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Review

Scientometric review on multiple climate-related hazards indices

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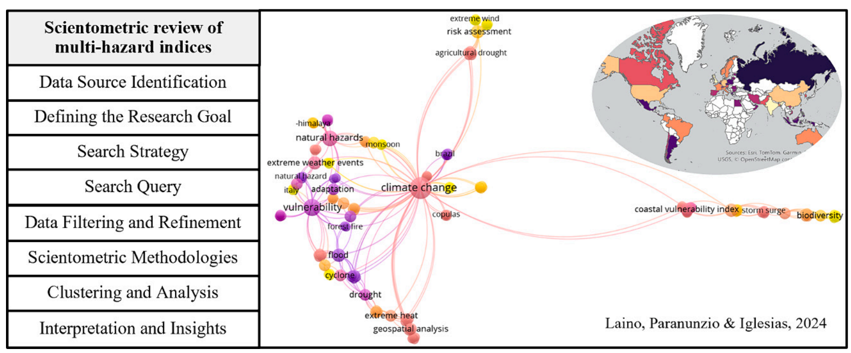
HIGHLIGHTS

- Index-based methodologies as key tools for multi-hazard assessment.
- Systematic review following PRISMA guidelines.
- Thematic analysis of existing literature.
- Advancements in multi-hazard indices through scientometrics.
- Strategic insights for policymakers and practitioners.

GRAPHICAL ABSTRACT



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ABSTRACT

As the spectre of climate change looms large, there is an increasing imperative to develop comprehensive risk assessment tools. The purpose of this work is to evaluate the evolution and current state of research on multi-hazard indices associated with climate-related hazards, highlighting their crucial role in effective risk assessment amidst the growing challenges of climate change. A notable gap in cross-regional comparative studies persists, presenting an opportunity for future research to enhance global understanding and foster universal resilience strategies. However, a significant surge in research output is apparent, following key global milestones related to climate change action. The research landscape is shown to be highly responsive to international policy developments, increasingly adopting interdisciplinary approaches that integrate physical, social, and technological dimensions. Findings reveal a robust emphasis on geospatial analysis and the development of various indices that transform abstract climate risks into actionable data, underscoring a trend towards localized, context-specific vulnerability assessments. Based on dataset systematically curated under the PRISMA guidelines, the review explores how prevailing research themes are reflected in influential journals and author networks, mapping out a dynamic and expanding academic community. Moreover, this work provides critical insights into the underlying literature by conducting a thematic analysis on the typology of studies, the focus on coastal areas, the inclusion of climate change scenarios, the geographical coverage, and the types of climate-related hazards. The practical implications of this review are profound, providing policymakers and practitioners with meaningful insights to enhance climate change mitigation and adaptation efforts through the application of index-based methodologies. By charting a course for future scholarly endeavours, this article aims to strengthen the

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scientific foundations supporting resilient and adaptive strategies for regions worldwide facing the multifaceted impacts of climate change.

1. Introduction

The effects of climate change on urban environments have become increasingly evident and consequential on urban environments, both coastal and inland (Charlson et al., 1992; Hallegatte et al., 2013; Hulme et al., 1999; Rodell et al., 2015; Rodriguez-Delgado et al., 2018). These urban areas, representing a confluence of high population density, economic activity, and infrastructural complexity, are at the front lines of experiencing and responding to climate-induced alterations (Adger et al., 2003; Chan et al., 2010; Thomas et al., 2021; Zscheischler et al., 2018). The shift in climate patterns is not just a future prediction but a present reality, altering the daily lives of millions and reshaping the natural and built landscapes of cities (Dessai and Hulme, 2004; Glavovic et al., 2022; Kundzewicz et al., 2014; Van Aalst, 2006). This scenario underscores the critical need for a deeper understanding of the local impacts of climate change, beyond the broader global perspective (Adger et al., 2009; Berrang-Ford et al., 2021; Jongman et al., 2014; Miller et al., 2023). Such insights are pivotal in devising effective, location-specific strategies for adaptation and resilience, tailored to the unique vulnerabilities and capacities of diverse urban settings (Birkmann, 2007; Buizer et al., 2016; Lemos and Morehouse, 2005; Mechler et al., 2020).

The escalating impact of climate change presents formidable challenges in relation to climate-related hazards, which are increasingly at the forefront of global concern (Barkanov et al., 2024; Blythe et al., 2020; Dessai, 2003; Martinez and Iglesias, 2024, 2022, 2021; Ruane et al., 2022; Simpson et al., 2021). Evidence of this mounting alarm is the surge in international policy initiatives and scientific research dedicated to addressing these challenges (IPCC, 2012; Laino and Iglesias, 2023a; Liu et al., 2022). This unprecedented upsurge highlights a global consensus on the urgent need for action to mitigate the multifaceted risks posed by climate-related hazards, including landslides, droughts, sea-level rise, intensified storm events, heat waves, coastal erosion and flooding, among others (Beden and Ulke, 2020; Bergillos et al., 2019b, 2019a; Paranunzio et al., 2021; Santos et al., 2010). As such, understanding the scale and scope of these initiatives and the knowledge generated becomes critical in orchestrating effective responses to safeguard vulnerable areas (Riaz et al., 2023; Rosendahl Appelquist and Balstrøm, 2014).

The challenge posed by climate change is characterized by its complexity and the multiple climate-related hazards that it encompasses, each contributing to a complex landscape of risk (Rafael J Bergillos et al., 2020; Collins et al., 2013; Laino and Iglesias, 2023b; Singh et al., 2015). In this context, index-based methodologies emerge as a key tool for systematically evaluating the vulnerability and risk posed by these hazards (Gallina et al., 2016; Nguyen et al., 2016). By converting diverse climate-related hazards into quantifiable indices, these methods provide a structured framework to break down, understand, and confront these challenges (Kunte et al., 2014; Laino and Iglesias, 2024; Mafi-Gholami et al., 2019). Indices provide stakeholders with a synthesized view of data, helping to identify patterns and direct resources and efforts where they are most needed (Coelho et al., 2008; Mpelasoka et al., 2008). Embracing index-based methods is thus a critical step in creating cohesive responses to the widespread effects of climate change (Ashraful Islam et al., 2016; Tiepolo et al., 2019). Moreover, the integration of emerging disciplines and technologies such as Artificial Intelligence, Machine Learning (ML), Internet of Things (IoT), and remote sensing has the potential to revolutionize multi-hazard indices, enhancing their predictive capabilities and real-time monitoring effectiveness (Barzehkar et al., 2021).

A wide array of approaches can be found in the literature addressing climate-related hazards, each offering unique methodologies and insights. These approaches include impact, hazard, vulnerability, and risk assessments, each serving a specific purpose in the broader context of climate resilience. Impact assessments focus on quantifying the consequences of climate-related events on various sectors, such as agriculture, health, and infrastructure (Birkmann, 2007; Mechler et al., 2020). Hazard assessments, on the other hand, concentrate on identifying and characterizing the physical processes and events that pose potential threats (Kappes et al., 2012). Vulnerability assessments aim to determine the susceptibility of populations, ecosystems, and infrastructure to these hazards, often integrating socio-economic factors to provide a comprehensive understanding (Adger, 2006). Risk assessments combine elements of hazard and vulnerability assessments to estimate the probability and potential severity of adverse outcomes (Ghosh et al., 2019). Furthermore, studies on adaptation and resilience measures explore strategies to mitigate these risks and enhance the capacity of systems to recover from adverse events (Xian et al., 2018). Additionally, there are reviews and databases that compile information on multiple past weather events, providing valuable historical context and facilitating the analysis of trends over time (Kašpar et al., 2023; Tappi and Santeramo, 2022). Conceptual frameworks propose definitions and methodologies for assessing these hazards, contributing to the development of standardized approaches and facilitating comparative studies across different regions and contexts (Ruane et al., 2022).

Typically, various studies focus on specific groups of climate-related hazards, reflecting the diverse nature of climate impacts. Coastal hazards, such as storms, sea-level rise, coastal flooding, and coastal erosion, are extensively studied due to the high vulnerability of coastal areas and the significant economic and social implications of these events (Rangel-Buitrago et al., 2020; Thakur and Mohanty, 2023). Temperature extremes, including cold spells and heatwaves, are another critical focus, as they have direct and often severe impacts on human health, agriculture, and energy demand (Deen et al., 2021; Szalińska et al., 2021). Hydrological hazards, such as heavy precipitation, land flooding, and landslides, are also commonly analysed, given their potential to cause widespread damage and disrupt communities (Avila-Diaz et al., 2016; Canli et al., 2018; Rivas et al., 2020). It is also possible, albeit infrequent, to find research that integrates a wide range of these hazards simultaneously, as it will be explored in this work. Such comprehensive studies provide a holistic view of the multifaceted nature of climate risks and the interconnectedness of different hazard types (Sekhri et al., 2020; Shi et al., 2016). By examining these integrated assessments, we can better understand the cumulative impacts of multiple hazards and develop more effective strategies for managing these risks.

The geographical coverage of these studies varies significantly, ranging from local to regional, national, and even supranational and global scales (Hanson et al., 2011; Rosendahl Appelquist and Balstrøm, 2015; Zanetti et al., 2016). Local studies offer detailed insights into specific areas, identifying particular vulnerabilities and resilience capacities that are unique to those settings (Castro Rodríguez et al., 2023). Regional and national studies provide broader overviews, identifying patterns and trends that can inform policy and management strategies at larger scales (Changnon et al., 2013; Liang et al., 2019). Supranational and global studies are crucial for understanding transboundary and global-scale climate impacts, fostering international cooperation and comprehensive mitigation strategies (Hagenlocher et al., 2018; Laino and Iglesias, 2024). These broader studies often reveal the interconnectedness of climate risks across different regions and the need for coordinated efforts to address these challenges effectively.

Regarding temporal coverage, studies may focus on past events, providing valuable historical data that can help identify trends and inform future projections (Kašpar et al., 2023; Laino and Iglesias, 2023b). Baseline characterizations offer a snapshot of the current situation, serving as a reference point for measuring future changes and the effectiveness of adaptation measures (Laino and Iglesias, 2024; Liu et al., 2019). Future scenario analyses, often employing well-known Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP), model potential outcomes under different climate and socio-economic conditions (Jones and O'Neill, 2016; Malakar et al., 2021). These scenarios are essential for anticipating future risks and planning effective adaptation and resilience measures (Tamura et al., 2019). By exploring a range of possible futures, these studies help policymakers and stakeholders understand the potential impacts of different decisions and actions, enabling them to develop robust strategies that can accommodate a variety of possible outcomes (Ranasinghe et al., 2021).

A variety of models and frameworks have been developed to assess multi-hazard risks, each with its unique approach and focus. Among these, CLIMADA by ETH Zurich stands out for its emphasis on quantifying and monetizing the direct impacts of natural disasters on socio-economic factors, integrating hazard, exposure, and vulnerability data (Aznar-Siguan and Bresch, 2019). Another notable framework is DIVA (Dynamic Interactive Vulnerability Assessment) from the Global Climate Forum, which assesses the biophysical and socio-economic consequences of sea-level rise and socio-economic development (Fang et al., 2020; Hinkel and Klein, 2009). HAZUS, developed by the US Federal Emergency Management Agency, offers a comprehensive risk assessment software for earthquakes, floods and hurricanes, utilizing GIS technology to estimate impacts (Nastev and Todorov, 2013), while SLOSH (Sea, Lake, and Overland Surges from Hurricanes) is a critical tool for estimating storm surge and flooding impact from hurricanes (Forbes and Rhome, 2012). Additionally, the Coastal Storm Modeling System (CoSMoS) provides valuable insights into coastal flooding due to sea-level rise and storms, integrating climate change scenarios with physical process models (Barnard et al., 2014). In the conservation domain, the ADAPT tool evaluates the impact of climate change on biodiversity, demonstrating the importance of ecological considerations in hazard assessments.

Previous scientometric studies have paved various paths in multi-hazard risk assessment research (Kappes et al., 2012). Owolabi and Sajjad (2023) employed state-of-the-art tools to provide a panoramic view of the multi-hazard risk assessment (MHRA) field, covering different methodological tools to assess risk and revealing critical gaps in international collaboration and a predominant focus on landslide hazards. Curt (2021) took a textual analysis approach, categorizing the multi-risk literature into distinct thematic areas and calling for more comprehensive studies on the subject. Laino and Iglesias (2023c) combined bibliometric analysis with participatory processes involving European coastal cities to present an intricate picture of the impacts of climate change at the local level, introducing the innovative concept of Coastal City Living Labs (Paranunzio et al., 2024; Tiwari et al., 2022). Lima and Bonetti (2020) presented a historical and geographical perspective on social vulnerability in coastal populations, highlighting an increase in studies related to climate change impacts and the need for a consensus in terminology. Our study builds upon these foundations but stands out by zeroing in on index-based methodologies, due to their crucial role in simplifying complex climate data into understandable formats that aid decision-makers in managing climate risks (Wang et al., 2020).

The relevance of this work lies in its comprehensive scope and systematic approach to synthesizing existing research on climate-related multi-hazard indices. As climate change exacerbates the frequency and intensity of various hazards, understanding the interconnected nature of these risks is paramount. Effective responses to climate change require coordinated efforts across borders, leveraging diverse expertise and resources. In this context, index-based methodologies provide a structured way to synthesize complex climate data, making it accessible and actionable for decision-makers. They enable the identification of critical patterns and trends necessary for developing targeted adaptation and mitigation strategies. Hence, this work addresses a crucial gap in the scientometric literature on climate-related multi-hazard indices.

This review will systematically evaluate diverse index-related approaches to studying climate-related hazards, the consideration of coastal areas and climate change scenarios, (Bergillos et al., 2020a; Bergillos et al., 2020; Gallina et al., 2020; Godwyn-Paulson et al., 2022; Mathew et al., 2020; Thakur and Mohanty, 2023) and a varied hazard, geographical, and temporal coverage (Elia et al., 2023; Pourghasemi et al., 2019; Rusk et al., 2022; Yiran and Stringer, 2016). Additionally, a meta-analysis of academic contributions will be conducted, examining influential authors, primary journals, and prevailing keywords through scientometric methods. This multi-layered approach will provide a comprehensive understanding of the existing literature, uncover trends, reveal research gaps, and identify the most impactful contributions, guiding future studies towards areas with significant potential for advancements. This review also traces the evolution of publication focus, highlighting a shift from physical hazards to policy, adaptation social and technological dimensions. By doing so, it underscores the dynamic nature of climate change research and the increasing need for integrated, multidisciplinary approaches. Moreover, this work emphasizes the importance of international collaboration by proposing actionable pathways for enhancing global research partnerships.

Essentially, this review offers a thorough synthesis that is reflective of the field's past and anticipatory of its future, serving as a valuable resource for researchers, policymakers, and practitioners aiming to contribute to the field of climate risk assessment and management. Ultimately, this review is conceived to provide a robust understanding of the current state of index-based climate change research. In turn, it aims to contribute to advancing index-based approaches, informing better decision-making, fostering more resilient communities and ecosystems, enhancing our collective capacity to mitigate climate risks and adapt to changing conditions, and fortifying vulnerable areas against the detrimental effects of climate change.

2. Materials and methods

This work systematically reviews the publications on multiple climate-related hazards that incorporate indices. To ensure a systematic and transparent review process, this study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). The PRISMA methodology enhances the clarity and rigor of the review by providing a structured approach to literature search, selection, and synthesis.

The primary data source for this review is Scopus, a renowned scholarly publication database widely recognized for its comprehensive coverage of academic research (Mingers and Leydesdorff, 2015). The search strategy was designed to ensure the inclusivity of relevant publications. Specific keywords were selected based on their relevance and common usage in the literature to capture a comprehensive range of studies focusing on indices related to multiple climate-related hazard. These keywords were systematically applied to the Title, Abstract, and Keywords fields without imposing any additional search restrictions on 23rd October 2023. The search expression included variations such as "Climate multi-hazard index", "Climate multiple hazards index", "Climate-related hazard index", "Climate-induced hazard index", "Natural hazards index", "Natech hazards index", "Extreme climate events index", and "Multi-hazard assessment climate change". These terms broadly encompass the diverse terminology used by researchers in this field, ensuring a thorough inclusion of relevant studies. For example, "Natech hazards index" refers to indices that assess natural-technological hazards, while "Extreme climate events index" pertains to indices for extreme weather events. The complete query string applied was "TITLE-ABS-KEY (climate OR weather AND multi-hazard AND index) OR TITLE-ABS-KEY (climate OR weather AND multiple

AND hazards AND index) OR TITLE-ABS-KEY (climate-related OR weather-related AND hazard AND index) OR TITLE-ABS-KEY (climate-induced OR weather-induced AND hazard AND index) OR TITLE-ABS-KEY (natural AND hazards AND index) TITLE-ABS-KEY (natech AND hazards AND index) OR TITLE-ABS-KEY (extreme AND climate OR weather AND events AND index) OR TITLE-ABS-KEY (multi-hazard AND quantification OR assessment OR methodology AND climate AND change)". This comprehensive keyword search returned a total of 292 publications, which formed the initial dataset for the scientometric analysis.

The collected publications were filtered through a three-phase process (Fig. 1). Firstly, duplicate publications were identified and removed, along with studies lacking sufficient information. This initial phase resulted in the removal of 5 publications with insufficient information (5). Secondly, publications not in English (7) and those that did not focus on climate-related hazards (7) were eliminated. This phase involved a detailed examination of the title, abstract, and keywords to ascertain relevance. The third and final phase of filtering involved a thorough review of the full-text content of the remaining publications. Only those publications that unequivocally addressed the topic of "Studied on multiple climate-related hazards involving indices" were retained. This rigorous assessment led to the exclusion of 180 publications. Following these three filtering phases, a final dataset of 93 publications was established, forming the foundation for the subsequent review.

With this refined dataset, the review was conducted focusing on several key aspects. A thematic analysis was performed on the assessment methodologies, the focus on coastal areas, the inclusion of climate change scenarios, the geographical coverage, and the types of climate-related hazards covered by the publications. This was followed by a scientometric analysis to examine the historical evolution, geographical distribution, key authors and contributions, influential journals, citation patterns, and essential keywords within the research domain of climate-related multi-hazard indices. Ultimately, this work provides a comprehensive overview of the field, identifies significant trends, and discusses research gaps and strategic insights for policymakers and practitioners. A detailed workflow outlining the sequential steps from initial data collection to the final generation of insights is presented in Fig. 2.

The thematic analysis classified the publications according to their main focus, including hazard assessment, vulnerability assessment, risk assessment, impact study, database, review, adaptation solutions, or conceptual work. The publications were discussed within these categories. Special attention was given to works aimed at evaluating coastal areas and those that integrated climate change scenarios. Publications were also classified based on their geographical coverage, ranging from local, regional, national, to supranational levels. Additionally, the types of climate-related hazards assessed in the publications were catalogued. The analysis of storms encompassed cyclones, hurricanes, and tropical storms. While these could include other hazards such as strong winds, heavy precipitation, and flooding, these threats were considered separately depending on how each paper evaluated them. For example, some studies might assess heavy precipitation events without discussing storms. For clarity, coastal flooding analyses included its components, such as storm surge, tides, and waves. Other geohazards not directly attributable to climate, such as volcanoes, earthquakes, or tsunamis, as well as natural-technological (Natech) hazards, are outside the scope of this review.

Diverse software and visualization tools were employed in the scientometric review to effectively analyse the dataset and generate meaningful insights. Specifically, VOSviewer (van Eck and Waltman, 2010) was utilized to construct and analyse the complex co-authorship networks, citation networks, and co-occurrence networks of keywords. VOSviewer is an open-access tool that implements the visualization of similarities approach (VOS) (Waltman et al., 2010). Co-authorship networks were employed to identify key authors and collaborations in the field. Citation networks enabled the identification of influential publications and tracing the impact of research over time. Lastly, the co-occurrence networks of keywords were utilized to reveal the central themes and emerging trends within the domain of climate-related multi-hazard indices. Furthermore, the advanced clustering algorithms of VOSviewer assisted in categorizing the publications into distinct research clusters, providing a clearer understanding of sub-domains and thematic areas within the broader field. This granularity served as a valuable tool to unveil the specific areas of focus and gaps in current research.

By systematically reviewing the literature, this study seeks to provide

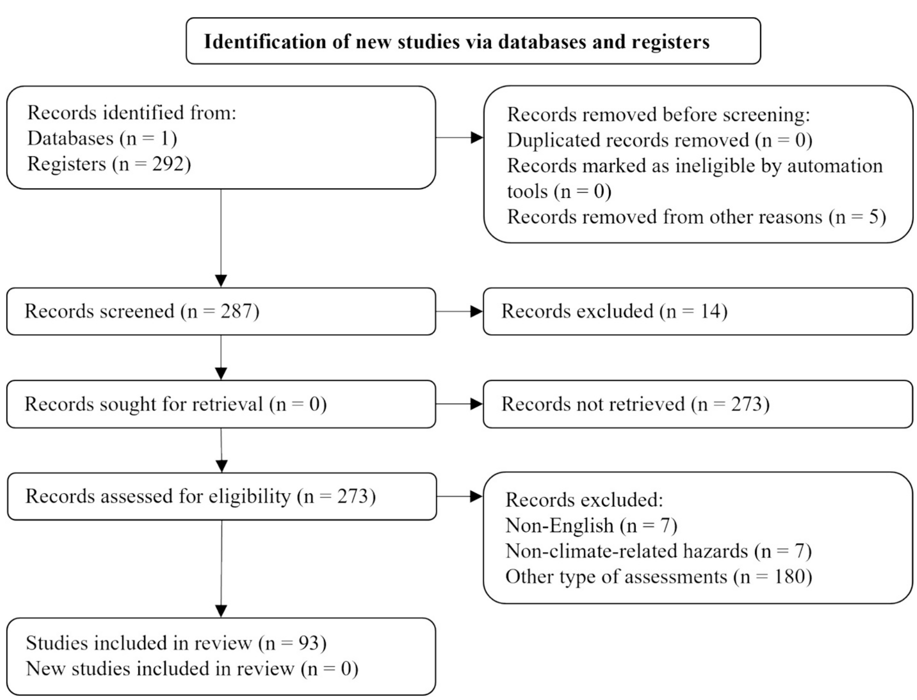

Fig. 1. Screening process, in alignment with PRISMA 2020 methodology.

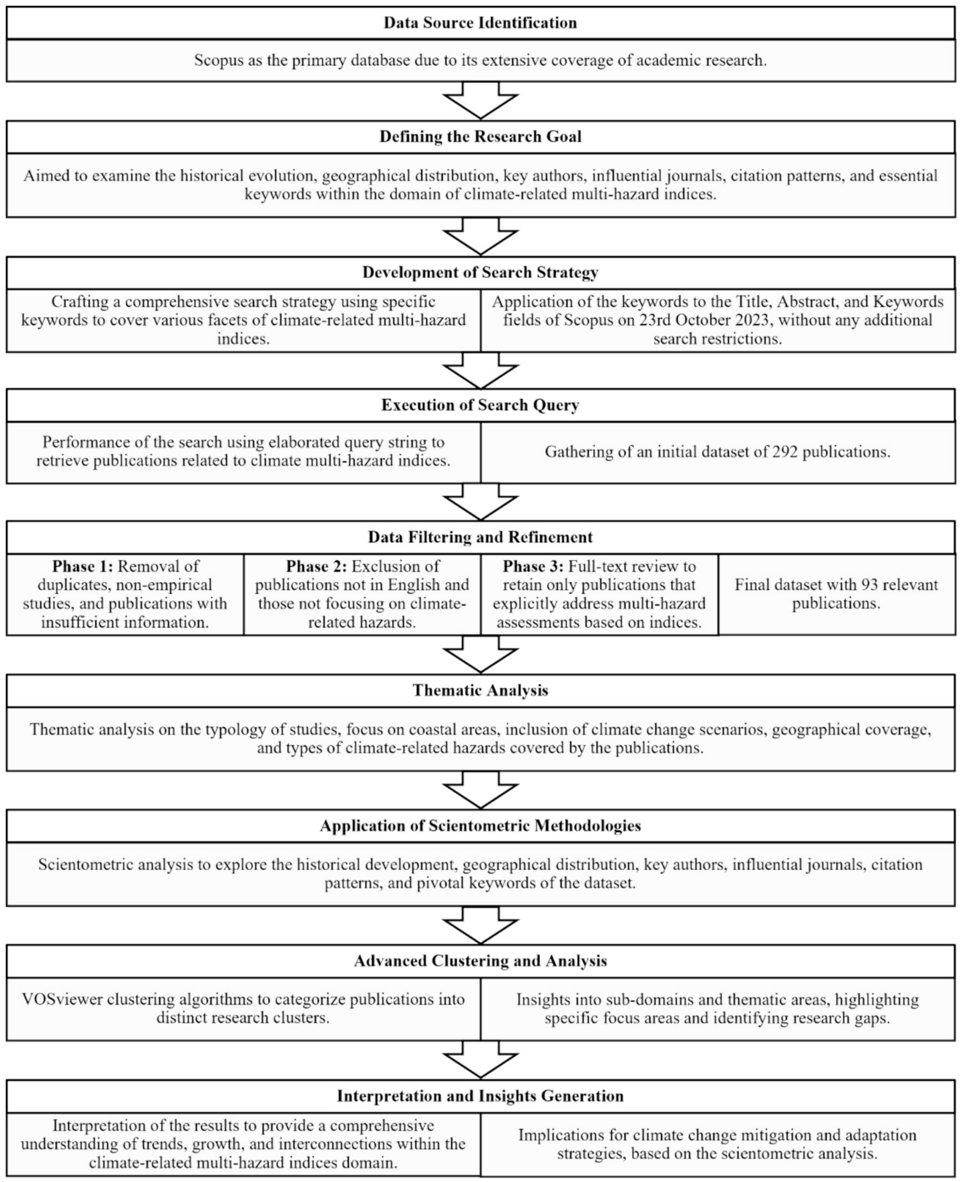

Fig. 2. Flowchart of the methodological approach.

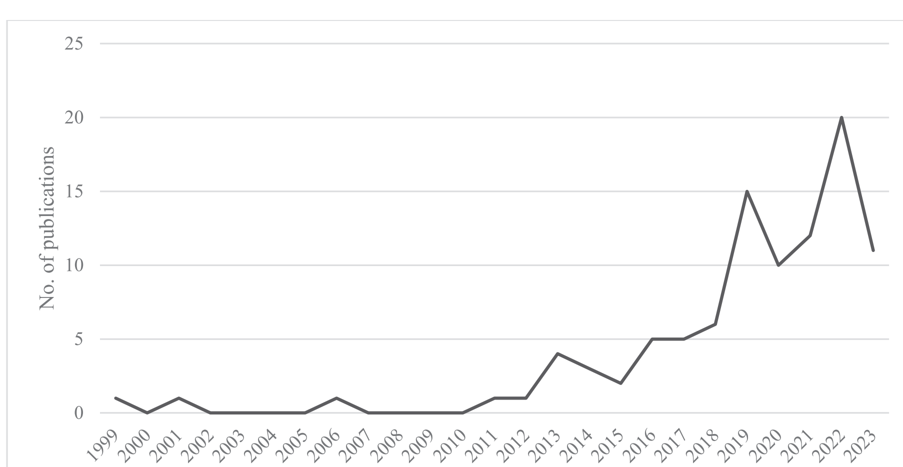

Fig. 3. Number of publications regarding multi-hazard indices by year.

a comprehensive understanding of the field, identifying significant trends, growth, and interconnections, and highlighting research gaps. This approach ensures that the findings are robust and reliable, offering valuable insights for future research directions and policy formulation in the context of climate-related multi-hazard indices.

3. Results

3.1. Trajectory of research

Fig. 3 illustrates the progression in the volume of publications related to multi-hazard indices and climate-related hazards from 1999 to 2023. The timeline depicts a clear growth trend in research interest and output, reflecting the increasing academic and practical significance of this field.

Initially, the field shows a nascent stage between 1999 and 2010, where the number of publications per year remains relatively low and consistent, suggesting a foundational period of research where key concepts and methodologies were being established.

The uptick in publication frequency beginning in 2011 suggests a growing interest that likely stems from an increased global recognition of climate change challenges. This period preludes critical events in the climate change discourse, including the release of the International Panel on Climate Change's 5th Assessment Report and the adoption of the Paris Agreement in 2015. These significant milestones likely provided the impetus for the research community to intensify their efforts, which is reflected in the rise of scholarly articles during this time.

The surge after 2015 can thus be interpreted as a direct consequence of these global frameworks taking shape, reflecting a period where the academic community actively engaged with the evolving discourse on climate change and a global push for sustainable development goals. This engagement may be further supported by advances in data collection and analytical technologies, alongside an increase in climate-related research funding (Dawkins et al., 2023a; IPCC, 2021; Oppenheimer et al., 2019). The momentum generated during this time appears to momentarily taper off during 2019-2020, a trend which may be attributable to the global disruption caused by the COVID-19 pandemic, suggesting a temporary shift in research priorities and capacities.

The subsequent recovery in 2021 and 2022 signifies the resilience of the field, with a potential increase in interdisciplinary research, policy-driven studies, and a focus on adaptation and mitigation strategies in response to escalating climate hazards (Garner et al., 2021).

The preliminary data for 2023 suggest a slight decrease from the previous year, which warrants further investigation to determine whether this is a temporary fluctuation or the start of a new trend. Overall, the trajectory of publications mirrors the dynamic nature of the field, with a clear upward trend indicative of its growing importance. This trend underscores the need for continued research and innovation to address the complex challenges posed by multi-hazard environments in the context of climate change.

3.2. Typology and focus of publications

The bar chart in Fig. 4a reveals that only 10 out of the 93 records

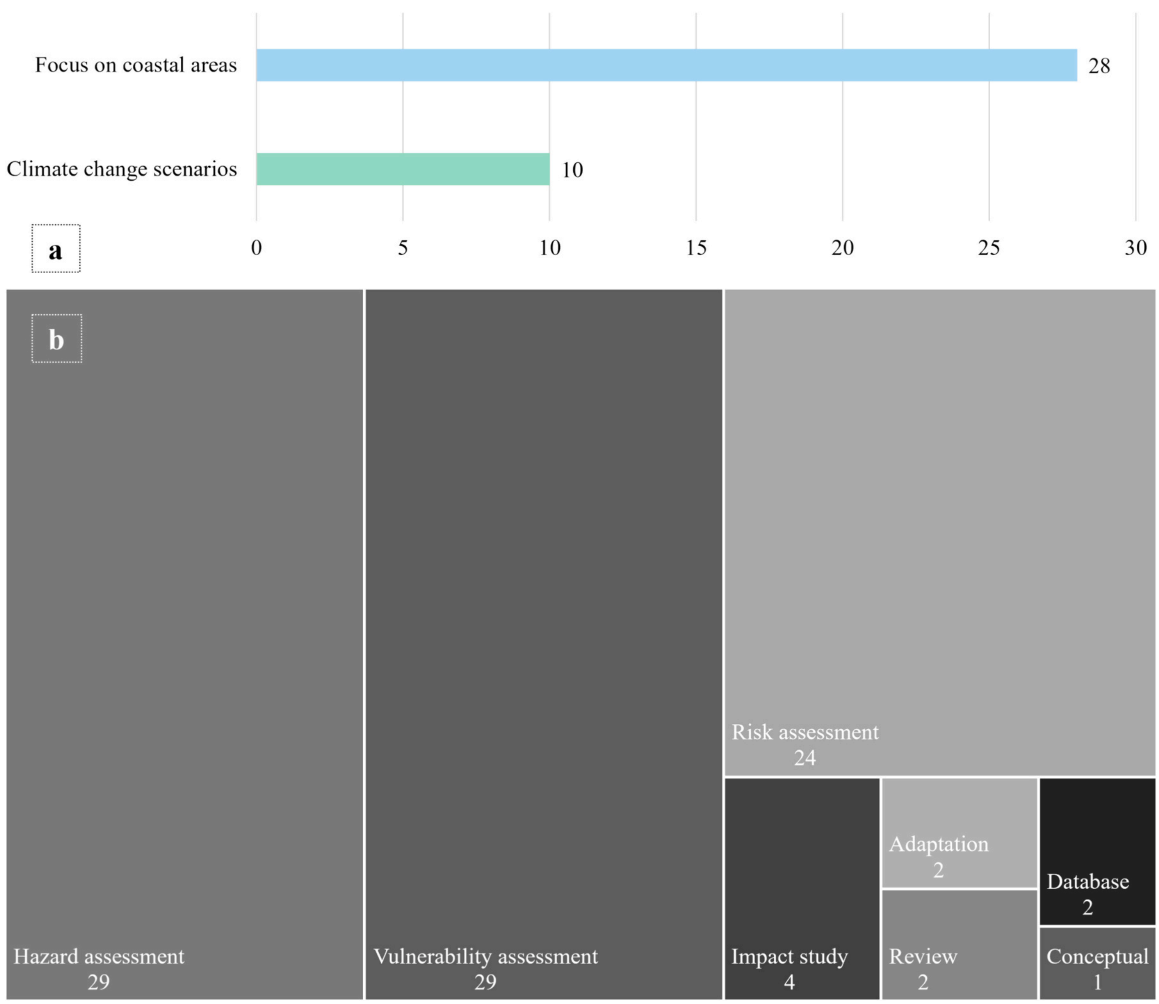

Fig. 4. Number of studies according to the consideration of coastal areas or climate-change scenarios (a) and their typology (b).

incorporate future scenarios using RCP (Representative Concentration Pathways) or SSP (Shared Socioeconomic Pathways). Additionally, 28 records focus on coastal areas. Among the studies dedicated to coastal zones, most concentrate on coastal hazards, traditionally employing the Coastal Vulnerability Index (CVI) (Ashraful Islam et al., 2016; Kunte et al., 2014; Sahoo and Bhaskaran, 2018). An exception is the study by Zanetti et al. (2016), which integrates indicators of land flooding and landslides with the CVI to assess joint vulnerability in Santos, a coastal municipality in São Paulo state, Brazil.

Studies focusing on coastal areas that use the CVI typically do not evaluate future scenarios. The three studies that do incorporate future scenarios employ different indices. For example, Antunes et al. (2019) uses the Extreme Flood Hazard Index to assess sea-level rise and coastal flooding for the years 2025, 2050, and 2100. Kapsomenakis et al. (2023) employs climate indices to evaluate hazards such as sea-level rise, heavy precipitation, droughts, extreme temperatures, and wildfires at UNESCO cultural and natural heritage sites in the Mediterranean. Mondal et al. (2022) assessed risks from storms, sea-level rise, coastal flooding, and land flooding in 15 villages in the Indian Sundarbans deltaic region using the DEMATEL methodology combined with the Livelihood Vulnerability Index and incorporating the RCP4.5 scenario.

The filtered dataset was classified into several categories based on their primary focus and contribution to the field of multi-hazard assessments (Fig. 4b). The findings indicate a balanced distribution of studies across hazard, vulnerability, and risk assessments, with additional contributions in impact assessments, adaptation solutions, datasets and theoretical frameworks. Risk assessments were the focus of 24 publications in the dataset. These studies integrated hazard and vulnerability data to provide a comprehensive view of potential impacts. The proportion of risk studies is significantly lower compared to partial studies focusing on hazard (29) or vulnerability (29) assessments, considering these components together as part of risk studies. Multi-hazard assessments typically involved the identification and quantification of various climate-related hazards in different geographical regions and under varying climatic conditions (Bärring and Persson, 2006; Christenson et al., 2014; Coscarelli et al., 2021). The vulnerability assessments generally quantify the susceptibility of populations, infrastructures, and ecosystems to multiple climate-related hazards (Ariffin et al., 2023; Corbau et al., 2022; Lopes et al., 2022). Impact assessments, which examine the direct and indirect effects of climate-related hazards on specific sectors or regions, comprised 4 publications (Changnon et al., 2013; Hoyos et al., 2013a; Huang et al., 2017; Muduli et al., 2022).

In addition to these categories, 2 publications explored adaptation strategies and solutions to mitigate the impacts of climate-related hazards in historic areas and the Indian Sundarbans (Briz et al., 2022; Sahana et al., 2021). The dataset also included 2 review publications. Lima and Bonetti (2020) applied scientometric techniques to the scientific production on social vulnerability of coastal populations, whereas Tappi and Santeramo (2022) reviewed the literature on index-based insurance with a focus on risk management policies in Italy. Furthermore, 2 databases were identified: one covering socioeconomic and climate risk scores through the Federal Emergency Management Agency National Risk Index, evictions, and housing indicators for Miami (Tedesco et al., 2021), and another encompassing various past extreme climate events (heat waves, cold waves, extreme temperatures, windstorms, and heavy precipitation events, including rainfall and snowfall) through the Weather Extremity Index (Kašpar et al., 2023). Lastly, 1 publication focused on conceptual work, presenting a framework for the definition and assessment of Climatic Impact-Drivers. This conceptual study by Ruane et al. (2022) proposed a novel approach to understanding and evaluating the complex interactions between climatic factors and their impacts, offering a foundational framework for future research.

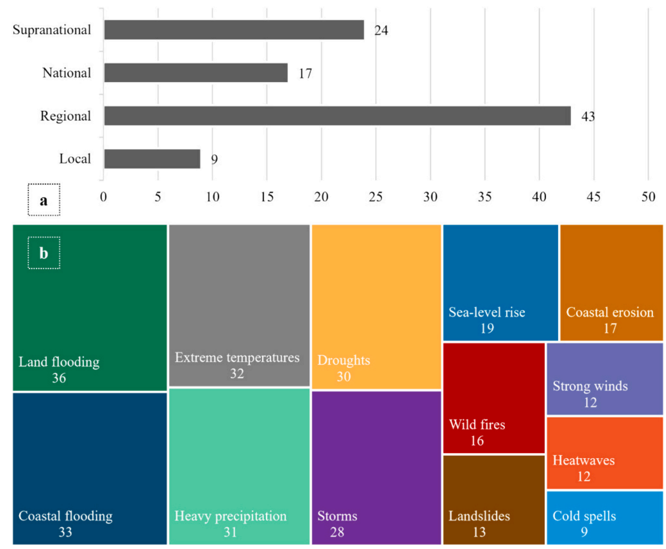

Fig. 5. Number of studies according to their geographical coverage (a) and the climate-related hazards included (b).

3.3. Geographical coverage and climate-related hazards

The geographical distribution of studies, illustrated in Fig. 5a, indicates that regional studies constituted the largest portion, with 43 publications indicating a strong emphasis on localized assessments. National-level assessments also represented a significant part of the dataset, with 17 publications focusing on country-specific studies. Notable national-level studies cover countries such as the Czech Republic (Kašpar et al., 2023), Bangladesh (Chowdhury et al., 2022; Rahman et al., 2023), Italy (Mastronardi et al., 2022), Mexico (Rivera-Arriaga et al., 2023), the USA (Bateman et al., 2020; Changnon et al., 2013; Preston, 2013; Schmeltz and Marcotullio, 2019), Portugal (Antunes et al., 2019), Colombia (Hoyos et al., 2013a), China (Wang et al., 2016), and Brazil (Avila-Diaz et al., 2016). However, these studies cover a limited number of countries globally, with a significant number concentrated in the USA. Supranational studies, comprising 24 publications, underscore the importance of understanding climate-related hazards in a broader context. Notable examples include the comprehensive multi-hazard risk assessment proposal for deltaic regions worldwide by Hagenlocher et al. (2018), the multi-hazard assessment for European regions incorporating climate-change scenarios by Lung et al. (2013), and the global mapping and ranking of mortality, affected populations, and GDP loss risks by Shi et al. (2016), covering a wide array of climate-related hazards such as storms, coastal and land flooding, droughts, landslides, heatwaves, cold spells, and wildfires. This subset also includes the review studies, one of the adaptation studies, and the conceptual work. Additionally, 9 publications focused on specific cities and localities, demonstrating detailed analyses of multi-hazard impacts at finer scales, e.g., city (Szalińska et al., 2021; Tedesco et al., 2021; Zanetti et al., 2016), industrial facility (Castro Rodríguez et al., 2023), or port (Lara Carvajal et al., 2022).

The climate-related hazards covered in the 93 publications were classified into several categories, as shown in the treemap (Fig. 5b). These categories include land flooding, extreme temperatures, coastal flooding, droughts, heavy precipitation, storms, sea-level rise, coastal erosion, wildfires, strong winds, heatwaves, landslides, and cold spells. Land flooding was the most frequently studied hazard, appearing in 36 publications, reflecting the significant impact of flooding on various regions and the critical need for effective flood risk management strategies. Coastal flooding (33 publications), heavy precipitation (31 publications), and storms (28 publications) were also extensively studied, indicating a strong research focus on hydrological hazards (De Luca et al., 2020; Rashid and Wahl, 2022; Tiepolo et al., 2019). In contrast, coastal erosion (17 publications) and landslides (13 publications) appeared less frequently, suggesting these areas might require additional research attention. Extreme temperatures (32 publications) and droughts (30 publications) were prominent focuses, highlighting widespread concerns over temperature extremes and aridity and their effects on human health, agriculture, and infrastructure (Sun et al., 2019; Szalińska et al., 2021; Zhang et al., 2022). It was noted that precipitation and temperature variables are often studied together (Deen et al., 2021; Micu et al., 2021; Song et al., 2022). Cold spells were the least frequently studied hazard, appearing in only 9 publications, indicating a relatively lower research emphasis on cold-related events compared to other climate hazards, possibly due to their lesser frequency or impact in certain regions. Heatwaves and strong winds also appeared less frequently, each addressed in 12 publications. However, it should be noted that heatwaves and cold spells are partially covered by assessments of extreme temperatures. This distribution of hazards highlights the diverse range of climate-related threats that researchers have focused on, emphasizing the comprehensive nature of multi-hazard assessments.

3.4. Advances in multi-hazard indices

The scientometric analysis of the five most cited papers in this domain, summarised in Table 1, reveals both unique approaches and common themes that have emerged over time. This groundbreaking research and related methodologies have shaped the understanding of multi-hazard indices in the context of climate-related hazards (Ashraful Islam et al., 2016; Holand et al., 2011; Hoyos et al., 2013b; Lung et al., 2013; Sahoo and Bhaskaran, 2018).

A number of common aspects and trends may be identified in these papers. A recurring theme is the development and application of various indices, such as the Socioeconomic Vulnerability Index (Ahsan and Warner, 2014), Coastal Risk Index (Bagdanavičiūtė et al., 2019), Built Environment Index (Rodriguez and Young, 2006), and Coastal Vulnerability Index (Gornitz, 1991). These indices are critical for quantifying and visualizing the vulnerability and risks associated with climate-related hazards.

Table 1
Top cited five articles.

Authors	Title	Year	Journal	Citations
I.S. Holand, P. Lujala and J. K. Rød	Social vulnerability assessment for Norway: A quantitative approach	2011	Norsk Geografisk Tidsskrift	149
A.Islam, D. Mitra, A. Dewan and S. H. Akhter	Coastal multi-hazard vulnerability assessment along the Ganges deltaic coast of Bangladesh-A geospatial approach	2016	Ocean and Coastal Management	142
N. Hoyos, J. Escobar, J.C. Restrepo, A. M. Arango and J.C. Ortiz	Impact of the 2010-2011 La Niña phenomenon in Colombia, South America: The human toll of an extreme weather event	2013	Applied Geography	120
T. Lung, C. Lavalle, R. Hiederer, A. Dosio and L. M. Bouwer	A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change	2013	Global Environmental Change	105
B. Sahoo and P. K. Bhaskaran	Multi-hazard risk assessment of coastal vulnerability from tropical cyclones – A GIS based approach for the Odisha coast	2018	Journal of Environmental Management	99

Many studies focus on a specific geographic region, underscoring the importance of localized research in understanding and mitigating the impacts of climate hazards (Feldmeyer et al., 2020). This regional specificity allows for more accurate assessments and tailored mitigation strategies. These studies often integrate data from diverse sources, including physical parameters, socio-economic data, and environmental factors (Cunha et al., 2018). This multidisciplinary approach enriches the analysis and provides a more holistic understanding of the hazards.

Another common thread in these studies is the acknowledgment and analysis of the impact of climate change on the increasing frequency and severity of hazards (Ehsan et al., 2022), which highlights the growing importance of climate change considerations in multi-hazard research (Pryor et al., 2012; Skougaard Kaspersen et al., 2017). Several papers not only assess current vulnerabilities but also project future scenarios (Binita et al., 2021; Pryor et al., 2012; Skougaard Kaspersen et al., 2017). This forward-looking approach is crucial for planning and preparing for upcoming challenges in hazard management (Garschagen et al., 2021).

Notwithstanding, the analysis of the existing literature provides relevant insights for future research. For instance, whereas regional studies are invaluable, there is a potential research gap in cross-regional comparative analyses, which could provide broader insights into global patterns and differences in vulnerability and resilience (Panagos et al., 2017). For instance, the integration of different fields of study, such as climatology, geography, social science, and urban planning, can further enhance our understanding and response to multi-hazard risks (Araya-Muñoz et al., 2017).

There is a need for further exploration of how these research findings can be translated into effective policy and practical solutions, especially in regions most vulnerable to climate-related hazards (Laurien et al., 2022). Multi-hazard indices can be integrated into urban planning frameworks, informing land use decisions, infrastructure development, and building codes. These indices may guide resource allocation, emergency preparedness, and response strategies, ensuring that adequate support mechanisms are in place before a disaster strikes. Moreover, raising public awareness and engaging communities in the development and implementation of these indices are crucial for their effectiveness and acceptance.

Leveraging advancements in remote sensing, GIS technologies, and big data analytics could provide new dimensions to multi-hazard index research (Dawkins et al., 2023b). The integration of Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and remote sensing technologies can enhance the precision, granularity, and predictive power of multi-hazard indices. AI and ML algorithms process vast datasets to identify trends and correlations, offering predictive insights into potential hazards. IoT devices enable real-time data collection, ensuring that indices are responsive to current conditions. Advanced remote sensing provides comprehensive data on geographical and environmental conditions, enriching the multi-hazard indices with high-resolution information.

3.5. Author connections and research topic evolution

The analysis utilized a filtered dataset comprising 93 publications from Scopus, revealing interesting insights into author collaborations and keyword trends. The most prolific author in our dataset has only two publications, indicating a nascent stage in this research domain. As depicted in Fig. 6, the interrelationship among authors, each with at least one publication, is somewhat limited. This figure also shows the averaged publishing years for each author. These calculations are restricted between 2016 and 2024 for better comparability. As previously shown, the yearly number of publications reaches 5 from 2016 onwards. Altogether, results showcase an early development stage for

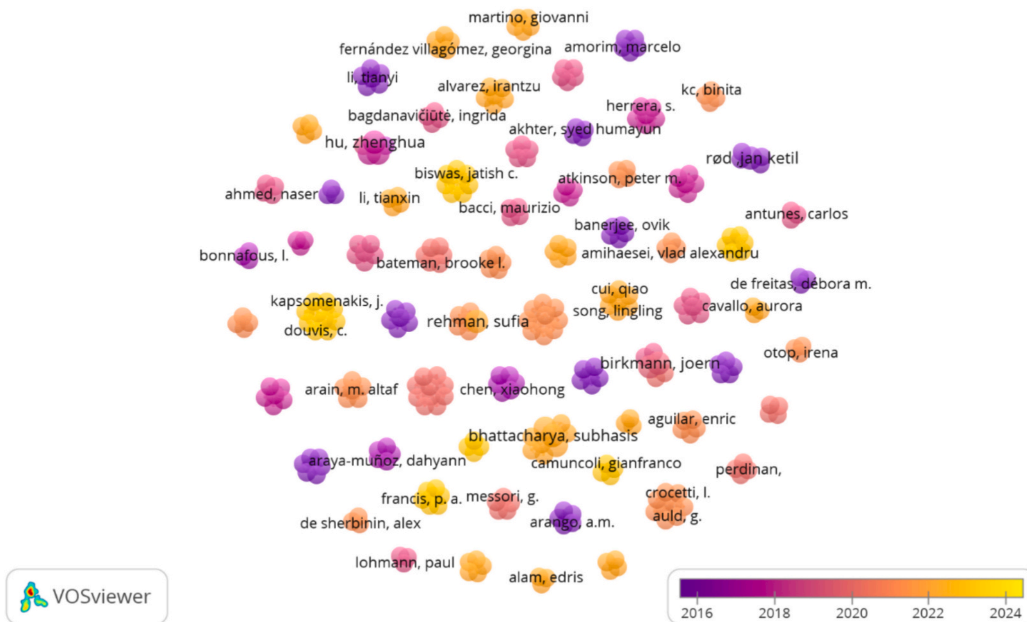

Fig. 6. Temporal evolution and linkage between authors related to multi-hazard indices.

the research topic, with authors predominantly working in small, isolated groups.

Interestingly, keyword analysis illustrates a more interconnected landscape. Dominated by ‘climate change’, the research field connects a diverse array of topics, as shown in Fig. 7. After averaging the number of occurrences for each keyword between 2016 and 2022, a notable evolution in research focus may be observed:

- Early-Stage Keywords (2016-2018): Focused on hazard and physical system components, including “vulnerability”, “flood”, “forest fire”, “natural hazard”, “extreme events”, “coastal areas”, “multiple climate hazards”, “exposure”, “urban” and “rural”, among others.
- Intermediate Stage Keywords (2019-2020): Shift towards policy and adaptation, with terms such as “Paris Agreement”, “climate change policy”, “sea-level rise”, “climate change adaptation”, “disaster risk reduction” and “resilience” gaining prominence.
- Recent Stage Keywords (2021–2022): Emerging focus on social and technological aspects, with “machine learning”, “ecoregion”, “composite fragility index”, “socioeconomic factors”, “emissions”,

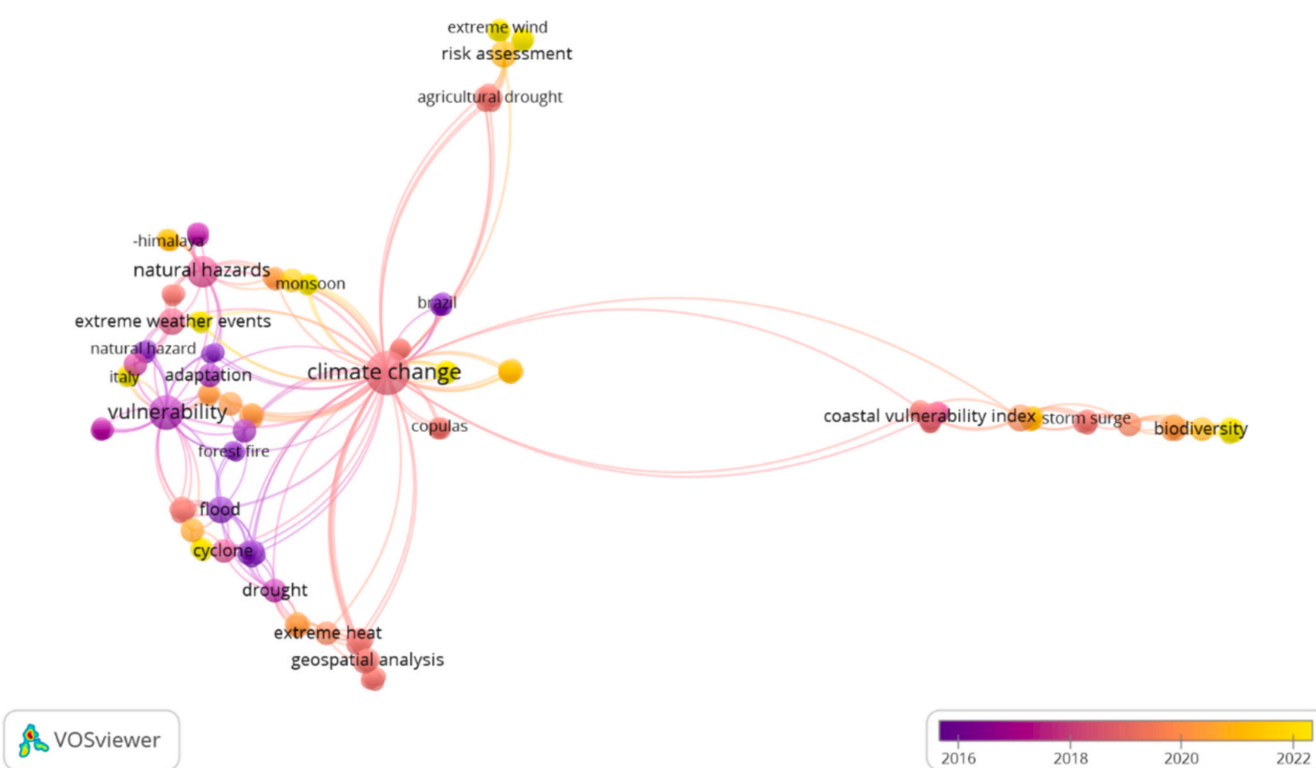

Fig. 7. Temporal evolution and linkage between keywords related to multi-hazard indices.

"gender composition", "threat perception", "emergency preparedness", "ecosystem services", "green infrastructure" being key topics.

This trend suggests a shift from studying the physical aspects of climate change to incorporating social dynamics and technological solutions, possibly reflecting the growing global concern about climate change impacts. In this regard, the integration of cutting-edge technologies in the development and application of multi-hazard indices represents a pivotal shift towards more dynamic, predictive, and responsive urban planning and disaster management strategies. The advent of AI, ML, IoT, and advanced remote sensing technologies has the potential to significantly enhance the precision, granularity, and predictive power of these indices.

ML algorithms can process vast datasets from diverse sources to identify patterns, trends, and correlations that might not be evident through traditional analysis (de Burgh-Day and Leeuwenburg, 2023). For multi-hazard indices, this means the ability to predict the likelihood of specific hazards, their potential impact, and the vulnerability of different urban areas with a high degree of accuracy (Assem et al., 2017; Moradian et al., 2023). For instance, ML models can forecast the progression of coastal erosion, or the impact of an urban heat island based on historical data, current trends, and future projections, allowing city planners to allocate resources effectively and design proactive mitigation strategies.

IoT devices enable the real-time collection and transmission of data from various sources, including sensors placed in buildings, infrastructure, and natural environments (Kumar et al., 2019). These real-time data can be fed into multi-hazard indices, offering up-to-date information on risk factors such as air quality, water levels, ground stability, or structural integrity of buildings. The integration of IoT into dynamic indices which are responsive to current conditions can facilitate timely decision-making and resource allocation in response to emerging risks, as shown in early warning systems and digital twins (Riaz et al., 2023).

Advances in remote sensing technologies, including satellite imagery and aerial drones, provide comprehensive, high-resolution data on geographical and environmental conditions (Sirmacek and Vinuesa, 2022). These data are convenient for assessing risks associated with climate-related hazards over large areas and inaccessible terrains. By incorporating remote sensing data, multi-hazard indices can offer a more complete view of risk factors, spanning from topographical changes due to erosion or landslides to changes in vegetation patterns indicative of drought or fire risk (Moreno-de-las-Heras et al., 2023).

3.6. Leading journals in climate-related multi-hazard indices research

Fig. 8 presents a list of journals that have significantly contributed to the discourse on multi-hazard indices in the context of climate-related hazards, as evidenced by their citation counts. It showcases journals with more than one publication on the topic that have accumulated a significant number of citations, reflecting their impact and relevance in the field. The number in parentheses next to each citation count represents the number of publications from each journal, providing a quantitative measure of productivity and influence within the field. This analysis not only signifies the journals' scientific contributions but also guides researchers in identifying key platforms for literature in the domain of climate-related hazard indices.

Ocean and Coastal Management leads with the highest number of citations (282), indicating its prominent role in publishing influential research that addresses the intersection of marine systems and human activities, particularly with a focus on management strategies in the face of climate hazards. It may also indicate the relevance of coastal hazards within the study of climate-related risks (Paranunzio et al., 2022).

Natural Hazards follows closely, which is consistent with its focus on the multidisciplinary nature of risks associated with natural phenomena. The journal's significant citation count (167) underscores the importance of integrative approaches to understanding and mitigating natural hazards.

Science of the Total Environment (156) stands out as well, reinforcing its reputation for covering a broad spectrum of environmental science research, including the study of multi-hazard risks and their implications on ecosystems and human health.

Other notable journals, such as Global Environmental Change (159), Journal of Environmental Management (136), and Sustainability (117), contribute a substantial body of work, reflecting a sustained interest in sustainable management practices and the broader implications of environmental change. Similarly, Ecological Indicators (78) and International Journal of Disaster Risk Reduction (71) also make notable contributions, highlighting the trend towards using indicators and risk reduction strategies in environmental research.

Somewhat less cited perhaps, yet significant, contributions originate from journals such as Earth's Future (58) and Climatic Change (42), International Journal of Environmental Research and Public Health (40) and Theoretical and Applied Climatology (34) which may focus on emerging themes – forward-looking research that integrates future scenarios, predictive modeling, and theoretical and applied aspects of climate science.

3.7. Geographical distribution of the research

Results elucidate the spatial dynamics underpinning multi-hazard indices research, leveraging an integrative analysis that combines VOSviewer network insights with geographical mapping. The focal

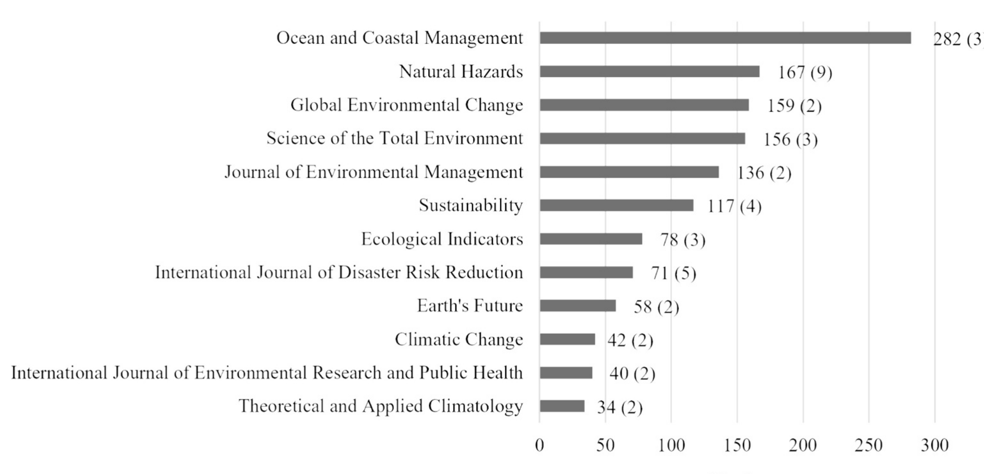

Fig. 8. Citations and, in brackets, number of articles for the journals with more than two publications regarding multi-hazard indices.

point of this exploration is the identification of key contributors and the examination of their collaborative and temporal research patterns, offering a panoramic view of the evolution of the field.

The distribution of research output and collaboration is not merely widespread but illustrates a strategic alignment among nations. Fig. 9 delineates the core group of countries at the forefront of this domain, including but not limited to India, United Kingdom, United Stated of America, Germany, China, Bangladesh, Italy, Netherlands, Australia, France, Sweden and Norway. This visual representation underscores the connectivity and cooperative endeavours among 37 actively participating countries, emphasizing those with substantial contributions in terms of publications and citations.

A noteworthy aspect of the analysis is the temporal progression of research contributions across different regions. For instance, the Netherlands, the USA, Brazil, and Australia are identified as the trailblazers, having initiated research efforts earlier than their counterparts. This temporal stratification reveals an evolving landscape where countries like China, the United Kingdom, Germany, and India have rapidly caught up, contributing significantly to the body of knowledge. Meanwhile, nations such as France, Italy, Spain, Portugal, and Iran represent a middle tier of contributors, with Switzerland, Malaysia, Greece, Argentina, and the United Arab Emirates emerging as the newest entrants in the research scene. The collaboration pattern suggests a robust network of knowledge exchange that transcends geographical boundaries, hinting at the global prioritization of multi-hazard indices research. Moreover, the evolving leadership, with newer entrants making significant contributions, underscores the dynamic nature of the field and its expansion beyond traditional research powerhouses.

Further dissecting the geographical distribution of impact, as depicted in Figs. 10 and 11, it is observed a differentiation between the volume of research output and the accumulation of citations. The data reveal that the top five citation-accumulating countries are India (533 citations), the United Kingdom (522), the United States (365), China (362), and Germany (354). Conversely, when focusing on the volume of documents produced, the leading countries slightly shift, with China (24 documents) at the forefront, followed by the United States (16), the United Kingdom (15), India (14), and Italy (13). Notably, India leads in citations, a testament to the influential nature of its research. In contrast, China dominates in the number of documents produced, indicating a prolific research output. The discrepancy between citation impact and publication volume among leading countries may reflect differing research strategies and capacities or the focus areas of national research agendas. These insights not only enrich the understanding of the geographical distribution of multi-hazard indices research but also highlight the importance of fostering international collaborations and adapting research strategies to address global challenges effectively.

4. Discussion

The scientometric analysis of the publication landscape in multi-hazard indices in relation to climate-related hazards permits exploring the evolution of the field, closely echoing the intensifying global dialogue on climate change. The marked increase in scholarly output following key international climate milestones demonstrates the responsiveness of the research community to global policy shifts and emerging environmental concerns.

The prominence of geospatial analysis and index development across the most cited papers underlines the field's prioritization of tangible, actionable frameworks to approach the abstract complexities of climate risks. The progression from vulnerability assessment tools to more granular, localized indices underscores a change of paradigm towards context-specific methodologies that take into account the unique characteristics and needs of individual regions. Yet, the current scientometric landscape reveals a notable scarcity in cross-regional comparative studies – a gap that presents a fertile opportunity for future research. Bridging this divide may be expected to result in the development of a more cohesive global understanding of multi-hazard dynamics, fostering a platform for shared learning and cooperative

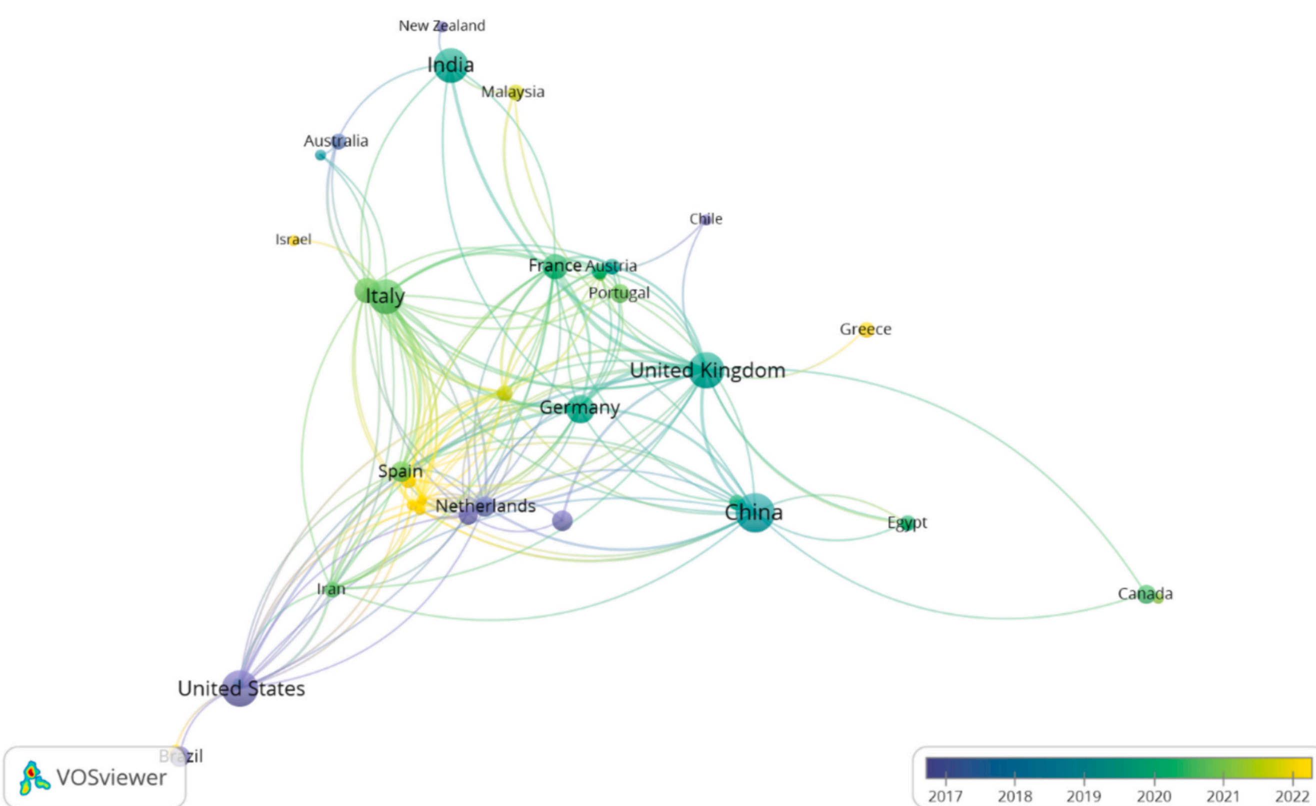

Fig. 9. Network visualization of countries.

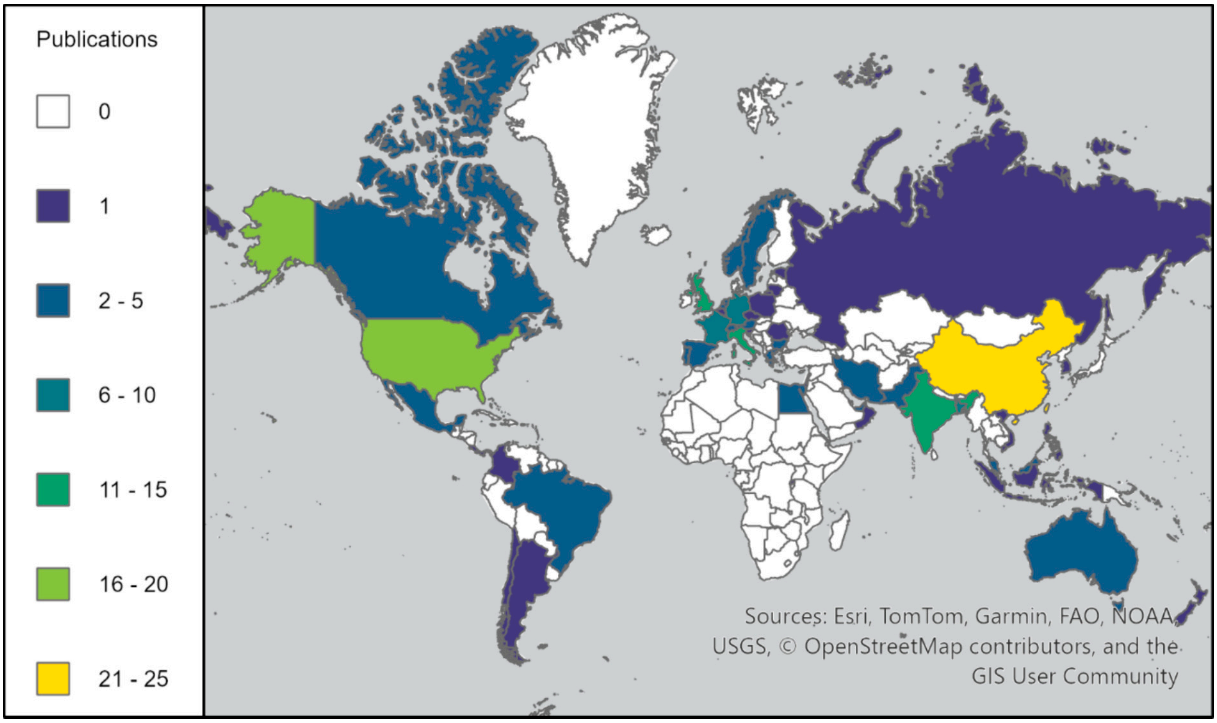

Fig. 10. Geographical distribution of publications.

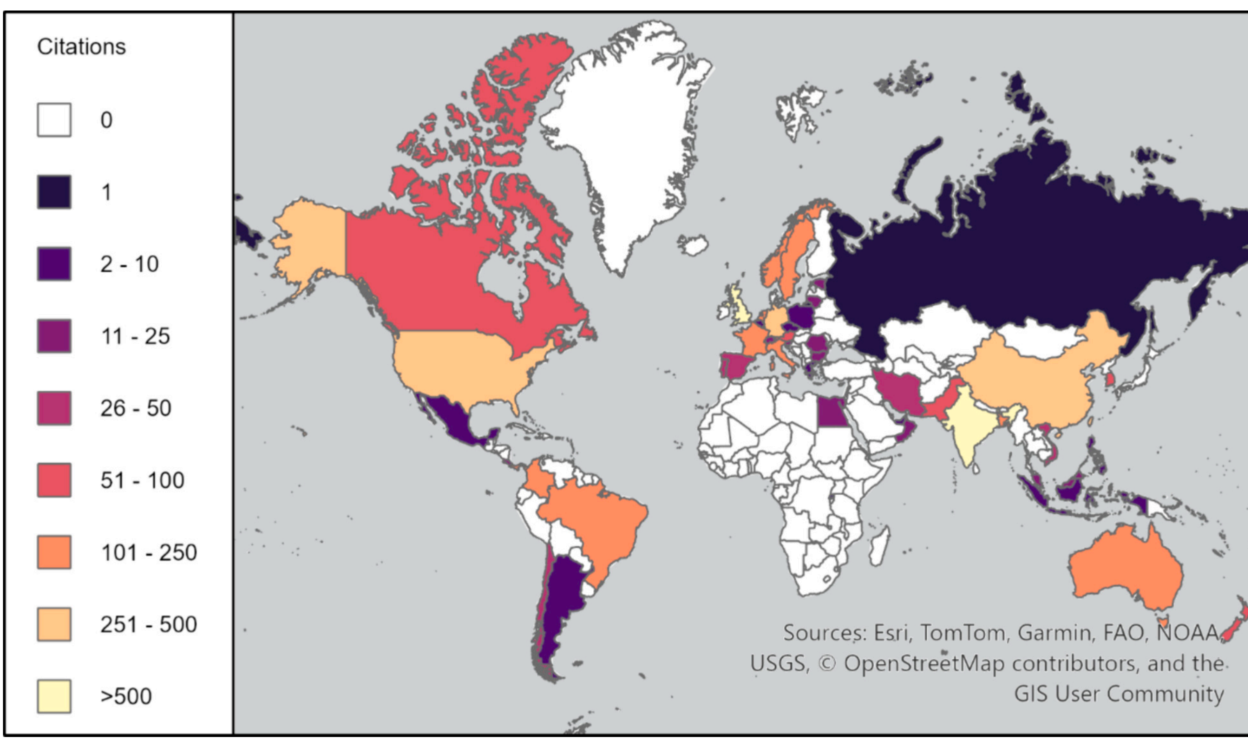

Fig. 11. Geographical distribution of citations.

mitigation efforts.

The collaborative networks and keyword trends shown after VOSviewer analysis reveals a blossoming academic community. The thematic evolution from physical aspects of hazards towards policy, adaptation, and the increasing interest in social and technological dimensions can indicate that the research production is maturing and diversifying. The emergence of keywords related to social dynamics and cutting-edge technology signals a field that is increasingly interdisciplinary and innovative, incorporating insights from a spectrum of scientific domains and societal concerns. The potential for expanding these networks is significant, with opportunities for more robust interdisciplinary partnerships and knowledge exchange poised to enrich the field further. Journals leading the research related to climate-related hazard indices serve as platforms for the dissemination of influential research, mirroring the urgency of coastal hazard adaption. These journals play a critical role not just in the academic field but also in guiding policy and practice.

The analysis of the spatial dynamics underlying multi-hazard indices research reveals a compelling narrative of global engagement and evolving leadership. The diverse geographical distribution of contributions, with significant outputs from countries like India, the United Kingdom, the United States, China, and Germany, underscores the universal recognition of the critical importance of multi-hazard assessment frameworks. This widespread participation reflects a collective endeavour towards understanding and mitigating the risks posed by multiple simultaneous hazards, a crucial step for enhancing resilience at both national and global levels.

The temporal progression in research contributions highlights an expanding field where newer entrants are rapidly contributing to the discourse. This temporal trend signifies a shift towards more inclusive and diversified research ecosystems, encouraging fresh perspectives and novel methodologies in tackling complex multi-hazard challenges. The discrepancy between citation impact and publication volume among the leading countries offers another layer of insight. This variation suggests differing strategic focuses or research capacities, potentially indicative of varying national priorities or the influence of research infrastructure and funding mechanisms. It prompts a deeper inquiry into how research policies and resource allocation affect the development and dissemination of knowledge in the field of multi-hazard indices.

The integration of AI, ML, IoT, and remote sensing into multi-hazard indices represents a paradigm shift, offering dynamic, predictive, and responsive tools for urban planning and disaster management. However, challenges such as data privacy, the complexity of model interpretation, and the need for cross-disciplinary expertise must be addressed to fully leverage these technologies. Future research should explore the potential of emerging technologies in enhancing the capabilities of multi-hazard indices. Investigating how these technologies can be effectively integrated into existing frameworks to offer real-time, predictive insights into multi-hazard risks should be a priority.

The scientometric analysis underscores the necessity of translating research insights into actionable policy recommendations. Policymakers must leverage the insights from multi-hazard indices to inform strategic planning and resource allocation. The integration of these indices into policy frameworks can foster resilient urban environments capable of adapting to climate change impacts. Longitudinal studies that track the effectiveness of multi-hazard indices over time can provide valuable data on their efficacy, adaptability, and impact on urban resilience.

While the scientometric analysis provides valuable insights, it is imperative to acknowledge its limitations. The review might be constrained by the scope of databases used, the selection criteria for publications, or the inherent biases in the literature. Future research should aim to include a broader range of databases, incorporate grey literature, and employ more inclusive criteria to capture a wide spectrum of research in this field. Future research should aim to include a broader range of databases, incorporate longitudinal studies, and explore the potential of emerging technologies in enhancing multi-hazard indices.

5. Conclusions

This scientometric review provides a holistic understanding of the research activity on multi-hazard indices in the realm of climate-related hazards, reflecting a growing academic and practical concern aligned with the escalating urgency of climate change impacts. The analysis has shown key trends in publication frequency, thematic focus, regional studies, and the emergence of innovative methodologies, all within the context of an expanding and evolving scholarly landscape.

Several key conclusions can be drawn from this review. The uptick in research publications correlates with major international climate reports and agreements, indicating that global policy developments significantly influence scholarly focus and productivity. The temporary decline observed in recent data suggests the need for ongoing monitoring to understand the long-term impacts of global events, such as the COVID-19 pandemic, on research trends.

The critical role of geospatial analysis and the development of various indices highlight the dedication of the field to translating complex climate hazards into quantifiable, actionable data (Hawchar et al., 2020). The diversity of indices reflects a robust effort to encapsulate the multifaceted nature of climate risks into tools for effective decision-making.

Although the focus on localized research has enhanced the precision of vulnerability assessments, there is a clear opportunity for comparative studies that can broaden our understanding across different regions (Koks et al., 2019). Such comparative work is essential for identifying global patterns, sharing best practices, and developing universally applicable strategies.

The shift from physical components of hazards to policy, adaptation, and social and technological aspects reveals a field that is responsive and adaptive (Huynh and Stringer, 2018). The integration of disciplines, including social sciences and technology, underscores the need for continued innovation and collaboration.

Furthermore, the analysis points towards several avenues for future research, including the development of cross-regional comparative studies, the exploration of interdisciplinary methodologies, and the incorporation of emerging technologies such as machine learning into climate hazard assessment (Argyroudis et al., 2022).

These conclusions have significant implications for policy and practice. They urge policymakers and practitioners to leverage insights from index-based methodologies to inform strategic planning and resource allocation in climate hazard mitigation. There is a need for fostering stronger collaborative networks among researchers, policymakers, and practitioners to enhance the effectiveness of climate adaptation and resilience initiatives (van den Hurk et al., 2022). The review suggests a critical evaluation of current policies and practices in light of the most recent research findings, particularly those related to the integration of social and technological factors into climate hazard assessments.

This scientometric review reaffirms the dynamic and responsive nature of the multi-hazard index research field. As the climate crisis unfolds, it is incumbent upon the academic community to continue advancing knowledge, tools, and collaborations that not only respond to emerging hazards but also pre-emptively shape resilient and sustainable futures for coastal cities worldwide. The foundation laid by past and current research efforts must now be leveraged to propel the field into new realms of inquiry and application, thereby fortifying societal responses to the multiple challenges posed by climate change.

CRediT authorship contribution statement

Emilio Laino: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roberta Paranunzio:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Gregorio Iglesias:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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