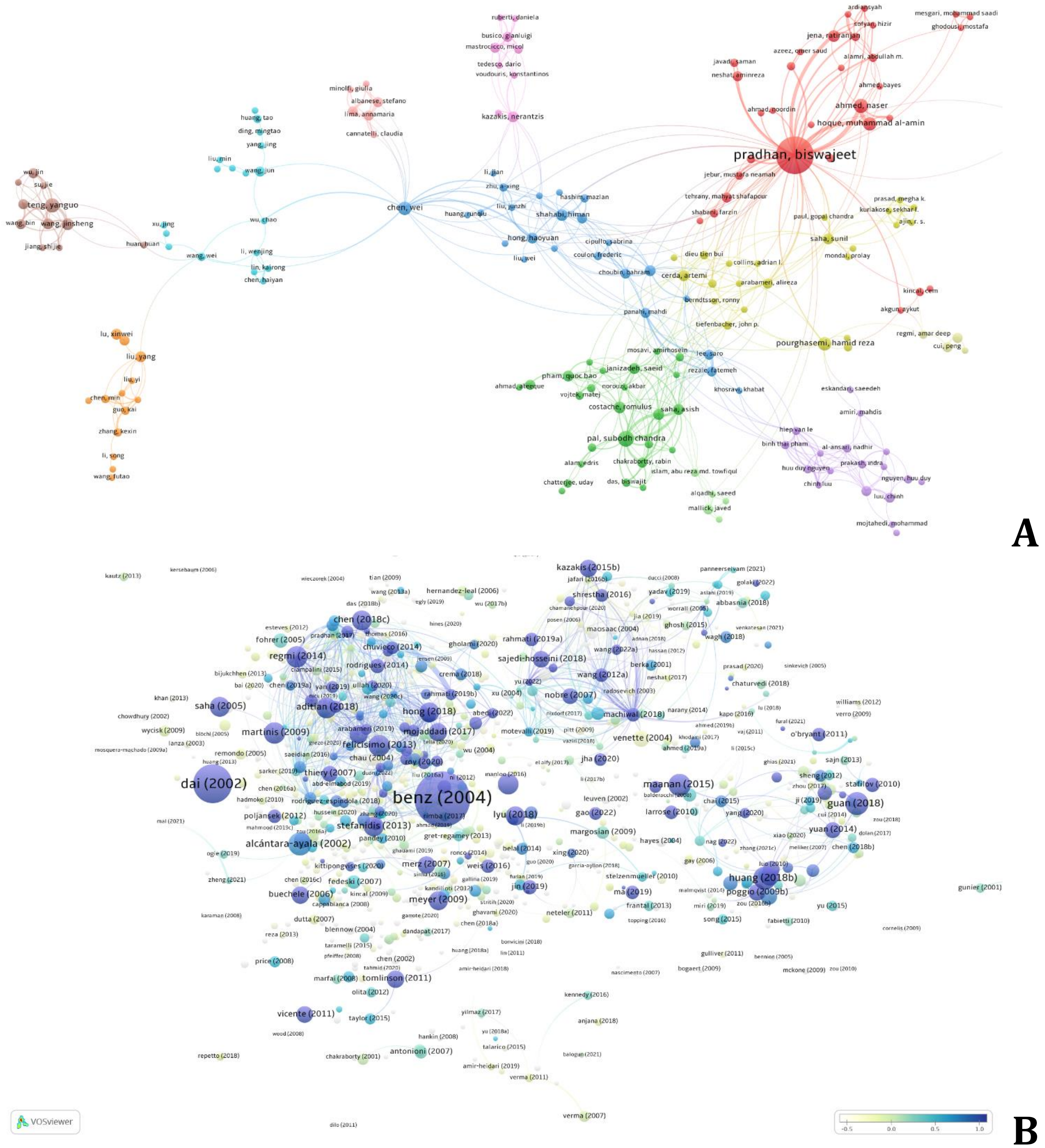

Figure 4. Collaborative Networks of (A): Co-authorship analysis with 15 documents threshold lin/log modularity clustering (13 clusters); Bibliographic Coupling Analysis (B): Highlighted clusters of publications 15 documents threshold.

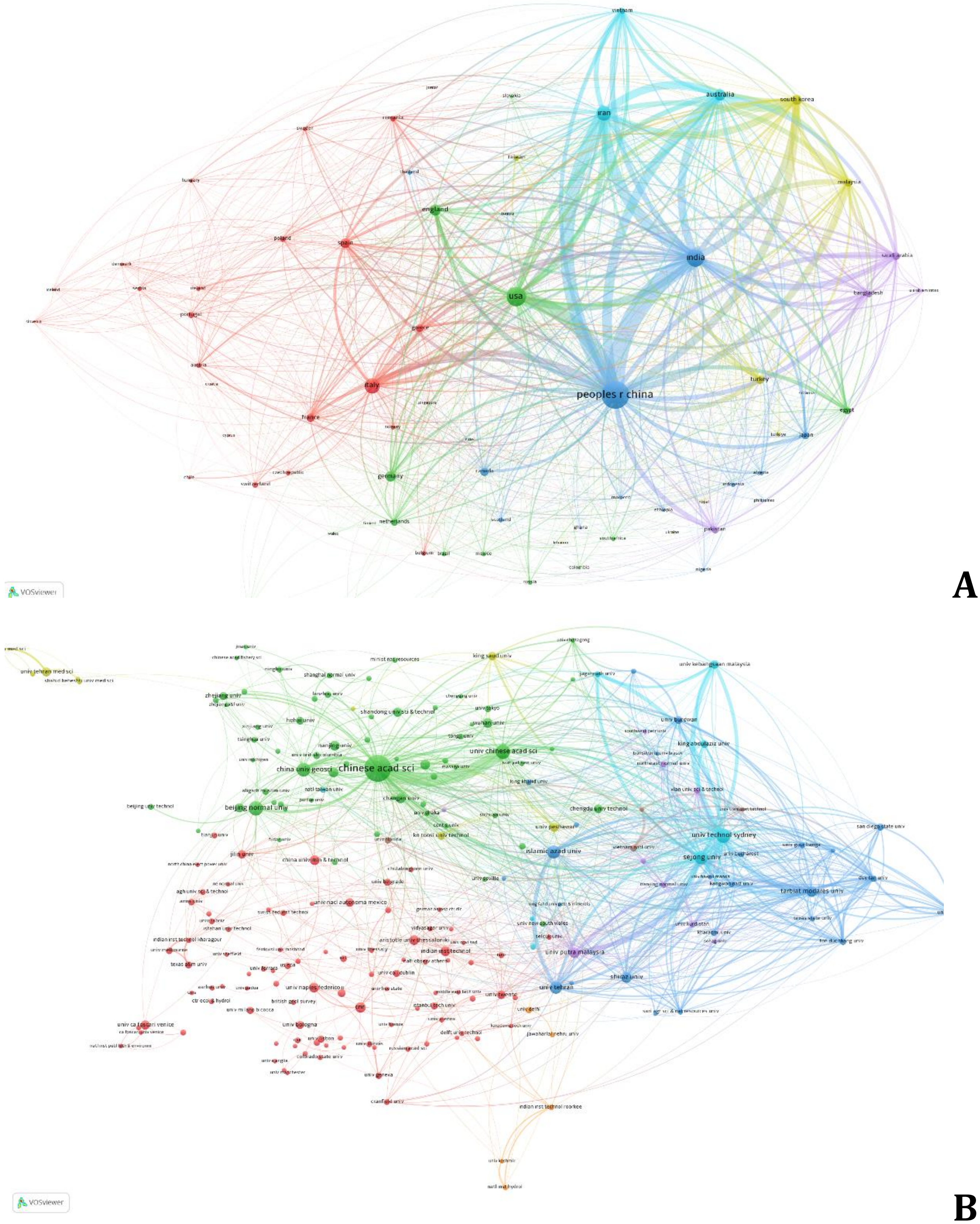

Figure 5. Cooperation network of (A): Countries with 15 documents threshold; (B): Organizations with 20 documents threshold.

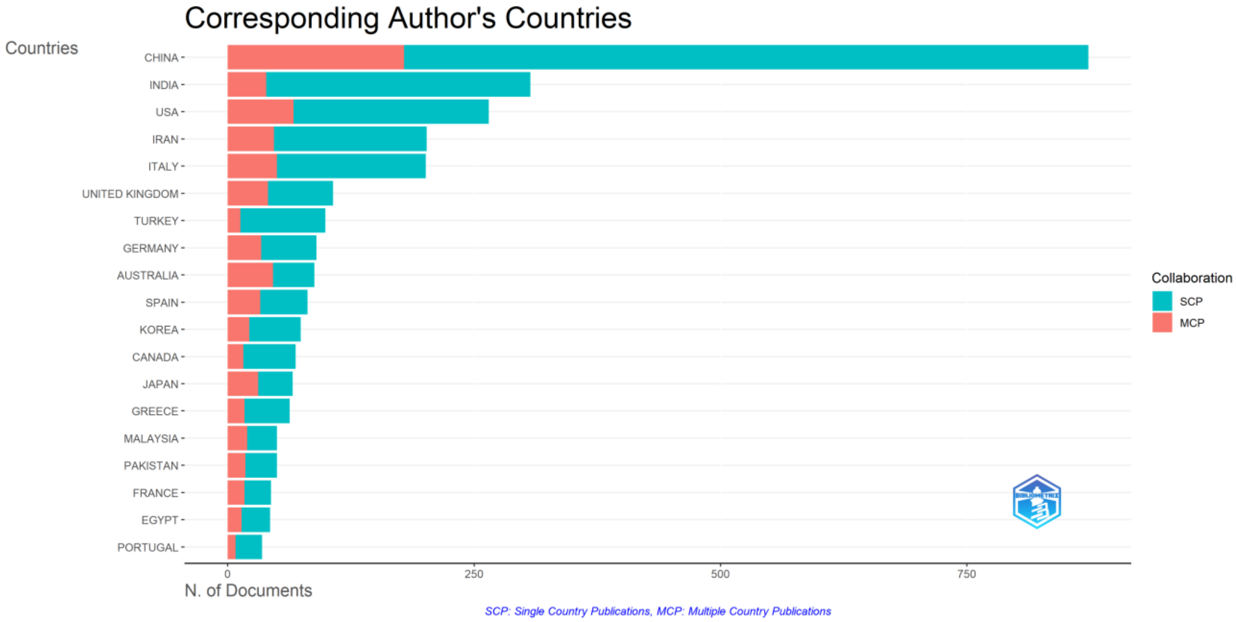

Figure 6. Corresponding Author's Countries

By identifying and highlighting these collaborative patterns, our study contributes to a deeper understanding of the research dynamics within the GIS domain for disaster management and underscores the importance of fostering international and interinstitutional partnerships.

The investigation into multi-country publications (MCP) versus single country publications (SCP) reveals the extent and nature of global cooperation, offering insights into how collaborative efforts are distributed across nations. The examination of publication data from 2000 to 2024 highlights significant international collaborations, with certain countries emerging as central nodes in the research network. The distribution of articles, both SCP and MCP, alongside the frequency of collaborations, points to the dynamic interplay of national strengths and international partnerships in advancing GIS applications for disaster management.

Predominantly, China emerges as the leading contributor with an impressive tally of 873 articles, underpinning its substantial role in advancing GIS applications for disaster management. Notably, the Single Country Publications (SCP) to Multi-Country Publications (MCP) ratio for China underscores a balanced approach to both independent research and international collaboration. India and the United States also demonstrate considerable contributions, with 307 and 265 articles, respectively, highlighting their active engagement in GIS research. Remarkably, Australia and Spain exhibit a higher propensity for collaboration, as evidenced by their MCP ratios, which are among the highest, signalling a strong inclination towards international partnerships in addressing complex disaster management challenges.

3.3. Keyword Analysis

In examining the landscape of GIS research applied to disaster management over the past 25 years, keyword analysis emerges as a crucial tool for uncovering prevailing themes, research foci, and evolving trends within the field. This subsection delves into the frequency of specific terms, showcasing the core subjects that have shaped the domain's trajectory.

3.3.1. Frequency of Words over 25 years

To gauge the thematic concentration and identify the most prevalent topics in GIS research related to disaster management from 2000 to 2024, we analyzed the occurrence of Author Keywords and Keywords Plus. This analysis provides insights into the research community's priorities and the terminological backbone supporting scholarly discourse within the field (Table 6).

The Table 6 highlights "GIS," "risk assessment," and "remote sensing" as the most frequently cited Author Keywords, underscoring the centrality of these concepts in shaping research efforts. Similarly, Keywords Plus reiterates the importance of "GIS" and "risk-assessment," while also emphasizing "model," "management," and "vulnerability" as key areas of focus. The prevalence of terms such as "vulnerability," "hazard," and "risk assessment" underscores the field's emphasis on understanding and mitigating the adverse impacts of disasters. Meanwhile, the recurrence of "remote sensing" and "geographic information system" points to the significant role of technological advancements in enhancing data collection, analysis, and application in disaster management contexts.

Table 6. Most frequent Author keywords and Keyword Plus (2000-2024)

Author Keywords		Keywords Plus	
Words	Occurences	Words	Occurences
gis	919	gis	911
risk assessment	541	risk-assessment	656
remote sensing	196	model	393
risk	181	management	300
vulnerability	180	vulnerability	289
assessment	129	hazard	235
Geographici nformation system	110	contamination	232
groundwater	100	area	218
heavy metals	98	pollution	218
hazard	92	prediction	186

The word cloud visualization (Figure 7), derived from the frequency data of Author Keywords, graphically represents the most prominent themes in the research landscape. In this visualization, the size of each term corresponds to its frequency of occurrence, thereby offering a visual representation of the thematic emphasis within the corpus of GIS research for disaster management. Key observations include:

The term "GIS" and its variations, including "geographic information system(s)" and "geographic information system (GIS)," underline the central role of Geographic Information Systems in disaster management research, serving as the technological backbone for spatial analysis and modeling. "Risk assessment" and related terms like "health risk assessment," "flood risk," and "ecological risk assessment" underscore the field's focus on evaluating and mitigating the impacts of various hazards, from environmental contaminants to natural disasters. Keywords such as "heavy metals," "groundwater," "soil erosion," and "pollution" reflect a strong environmental component within disaster management research, pointing to concerns over the effects of environmental factors on disaster risk and vulnerability. The presence of terms like "remote sensing," "AHP" (Analytical Hierarchy Process), "fuzzy logic," and "machine learning" indicates the diverse methodological approaches employed in the field, from traditional spatial analysis techniques to advanced computational models. Emerging themes are evident in the inclusion of "climate change," "machine learning," and "spatial distribution," suggesting a growing interest in understanding the implications of global environmental changes and leveraging advanced analytics in disaster management.

Figure 7. Word Cloud Map of Author Keywords (Left) and Keyword Plus (Right)

Analyzing the evolution of GIS research in disaster management over a span of 25 years, from 2000 to 2024, provides profound insights into the thematic priorities and technological advancements within the field. The cumulative keyword analysis, depicted through author keywords and Keywords Plus, illuminates a significant emphasis on "GIS," "risk assessment," and "remote sensing" as central pillars of research focus. The persistence of "GIS" across both datasets, with occurrences nearing 919 for author keywords and 911 for Keywords Plus by 2024, underscores the foundational role of geographic information systems in disaster management research (Figure 8). Remarkably, "risk assessment" emerges as a critical theme, witnessing a steep increase in mentions, indicative of the growing concern and emphasis on preemptive strategies and methodologies within the domain. Additionally, the ascent of "remote sensing" highlights the expanding reliance on and integration of technological innovations to enhance disaster preparedness and response mechanisms. This 25-year trajectory not only showcases the dynamic nature of GIS research in addressing complex disaster management challenges but also reflects an expanding scope, incorporating emerging technologies and interdisciplinary approaches to foster resilience and mitigate risks associated with natural hazards.

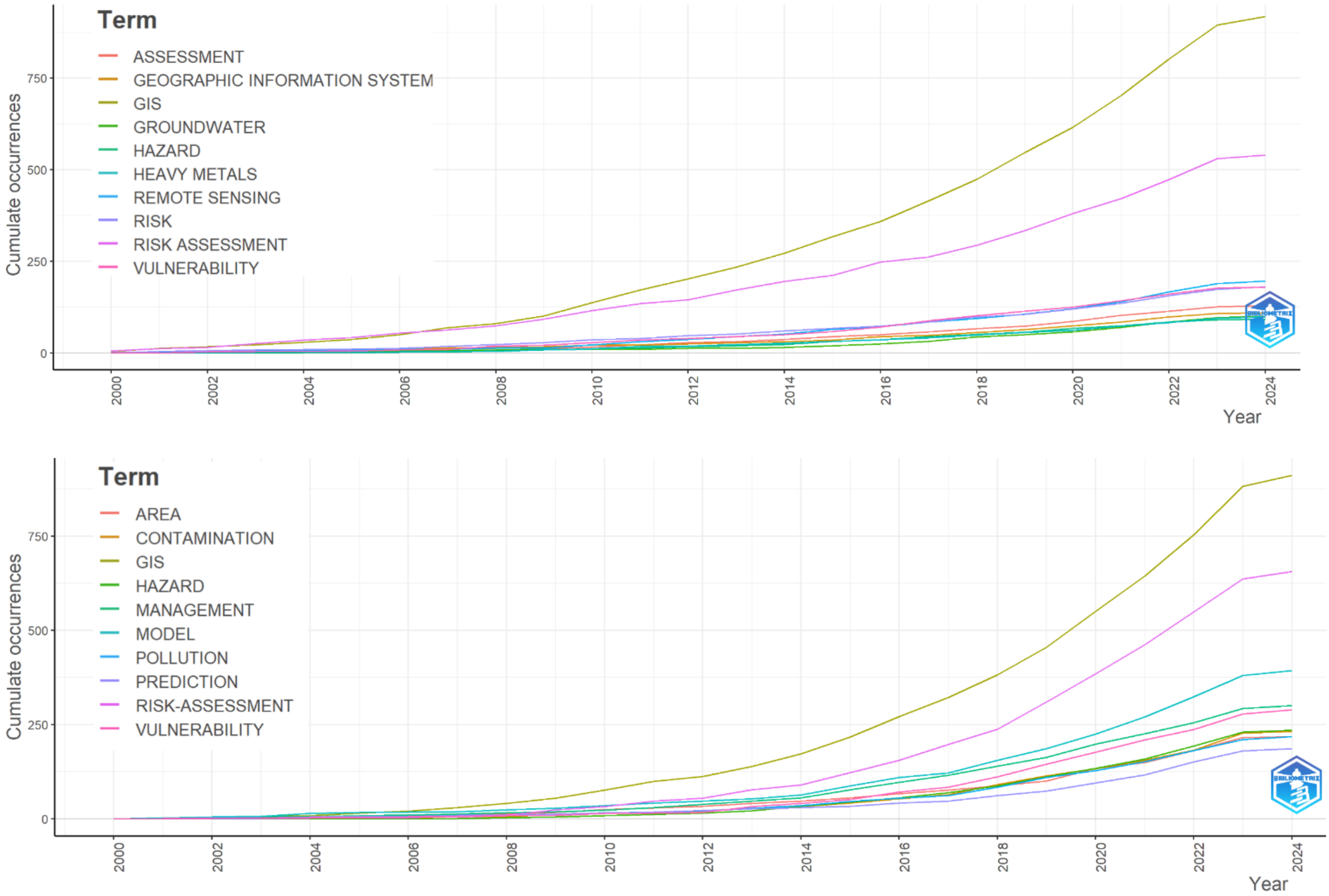

Figure 8. Words' Frequency over Time: Top Author Keywords and Bottom Keywords Plus

3.3.2. Thematic Map and Trend Topic Analysis

The thematic map of author keywords over the 25-year period provides a rich, multifaceted view of the evolution and dynamics within the field of GIS applications in disaster management (Figure 9). The map is categorized into four quadrants, each representing a specific type of theme based on their centrality (relevance degree) and density (development degree).

Occupying the top right quadrant are the 'Motor Themes', with "GIS," "risk assessment," and "remote sensing" as the most dominant. The substantial size of the "GIS" bubble indicates its extensive coverage and centrality, confirming that GIS remains the backbone technology driving research in this domain. The proximity of "risk assessment" to "GIS" signifies their intertwined nature, suggesting that GIS's primary application in disaster management is for assessing risks. "Remote sensing," while slightly less central, remains crucial, likely due to its importance in data collection and analysis. The bottom right quadrant is dedicated to 'Basic Themes' such as "geographic information system," "analysis," and "spatial analysis," which, despite lower density, exhibit a high degree of centrality. These terms represent foundational elements of the research field that maintain essential links across various studies, reflecting their ongoing significance. In the top left quadrant, 'Niche Themes' display high density but lower centrality. This area is populated by terms like "AHP," "flood risk," and "landslide susceptibility," which suggest concentrated areas of study with specific, in-depth research focus. Finally, the bottom left quadrant reveals 'Emerging or Declining Themes'. Here, we find terms like "soil erosion," "rusle," and "watershed," which have high specificity but are less central to the overall research discourse. Their placement indicates they are either developing areas of interest or potentially diminishing topics within the field. The positioning of keywords such as "heavy metals" and "health risk assessment" within the 'Niche Themes' indicates a growing focus on environmental health within disaster management studies. The presence of terms like "climate change" within the 'Motor Themes' implies an increasing recognition of climate impacts on disaster risk.

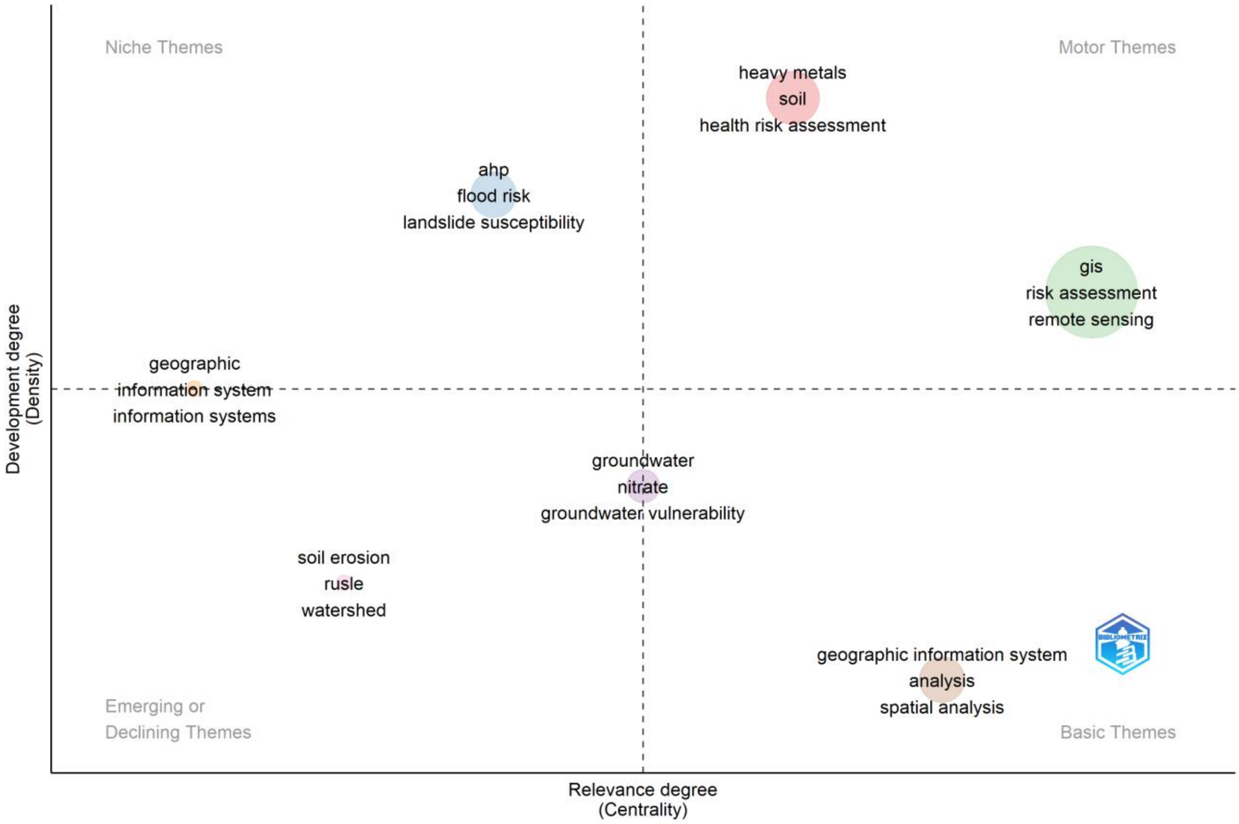

Figure 9. Thematic Map of Author keywords(2000-2024)

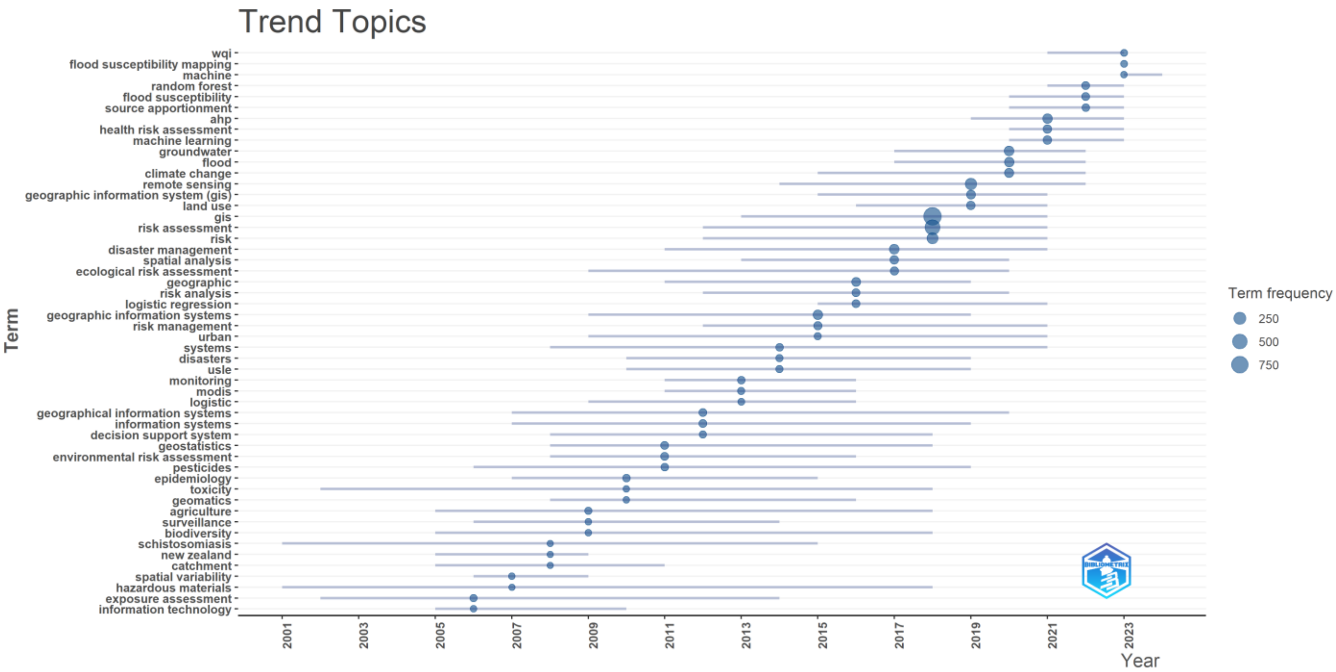

Figure 10. Trend Topic of Author Keyword over 25 years

The trend topics visualization illustrates the frequency and trajectory of key terms in GIS-related disaster management research from 2000 to 2024 (Figure 10). Each horizontal line represents the lifespan of a term within the literature, with the size and shade of the bubbles indicating the frequency of the term's occurrence. Larger and darker bubbles denote higher frequencies, making it immediately apparent which terms have dominated the discourse at various points in time.

At the forefront of the visualization are terms like "GIS," "risk assessment," and "remote sensing," which not only show considerable longevity but also peak frequencies, underscoring their central role in the field throughout the observed period. Their sustained presence across the years highlights the ongoing relevance of these foundational concepts in disaster management research. Emerging terms like "health risk assessment" and "machine learning" demonstrate an increasing frequency in later years, indicating that new technologies and health considerations are becoming more integral to the field. Meanwhile, specialized terms like "flood susceptibility mapping" and "AHP" (Analytical Hierarchy Process) appear as more recent entrants, suggesting an evolution of focus areas over time. The trend towards these terms may reflect a shift towards more granular risk modeling and decision-making frameworks in disaster management. The visualization acts as a dynamic timeline, revealing the ebb and flow of research priorities, methodological advancements, and the integration of new technologies into the discipline. It offers a clear, at-a-glance understanding of the changing landscape of GIS research in the context of disaster management and risk assessment.

3.4. 5 Year Interval Based Analysis

3.4.1. Keyword Frequencies and Co-occurrences per Interval

The Table 7 illustrating the analysis of keyword frequencies and co-occurrences over five distinct five-year intervals reveals significant shifts and evolving trends in GIS literature as it pertains to disaster management and risk assessment from 2000 to 2024.

- During the initial interval, the focus seems to have been on developing foundational models, with "model" and "gis" being the most frequent keywords. These years laid the groundwork for GIS applications in risk and disaster management. Terms like "exposure," "management," "prediction," and "risk" suggest an early interest in applying GIS to a variety of predictive and management tasks within the environmental context, including biodiversity and soil studies.
- In the subsequent interval, "gis" gained prominence, indicating a surge in its application and possibly an expansion of GIS technology's capabilities. The term "risk assessment" also began to rise, showing an increased focus on using GIS for evaluating disaster-related risks. Keywords like "area," "exposure," and "contamination" highlight a growing concern for the environmental impacts of disasters and the spatial dimensions of risk.
- By this period, "gis" and "risk assessment" continued their upward trend, firmly establishing themselves as central to the field. The emergence of "management" alongside "model" as top keywords indicates a shift toward integrating GIS into disaster management strategies. The attention to specific risks such as "pollution" and "hazard" reflects a more nuanced application of GIS in identifying and managing environmental threats.
- The penultimate interval saw "gis" reaching even higher occurrences, which could be attributed to advancements in GIS technology and broader adoption. "Risk assessment" remained a key focus, while "vulnerability" surged, marking a shift toward understanding the susceptibility of systems and populations to disasters. The appearance of "climate change" as a frequent term highlights the increasing concern for long-term environmental changes affecting disaster risk.
- In the most recent interval, "gis" and "risk assessment" continued to dominate, underscoring their enduring importance. The substantial rise in mentions of "vulnerability," "management," and "hazard" alongside "gis" reflects the consolidation of these concepts in disaster management literature. "Model" remains significant but is now accompanied by terms like "area" and "contamination," suggesting a focus on specific disaster impacts and the need for precise risk delineation.

Table 7. Author Keyword Occurences for 5 years interval

2000-2004		2005-2009		2010-2014		2015-2019		2020-2024	
Words	Occurences	Words	Occurences	Words	Occurences	Words	Occurences	Words	Occurences
model	14	gis	47	gis	117	gis	283	gis	456
gis	8	risk-assessment	22	risk-assessment	66	risk-assessment	220	risk-assessment	346
exposure	6	area	15	management	37	model	123	model	207
management	6	exposure	14	model	35	management	107	vulnerability	144
prediction	5	model	14	vulnerability	32	vulnerability	104	management	137
risk	5	management	13	area	30	contamination	82	hazard	124
biodiversity	4	contamination	10	hazard	28	hazard	78	area	118
risk assessment	4	impact	9	pollution	25	pollution	75	contamination	118
scale	4	models	9	risk	23	climate-change	63	prediction	112
soil	4	lead	8	contamination	20	area	53	pollution	108

Across the intervals, the growth in keyword occurrences reflects the expanding role of GIS in disaster management, from initial modeling efforts to comprehensive risk assessments, management strategies, and addressing emerging challenges like climate change. The consistent increase in the frequency of these keywords over time demonstrates the field's maturing focus on leveraging GIS to understand, mitigate, and manage disasters, with an evolving emphasis on technological integration, vulnerability analysis, and the environmental impacts of disasters.

The interval analysis of keyword frequencies and co-occurrences provides an insightful perspective on the evolving landscape of GIS in disaster management and risk assessment research from 2000 to 2024. The Table 8 employs multidimensional scaling to project the prevalence and association of terms across different intervals, revealing shifts in research foci and thematic correlations within the field.

As observed in Table 8, multidimensional scaling (MDS) reveals distinct thematic shifts and continuities over the 25-year span. For instance, the keyword 'gis' consistently shows a central position throughout the intervals, indicating its sustained prominence in the field. Conversely, the keyword 'model' transitions from a prominent role in early intervals to less centrality later on, suggesting an evolution in research focus. The table also highlights emerging keywords such as 'vulnerability' and 'contamination,' which gain centrality in later years, reflecting the field's adaptive responses to evolving environmental and societal challenges.

Table 8. Multidimensional Scaling (MDS) Analysis of GIS-Related Keyword Frequencies and Co-occurrences (2000-2024)

2000-2004			2005-2009			2010-2014			2015-2019			2020-2024		
word	Dim. 1	Dim. 2	word	Dim. 1	Dim. 2	word	Dim. 1	Dim. 2	word	Dim. 1	Dim. 2	word	Dim. 1	Dim. 2
model	0.78	0.15	gis	0.04	0.54	gis	-0.03	0.74	gis	-0.11	-0.1	gis	-0.33	0.06
gis	0.92	-0.52	risk.assessment	-0.86	1.12	risk.assessment	0.47	0.46	risk.assessment	0.02	-0.41	risk.assessment	-0.42	0.22
exposure	-1.26	0.47	area	-0.59	1.02	management	-0.46	-0.5	model	-0.62	0.23	model	-0.37	-0.41
management	0.06	-0.1	exposure	-0.61	-1.52	model	-0.64	0.14	management	-0.54	0.74	vulnerability	-0.35	-0.62
prediction	0.32	-0.57	model	1.47	0	vulnerability	-0.47	-0.43	vulnerability	-0.64	0.31	management	-0.25	-0.92
risk	1.44	-0.93	management	1.73	0.66	area	0.18	1.34	contamination	1.74	0.32	hazard	-0.83	0.18
biodiversity	-1.6	-0.22	contamination	-1.75	0.77	hazard	-0.75	0.48	hazard	-0.68	-1.24	area	0.07	0.95
risk.assessment	-1	-0.52	impact	0.65	-0.73	pollution	1.42	0.08	pollution	1.79	0.15	contamination	1.58	0.85
scale	0.74	-1.08	models	1.27	0.91	risk	-0.27	-0.44	climate.change	-0.81	0.47	prediction	-0.77	0.23
soil	-0.13	0.35	lead	-2.19	1.12	contamination	2.26	-0.25	area	0.23	-0.66	pollution	1.48	0.76

In the earliest interval (2000-2004), the term 'model' held a predominant position (Dim.1 = 0.78, Dim.2 = 0.15), indicating an initial focus on developing and refining GIS models. As we progress to 2005-2009, 'GIS' emerges as a central theme (Dim.1 = 0.04, Dim.2 = 0.54), with 'risk assessment' following closely behind, suggesting a pivot towards applying GIS in evaluating and managing risks. From 2010 to 2014, 'risk assessment' maintains its centrality (Dim.1 = 0.47, Dim.2 = 0.46), while 'management' appears significant but starts to shift negatively along Dim.2 (Dim.1 = -0.46, Dim.2 = -0.5), indicating an evolving discourse that perhaps integrates management with other emerging issues. The trend continues into the 2015-2019 interval, with 'contamination' (Dim.1 = 1.74, Dim.2 = 0.32) and 'pollution' (Dim.1 = 1.79, Dim.2 = 0.15) gaining prominence, potentially reflecting an increased awareness of environmental hazards within the field. In the most recent period (2020-2024), 'GIS' takes the most negative position along Dim.1 (Dim.1 = -0.33), yet remains positive along Dim.2 (Dim.2 = 0.06), signifying its entrenched yet evolving role in the research landscape. Interestingly, 'hazard' is observed with a significant shift towards the positive along Dim.2 (Dim.1 = -0.83, Dim.2 = 0.18), indicating its growing importance.

When synthesizing the entire 25-year period (2000-2024), 'GIS' and 'risk assessment' consistently appear as core themes with their position in quadrant one (Dim.1 < 0, Dim.2 > 0), underscoring their sustained relevance. Notably, 'contamination' and 'pollution' dominate along both dimensions (Dim.1 > 1, Dim.2 > 0), revealing their critical and increasing impact on the discourse. This keyword trajectory demonstrates a field in flux, responsive to global trends and challenges. As these terms signify the focal points of research throughout the years, their dimensional positions provide a nuanced understanding of the field's direction and priorities.

3.4.2. Historiographical Development of GIS in Disaster Management and Risk Assessment

The historiograph analysis reveals the evolutionary trajectory of research themes and their interconnections over the 24-year period. Using bibliometric data, including author keywords, KeywordsPlus, citation scores, and DOI information, we've charted the course of how the GIS application in disaster management and risk assessment has developed, matured, and diversified.

In this historiographical mapping, it becomes evident that the integration of GIS into disaster management and risk assessment is not just growing, but is becoming ever more complex and multifaceted, reflecting the field's dynamic response to emerging challenges and technological advancements. The table showcases a curated collection of influential studies published between 2000 and 2024, shedding light on the progress and focus areas within GIS applications for disaster management and risk assessment. The clustering indicates the grouping of research themes or methodologies, which aids in understanding the evolution of the field across the intervals.

- Early Adoption and Conceptual Exploration (2000-2004): The inception of GIS applications in disaster management was marked by studies such as [27] work, which emphasized the importance of geomorphology and vulnerability in developing countries. This period set the stage for the future trajectory of the field, focusing on laying down the foundational understanding of natural hazards and their prevention.
- Methodological Advances and Specialized Applications (2005-2009): Progressing into the mid-2000s, studies like those of [34] and [35] highlighted the application of statistical methods for landslide susceptibility zonation using GIS, reflecting a shift towards more quantitative and model-based approaches.
- Sophistication of Techniques (2010-2014): The following decade was characterized by a sophistication of techniques, where the emphasis was placed on integrating various statistical models with GIS for enhanced predictive modeling of hazards, as seen in works by [36] and [33]. This period also witnessed the adoption of ensemble methods, indicating an increased complexity in analytical approaches.
- Integration of Novel Data Sources (2015-2019): As we approached the late 2010s, research by [37] incorporated novel data sources like LiDAR into GIS for multi-hazard risk assessment, showcasing the field's inclination towards leveraging advanced remote sensing technologies.
- Consolidation of GIS in Disaster Risk Reduction (2020-2024): The most recent phase solidifies the role of GIS in disaster risk reduction. [37] hydro-geomorphic approach to flood risk, incorporating multi-criteria decision analysis, illustrates the culmination of decades of progression into a toolset that is integral to disaster management strategies.

Throughout the intervals, there has been a consistent climb in both local and global citation scores, emphasizing the growing impact and recognition of GIS-based research (Table 9). The thematic clusters reveal a field that is increasingly data-driven, with a focus on practical applications and interdisciplinary integration. Terms such as "vulnerability," "hazard assessment," and "remote sensing" within the same clusters highlight the fusion of social science perspectives with technical geospatial analysis, reflecting a comprehensive approach to understanding and mitigating disaster risks.

In summation, the historiograph (Figure 11) demonstrates that GIS has become an indispensable tool in the disaster management toolbox. From the initial applications focused on mapping and basic analyses, the field has grown to incorporate complex models, diverse data sources, and sophisticated prediction tools, contributing significantly to reducing vulnerabilities and enhancing preparedness for natural disasters.

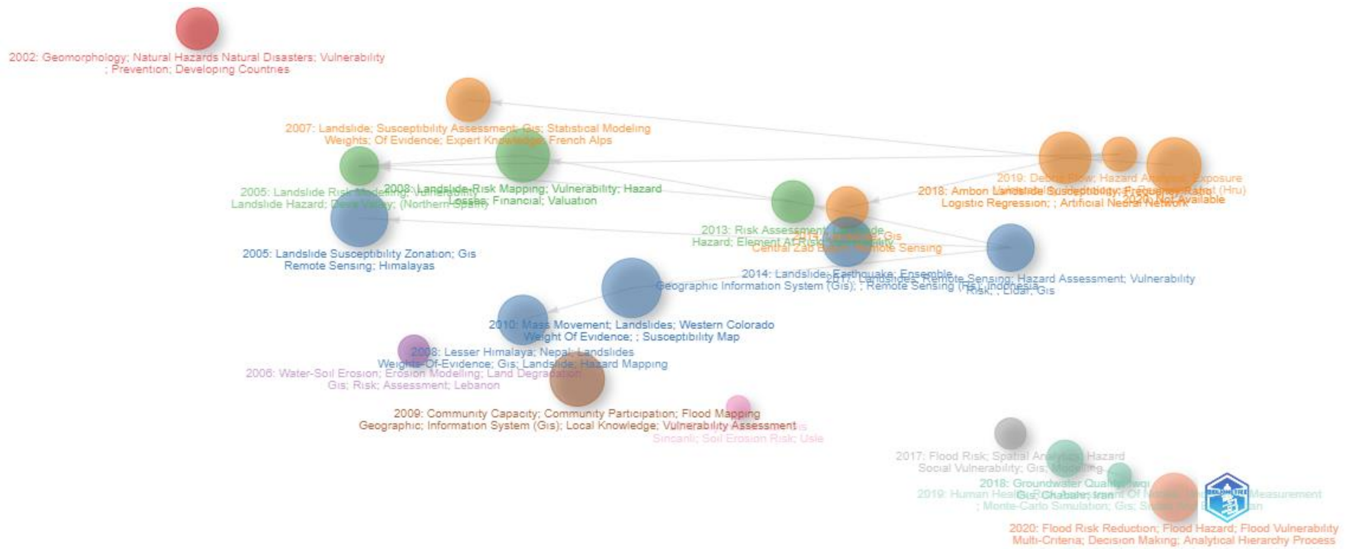

Figure 11. The interconnections and evolutionary trajectory of research themes.

Table 9. Evolution of Author Keywords in GIS for Disaster Management and Risk Assessment (2000-2024)

Publication	Author_Keywords	LCS	GCS	Cluster
[35]	Geomorphology; Natural Hazards Natural Dısasters; Vulnerabılıty;; Preventıon; Developıng Countrıes	12	349	1
[41]	Landslıde Susceptıbılıty Zonatıon; Gıs; Remote Sensıng; Hımalayas	26	269	2
[46]	Lesser Hımalaya; Nepal; Landslıdes; Weıghts-Of-Evıdence; Gıs; Landslıde; Hazard Mappıng	18	179	2
[40]	Mass Movement; Landslıdes; Western Colorado; Weıght Of Evıdence;; Susceptıbılıty Map	29	279	2
[47]	Landslıde; Earthquake; Ensemble; Geographıc Informatıon System (Gıs);; Remote Sensıng (Rs); Indonesıa	18	246	2
[49]	Landslıdes; Remote Sensıng; Hazard Assessment; Vulnerabılıty; Rısk;; Lıdar; Gıs	16	65	2
[50]	Landslıde Rısk Modellıng; Vulnerabılıty; Landslıde Hazard; Deva Valley; (Northern Spaın)	10	89	3
[44]	Landslıde-Rısk Mappıng; Vulnerabılıty; Hazard; Losses; Fınancıal; Valuatıon	22	118	3
[51]	Rısk Assessment; Landslıde; Hazard; Element At Rısk; Vulnerabılıty	12	45	3
[52]	Water-Soıl Erosıon; Erosıon Modellıng; Land Degradatıon; Gıs; Rısk; Assessment; Lebanon	7	62	4
[53]	Landslıde; Susceptıbılıty Assessment; Gıs; Statıstıcal Modelıng; Weıghts; Of Evıdence; Expert Knowledge; French Alps	13	185	5
[54]	Landslıde; Gıs; Central Zab Basın; Remote Sensıng	12	229	5
[45]	Ambon Landslıde Susceptıbılıty; Frequency Ratıo; Logıstıc Regressıon;; Artıfıcıal Neural Network	20	284	5
[55]	Debrıs Flow; Hazard Analysıs; Exposure; Vulnerabılıty; Hydrologıcal; Response Unıt (Hru)	8	37	5
[42]	Communıty Capacıty; Communıty Partıcıpatıon; Flood Mappıng; Geographıc; Informatıon System (Gıs); Local Knowledge; Vulnerabılıty Assessment	23	129	6
[56]	Afyonkarahısar; Gıs; Sıncanlı; Soıl Erosıon Rısk; Usle	6	7	7
[57]	Flood Rısk; Spatıal Analytıcs; Hazard; Socıal Vulnerabılıty; Gıs; Modellıng	7	48	8
[58]	Groundwater Qualıty; Iwqı; Gıs; Chabahr; Iran	9	78	9
[59]	Human Health; Rısk Assessment Of Nıtrate; Uncertaınty Measurement;; Monte-Carlo Sımulatıon; Gıs; Sıstan And Baluchıstan	6	38	9
[48]	Flood Rısk Reductıon; Flood Hazard; Flood Vulnerabılıty; Multı-Crıterıa; Decısıon Makıng; Analytıcal Hıerarchy Process	17	94	10

3.4.3. Thematic Evolution

The thematic evolution visualization (Figure 12) vividly encapsulates the dynamic and interwoven development of GIS applications in disaster management and risk assessment over a span of twenty-five years, from 2000 to 2024. This analysis provides a clear narrative of how the focus areas within GIS research have evolved, reflecting broader trends in technology and societal needs. In the early period (2000-2004), the focus was heavily centered on fundamental concepts such as 'geographic information systems', 'risk assessment', and 'ecological risk assessment'. This foundation set the stage for the utilization of GIS in environmental and disaster-related studies, with an emphasis on assessing risks related to heavy metals and other pollutants, as seen in the keywords 'pollution' and 'heavy metals'.

As we transition into the period from 2005-2009, the analysis indicates a broadening of themes with the introduction of terms like 'spatial distribution', 'seismic risk', and 'volcanic risks'. This suggests an expansion of GIS applications from basic mapping and data collection to more complex analyses involving natural disaster risks and their spatial dynamics, reflecting a deeper integration into environmental sciences. The period of 2010-2014 highlights a consolidation of GIS capabilities, with emerging themes such as 'desertification risk' and 'drought', indicating a shift towards the application of GIS in broader environmental issues that affect large geographic areas. The presence of 'volcanic hazard' and 'sis' (presumably a technical term related to specific software or systems in GIS) during this interval underscores the increasing complexity and technical enhancement of GIS tools. From 2015-2019, the themes diversify significantly, pointing to a matured integration of GIS across various aspects of disaster management. Keywords such as 'disaster', 'heritage', and 'indicators' suggest that GIS tools have begun to influence policy-making and heritage management in disaster-prone contexts. The inclusion of 'heritage' highlights a novel application of GIS in preserving cultural heritage against natural disasters. The latest period, 2020-2024, shows an advanced and specialized application of GIS in environmental risk management, particularly through the focus on 'groundwater', 'soil erosion', and the use of 'ahp' (Analytic Hierarchy Process). This indicates a sophisticated use of GIS in detailed environmental risk analysis and decision-making processes, showcasing the technological advancements in GIS software and methodologies.

This visual representation serves as an effective tool for understanding the progression and expanding scope of GIS in disaster management. It illustrates not only the persistence of certain core themes but also the introduction of new technologies and methodologies that enhance the capabilities of GIS. This evolution mirrors the growing complexity of disaster management challenges and the corresponding need for advanced tools to address these issues comprehensively.

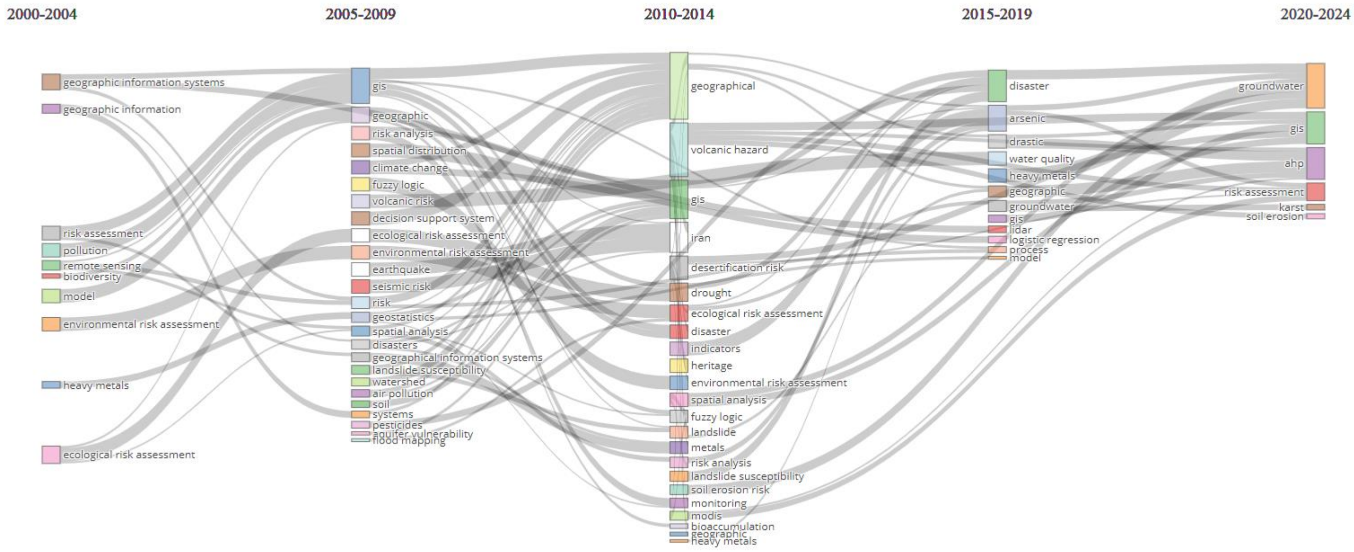

Figure *12*. A Five-Field Sankey Diagram of Thematic Evolution of Keywords in GIS and Disaster Management Research (2000–2024).

4. Discussion

4.1. Integration and Evolution of GIS in Disaster Management

Over the past 25 years, Geographic Information Systems (GIS) have undergone remarkable evolution, transitioning from basic mapping tools to cornerstone technologies in disaster management. Initially, GIS applications in disaster management were primarily focused on mapping and data collection, crucial for visualizing hazard areas, critical infrastructure, and vulnerable populations. For instance, during the 2005 Hurricane Katrina, GIS mapping was pivotal in the evacuation and resource allocation strategies. These initial steps underscored the potential of GIS as a pivotal tool in understanding and mitigating disaster risks. As the technology matured, GIS began to integrate more sophisticated analytical capabilities, evolving from static mapping to dynamic, predictive modeling. For example, during the 2011 Japan earthquake and tsunami, GIS-based predictive models provided critical insights for emergency response. The integration of spatial analysis and modeling techniques enabled the assessment of disaster risks and vulnerabilities with greater accuracy and detail, marking a significant shift towards utilizing GIS not only for visualization but also for the prediction and simulation of disaster scenarios, facilitating more proactive disaster management strategies [60]. These initial steps underscored the potential of GIS as a pivotal tool in understanding and mitigating disaster risks.

As the technology matured, GIS began to integrate more sophisticated analytical capabilities, evolving from static mapping to dynamic, predictive modeling. The integration of spatial analysis and modeling techniques enabled the assessment of disaster risks and vulnerabilities with greater accuracy and detail [61]. This period marked a significant shift towards utilizing GIS not only for visualization but also for the prediction and simulation of disaster scenarios, facilitating more proactive disaster management strategies.

The advent of advanced computing and the proliferation of big data analytics have further propelled GIS into the realm of real-time decision support systems. Today, GIS technologies are instrumental in real-time monitoring, early warning systems, and emergency response management [15, 62]. These systems leverage real-time data feeds, such as satellite imagery and sensor networks, integrating them with GIS to provide timely information for decision-making during disaster events. This real-time capability has transformed GIS from a planning and analysis tool into an operational asset critical for immediate disaster response and management. Moreover, the integration of GIS with other technologies, such as remote sensing, social media analytics, and machine learning, has enhanced its applicability and efficiency in disaster management [20]. These integrations have enabled the development of more comprehensive and nuanced understandings of disaster risks and have facilitated the creation of more effective and tailored disaster response strategies.

In conclusion, the past 25 years have witnessed GIS transitioning from a novel mapping technology to a foundational tool in disaster risk management and assessment. Its evolution reflects not only technological advancements but also a paradigm shift in disaster management—from reactive measures to proactive, informed decision-making processes. As GIS continues to integrate with emerging technologies, its role in enhancing the resilience of communities against disasters is poised to grow even further, underscoring its indispensability in contemporary disaster risk management practices.

4.2. Thematic Shifts and Technological Advancements

The thematic landscape of Geographic Information Systems (GIS) in disaster management has experienced significant shifts over the past 25 years, a journey mirrored by the evolution of keywords and research focuses within the field. Central to this evolution has been a move towards a deeper understanding of vulnerability assessment, the impacts of climate change on disaster risks, and the innovative integration of remote sensing data. These thematic shifts are not only reflective of the broader technological advancements in GIS and related fields but also indicative of a maturing discipline increasingly focused on nuanced and comprehensive approaches to disaster risk management.

Initially, the use of GIS in disaster management was heavily centered around hazard mapping and the physical aspects of disasters. Over time, however, there has been a noticeable shift towards vulnerability assessment, underscoring a holistic view that considers the socio-economic factors, resilience capacities, and the specific vulnerabilities of communities to disasters [17, 63, 72]. For example, the San Francisco Bay Area's integration of GIS in urban planning has enhanced its resilience against seismic risks by aligning development with detailed risk assessments. This shift reflects a broader understanding that the impact of disasters is not solely determined by the hazard itself but also by the vulnerability and preparedness of the affected communities. Parallel to the emphasis on vulnerability, the field has seen a growing focus on climate change and its implications for disaster risk. Studies leveraging GIS to model and predict the impacts of climate change on the frequency and severity of natural disasters have become increasingly prevalent [64]. This shift is in part due to technological advancements that have enhanced the ability to analyze and model complex climate systems and their interactions with human and natural environments, providing valuable insights into long-term disaster risk reduction strategies.

The integration of remote sensing data into GIS for disaster management represents another significant technological and thematic advancement. The availability of high-resolution satellite imagery, LiDAR data, and other forms of remote sensing has dramatically increased the accuracy and detail of risk assessments and disaster response mechanisms [1, 8, 65]. Remote sensing technologies have enabled the monitoring of real-time conditions, the assessment of post-disaster damages, and the development of predictive models with unprecedented precision, further enhancing the capabilities of GIS in disaster management. These thematic and technological advancements have profound implications for future research and practice in disaster management. The integration of socio-economic vulnerability assessments with physical hazard data calls for interdisciplinary research approaches that blend GIS with social sciences, economics, and urban planning. Similarly, the need to understand and mitigate the impacts of climate change demands long-term, globally coordinated research efforts that leverage the full potential of GIS and remote sensing technologies. Lastly, the ongoing improvement and accessibility of remote sensing data present both opportunities and challenges for disaster management professionals, necessitating continuous skill development and the adoption of new analytical techniques.

In summary, the evolution of GIS in disaster management over the past 25 years has been characterized by significant thematic shifts and technological advancements. The move towards vulnerability assessment, the integration of climate change impact studies, and the use of remote sensing data are indicative of a field that is increasingly focused on comprehensive, forward-looking strategies for disaster risk management. These changes underscore the necessity for ongoing research, interdisciplinary collaboration, and the development of innovative GIS applications to meet the challenges of a changing world.

4.3. Collaboration Networks and Scholarly Contributions

The realm of Geographic Information Systems (GIS) in disaster management has witnessed a flourishing of collaborative networks, a trend vividly illustrated by the cooperation analysis within this research community. These networks signify a robust framework of scholarly contributions, fostering an environment where knowledge, methodologies, and technologies transcend geographic and disciplinary boundaries. The role of international collaborations in this domain cannot be overstated; they serve as the linchpin in the advancement of disaster management strategies, fueling innovation and enhancing the global response to natural hazards. For instance, the Global Earthquake Model (GEM) initiative exemplifies such collaboration, combining resources from various countries to develop open-source, high-quality seismic risk assessment tools using GIS. The cooperation analysis highlights a vibrant tapestry of collaborations spanning across continents, underscoring the global nature of disaster management challenges and the universal utility of GIS as a tool for addressing these issues. Institutions from diverse countries have contributed significantly to the corpus of research in this field, reflecting a shared commitment to leveraging GIS for disaster risk reduction. Notably, countries with frequent exposure to natural hazards, such as China, the United States, Japan, and India, have been at the forefront of these efforts, bringing valuable insights and experiences to the collective knowledge pool [28, 55, 66-67]. These nations, alongside leading academic and research institutions within them, have spearheaded numerous initiatives aimed at enhancing the integration of GIS technologies in disaster risk assessment and response. International collaborations facilitate the exchange of knowledge and best practices, enabling researchers and practitioners to draw upon a wide range of experiences and expertise [68, 71]. This collaborative ethos is instrumental in tackling the multifaceted challenges posed by natural disasters, which often require interdisciplinary approaches and solutions that are adaptable to diverse cultural and geographical contexts. The networks formed through these partnerships are pivotal in advancing the science of disaster management, driving the development of more accurate, efficient, and user-friendly GIS applications tailored to the needs of vulnerable communities worldwide. Key institutions that have emerged as hubs of excellence within these networks include the Chinese Academy of Sciences, the United States Geological Survey, and the European Space Agency, among others. These entities have played a crucial role in pioneering research initiatives, developing innovative GIS tools, and fostering international cooperation. The collaborative projects spearheaded by these institutions have not only contributed to the scientific understanding of disaster risks but have also directly impacted disaster preparedness and response strategies on the ground.

In conclusion, the collaborative dynamics within the GIS and disaster management research community are a testament to the field's progress and its potential for future advancements. International collaborations have proven to be a cornerstone in pushing the boundaries of what is possible with GIS in disaster risk management, highlighting the importance of sustained partnerships and knowledge sharing. As the field continues to evolve, fostering and expanding these collaborative networks will remain essential in harnessing the full potential of GIS technologies to safeguard communities against the ever-present threat of natural disasters.

4.4. Challenges and Opportunities

The integration of Geographic Information Systems (GIS) in disaster management, while transformative, has encountered significant challenges that demand attention for its full potential to be realized. A prominent issue is the accuracy and availability of data, which is crucial for effective disaster management but often difficult to secure due to various constraints, including geographical, political, and financial barriers. Furthermore, the problem of interoperability between different systems and data formats poses a technical challenge, impeding the seamless integration and utilization of GIS tools across different platforms and organizations. For example, during the 2018 California wildfires, disparate data systems among firefighting agencies complicated the coordination of response efforts. Additionally, the necessity for interdisciplinary collaboration, bridging the gap between technologists, environmental scientists, urban planners, and emergency responders, highlights the complexity of disaster management and the need for a cohesive approach that often remains elusive in practice.

Despite these challenges, there are significant opportunities for advancement. Technological innovations, particularly in artificial intelligence, cloud computing, and big data analytics, offer new horizons for enhancing GIS capabilities, enabling more accurate predictive modeling and real-time decision-making processes. Moreover, the development and implementation of policies that encourage data sharing and standardization can address some of the interoperability issues, facilitating more efficient disaster response and management efforts. Lastly, the expansion of research and education in the field of GIS and disaster management can foster a new generation of professionals equipped with the knowledge and skills to leverage GIS technology effectively, thereby driving the field forward.

5. Conclusion

The bibliometric analysis conducted on the evolution of Geographic Information Systems (GIS) in disaster management over a 25-year period has unveiled significant findings, highlighting the growth, thematic evolution, role of international collaboration, and the impact of technological advancements on the field. This conclusion summarizes the main insights derived from the comprehensive review of scholarly literature and the analysis of publication trends, collaboration networks, thematic clusters, and technological innovations within the domain of GIS in disaster management.

- The field has seen a prolific expansion in the number of scholarly publications, from foundational GIS applications in hazard mapping and vulnerability assessments to sophisticated predictive modeling and real-time disaster response systems.
- A marked increase in scholarly publications, reflecting the expanding role of GIS in disaster risk management, underscored by a progression from fundamental applications to the integration of cutting-edge computational techniques and models.
- An extensive network of 14,256 researchers and a diverse array of institutions worldwide have contributed to advancing GIS applications in disaster management, emphasizing the field's broad scholarly engagement and interdisciplinary nature.
- The thematic focus within the field has evolved from basic hazard mapping to incorporating advanced predictive modeling, vulnerability assessments, and integration with other technologies such as remote sensing, AI, and machine learning.
- There has been a noticeable shift towards vulnerability and risk assessment, reflecting a broader understanding that disaster impacts are determined not only by the hazards themselves but also by the vulnerability and preparedness of communities.
- International collaborations have flourished, underpinning the field's advancements and facilitating the exchange of knowledge, methodologies, and best practices across geographical and disciplinary boundaries.
- The integration of GIS with cutting-edge technologies such as real-time data feeds, cloud computing, and big data analytics has transformed disaster management practices, enabling more accurate risk assessments and efficient disaster response strategies.
- The advancements in GIS technologies and their

applications in disaster management have significantly contributed to enhancing disaster preparedness, facilitating efficient disaster response, and supporting recovery and reconstruction efforts.

- The flexibility and adaptability of GIS make it a powerful tool for addressing the complex and dynamic nature of disasters, with real-world applications ranging from improving early warning systems to optimizing resource allocation during disaster response operations.

Further exploration of the integration of GIS with emerging technologies such as artificial intelligence, machine learning, and big data analytics, to enhance predictive modeling and decision support systems. Investigating the socio-economic and environmental impacts of disasters through the lens of GIS, with a focus on vulnerability assessments and resilience planning. Expanding the scope of international collaborations to include a wider range of disciplines and perspectives, fostering a more holistic approach to disaster risk management.

In conclusion, this bibliometric analysis has provided a comprehensive overview of the evolution of GIS in disaster management and risk assessment over the past 25 years. The findings highlight the field's dynamic nature, driven by technological innovations, thematic expansions, and a robust framework of international collaboration. As we look towards the future, it is clear that GIS will continue to play a pivotal role in enhancing disaster resilience, informed by the rich tapestry of research and practice that has been woven over the past two and a half decades. The ongoing advancements in GIS technologies, coupled with the sustained efforts of the global research community, promise to further advance our capabilities in managing and mitigating disaster risks, contributing to safer and more resilient societies worldwide.

Author contributions

Yusuf Eminoğlu: Methodology, Data Processing, Writing-Original draft preparation **Çiğdem Tarhan:** Conceptualization, Methodology, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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