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Review Article

Environmental and Physical Vulnerability: A Systematic Literature Review

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Abstract - *This study presents a bibliometric analysis of research on environmental and physical vulnerability in surface water areas, specifically in coastal regions, from 2015 to 2024. Using VOSviewer for co-authorship, active sources for publications, co-citation, and keyword co-occurrence analysis, the study identifies key authors, countries, and journals while highlighting the major themes driving vulnerability research. The analysis reveals that China and India are significant contributors to environmental vulnerability research, whereas India, Australia, and the UK lead in studies focused on physical vulnerability. Key topics of interest include GIS-based vulnerability mapping, coastal zone management, and disaster risk assessment. There is a growing emphasis on integrated socio-ecological approaches and advanced modeling techniques. The study underscores the importance of geospatial tools and remote sensing in improving vulnerability assessments and emphasizes the need for greater interdisciplinary collaboration. Notably, the research landscape appears more fragmented regarding environmental vulnerability, while physical vulnerability studies demonstrate increasing interconnectivity. Emerging research areas include marine pollution, oil spill management, and integrated disaster risk management. The study advocates for future research to adopt multi-hazard frameworks, integrate technological tools with socioeconomic data, and enhance policy frameworks to support effective adaptation strategies. These findings provide valuable insights for advancing climate change adaptation and improving resilience in vulnerable coastal and urban areas.*

Keywords - *Geographic Information System, Remote sensing, Bibliometric analysis, Riverside, Coastal.*

1. Introduction

The role of coastal areas is crucial for representing diverse populations and assets, contributing to economic, sociocultural, and geopolitical development. Coastal and riverside regions are highly at risk from both natural and human impacts. The construction of infrastructure in these areas, such as breakwaters, roads, hotels, housing, and ports, directly leads to the swift degradation of the coastline [1], resulting in the loss of rare habitats and disruption of the natural balance and functions of the coast [2]. Environmental degradation caused by human activities, such as the removal of mangrove forests and the erosion and dredging of rivers, estuaries, and deltas for shipping purposes [4, 5] raises the vulnerability to disasters in coastal areas. A study conducted by Oubennaceur et al. [5] shows urbanization and climate change exacerbate the occurrence and impact of floods in riverside areas. Furthermore, global climate change is leading to an increase in the frequency of disasters worldwide, such as flood hazards in Central Shanghai, Indonesia, Italy, Southern Quebec, and the USA [6, 7, 8, 9, 10]. Frequent disasters in coastal areas, including rising sea levels, floods, high waves, and storms, profoundly impact the residents living in these regions [5, 11, 12]. Furthermore, floods frequently occur in basins [13, 14, 15]. Understanding the impact of disasters, human adaptive capacity, and natural systems is crucial for conducting a thorough vulnerability assessment. According to physical scientists, vulnerability is intertwined with natural hazards, encompassing both physical and socioeconomic factors. Conversely, social scientists assert that vulnerability is tied to the unique characteristics of populations and urban systems, rendering them susceptible to harm under stress [15]. In recent decades, the assessment literature has seen the development and convergence of conceptual models of vulnerability. These models stress the equal importance of economic, social, physical, cultural, and environmental factors [16]. Presenting vulnerability assessment results visually enhances their accessibility and comprehensibility [16], thus supporting informed decision-making and policy formulation. The rise in coastal and riverside disasters has far-reaching effects on the region's physical, environmental, and socioeconomic losses. Recent global literature underscores the urgency of mapping the vulnerability of coastal areas, both physically and environmentally. Birkmann [17] groundbreaking study in 2007 used advanced GIS technology and innovative conceptual diagrams to analyze environmental vulnerability in Jakarta, Indonesia. Despite significant advancements in understanding environmental and physical vulnerabilities to coastal and surface water hazards, important gaps remain in comprehending how these dimensions interact in these regions. Existing literature often addresses climate-related impacts and infrastructure development separately, lacking an integrated analysis of both aspects in vulnerability assessments. For example, studies have demonstrated that a thorough vulnerability evaluation requires an integrated approach that considers environmental and physical factors together. Wang et al. [18] utilized physically based models in conjunction with Geographic Information System (GIS) techniques to perform a thorough assessment of storm surge risks, thereby underscoring the critical importance of this methodological approach. Employed physically based models and GIS techniques to comprehensively assess storm surge risks, highlighting this need. Additionally, Hidayah [19] points out that an integrated assessment of flood vulnerability, incorporating various elements through GIS, can provide a more nuanced understanding of vulnerability levels in specific locations. This underscores the need for studies that connect climate impacts with infrastructure development in vulnerability assessments.

While vulnerability and risk assessment frameworks have evolved, there is still a lack of comprehensive studies that examine the multidimensional aspects of vulnerability. This includes integrating environmental factors and physical infrastructure into a unified approach. Badawy et al. [20] emphasize the importance of using a multidimensional model to assess vulnerability in underdeveloped regions, considering criteria such as exposure to environmental factors. Similarly, Guragain and Doneys [21] present an index-based gender analysis focused on areas prone to flooding, highlighting the need to consider social, economic, environmental, and physical vulnerabilities in assessments. These studies underline the necessity for frameworks that address the complex nature of vulnerability rather than treating its components in isolation.

Most prior studies have primarily focused on specific regions, with limited global comparisons that explore the major contributors in the field. For example, Souza et al. [22] conducted a comprehensive analysis of climate change risks in small municipalities in the Amazon; however, the findings are often not applicable to broader contexts. While a growing number of influential authors and journals are dedicated to environmental vulnerability, systematic efforts to identify and map these contributors are still scarce. Liu et al. [23] highlight that previous studies evaluating vulnerability to storm surges in coastal regions of China have inadequately addressed the multidimensional aspects of vulnerability. This vulnerability is shaped by various social, economic, physical, and environmental factors. This underscores the need for a global vulnerability research perspective that surpasses regional boundaries. The changing trends in research keywords have not been thoroughly explored, resulting in an incomplete understanding of the key themes that drive the discourse. This study's bibliometric analysis aims to fill this gap by identifying influential authors, journals, and countries contributing to environmental and physical vulnerability discussions. This approach is supported by the work of Molenaar et al. [24], who highlight the importance of utilizing routinely collected data to predict multidimensional vulnerability. Molenaar suggests systematically mapping research trends can improve understanding of evolving research priorities.

The literature analysis was approached with a clear focus on four key research questions as follows:

1. Who are the most influential authors, and which countries have contributed significantly to the literature on environmental and physical vulnerability in coastal and riverside areas?
2. Which journals are the most influential, and what are the highly cited publications that significantly advance the literature on environmental and physical vulnerability in coastal and riverside areas?
3. What are the relevant keyword perspectives in the research field?
4. What is the most popular research topic based on?

2. Methodology

The method being utilized is known as Systematic Literature Review, a systematic, explicit, and comprehensive approach that enables the identification, evaluation, and synthesis of existing research conducted by researchers. The Systematic Literature Review adoption involves six stages [26, 27] described in Figure 1; they are:

1. Clearly delineate the research question that the study intends to address.
2. Employ search terms that incorporate all pertinent studies that satisfy the eligibility criteria.
3. Conduct a thorough assessment of the quality and validity of the chosen studies, ensuring a thorough assessment of the risk of bias and the level of confidence in the cumulative estimates.
4. Present and synthesize the extracted data from the selected studies systematically and comprehensively.
5. Analyze data using quantitative categories, descriptions, etc., and show the trends, gaps, and discussion of results.
6. Ensure the study findings are readily accessible for scientific purposes and informed decision-making.

In this study, a carefully selected dataset was subjected to quantitative exploration in conjunction with a bibliometric analysis. This study aims to identify and analyze environmental and physical vulnerability literature to map the knowledge structure. In the initial part of the study, a performance analysis and scientific mapping were conducted. Scientific or bibliometric mapping provides a visual representation of the relationships between different disciplines, fields, specialities, individual papers, and authors [31]. This study uses a database to search the literature. The database used is Scopus.

The application allows for search and filtering. Tools are selected to aid in finding specific journals and restrict the search to published journals the researcher desires.

The data search was conducted on July 9, 2024, using published data from 2015 to 2024 in the publication database Scopus. This research used the following data string in Table 1.

To improve the clarity of the study's methodology, this study has outlined the inclusion and exclusion criteria for selecting articles for this review:

2.1. Inclusion Criteria

- Studies that address both climate-related and non-climate-related hazards, particularly those focused on the development and risks associated with coastal or surface water infrastructure.
- Research must analyze environmental and physical vulnerability or risk, specifically concerning the impact on people, populations, or infrastructure due to coastal or surface water hazards.
- Studies must include at least one map that illustrates vulnerability or risk, demonstrating the integration of environmental and physical dimensions or highlighting indirect coastal or surface water hazards affecting these dimensions.

2.2. Exclusion Criteria

- Articles that do not focus on coastal or surface water hazards or that do not discuss vulnerability and risk.
- Studies that fail to provide relevant maps or visualizations integrating environmental and physical vulnerability dimensions.
- Non-English publications or those lacking clear, actionable insights related to the research question.
- In order to maintain a focus on peer-reviewed journal articles, non-journal publications, including conference proceedings, books, and reports, have been excluded from consideration.

After applying the search strings and obtaining initial results, a manual review was conducted to ensure all included papers met the predefined inclusion criteria. The quality of the studies was assessed based on their relevance to the thematic focus and methodological rigor. This review process involved thorough checks of each paper's relevance, rigor, and data quality.

2.3. Results of the Selection Process

Initially, 160 articles pertaining to environmental vulnerability and 134 articles related to physical vulnerability were retrieved from the Scopus database. After applying the inclusion and exclusion criteria, the final selection comprised:

- 53 articles on physical vulnerability (from the original 134).
- 37 articles on environmental vulnerability (from the original 160).

This final set of articles was utilized to perform a bibliometric analysis using VOSviewer, resulting in a comprehensive scientific map of the field.

Table 1. Documents obtained from searches in scopus

Search String	Results
TITLE-ABS-KEY (environmental AND vulnerability) AND PUBYEAR > 2014 AND (LIMIT-TO (SUBJAREA , "ENVI")) AND (LIMIT-TO (EXACTKEYWORD , "Environmental Vulnerability")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))	160
TITLE-ABS-KEY (physical AND vulnerability) AND PUBYEAR > 2014 AND (LIMIT-TO (EXACTKEYWORD , "GIS")) AND (LIMIT-TO (SUBJAREA , "ENVI")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))	134

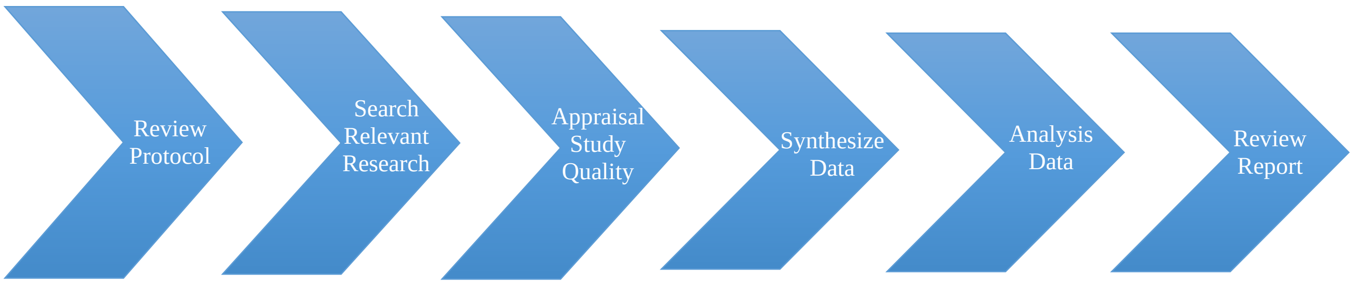

Fig. 1 Step followed for systematic literature review

Sources: Modified from Mengist et al. (2020)

2.4. Limitation of the Bibliometric Approach

While bibliometric analysis offers valuable insights into the research landscape, it has several limitations that should be acknowledged [32]:

1. The analysis results rely heavily on the quality and comprehensiveness of the data available in the selected databases. Scopus was the primary source of this study; however, there may be relevant studies that were not indexed in this database.
2. Although the manual review process was thorough, it may introduce subjective bias in selecting studies, particularly when assessing the relevance and quality of each article.
3. Bibliometric analysis depends on citation data, which may not accurately reflect the true impact or quality of a paper. Some important studies may not receive heavy citations but still significantly contribute to the field.
4. The studies selected were restricted to those published between 2015 and 2024, potentially overlooking older yet foundational research. Furthermore, the geographic focus was limited to coastal or surface water hazards, which may exclude relevant studies from other environmental contexts.

3. Results and Discussion

This section discusses the results of a thorough analysis of scientific publications from 2015 to 2024 related to physical and environmental vulnerability in surface water areas, particularly coastal areas. The results are presented in alignment with the research questions outlined in the introduction section. The main objective of this bibliometric analysis is to provide a thorough overview of historical, current, and upcoming trends in research on the susceptibility of physical and environmental factors in surface water areas.

3.1. Authors and Countries Contributed to the Publication of the Literature on Environmental and Physical Vulnerability

3.1.1. Co-Authorship

Co-authorship analysis investigates the collaborative relationships among researchers and institutions by assessing the quantity of jointly authored publications. This approach provides valuable insights into academic partnerships and the interconnectedness of scholarly work. This analysis is conducted to comprehend the patterns of scientific collaboration within specific research fields.

After conducting a thorough manual review of articles focusing on the environmental vulnerability of surface water areas, 37 relevant articles were obtained and analyzed. Using VOSviewer for bibliometric analysis, a total of 182 authors were identified who met the minimum publication threshold of one publication per author. Figure 2 and Table 2 present the top fifteen authors ranked according to the total link strength of their co-authorship in the academic literature on environmental vulnerability in surface water areas. The co-authorship analysis within the field of environmental vulnerability highlights a robust network of collaboration among prominent researchers, with authors such as Campos Jasmines Alves, Demetrius David Da Silva, and De Menezes Filho emerging as the most influential contributors. These authors have published three notable papers and garnered significant citations, demonstrating their critical role in furthering the study of environmental vulnerability. Their research has been instrumental in guiding the exploration of climate change impacts and other environmental threats to ecosystems and communities. For instance, studies conducted by these authors have utilized GIS-based methodologies to evaluate the vulnerability of coastal regions, providing essential insights into the risks associated with sea-level rise and storm surges [33, 34].

Such research is vital for local governments as they plan infrastructure investments and develop policies to mitigate environmental risks. Other noteworthy contributors, including Aires, Amorim, and De Melo Ribeiro, have made significant strides in the field despite having fewer publications. Their research has predominantly concentrated on localized aspects of environmental vulnerability, particularly examining the effects of land-use changes and urban expansion on natural habitats [33, 35].

This work offers valuable insights into how human activities intensify environmental risks, especially in rapidly developing urban areas. For example, Aires and collaborators have focused on pinpointing regions along Brazil's Atlantic coast most susceptible to coastal erosion [36]. They have proposed targeted recommendations for erosion control, such as dune restoration and beach nourishment. These strategies are crucial for safeguarding vulnerable coastal communities and their livelihoods.

Using the approach mentioned earlier, a total of 53 articles were collected and assessed regarding the physical vulnerability of surface water areas. Employing VOSviewer for bibliometric analysis and setting the minimum publication threshold at one per author resulted in the identification of 205 authors meeting the threshold. Figure 3 and Table 3 present the top fifteen authors ranked by the total link strength of their co-authorship in the literature on physical vulnerability in surface water areas.

The co-authorship analysis of the literature on physical vulnerability underscores the collaborative nature of research in this domain. Key authors, including Anita Arguedas, Daniela De Gregorio, and Susanne Ettinger, each with one publication, 64 citations, and a total link strength of 13, have made significant contributions to the field despite a limited number of publications. Their work is highly regarded and frequently cited, reflecting the meaningful impact they have had on the landscape of physical vulnerability. For instance, the researchers have concentrated on assessing vulnerability in regions affected by natural hazards, thereby contributing to vulnerability assessments that inform disaster risk management policies [37]. The research has practical implications in disaster-prone areas, where a better understanding of vulnerability can aid in making informed decisions regarding infrastructure development and resilience planning. Biswajeet Pradhan, distinguished by his four significant publications and 203 citations, is recognized for his extensive contributions to the field, particularly in multicriteria decision-making methods for vulnerability mapping. His research on landslide risk assessment and coastal vulnerability is especially impactful in countries such as India and Bangladesh, where rapid urbanization and coastal development heighten the risks associated with natural hazards. Pradhan's methodologies effectively identify the most vulnerable regions and prioritize resources for disaster preparedness, thereby enhancing informed and efficient disaster management practices [38, 39].

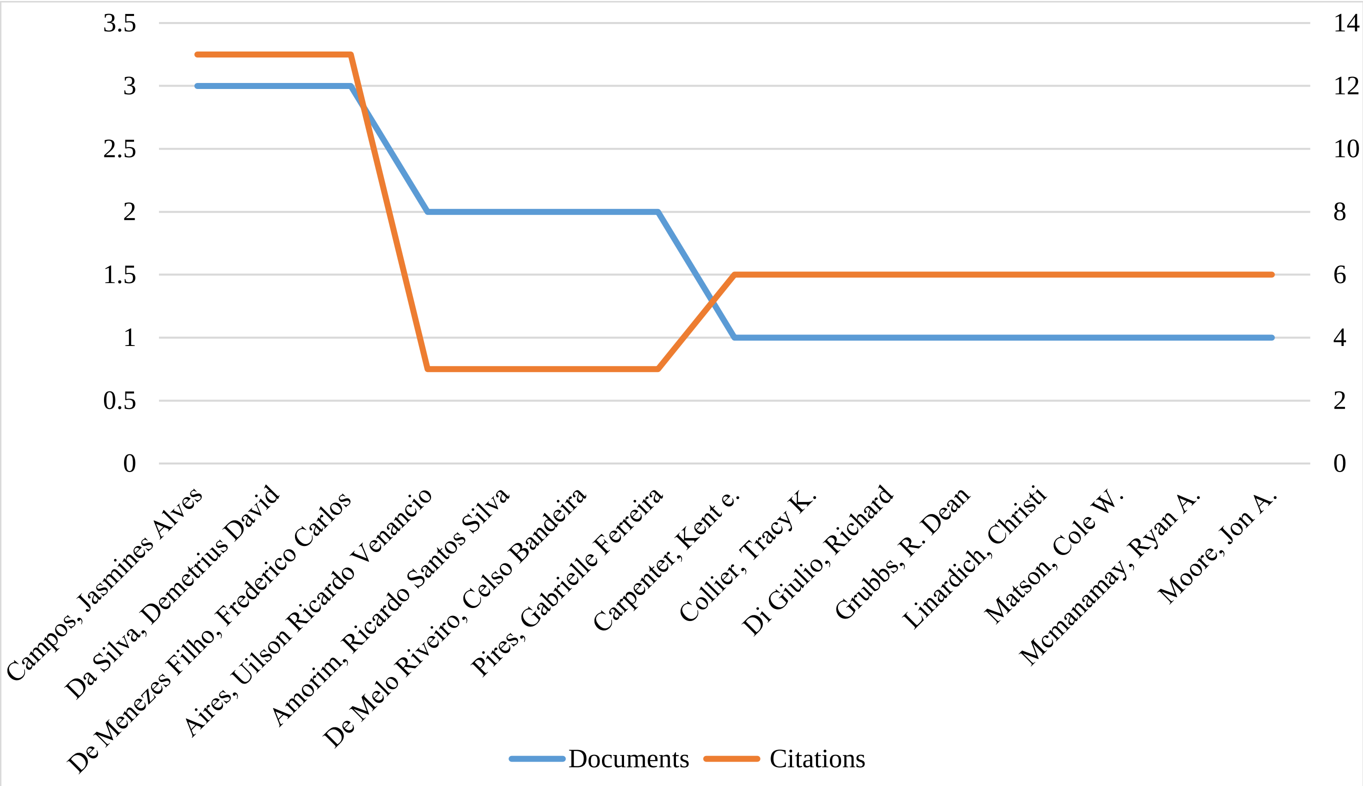

Fig. 2 The top fifteen authors ranked by total co-authorship link strength in environmental vulnerability literature

Table 2. The fifteen most collaborative authors in the sample on environmental vulnerability

No	Authors	Documents	Citations	Total Link Strength
1	Campos, Jasmines Alves	3	13	19
2	Da Silva, Demetrius David	3	13	19
3	De Menezes Filho, Frederico Carlos	3	13	19
4	Aires, Uilson Ricardo Venancio	2	3	16
5	Amorim, Ricardo Santos Silva	2	3	16
6	De Melo Riveiro, Celso Bandeira	2	3	16
7	Pires, Gabrielle Ferreira	2	3	16
8	Carpenter, Kent e.	1	6	13
9	Collier, Tracy K.	1	6	13
10	Di Giulio, Richard	1	6	13
11	Grubbs, R. Dean	1	6	13
12	Linardich, Christi	1	6	13
13	Matson, Cole W.	1	6	13
14	Mcmanamay, Ryan A.	1	6	13
15	Moore, Jon A.	1	6	13

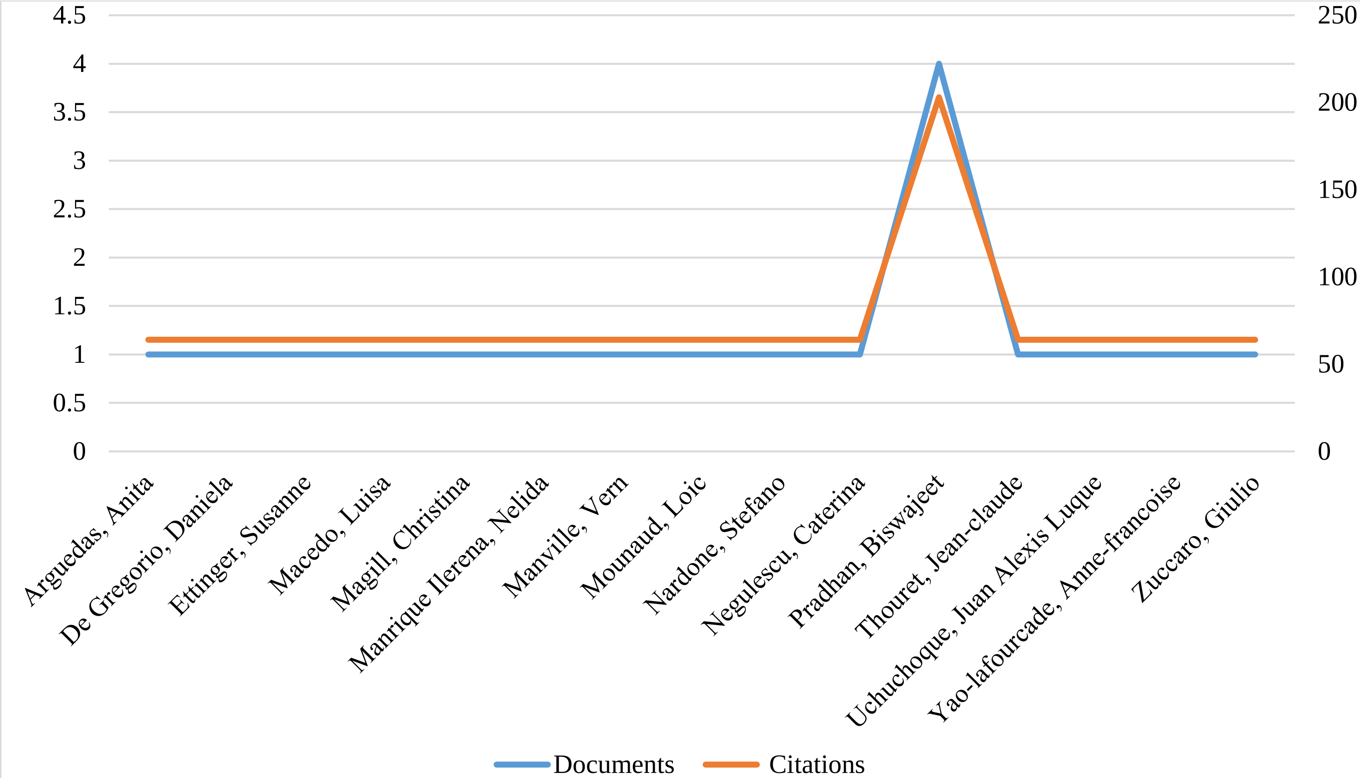

Fig. 3 The top fifteen authors ranked by total co-authorship link strength in the literature on physical vulnerability

Table 3. The top fifteen authors ranked by total link strength in the co-authorship literature on physical vulnerability

No	Authors	Documents	Citations	Total Link Strength
1	Arguedas, Anita	1	64	13
2	De Gregorio, Daniela	1	64	13
3	Ettinger, Susanne	1	64	13
4	Macedo, Luisa	1	64	13
5	Magill, Christina	1	64	13
6	Manrique Ilerena, Nelida	1	64	13
7	Manville, Vern	1	64	13
8	Mounaud, Loic	1	64	13
9	Nardone, Stefano	1	64	13
10	Negulescu, Caterina	1	64	13
11	Pradhan, Biswajeet	4	203	13
12	Thouret, Jean-claude	1	64	13
13	Uchuchoque, Juan Alexis Luque	1	64	13
14	Yao-lafourcade, Anne-francoise	1	64	13
15	Zuccaro, Giulio	1	64	13

3.1.2. Countries

Figure 4 presents an overview of the 15 countries at the forefront of research on environmental vulnerability in coastal areas, categorized by the number of published articles. This analysis aims to thoroughly explore the importance of these nations in this field of study. Furthermore, Table 4 details the total number of citations and the average number of citations per publication. It is noteworthy that China, with 8 articles cited 326 times, and India, with 4 articles cited 254 times, are identified as the most influential contributors to the research and dissemination of knowledge regarding environmental vulnerability in surface water areas. The growth and direction of environmental vulnerability research are greatly influenced by governmental and international policies, especially in rapidly developing countries like China and India. These nations have implemented national policies aimed at tackling urgent environmental challenges, which in turn stimulates research into environmental vulnerability. In China, for example, the government has incorporated environmental protection, climate change mitigation, and sustainable development into its national frameworks. This has resulted in a significant increase in research focused on environmental vulnerability, particularly in coastal areas, as researchers are motivated to create comprehensive methodologies that align with governmental objectives [40]. China's strategy involves integrating environmental targets into its five-year plans and using market-based mechanisms in conjunction with traditional regulatory measures. These policies have been crucial in encouraging corporate environmental responsibility and boosting research efforts related to environmental vulnerability [41]. The focus on incorporating vulnerability assessments into national frameworks not only aids the scientific community in developing effective methodologies but also aligns with broader sustainable development goals [42]. Similarly, India has seen a growing focus on sustainability and urban ecology, driven by national policies that aim to address urbanization and environmental sustainability. Achieving Sustainable Development Goals (SDGs) is complex and requires a balanced policy framework that takes into account both urban and rural dynamics [34]. The relationship between government policies and research initiatives is vital, as these policies often promote migration to urban areas. This migration increases the need for environmental vulnerability assessments in these rapidly changing landscapes [34]. Chile has made notable contributions to environmental vulnerability research, particularly concerning coastal erosion, although its efforts are smaller compared to those of countries like India or China. The country's unique coastline, with its rugged terrain and urban settlements, has been a focal point for vulnerability studies. Recent research highlights the impacts of coastal erosion on ecosystems and infrastructure, documenting significant changes in areas such as La Herradura and Tongoy, which have been affected by urban development and tourism [43]. The National Coastal Management Plan employs vulnerability assessments to identify erosion-prone zones. Véliz [44] emphasizes the importance of the Coastal Vulnerability Index (CVI) and its application in the Valparaíso region. Additionally, Martínez et al. [45] provide insights into how tectonic activity influences coastal erosion, underscoring the necessity for adaptive management strategies. Villagrán et al. [46] further illustrate the sensitivity of Chilean beaches to environmental changes, highlighting the importance of incorporating scientific research into policy frameworks. Meanwhile, Figure 5 and Table 5 provide a comprehensive overview of the countries making impactful contributions to physical vulnerability research. Notably, India has emerged as the leading influencer in developing and disseminating publications on physical vulnerability research in coastal areas, with 12 articles cited a remarkable 421 times.

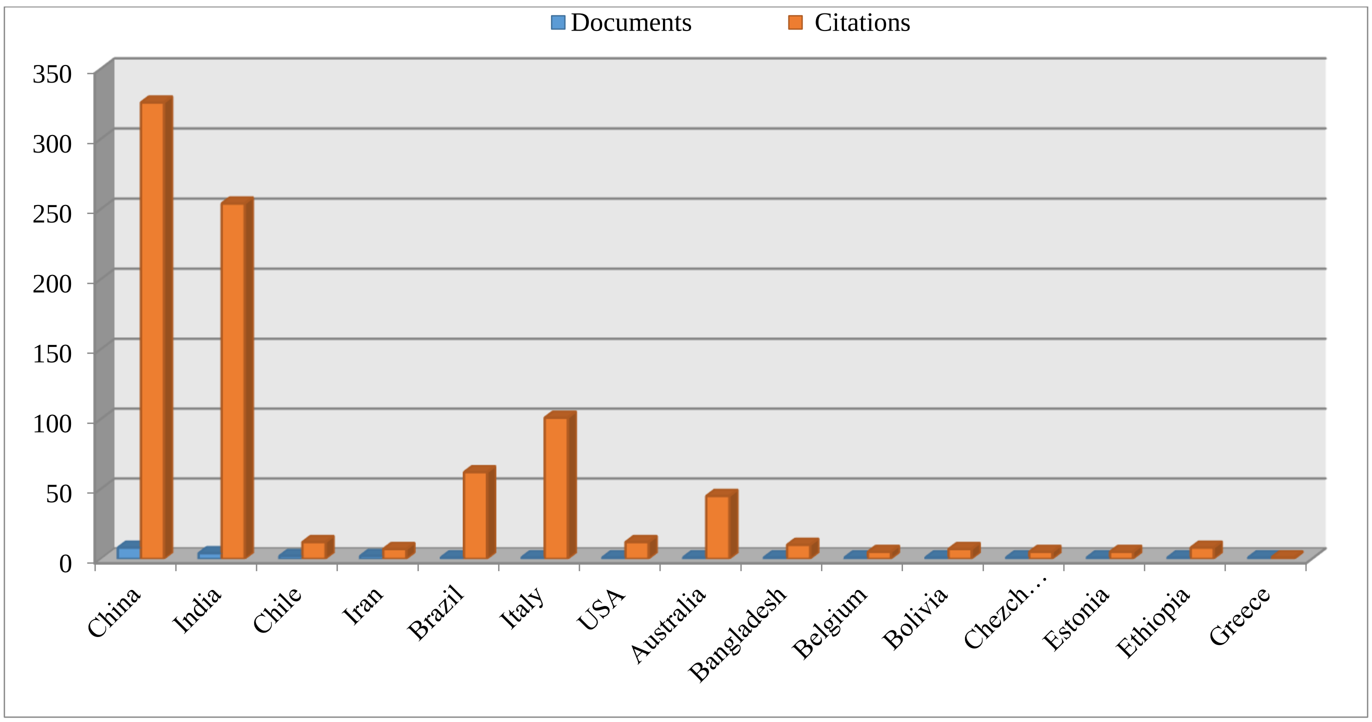

Fig. 4 The top fifteen countries contributed to publications related to environmental vulnerability in surface water areas

Table 4. The top fifteen countries that contributed to publications on environmental vulnerability in surface water area

No	Countries	Documents	Citations	Total Link Strength
1	China	8	326	4
2	India	4	254	1
3	Chile	2	12	0

4	Iran	2	7	0
5	Brazil	1	62	1
6	Italy	1	101	1
7	USA	1	12	1
8	Australia	1	45	0
9	Bangladesh	1	10	0
10	Belgium	1	5	0
11	Bolivia	1	7	0
12	Czech Republic	1	5	0
13	Estonia	1	5	0
14	Ethiopia	1	8	0
15	Greece	1	1	0

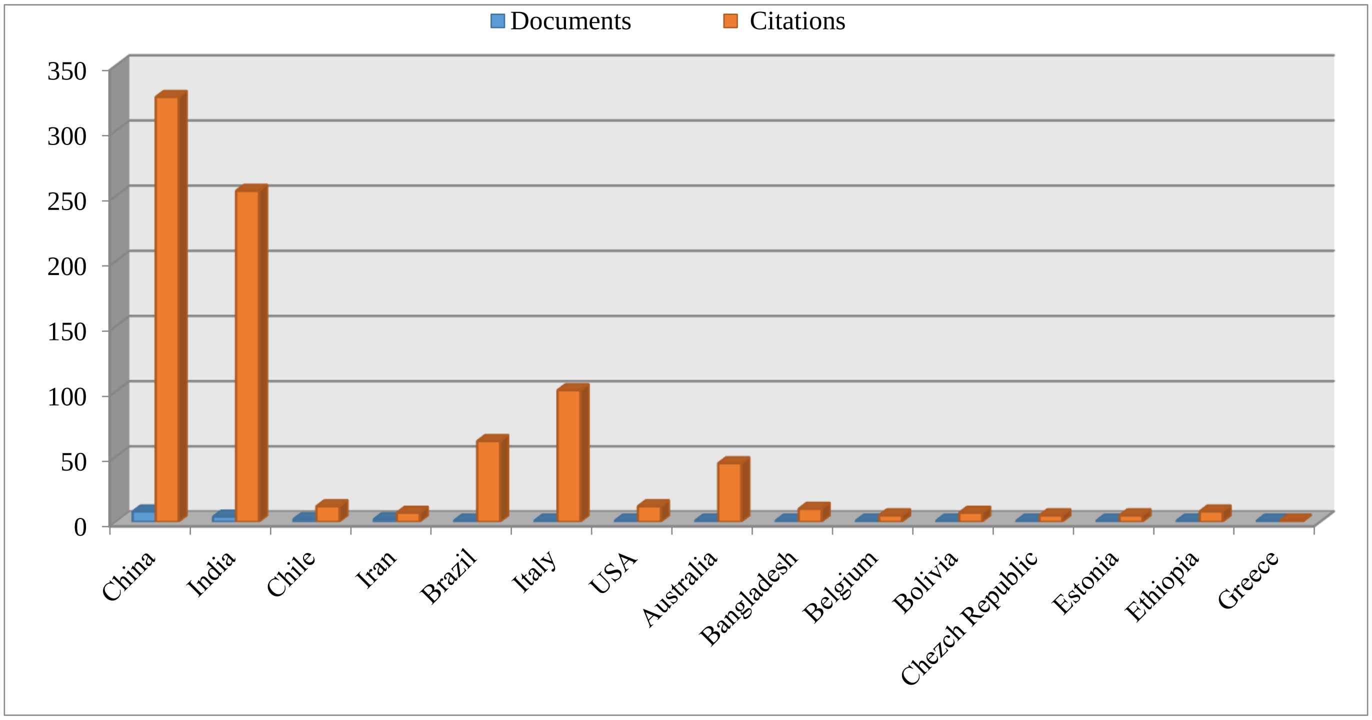

Fig. 5 The top fifteen countries contributed to publications related to physical vulnerability in surface water areas

Table 5. The top fifteen countries contributed to publications related to physical vulnerability in surface water areas

No	Countries	No. of. Articles	Citations	Total Link Strength
1	India	12	421	23
2	Australia	6	427	5
3	UK	6	189	2
4	Bangladesh	5	327	5
5	Egypt	5	92	2
6	Italy	5	278	2
7	Malaysia	4	131	3
8	South Korea	4	155	3
9	Saudi Arabia	3	131	3
10	Portugal	3	84	2
11	China	3	44	1
12	Lebanon	1	35	7
13	Algeria	2	34	2
14	Oman	2	33	2
15	Brazil	1	42	4

India's contribution to physical vulnerability research, particularly in the context of climate change, is significant and multifaceted. The country's extensive coastline, which supports vital economic activities such as fishing, agriculture, and tourism, is increasingly threatened by climate change impacts, including flooding, storm surges, and rising sea levels. This vulnerability has spurred a robust body of research, with Indian scholars leading the way in physical vulnerability assessments. Recent studies indicate that India has produced a notable number of publications in this area, focusing on physical vulnerability assessments, positioning it as a global hub for vulnerability studies in coastal regions [47, 48]. A key initiative in this context is the Indian National Adaptation Programme of Action (NAPA), which emphasizes the importance of integrating vulnerability assessments into its strategies. NAPA aims to protect coastal populations by addressing the risks associated with climate change, thus informing policy recommendations that promote the development of adaptive infrastructure and community-based management strategies [47, 49]. The need for such adaptive measures is underscored by research highlighting the increasing frequency and intensity of climate-related events, which require a proactive approach to enhance infrastructure resilience [48]. For example, the adaptation strategies outlined in NAPA are crucial for mitigating the adverse effects of climate change on vulnerable communities, particularly in coastal areas where economic activities heavily depend on stable environmental conditions [49].

Additionally, research conducted by Indian scholars not only contributes to academic discussions but also plays a vital role in shaping policies to improve resilience to climate change. Studies have demonstrated that effective adaptation strategies, such as community-based approaches and infrastructure improvements, are essential for protecting livelihoods in vulnerable sectors [49, 50]. Focusing on local adaptive strategies is particularly relevant in India's diverse socioeconomic landscape, where tailored interventions can significantly enhance resilience to climate-induced vulnerabilities [51]. Moreover, The influence of international frameworks, particularly the United Nations' Sustainable Development Goals (SDGs), plays a significant role in shaping national policies and research priorities related to climate change impacts on vulnerable populations, especially coastal communities. For example, SDG 13 emphasizes the urgent need for action against climate change, prompting countries like Australia and the UK to focus on adaptation strategies for their coastal regions [52, 53].

In Australia, incorporating the Sustainable Development Goals (SDGs) into national policies has led to reevaluating public health frameworks to address vulnerabilities related to climate change. Recent studies indicate that the New South Wales government has adopted these frameworks to improve public health adaptation strategies in response to climate challenges [54]. This approach aligns with a broader trend observed in various coastal communities, where awareness of climate risks has increased, often fueled by local adaptation plans and community engagement initiatives [55]. Such proactive measures are essential for building resilience among populations increasingly aware of their susceptibility to climate-related risks. Research in the UK has highlighted the importance of understanding the socioeconomic factors contributing to coastal vulnerability. The Sustainable Development Goals (SDGs) have spurred investigations into the spatial and temporal relationships between socioeconomic development and changes along shorelines. This emphasizes the necessity for comprehensive management strategies considering environmental and human factors. Implementing frameworks that evaluate sustainability performance in coastal management has been crucial for developing effective adaptation strategies, ensuring that coastal communities can endure the challenges posed by climate change [52, 56].

Similarly, Research in the UK has highlighted the importance of understanding the socioeconomic factors that contribute to coastal vulnerability. The Sustainable Development Goals (SDGs) have spurred investigations into the spatial and temporal relationships between socioeconomic development and changes along shorelines. This emphasizes the necessity for comprehensive management strategies that take into account both environmental and human factors [57, 58] Implementing frameworks that evaluate sustainability performance in coastal management has been crucial for developing effective adaptation strategies, ensuring that coastal communities can endure the challenges posed by climate change [52, 56].

3.2. Most Active Source Titles For Publications And Highly Cited Publications Related to Environment and Physical Vulnerability

3.2.1. Active Source Titles for Publications

A sample of 37 articles revealed that 17 distinct journal sources have contributed to the literature on environmental vulnerability, with each source publishing at least one article. The Science of the Total Environment is the leading journal in terms of publication volume, featuring 9 articles and 59 citations. This highlights its significant role in advancing research on environmental vulnerability, particularly in surface water areas. Ecological Indicators follows closely, with 7 articles but a much higher citation count of 477, indicating its substantial influence in the field. Conversely, Environmental Monitoring and Assessment has published only 4 articles yet remains a key source, boasting a respectable citation count of 8. The variety of sources listed in Figure 6 and Table 6 underscores the breadth of research being conducted in this area. A noteworthy observation is the diverse citation patterns among the journals. For instance, while journals like Ecological Indicators enjoy high citation rates despite a moderate number of publications, others such as Environmental Science and Policy and Marine Pollution Bulletin have seen minimal citation impacts. This variability suggests that some may have a more niche audience or represent a newer body of work. Understanding these citation patterns is crucial for researchers as it can help identify leading publications in the study of environmental vulnerability. A larger sample of 53 articles from 28 different journals was analyzed for physical vulnerability, maintaining a minimum threshold of one publication per source. The findings indicate that Natural Hazards is the most prolific journal, publishing 9 articles with a total of 108 citations. Ocean and Coastal Management closely follows, having published 8 articles and accumulating 549 citations, which highlights not only its productivity but also its significant influence in the field. Additionally, Environmental Earth Sciences and Journal of Coastal Conservation, each with 4 articles, make notable contributions, underscoring the importance of journals focused on environmental and coastal sciences. As illustrated in Figure 7 and Table 7, several journals stand out regarding citation impact. Notably, Ocean and Coastal Management has a high citation count relative to the number of articles it has published. The clustering of citation data around key journals reveals important intersections in research on physical vulnerability, especially between Ocean and Coastal Management and Natural Hazards, with numerous citations linking them from 2019 to 2021.

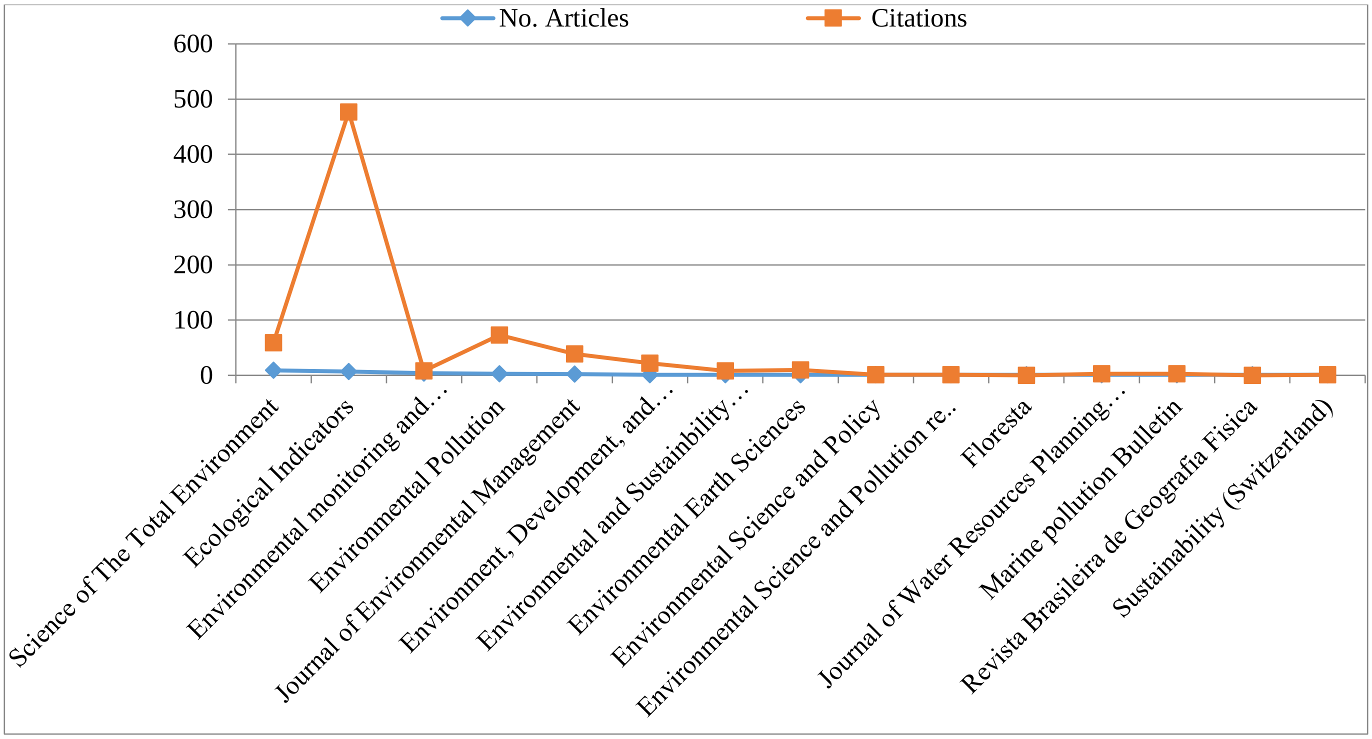

Fig. 6 The most active source titles for publications related to environmental vulnerability in surface water area

Table 6. The most active source titles for publications related to environmental vulnerability in surface water area

No	Publication Titles	No. of. Articles	Citations	Total Link Strength
1	Science of the Total Environment	9	59	0
2	Ecological Indicators	7	477	1
3	Environmental monitoring and Assessment	4	8	1
4	Environmental Pollution	3	73	0
5	Journal of Environmental Management	2	39	0
6	Environment, Development, and Sustainability	1	22	0
7	Environmental and Sustainability Indicators	1	8	0
8	Environmental Earth Sciences	1	10	0
9	Environmental Science and Policy	1	1	0
10	Environmental Science and Pollution	1	1	0
11	Floresta	1	0	0
12	Journal of Water Resources Planning and Management	1	3	0
13	Marine Pollution Bulletin	1	3	0
14	Revista Brasileira de Geografia Fisica	1	0	0
15	Sustainability (Switzerland)	1	1	0

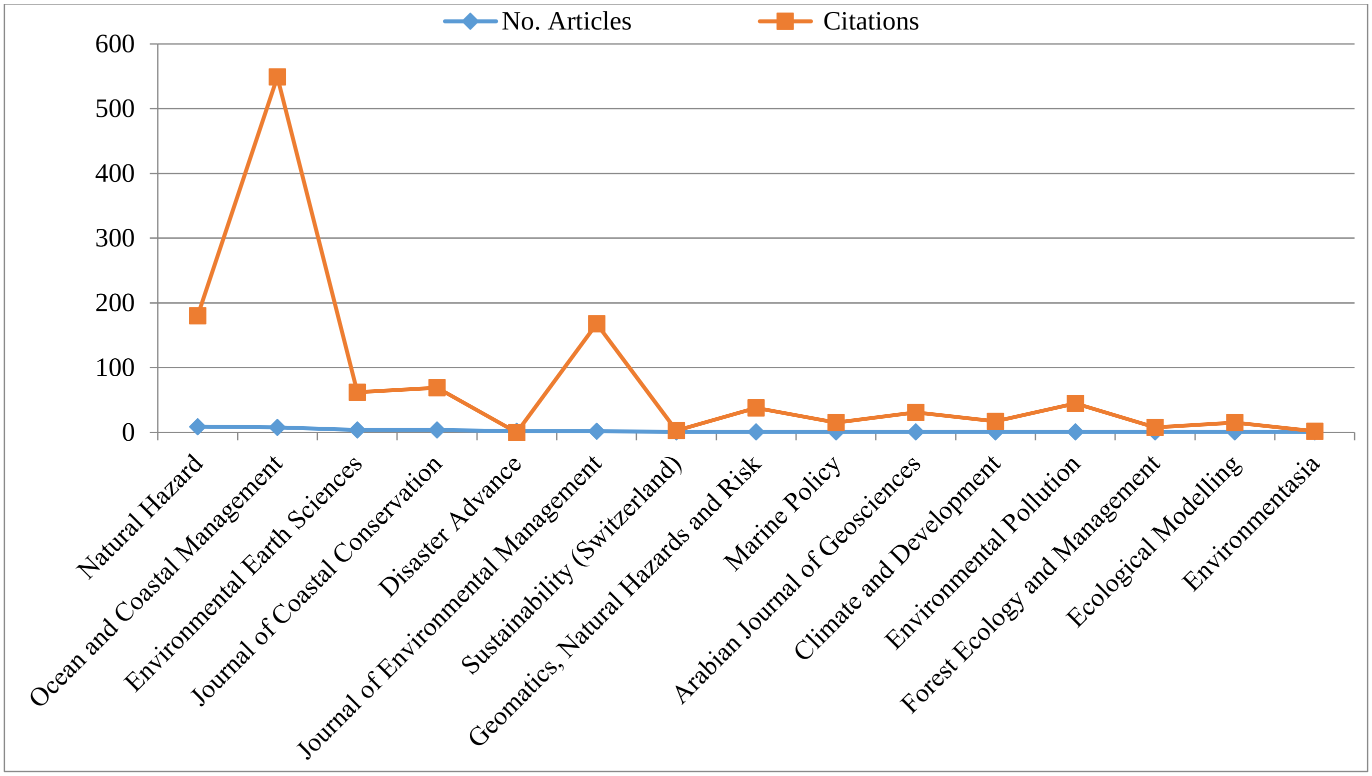

Fig. 7 The most active source titles for publications related to physical vulnerability in surface water area

Table 7. The most active source titles for publications related to physical vulnerability in surface water area

No	Source Titles	No. of. Articles	Citations	Total Link Strength
1	Natural Hazard	9	180	1
2	Ocean and Coastal Management	8	549	5
3	Environmental Earth Sciences	4	62	2
4	Journal of Coastal Conservation	4	69	2
5	Disaster Advance	2	0	0
6	Journal of Environmental Management	2	168	6
7	Sustainability (Switzerland)	1	3	2
8	Geomatics, Natural Hazards and Risk	1	38	1
9	Marine Policy	1	15	1
10	Arabian Journal of Geosciences	1	31	0
11	Climate and Development	1	17	0
12	Environmental Pollution	1	45	0
13	Forest Ecology and Management	1	8	0
14	Ecological Modelling	1	15	0
15	Environmentasia	1	2	0

The analysis of citation data, particularly the clustering observed in Figures 8 and 9, provides valuable insights into the dynamics of research on environmental and physical vulnerability. In Figure 8, the yellow cluster represents environmental vulnerability research published in 2024, featuring prominent journals such as Environmental Science and Policy and Environmental Science and Pollution.

The strong connections between journals published in later years correlate with the higher citation counts for these more recent publications, highlighting the increasing importance and recognition of newer studies in the environmental vulnerability field. Similarly, Figure 9 illustrates physical vulnerability research through notable clusters of interconnected journal sources.

For instance, the Ocean and Coastal Management cluster from 2019 to 2020 demonstrates the long-term academic influence of this journal. The Journal of Environmental Management and Natural Hazards also contribute to significant clusters, representing their ongoing relevance in physical vulnerability research.

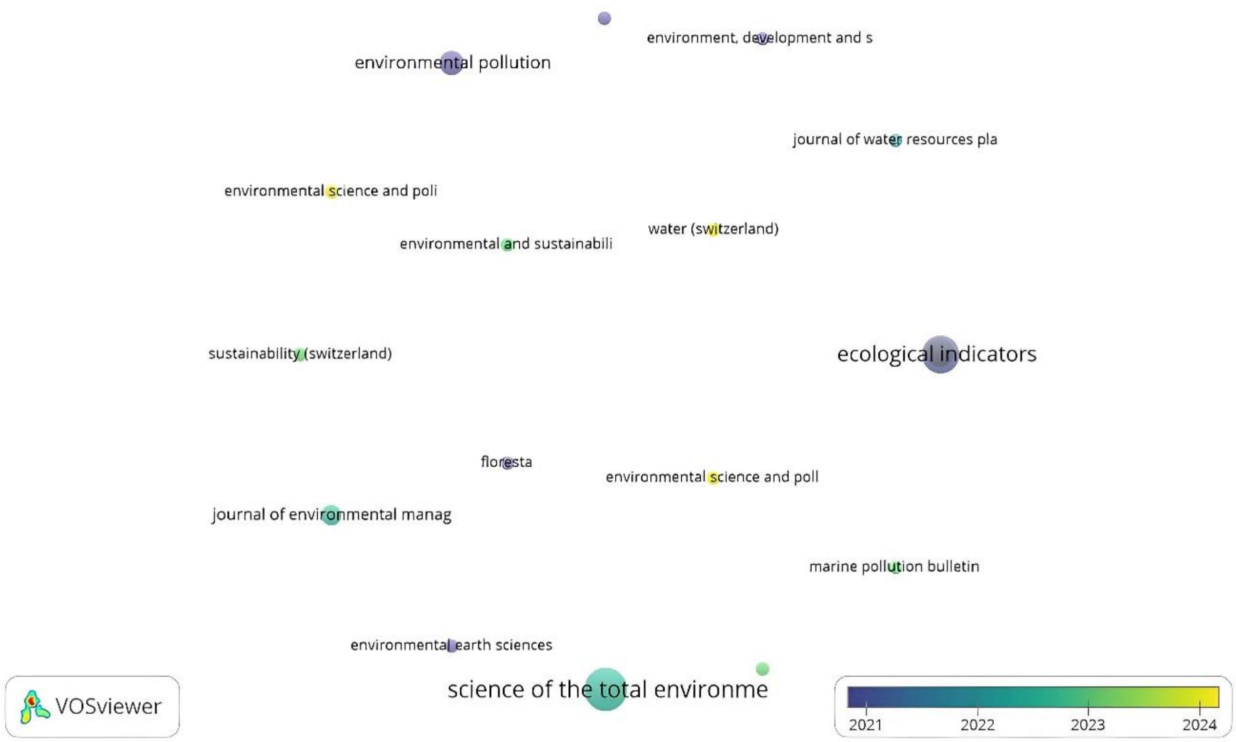

Fig. 8 Mapping of sources for environmental vulnerability research journals by year of publication

Interestingly, Figure 9 showcases the interconnections among key journals in physical vulnerability. Figure 8 reveals a lack of interconnectedness in environmental vulnerability research. This suggests that the landscape of environmental vulnerability research is currently more fragmented, with less direct citation overlap among journals. This fragmentation may indicate the emergence of new areas of study or a more dispersed academic focus within the field.

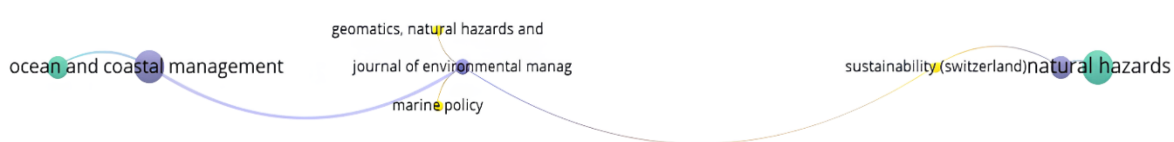

Fig. 9 Mapping of sources for physical vulnerability research journals by year of publication

3.2.2. Co-Citation Analysis

Co-citation analysis is essential for understanding the relationships between publications and identifying key themes within a research field. By examining how often certain references are cited together, this study gains valuable insights into the interconnectedness of research topics and their evolution over time. Ferreira [59] emphasizes that this method is particularly effective for uncovering meaningful connections between publications that may not be immediately apparent through traditional citation analysis. This study conducted a co-citation analysis of 37 articles related to environmental vulnerability, which collectively cited 2,494 sources. To ensure the relevance of these findings, a minimum citation threshold of 2 was applied, resulting in the inclusion of 46 references that met this criterion. Figure 10 presents a network diagram that visualizes the co-citation relationships among researchers in environmental vulnerability. The figure reveals three main clusters of cited references: a large red cluster containing 9 interconnected references, a green cluster with 4 references, and a blue cluster with 3 references. Within the Red Cluster, several authors utilize holistic, GIS-based methods that integrate ecological, physical, and socioeconomic data to offer multidimensional insights into environmental vulnerability. For example, Depellegrin and colleagues [60] studied the Northern Adriatic Sea by combining shoreline morphology, land-use patterns, and ecological sensitivity to identify erosion and pollution "hotspots." Their findings informed coastal planning policies in Italy and Slovenia, balancing tourism development with ecosystem protection. Besides, Pereira and collaborators [61] focused on wildfire risk in Portugal and Spain, employing remote sensing, field surveys, and multicriteria evaluation to identify high-risk forested and rural areas.Their work guided local agencies in reforestation, soil conservation, and firefighting resource allocation.

Meanwhile, Amir-Heidari et al. [62] created composite indices for coastal Iran in the Persian Gulf, incorporating wave energy, tidal range, and settlement density. This approach pinpointed critical areas vulnerable to sea-level rise and oil spills, assisting municipal authorities in planning more effectively for climate change and industrial hazards. The Green Cluster addresses physical and geomorphological vulnerability, particularly shoreline sensitivity and oil spill risks. Anfuso G. and Postacchini M. [63] lead research on coastal erosion and morphodynamic processes in regions like the Spanish Mediterranean and Italian Adriatic coasts.

Their sediment transport and shoreline retreat studies inform effective erosion control strategies, including beach nourishment and dune restoration. Environmental agencies and local governments rely on these classifications to prepare for oil spills and guide protective measures and construction planning. The Blue Cluster focuses on specialized, region-specific studies that connect conceptual frameworks with localized assessments. Alves et al. [64] and Kokinou et al. [64], who appear in both the red and blue clusters, combine geophysical hazard data with GIS risk assessments. For instance, the studies utilize fault mapping and submarine slope analyses in the Eastern Mediterranean to inform spatial vulnerability indices. Meanwhile, the analysis of 53 articles on physical vulnerability revealed a total of 3347 cited references. By setting a minimum threshold of 2 citations for a referenced work, 79 cited references meeting this criterion were identified. The results of this analysis are visually represented in Figure 11, which shows a co-citation network diagram of researchers in the field of physical vulnerability.

This network is organized into six distinct clusters, each representing a group of highly interconnected references. The red cluster is the largest, consisting of 18 references. It represents foundational works in the field of physical vulnerability, emphasizing the relationships between environmental hazards and human systems.

Notable publications in this cluster focus on methodologies for assessing physical vulnerability, with significant contributions from authors such as Sahoo and Bhaskaran [65]. The study emphasizes the importance of combining meteorological data with Geographical Information Systems (GIS) to improve the accuracy of flood predictions. The authors employed a mix of historical cyclone data, topographical information, and hydrodynamic modeling to produce detailed inundation maps.

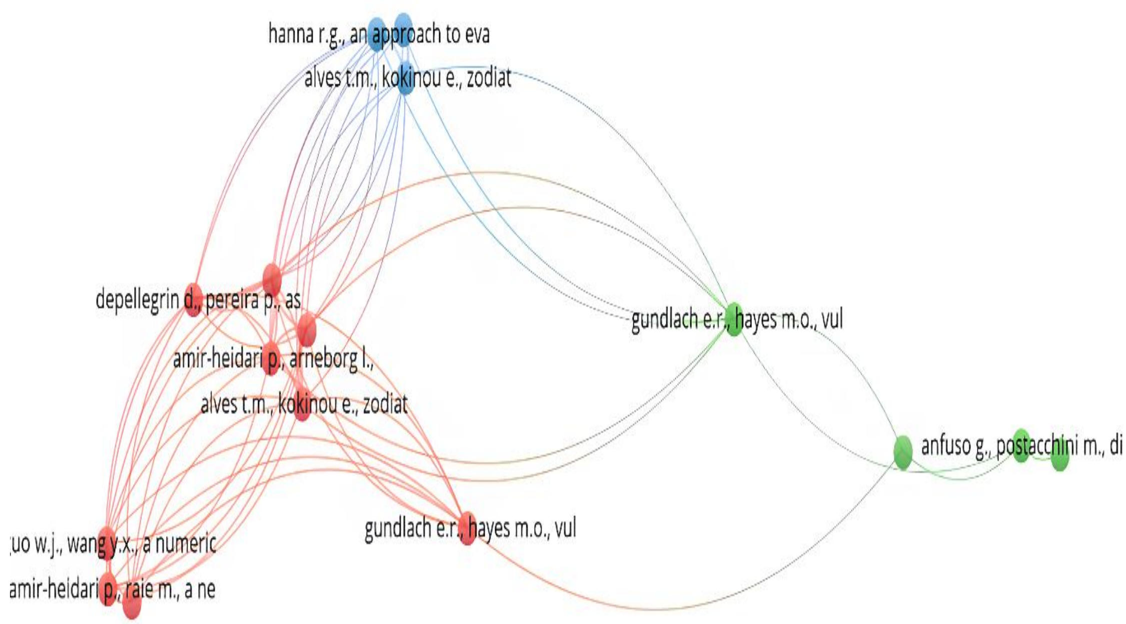

Fig. 10 The co-citation network diagram of cited references on environment vulnerability

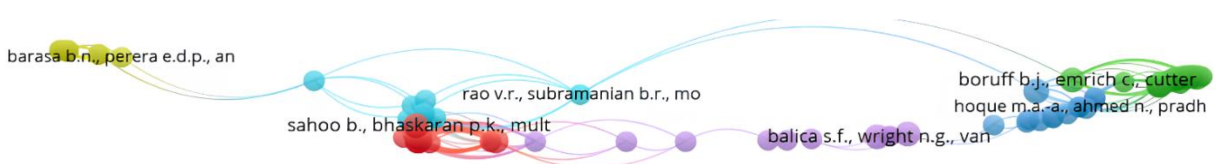

Fig. 11 The co-citation network diagram of cited references on physical vulnerability

This integration is vital for creating effective coastal management strategies and enhancing resilience against the impacts of climate change, especially in areas susceptible to extreme weather events. The purple cluster comprises 10 references focusing on the ecological aspects of physical vulnerability, particularly regarding biodiversity and ecosystem services. These studies highlight the impacts of environmental changes, such as deforestation and climate change, on the vulnerability of ecosystems and the services they provide to human populations. A relevant case study from this cluster is the research conducted by Balica et al. [66], which investigates the vulnerability of water ecosystems in Southeast Asia. This study demonstrates how changes in land use, combined with the effects of climate change, have increased the vulnerability of the region's water resources. The research provides valuable insights into how ecosystem-based approaches can be integrated into vulnerability assessments. Meanwhile, the yellow cluster, containing 10 references, highlights studies that emphasize the application of technological and computational tools for vulnerability assessment. This includes using remote sensing, big data analytics, and Artificial Intelligence (AI) in predicting and managing physical vulnerabilities. A notable example from this cluster is the application of remote sensing technology to assess drought vulnerability in the Sosiani River Basin, Kenya [67]. This study utilized satellite imagery to monitor changes in vegetation cover and soil moisture, which serve as early warning signs of impending flash flood events. This case demonstrates the innovative technological methods increasingly employed in vulnerability assessments.

3.3. Co-Occurrence Analysis of Keywords

The VOSviewer co-occurrence analysis of keywords provides a comprehensive overview of the primary themes within environmental vulnerability research, which is illustrated in Figures 12 and 13 and listed in Table 8.

This analysis is structured into three main clusters, each representing distinct yet interconnected areas of investigation. These clusters focus on critical aspects of the field, specifically human activities, technological tools, and pollution risks. The red cluster highlights the connection between environmental vulnerability, human impacts, and ecological protection. Key terms include "environmental vulnerability," "climate change," "human," and "vulnerability," reflecting research on how human activities—such as urbanization, deforestation, and industrialization—contribute to the degradation of ecosystems and increase vulnerability to environmental hazards. The inclusion of terms like "India," "China," and "ecology" indicates a specific focus on regions that are particularly susceptible to climate change and human-induced environmental changes. In India, vulnerability assessments have utilized Principal Component Analysis (PCA) to investigate the impacts of climate change and land-use changes on agricultural systems [68, 69]. These assessments identify areas most at risk from water scarcity and extreme weather events. Research on environmental protection strategies has contributed to the development of policies focused on sustainable agriculture and soil conservation aimed at mitigating these risks. In addition, research on human-environment interactions examines how urban growth in countries like China increases environmental vulnerability, particularly in coastal regions facing flooding and pollution [70, 71]. To address these challenges, ecological conservation strategies are employed to support sustainable urban planning and enhance green infrastructure. The green cluster emphasizes the importance of geospatial tools and monitoring technologies, such as remote sensing, GIS, and environmental monitoring, in assessing environmental vulnerability. Key terms like land use, erosion, vegetation, and decision-making highlight the application of satellite data and spatial analysis to monitor land degradation, vegetation loss, and the effects of natural processes like erosion.

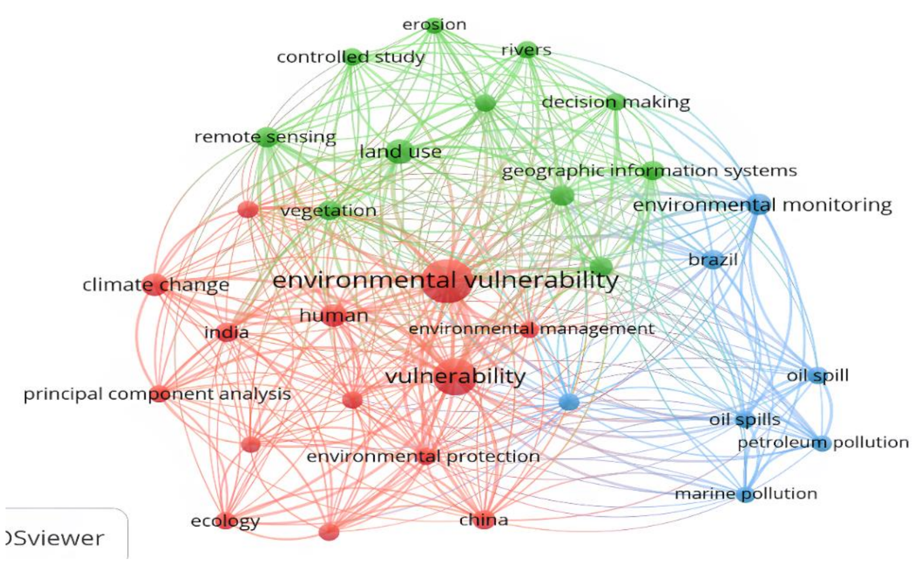

Fig. 12 The co-occurrence of keywords on environmental vulnerability

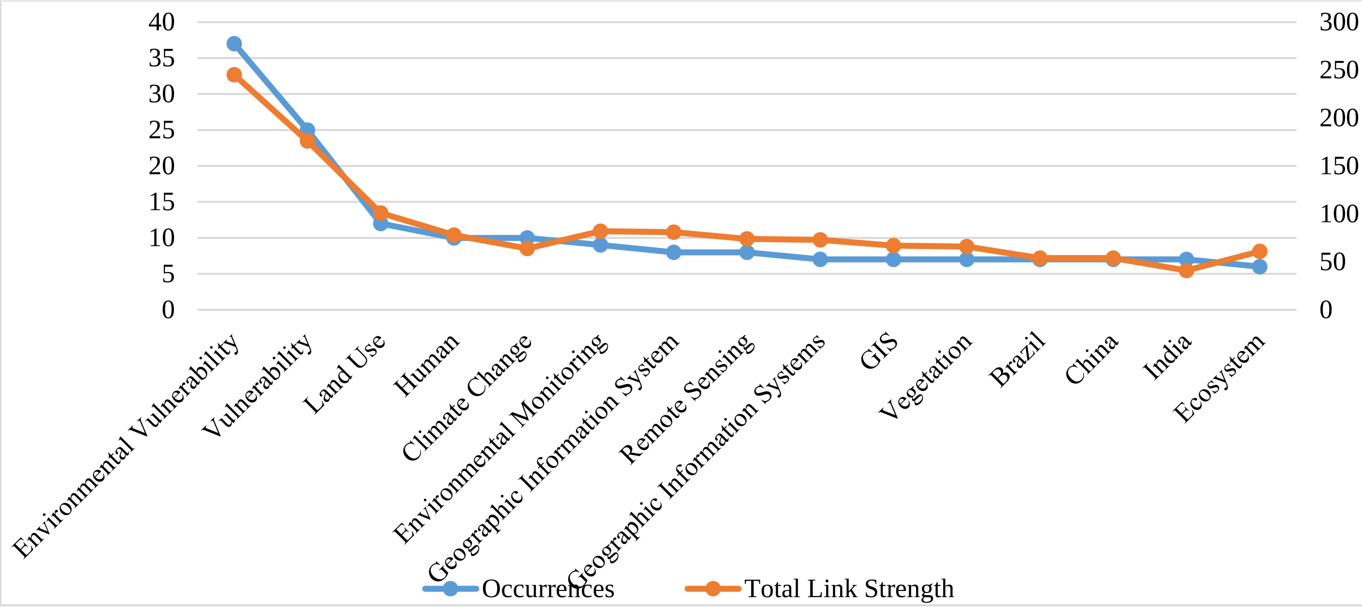

Fig. 13 The co-occurrence of keywords on environmental vulnerability

Table 8. The co-occurrence of keywords on environmental vulnerability

No	Keywords	Occurrences	Total Link Strength
1	Environmental Vulnerability	37	245
2	Vulnerability	25	176
3	Land Use	12	101
4	Human	10	78
5	Climate Change	10	64
6	Environmental Monitoring	9	82
7	Geographic Information System	8	81
8	Remote Sensing	8	74
9	Geographic Information Systems	7	73
10	GIS	7	67
11	Vegetation	7	66
12	Brazil	7	54
13	China	7	54
14	India	7	41
15	Ecosystem	6	61

This cluster focuses on integrating environmental data to facilitate informed decision-making for sustainable resource management. In Brazil, remote sensing and Geographic Information Systems (GIS) have been widely used to monitor deforestation in the Amazon rainforest [72, 73]. By combining these technologies, researchers can track changes in land use and identify areas at high risk for environmental degradation. This data is essential for local governments and environmental organizations as they implement policies aimed at reducing land use changes and promoting sustainable forestry practices. In regions affected by erosion, such as parts of Southeast Asia and the Mediterranean coast, remote sensing has been instrumental in assessing shoreline retreat and vegetation loss [74-76]. This information helps inform erosion control strategies, including dune restoration and beach nourishment. Environmental monitoring enables governments to make data-driven decisions to reduce vulnerability in coastal communities and improve their resilience to the impacts of climate change. The blue cluster focuses on oil spills and marine pollution, emphasizing the environmental risks of industrial activities, particularly in oil extraction areas. Keywords such as "oil spill," "petroleum pollution," and "marine pollution" highlight the ecological and economic consequences of these disasters. A significant real-world example is the Deepwater Horizon oil spill in the Gulf of Mexico [77], which has greatly influenced research on oil spill management. Studies stemming from this incident have improved response strategies and enhanced contingency planning for future occurrences. In Brazil, research on petroleum pollution, especially concerning Petrobras' offshore drilling activities, has identified vulnerable coastal areas and led to policy changes [78]. These changes have improved spill response measures to protect marine ecosystems and reduce environmental damage.

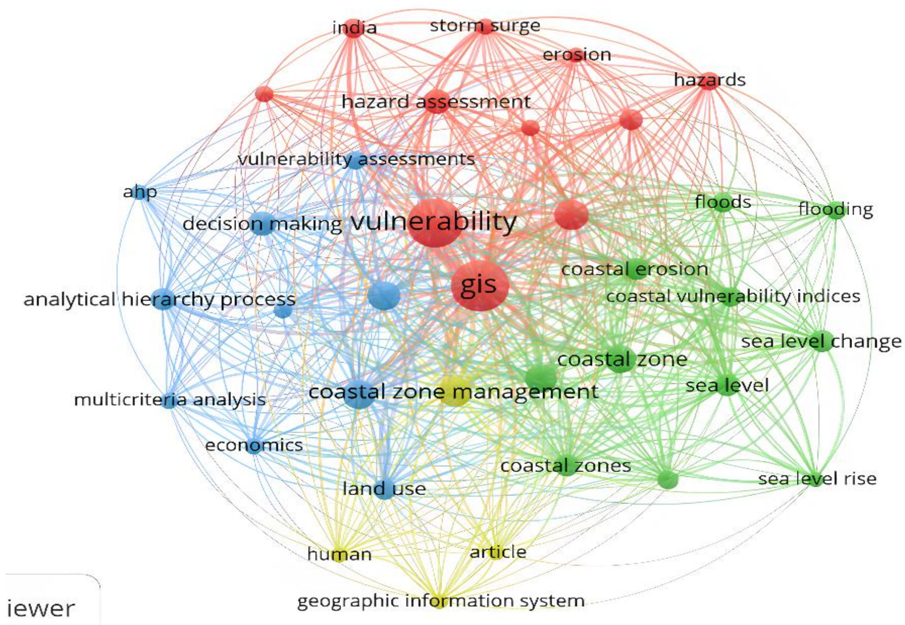

Fig. 14 The co-occurrence of keywords on physical vulnerability

The co-occurrence analysis of keywords reveals important themes within physical vulnerability research, specifically concerning coastal hazards, management, and decision-making, illustrated in Figures 14 and 15 and listed in Table 9. The red cluster focuses on hazard assessment and the impact of physical hazards such as storm surges, erosion, and flooding on coastal areas. For instance, hazard assessments are conducted in India to identify regions most vulnerable to storm surges and flooding, aiding disaster preparedness and infrastructure development [79, 80]. The green cluster emphasizes coastal zone management and strategies to address sea level rise and coastal erosion. This is often achieved through the use of coastal vulnerability indices that guide mitigation efforts. On the U.S. East Coast, these indices are utilized to assess areas at risk from sea-level rise and erosion, supporting efforts like beach nourishment and dune restoration [81, 82].The blue cluster highlights the importance of Geographic Information Systems (GIS) and decision-making tools, including multicriteria analysis and the analytical hierarchy process, in evaluating vulnerability and informing land-use planning. For example, in Brazil, GIS maps land-use patterns and assesses physical vulnerability to storm surges and sea-level rise, assisting local governments in managing coastal zones[33, 83].

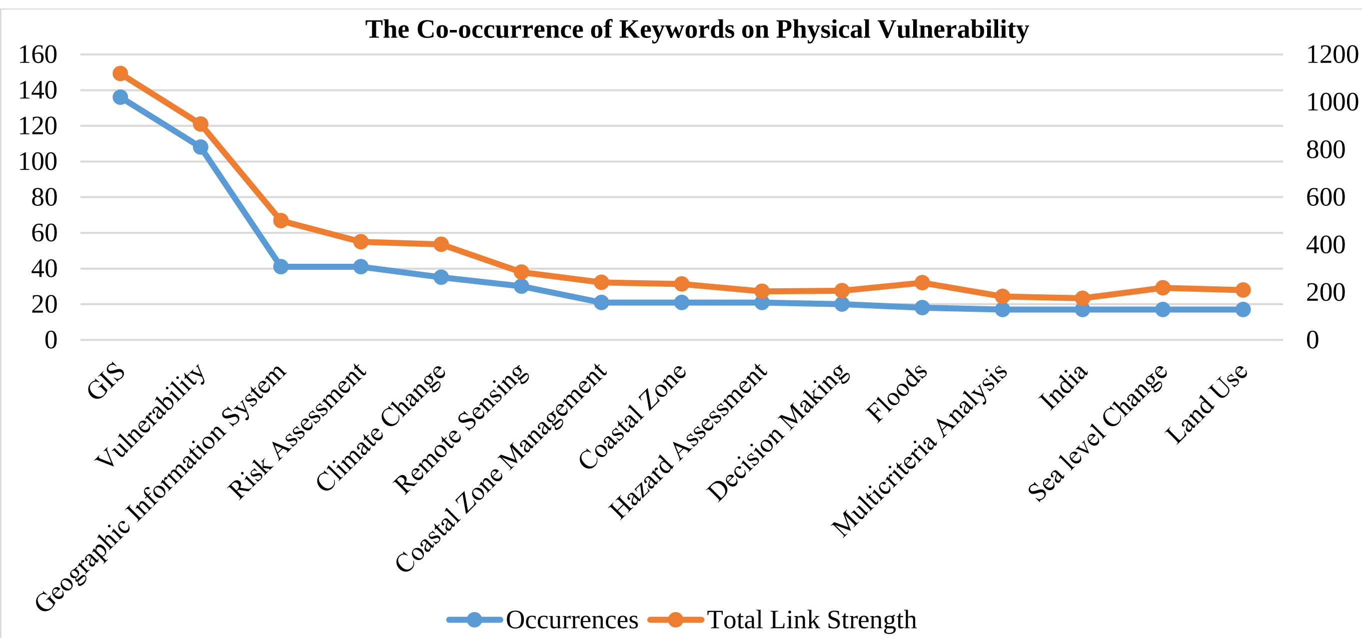

Fig. 15 The co-occurrence of keywords on physical vulnerability

Table 9. The co-occurrence of keywords on physical vulnerability

No	Keywords	Occurrences	Total Link Strength
1	GIS	136	1119
2	Vulnerability	108	907
3	Geographic Information System	41	501
4	Risk Assessment	41	412
5	Climate Change	35	401
6	Remote Sensing	30	285
7	Coastal Zone Management	21	241
8	Coastal Zone	21	235
9	Hazard Assessment	21	204
10	Decision Making	20	207
11	Floods	18	240
12	Multicriteria Analysis	17	182
13	India	17	175
14	Sea level Change	17	219
15	Land Use	17	209

3.4. The Most Popular Research Topic Based on Keyword Trend-Content Analysis

According to the keyword trend map, three key research themes emerge as priorities for future study in environmental vulnerability (Figure 16), each reflecting the evolving scientific focus and the urgent real-world issues. One emerging area of research highlighted by keyword trend analysis involves advanced geospatial tools for land use and watershed management. The map shows that terms such as “land use,” “watersheds,” “remote sensing,” and “GIS” are clustered around decision-making processes. This trend indicates a growing demand for more sophisticated methods to track and analyze how human activities impact environmental vulnerability. For instance, large-scale deforestation monitoring in the Amazon Basin demonstrates how satellite-based remote sensing can identify critical areas of soil degradation and biodiversity loss, prompting stricter land use regulations [72]. Spatial modeling has also guided flood management and sustainable agricultural planning in the Mekong Delta. These instances show that accurate geospatial data can effectively balance economic development with the vital need to protect ecosystems and local communities [84]. One important focus area is marine pollution and oil spill preparedness, highlighted by keywords related to oil spills, petroleum pollution, and marine ecosystems. This thematic connection underscores ongoing concerns about the environmental hazards linked to intensive offshore energy extraction and the expansion of global shipping routes. A notable example is the Deepwater Horizon spill in the Gulf of Mexico, which has significantly influenced research aimed at improving oil spill vulnerability indices and advancing the development of real-time monitoring and containment strategies [85]. To illustrate, In Brazil, evaluations of petroleum pollution in offshore drilling areas have led to stronger legislation that requires quicker spill detection and response protocols [86]. These measures not only protect marine habitats and fisheries but also emphasize how proactive monitoring can help mitigate the extensive consequences of oil spills. A third increasingly critical topic is the interplay between climate change, ecosystem restoration, and socio-environmental integration. This is highlighted by keywords such as "climate change," "environmental protection," "human," and "environmental restoration." Researchers recognise the need for holistic frameworks that address both natural processes and the social dimensions of vulnerability. For instance, in coastal India, mangrove restoration has become part of broader climate adaptation efforts to protect shorelines from storm surges [87].

This approach also supports local livelihoods through sustainable fisheries and eco-tourism. A similar synergy can be observed in small island developing states like the Maldives, where coral reef restoration is integrated with local community initiatives to create a comprehensive adaptation strategy [88]. This demonstrates the deep interdependence between ecosystem health and human well-being in the context of a changing climate. Meanwhile, the VOSviewer co-occurrence analysis of keywords provides insight into significant research trends concerning physical vulnerability, as depicted in Figure 17, focusing on the role of Geographic Information Systems (GIS), coastal zone management, and disaster risk assessment. The analysis of keyword clusters, derived from publication trends spanning 2018 to 2021, identifies three pivotal topics for future research in the area of physical vulnerability: the implementation of GIS in vulnerability mapping, the assessment of vulnerability in coastal zones and flood risk management, and the development of integrated disaster risk management and decision-making strategies. The first critical area of focus is the increasing application of Geographic Information System (GIS) technologies in assessing physical vulnerabilities. Terms such as GIS, remote sensing, land use, and flooding underscore the growing significance of spatial data for understanding and managing these vulnerabilities. These technologies are essential in mapping environmental hazards and evaluating communities' risks.

For instance, in Bangladesh, GIS and remote sensing have been utilized extensively to identify areas prone to flooding and to assess vulnerability to storm surges [39, 89, 90]. This facilitates the authorities' development of targeted disaster management strategies. Implementing these methodologies enables improved planning and decision-making processes, ultimately enhancing the protection of vulnerable populations and infrastructure from physical risks, including flooding, erosion, and storm-related damage. The second emerging research theme focuses on coastal zone management, particularly in relation to flooding and coastal vulnerability indices.

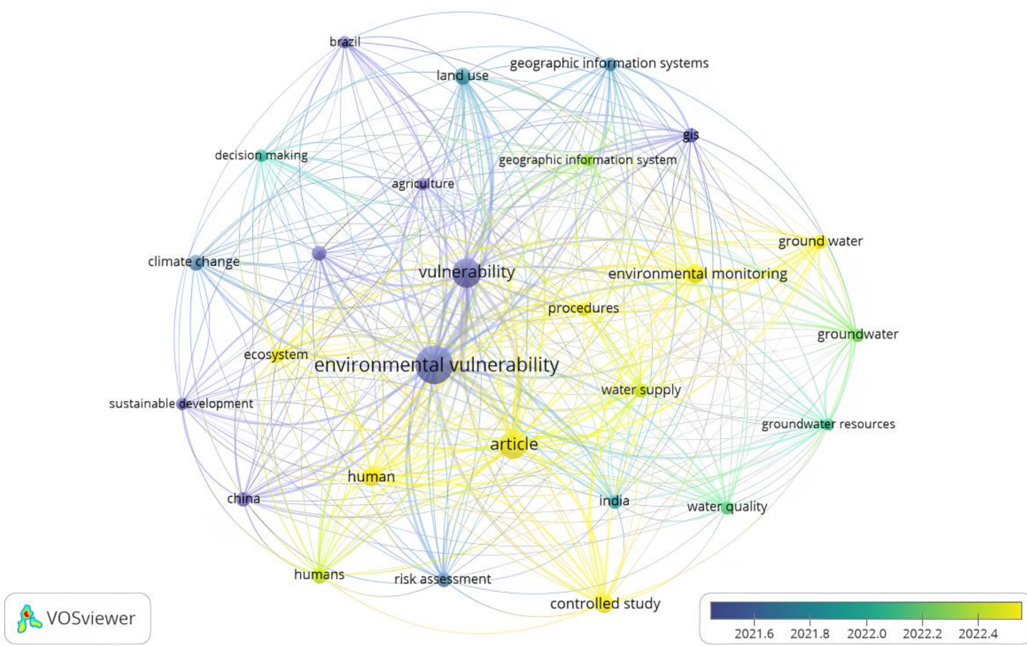

Fig. 16 The co-occurrence of keywords on environmental vulnerability based on years

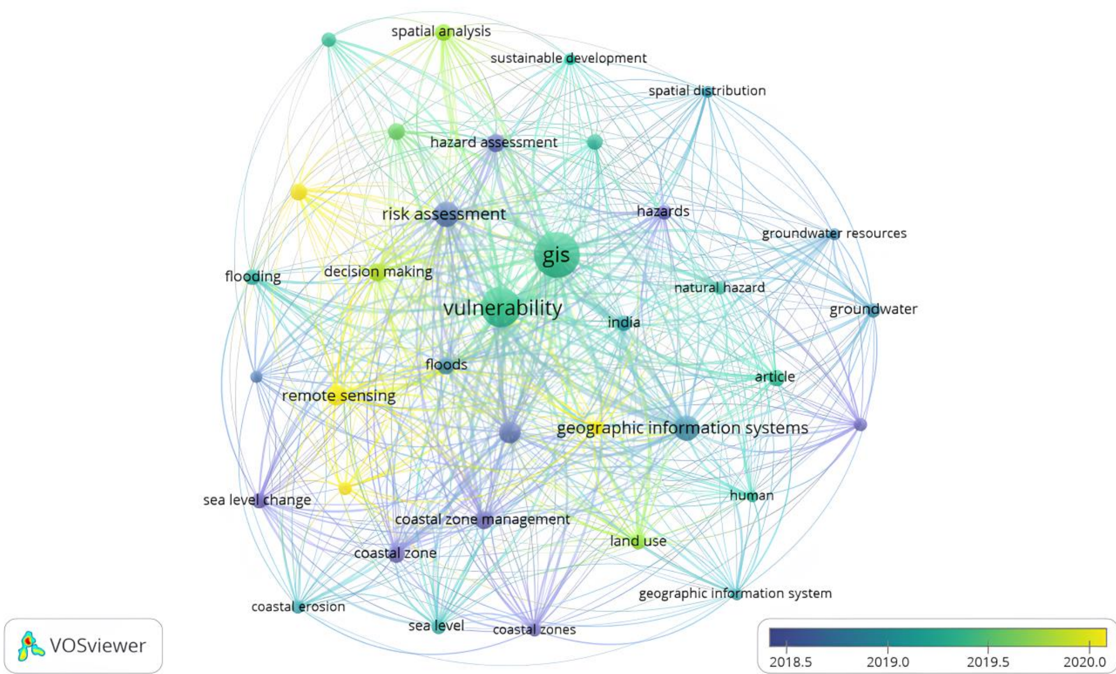

Fig. 17 The co-occurrence of keywords on physical vulnerability based on years

Key terms such as "coastal zone management," "coastal vulnerability indices," and "storm surge" highlight the emphasis on assessing and managing the physical vulnerabilities of coastal areas. Coastal areas face significant risks from rising sea levels and intensified storms caused by climate change. For example, in the Caribbean and Southeast Asia, vulnerability indices are utilized to evaluate the risks of coastal erosion and flooding [81, 91, 92]. These indices provide essential data for developing policies to protect coastal infrastructure and ecosystems. They also help identify high-risk areas, guiding decisions on land use and resource allocation to mitigate the impacts of storms and rising seas. The third key research theme pertains to integrated disaster risk management and decision-making strategies. The focus is on critical concepts such as disaster management, risk assessment, decision-making, and the impacts of climate change.

This research highlights the increasing importance of employing integrated approaches to effectively address physical vulnerabilities. The emphasis is on synthesizing environmental, social, and economic data to enhance the efficacy of disaster preparedness and response initiatives. For instance, in Japan, the utilization of GIS-based models within disaster risk management has proven to be essential for assessing the risks associated with earthquakes and tsunamis [93]. By merging real-time environmental monitoring with socioeconomic data, Japan has established robust strategies for evacuation planning, infrastructure resilience, and early warning systems [94]. Similarly, in the context of urban flood management, multicriteria analysis is utilized to evaluate physical vulnerabilities and to prioritize risk reduction measures for high-density areas susceptible to flooding and other natural hazards [27, 95].

3.5. Potential Research Pathways and Future Directions

Based on emerging trends, identified gaps in the literature, and findings from the bibliometric analysis, several promising research directions can be recommended. These directions address current knowledge gaps, emphasize the importance of integrated approaches, and respond to the evolving challenges posed by climate change, socioeconomic factors, and technological advancements. The following research pathways could significantly enhance the field of environmental and physical vulnerability studies.

3.5.1. Integrative Frameworks Uniting Socio-Ecological and Technological Dimensions

A recurring theme in environmental and physical vulnerability studies is the necessity of integrating ecological, socioeconomic, and technological components into cohesive models. Many existing approaches heavily rely on remote sensing and Geographic Information Systems (GIS) (e.g. [72, 74, 89]) but often treat social factors—such as governance, community resilience, and economic constraints—as separate or secondary elements. Future research should focus on developing integrative frameworks [96-98] that combine socioeconomic indicators (like income disparities, land tenure, and governance structures) with geospatial data (such as flood zones and erosion hotspots) to capture both human and ecosystem vulnerabilities in real-time. These multi-layered approaches will enable policymakers to identify high-risk areas and the populations most affected. Additionally, combining these models with participatory [99] can ensure local stakeholder knowledge informs adaptation measures. This is especially relevant in communities facing rapid land-use changes, such as deforestation in the Amazon [72, 73]or intensified coastal erosion along Chile's rugged coast [43, 44].

3.5.2. Advanced Modeling for Coastal and Urban Hazards Under Climate Change

The bibliometric findings underscore the urgent need to improve multi-hazard modeling in coastal and rapidly urbanizing areas. Rising sea levels, frequent storm surges, and inland flooding require dynamic flood models that combine machine-learning algorithms with high-resolution LIDAR or satellite data [100, 101]. These advanced tools can predict short-term disaster scenarios while considering long-term climate trends. For example, in countries like India, where increasing coastal urbanization coincides with extreme weather events, enhanced vulnerability indices [79] can help inform infrastructure investments and land-use planning. Similar initiatives in Brazil—where offshore drilling and coastal development present significant risks—demonstrate the effectiveness of real-time monitoring for petroleum pollution and erosion [33, 83]. By integrating these computational approaches with existing disaster warning systems, such as those in Japan [93, 94], preparedness and resilience in vulnerable regions can be significantly improved.

3.5.3. Transdisciplinary Disaster Risk Management and Policy Uptake

Many studies propose vulnerability assessments, but a significant challenge remains in translating these scientific insights into effective policies and real-world actions [102-104]. Future research should focus on developing transdisciplinary disaster risk management models that bring together climate scientists, geospatial experts, local authorities, and community stakeholders at all stages—from data collection to policy drafting. Such collaborations could help bridge gaps between different sectors and ensure the creation of solutions that are developed collectively [105, 106]. Importantly, governments in heavily impacted countries such as China and India have begun to incorporate vulnerability frameworks into their national development plans [40, 47].

However, further policy connections are needed to align research efforts with sustainable development goals [107]. Encouraging community-based adaptation measures, such as mangrove restoration in coastal India [87, 108]and reef protection in small island nations [88], illustrates how local engagement, scientific evidence, and policy frameworks can come together to enhance long-term resilience. Future researchers can greatly enhance the understanding of environmental and physical vulnerabilities in surface water areas by promoting integrative socio-ecological frameworks, utilising advanced modelling techniques, and strengthening science-policy partnerships. These approaches, informed by global case studies and innovative technologies, offer a roadmap for addressing the complex challenges presented by climate change and resource pressures in the coming decades.

4. Conclusion

This study provides a deeper insight into the trends and gaps in environmental and physical vulnerability research through a comprehensive bibliometric analysis. The approach encompasses co-authorship, co-citation, and keyword co-occurrence analyses, offering a holistic field perspective. In contrast to traditional bibliometric techniques, which typically emphasize basic measures such as citation counts or simple co-occurrence analysis, this methodology captures a wider range of relationships among key research themes, geographical patterns, and institutional contributions. By incorporating these various dimensions, the study presents a more nuanced and dynamic representation of vulnerability research compared to earlier studies. This methodology offers a significant advantage by enabling a more detailed mapping of research trends by integrating co-citation and keyword co-occurrence analysis. It uncovers evolving themes of environmental and physical vulnerability with greater accuracy. Traditional bibliometric techniques often overlook interdisciplinary connections and the complexity of vulnerability. Utilizing VOSviewer, this study identified research clusters over time, highlighting key developments in GIS-based vulnerability mapping, coastal zone management, and multi-hazard disaster management. Setting citation thresholds and focusing on influential clusters revealed emerging trends at the intersection of climate change, ecosystem restoration, and socioeconomic integration, which were largely neglected in prior studies. The study presents a unique geographical and interdisciplinary approach by focusing on high-risk coastal areas in developing countries, such as India, China, and Bangladesh, areas often neglected in traditional bibliometric analyses. The text underscores the significant influence of India's National Adaptation Programme of Action (NAPA) on research related to climate change adaptation. It also compares with frameworks such as China's five-year plans, highlighting the differences in their approaches and impacts. The analysis reveals increasing international collaboration among researchers from various countries, including Brazil, Australia, and Portugal, addressing common challenges like coastal erosion and sea-level rise. This research enhances understanding vulnerability assessments in developing regions and global research trends. This study presents a notable advancement in the field of vulnerability analysis through the integration of sophisticated technological tools. Distinct from previous bibliometric studies that predominantly relied on qualitative assessments or rudimentary indices, this research harnesses real-time data sourced from remote sensing technologies and advanced geospatial instruments, including Geographic Information Systems (GIS). This innovative methodology significantly enhances the accuracy of vulnerability assessments. This is exemplified by case studies conducted in Brazil and Bangladesh, where machine learning models have substantially improved the predictions of coastal vulnerability and the risks associated with storm surges. Moreover, the research emphasizes the importance of policy linkages in vulnerability studies, which were often overlooked in the past. By incorporating findings relevant to national and international climate frameworks, the study connects vulnerability research to practical applications, highlighting the role of action-oriented research. For instance, India's incorporation of vulnerability assessments into NAPA strategies illustrates how these assessments can drive significant policy changes for climate-responsive infrastructure development. Overall, this work bridges the gap between academic knowledge and practical solutions, positioning vulnerability research at the intersection of science, policy, and practice.

Author Contributions

H.S.D.K. and A.S.N. conceived and designed the research. H.H. and S.P. contributed analytical tools. H.S.D.K. and A.S.N. analyzed data. H.S.D.K. AND A.S.N. wrote the manuscript. All authors read and approved the manuscript.

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