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Review article: Rethinking Preparedness for Coastal Compound Flooding: Insights from a Systematic Review.

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Abstract.

Tackling the growing risks of Compound Flooding (CF) requires transformative preparedness strategies, particularly in estuarine and coastal regions, where interaction of drivers such as storm surges, rainfall, and river discharge exacerbates impacts. Despite progress, fragmented governance, sectoral silos, and the limited integration of scientific insights hinder effective responses.

This review explores how preparedness strategies are evolving to integrate technical, environmental, and social dimensions while evaluating the role of governance and collaboration in enhancing adaptive approaches. Hybrid early warning systems combining statistical and hydrodynamic models with real-time data are critical for forecast accuracy and timely decision-making. Balanced implementation of green, blue, and gray infrastructure provides sustainable responses, with nature-based solutions complementing traditional engineering to address the unique challenges of CF.

Strengthening governance and communication is essential to improve preparedness. Co-produced strategies engaging governments, communities, and private actors foster inclusive, locally relevant efforts. Involving communities in land-use planning, building regulations, and communication ensures measures are both actionable and context-specific. Incorporating psychological and behavioral insights into preparedness frameworks helps translate awareness into effective actions.

By embracing the complexity of CF, preparedness can transcend fragmented approaches, integrating scientific innovation, adaptive governance, and tailored strategies that foster resilience in the face of a changing climate.

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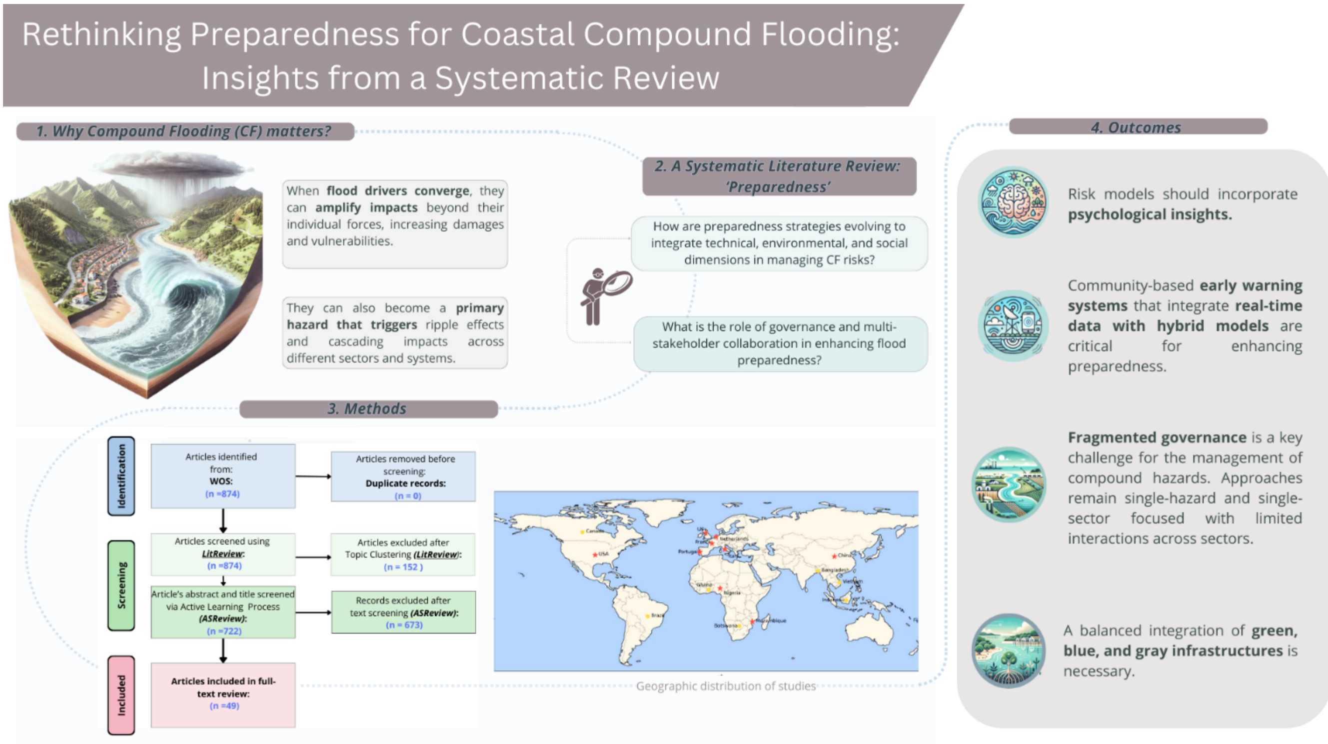

1 Introduction

The greatest risks from a changing climate may not come from individual impacts but from the interactions and interdependencies between different hazards, exposures, existing intersectional vulnerabilities, and multiple types of human responses (Simpson et al., 2023). Indeed, while single hazards can be damaging, the interconnected nature of our climate system means that simultaneous or sequential drivers and/or hazards can result in even more devastating effects, especially as global temperatures rise (AghaKouchak et al., 2020; Brett et al., 2024). Furthermore, although hazards alone do not necessarily result in disasters, when coupled with vulnerabilities and insufficient coping capacities, they can swiftly escalate into crises, causing severe and far-reaching impacts on communities and ecosystems(Eze and Siegmund, 2024).

Flooding is among the most frequent and destructive natural hazards, expected to intensify in frequency and severity as a result of climate change (Xu et al., 2023). Particularly, coastal areas are exposed to oceanographic, hydrological, and meteorological flood drivers, including rainfall, river discharge, winds, tides, and wave action. While each of these drivers can be damaging individually, their interaction can lead to compound risks with intensified flood impacts (Eilander et al., 2023). Compound risks arise from the interplay of hazards, which may be characterized by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors (Intergovernmental Panel On Climate Change (Ipcc), 2023).

For example, different drivers, such as heavy rainfall and storm surges, interact, leading to more severe flood risks than if these drivers acted independently. These combined hazards are especially critical for emergency management and the insurance industry, as these hazards have the potential to greatly amplify damage in low-lying areas (Catto and Dowdy, 2021).

While floods themselves cannot be avoided, the strategic management of floodplains and vulnerable areas is essential to mitigating the compounded threats to life and property (Mishra et al., 2022). Moreover, addressing these compound impacts requires recognizing their cascading effects on response options and preparedness (Simpson et al., 2023). More precisely, when dealing with compound flooding (CF) events, and considering the general shift in flood risk management policy from a singular focus on preventing floods through engineered structural solutions to a more holistic approach that incorporates nonstructural measures to reduce the impacts, it is essential to strengthen disaster preparedness while implementing engineering strategies to minimize risks and shield vulnerable areas (Fox-Rogers et al., 2016; Scolobig et al., 2015). Disaster preparedness involves developing the knowledge, capabilities and measures to respond to and recover from disasters, incorporating contingency planning, coordination, and simulations, while being influenced by personal attributes, socioeconomic conditions, risk perception, and prior disaster experiences (Eze and Siegmund, 2024).

In this regard, risk management is evolving from a traditional hazard-focused approach to a more integrated model that recognizes residents and property owners in risk areas as active participants in managing potential threats (Maidl and Buchecker, 2015). Building resilient communities is crucial to reduce potential losses. A practical example of this holistic approach is the Sendai Framework for Disaster Risk Reduction, which emphasizes the involvement of vulnerable communities in disaster preparedness strategies, particularly relevant for complex events like CF, recognizing that technical measures alone are insufficient (Monteil et al., 2022). By integrating local knowledge, fostering social cohesion, ensuring cultural relevance, and addressing the root causes of vulnerability, disaster risk reduction becomes more effective and sustainable. The framework advocates for inclusive participation to ensure that all segments of society are empowered and prepared to manage and reduce disaster risks.

This shift toward inclusive, community-centered approaches recognizes that disaster preparedness must go beyond technical solutions to adopt forward-looking strategies, such as prospective, corrective, compensatory, and community-based measures that actively engage local populations (Eze and Siegmund, 2024). Embedding local knowledge, fostering collaboration among diverse stakeholders, and addressing root vulnerabilities are essential for creating adaptive, equitable strategies capable of tackling systemic risks. A critical component of this transformation is the effective communication of the complexities of CF risks, ensuring that both individual and systemic perspectives are considered (Kruczkiewicz et al., 2021; Ward et al., 2022). By bridging gaps in knowledge and fostering trust among citizens, scientists, and policymakers, preparedness efforts can enhance flood management practices and enable more precise, timely responses. These efforts not only empower communities and strengthen resilience but also build collaborative networks that align societal and scientific goals, adding a transformative dimension to disaster risk reduction.

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Despite extensive research on disaster risk management, critical gaps remain in understanding how to effectively prepare for CF events. Research has largely focused on characterizing the physical processes that drive these hazards, while comparatively less attention has been given to strategies for preparedness and management. However, these events, with their cascading impacts and interdependent drivers, pose unique challenges that conventional response strategies are ill-equipped to address (Modrakowski et al., 2022). The scarcity of documented cases further limits the development of comprehensive frameworks, as current methodologies often overlook the nuanced interplay between environmental, technical, and social dimensions. Closing this gap requires innovative approaches that move beyond traditional linear models to account for the systemic nature of these risks. Such efforts are vital not only for reducing immediate physical damages but also for building long-term resilience, ensuring that communities and institutions are better prepared to navigate the growing complexities of climate-related hazards (Sacchi et al., 2023).

This paper conducts a systematic literature review to critically examine how climate risk management practices are evolving to address the intricate challenges of compound flooding in coastal areas—regions where the interplay of vulnerabilities and flood drivers increases risks. The analysis centers on two pivotal questions: i) how preparedness strategies are adapting to integrate technical, environmental, and social dimensions; and ii) the role of governance and multi-stakeholder collaboration in fostering effective and inclusive preparedness. By addressing these critical issues, this study seeks to contribute to the development of adaptive frameworks that strengthen resilience and enhance preparedness in the face of complex and evolving CF risks.

2 Background

As the frequency and severity of extreme weather events intensify, the limitations of traditional preparedness frameworks have become increasingly evident. Siloed approaches, which fail to address the interconnected nature of social systems, infrastructure, and compound as well as cascading hazards, often leave communities vulnerable to unforeseen impacts. This is particularly true for CF events, which challenge conventional preparedness strategies by amplifying risks and straining response capacities (Curtis et al., 2022; Eilander et al., 2023). For instance, CF events in Europe result in average annual damages of €1.4 billion, with Mediterranean regions particularly affected due to the combined impacts of rising sea levels and intense precipitation (Bevacqua et al., 2019; Lopes et al., 2022). Communities in this area are already grappling with the combined impacts of heavy precipitation and elevated sea levels (Bevacqua et al., 2019). In this evolving risk landscape, preparedness must transcend its traditional boundaries, integrating technical, environmental, and social dimensions. Achieving this integration demands a paradigm shift—embracing nonlinear and compound thinking to shape cohesive strategies that not only address complex interactions but also redefine resilience across all levels of society (Cegan et al., 2022; Van Den Hurk et al., 2023).

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This paradigm shift in preparedness is reflected in broader disaster risk management frameworks, which have evolved from single-hazard approaches to an all-hazards perspective that addresses complex and interacting threats (Sarmah et al., 2024). A notable example is the Sendai Framework for Disaster Risk Reduction (SFDRR), introduced in 2015. By promoting integrated and holistic strategies, the SFDRR moves away from fragmented, hazard-specific methods, providing a foundation for tackling the complexities of compound hazards like CF. While frameworks like the SFDRR emphasize the critical role of community involvement and resilience (Monteil et al., 2022), a significant gap remains in understanding how well the guidelines and protocols developed to achieve these goals apply to compound disasters.

Recent studies have provided valuable insights into CF preparedness, yet they also highlight areas that require further investigation. For example, (Van Den Hurk et al., 2023) emphasize the necessity of integrating compound event considerations into disaster risk reduction (DRR) frameworks, offering valuable insights into tools like advanced hydrometeorological forecasting, decision-support systems, and responsive emergency infrastructure. These measures hold potential to strengthen preparedness, particularly by anticipating cascading hazards and complex impact pathways. Yet, the study's broad focus on compounding risks leaves critical gaps in its application to compound flooding. The intricate interplay of drivers such as storm surges and heavy rainfall—key to understanding and managing compound flooding—is only superficially addressed. Furthermore, while the study advocates for scalable systems and decision-support tools, it does not provide clear guidance on how these approaches can be tailored to the specific challenges of compound flooding preparedness. Central to their recommendations is the call for a multi- and transdisciplinary approach, one that binds physical hazards, societal or ecological impacts, and statistical descriptions into cohesive strategies. However, this vision remains largely conceptual, lacking actionable methodologies to operationalize these elements in diverse and localized contexts. Addressing these gaps requires research that moves beyond general frameworks to deliver practical, context-sensitive solutions. Such work is essential to equip practitioners with the tools needed to navigate the evolving complexities of compound flooding under increasing climate uncertainty.

Chan and colleagues (Chan et al., 2024) investigate CF risks in Chinese coastal cities, focusing on storm surges and intensive rainfall as primary drivers, which are increasingly exacerbated by climate change and rapid urbanization. Their study highlights the co-production of response measures by the Chinese Central Government and municipal authorities, emphasizing practices such as real-time technological services (e.g., mobile apps), emergency response systems, and the integration of blue-green infrastructure through the "Sponge City Program." These efforts illustrate progress in combining engineering standards with nature-based solutions to enhance urban resilience. Critically, the study does not delve into how social dynamics, such as local risk perceptions, cultural factors, or community engagement, are woven into these strategies, leaving an important gap in understanding the social dimensions of preparedness. Furthermore, the analysis remains focused on storm surges and rainfall, with limited attention to other relevant drivers which could exacerbate flood risks. While the study provides valuable insights, its emphasis on the Chinese context—characterized by strong central governance and rapid urbanization—limits the generalizability of its findings to regions with differing socio-political and environmental conditions. Although climate change

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is acknowledged as a driver of future uncertainties, the study primarily emphasizes current practices, offering limited insight into adaptive pathways to address non-linear climatic feedback or cascading impacts.

Additionally, (Green et al., 2024) offer a detailed synthesis of compound flooding research, shedding light on critical challenges such as the absence of standardized methodologies and the limitations of current modeling frameworks in capturing the dynamic interplay of multiple flood drivers. Their recommendations emphasize the urgent need for inter-comparison projects and hybrid modeling approaches that bridge numerical and statistical techniques, aiming to enhance our understanding of spatiotemporal dependencies and climate-driven uncertainties. Furthermore, the study advocates for integrating compound flooding considerations into urban and coastal infrastructure planning, highlighting proactive measures such as blue-green infrastructure, updated hazard maps, and early warning systems. However, while Green and colleagues (Green et al., 2024) identify key research gaps, they offer limited guidance on translating these findings into actionable governance frameworks or addressing socio-economic barriers to implementation. Moreover, the discussion on stakeholder collaboration and community resilience remains underexplored, despite their importance in operationalizing the proposed strategies. These limitations underscore the need for future research that connects methodological advancements with inclusive, context-sensitive solutions to reduce compound flood risks.

While research has shed light on the interactions between multiple flood drivers and their cascading impacts, significant gaps remain in translating these insights into actionable frameworks. Many existing studies are either too broad to offer practical guidance or too narrow to address diverse contexts. Traditional approaches often fail to anticipate non-linear climate feedback or to incorporate adaptive strategies that account for the interconnected nature of social, environmental, and technical systems. Bridging these gaps requires integrated methodologies that prioritize inclusivity, scalability, and adaptability. Such frameworks must address both immediate challenges and the evolving uncertainties that define the risk landscape of CF.

3 Methods

This systematic literature review examines how preparedness strategies for CF are evolving in coastal and estuarine environments, where multiple flood drivers—such as storm surges, river flooding, and extreme rainfall—interact to create heightened risks. To capture the complexity of these interactions and the preparedness efforts that address them, the study was guided by two broad research questions designed to frame the exploration of this multifaceted topic:

I. **How are preparedness strategies evolving to integrate technical, environmental, and social dimensions in managing compound flood risks?**

The goal is to explore how current strategies combine technical solutions, such as resilient infrastructure, predictive models, and early warning systems, with critical environmental and social components, including nature-based

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solutions, community engagement, and risk perception. By examining these integrations, we assess how well they address the complex and compounding risks associated with multiple flood drivers.

II. What is the role of governance and multi-stakeholder collaboration in enhancing flood preparedness?

A key focus here is to understand how governance frameworks and collaborations between governments, local communities, and private actors shape preparedness efforts. This includes examining participatory governance, the inclusion of indigenous and local knowledge, and how these collaborative approaches contribute to more adaptive and inclusive flood management strategies.

By aligning with the SFDRR and concentrating on recent research trends, this study highlights the critical interplay between physical and social processes as essential to advancing preparedness strategies.

3.1 Research approach and database overview

The methodology follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al., 2021), ensuring a structured and transparent approach to analyzing relevant literature. To identify relevant studies, we carried out a systematic search in the Web of Science (WoS) database, applying a multi-layered strategy aimed at capturing research related to preparedness for compound flooding in coastal areas, with a particular focus on community resilience and risk management. This approach was informed by previous reviews on similar topics (Kuhlicke et al., 2023; Sun et al., 2024). The search was organized into two main steps, combined using an OR operator, allowing articles that matched either block to be included:

- **First Step:** A search based on topics (TS) that incorporated terms related to compound flooding, preparedness, and specific geographical features, enhanced by an Author Keywords (AK) query to ensure the inclusion of relevant terms connected to preparedness and flooding.

- **Second Step:** A more targeted search in the Title (TI) and Abstract (AB) fields, using terms directly related to compound flooding and preparedness, further complemented by an Author Keywords (AK) query for technical terms.

The specific search syntax used in WoS is presented in Table 1. This comprehensive approach allowed us to capture a broad range of studies focused on preparedness for flooding in coastal areas, including compound events, while ensuring relevance through multiple layers of keyword filtering. The selection was limited to peer-reviewed articles in English, with no restrictions on publication date.

The initial analysis of search results from the Web of Science database provided a broad perspective on flooding preparedness research, capturing diverse topics and approaches. A total of 874 articles met the defined criteria, addressing key themes such

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as disaster preparedness, resilience, and flood management across various environments, including coastal and estuarine regions. The decision to use the broad term “coastal flooding” allowed for the inclusion of studies conducted before the terminology of compound events became widely adopted. As a result, the retrieved articles spanned multiple areas of knowledge, reflecting the diverse strategies employed to address flood risk and preparedness. This broad scope highlights the importance of refining the analysis to focus more specifically on compound hazard scenarios, ensuring relevance to the study objectives.

Table 1. PRISMA flowchart detailing the systemic review process.

Search Structure	Search Terms
First Step	*(**TS**= ((“compound flood*” OR “coastal flood*” OR “compound coastal” OR “compound extreme*” OR “compound effect” OR “flood*” OR “inundation”) AND (“preparedne*” OR “disaster preparedness” OR “community resilience” OR “resilience” OR “coping capacity” OR “adaptive capacity” OR “early warning” OR “contingency planning” OR “community engagement” OR “decision making” OR “local knowledge” OR “indigenous knowledge” OR “traditional knowledge”) AND (“estuar*” OR “delta*” OR “lowland*” OR “river mouth*” OR “wetland*” OR “tidal area*” OR “marshland*” OR “bay*” OR “transition zones”)) AND **AK**=(“preparedne*” OR “disaster preparedness” OR “compound flood*” OR “coastal flood*” OR “compound coastal” OR “compound extreme*” OR ”compound effect” OR “flood*” OR “inundation”)*
Second Step	*(**TI**=(“compound flood*” OR ”coastal flood*” OR “combined risk” OR “compound effect” OR “compound climate”) AND **AB**=(“preparedne*” OR ”disaster preparedness” OR “resilience” OR “risk perception” OR “community resilience” OR “coping capacity” OR “early warning” OR ”adaptive behavior” OR “contingency planning” OR “estuar*”) AND **AK**=(“preparedne*” OR “disaster preparedness”))*

The abbreviations include: Topics (TS), Author Keywords (AK), Title (TI), and Abstract (AB).

To refine the initial dataset and enhance its focus and relevance, we used the Python package *litstudy*. This tool facilitated the selection and in-depth analysis of the identified publications through visualizations, bibliographic network analysis, and natural language processing techniques (Heldens et al., 2022). Figure 1 illustrates the *word cloud* generated by *litstudy*, highlighting key themes centered on adaptation, risk management, and community resilience. Prominent terms such as “risk,” “adaptation,” “communities,” and “vulnerability” emerged, reflecting the focus on preparedness strategies. Technical aspects of flood management, including forecasting and urban water governance, were also evident, with clusters emphasizing predictive models, early warning systems, and urban delta management. Additionally, ecological themes underscored the role of natural systems, particularly wetlands and floodplains, in flood mitigation. However, the word cloud analysis also revealed clusters

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related to ecological studies on biodiversity and disasters such as tsunamis and earthquakes, which were beyond the scope of this work. To address these divergences, the WOS query was adjusted to remove terms that did not align with the primary objectives of the study. Through this process, 152 articles were excluded, narrowing the dataset to 722 publications.

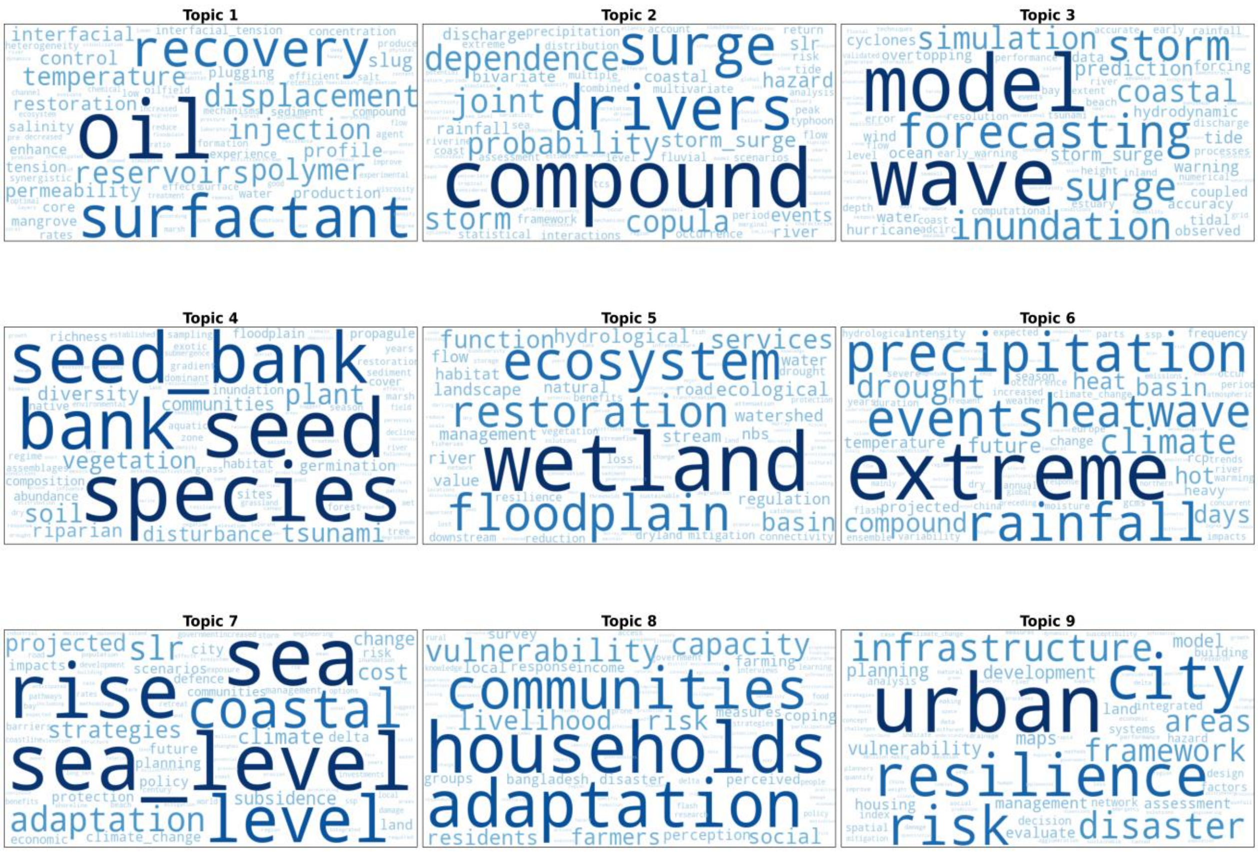

Figure 1. Word Cloud Visualization of Topics Generated from the Systematic Review of Articles. Word clouds provided by l*itstudy* highlight key themes such as compound flooding, risk management, and community resilience, while also identifying unrelated topics excluded from further analysis.

3.2 Article screening and data analysis using Active Learning Process (ALP)

Subsequently, the Python library ASReview Lab, an open-source machine learning tool, was used to streamline the systematic screening and labeling of large-scale textual datasets relevant for this study. ASReview focuses on the title and abstract screening phase—a critical bottleneck in systematic reviews—by combining human expertise with machine learning to prioritize relevant records efficiently.

The process begins with the researcher uploading the dataset containing metadata (titles, abstracts, and other relevant information) into the software. Initial *prior knowledge* is provided by selecting at least one relevant record and one irrelevant record, which serves as the foundation for training the first machine learning model. The model predicts the relevance of

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remaining records based on their textual features (titles and abstracts) while purposefully excluding author names and citation networks to prevent bias. This cycle, known as *Researcher-In-The-Loop (RITL)*, involves iterative collaboration between the reviewer and the machine learning model. The system ranks records by predicted relevance and presents them to the reviewer for labeling. The reviewer assigns binary labels (1 for relevant, 0 for irrelevant), and the model is retrained after each labeling session to refine its predictions. This process continues until a user-defined stopping criterion is met, such as the reviewer's confidence that all relevant records have been identified. By prioritizing the most probable records first, ASReview significantly reduces the effort required for title and abstract screening while maintaining transparency and control in the decision-making process. Studies have shown that this methodology can reduce screening time by up to 95% without compromising review quality (Van De Schoot et al., 2021).

To further enhance the efficiency of the review process, we incorporated a fine-tuned BERT (Bidirectional Encoder Representations from Transformers) model, a state-of-the-art natural language processing tool renowned for its ability to capture nuanced contextual relationships within text. BERT's bidirectional architecture enables it to process entire sentences in context, making it particularly effective for tasks such as document classification. By fine-tuning the model on a subset of labeled data specific to our study, we automated the initial classification of articles retrieved from the Web of Science database. While BERT provided an automated pre-screening, this step did not replace the critical role of the human reviewer. Instead, the pre-labeled data served as input for ASReview, which facilitated an iterative *Researcher-In-The-Loop* (RITL) process. In this process, the reviewer actively validated and refined the classification results, ensuring that relevant studies were accurately identified. The synergy between BERT's robust text analysis capabilities and the reviewer's expertise not only accelerated the screening of large datasets but also preserved the rigor and reliability of manual review. This combined approach enhanced the reproducibility of the methodology and reduced the inherent subjectivity of manual review.

After applying this methodology to the initial dataset, 49 articles were selected for their relevance and prioritized for an in-depth review. These articles were identified based on their alignment with the research questions, ensuring that only those with the greatest potential to contribute meaningfully to the study were included for further analysis. It is important to note that, considering the complexity involved in preparing for simultaneous or interacting drivers of flooding in such scenarios, this nuanced aspect of preparedness is likely only now gaining prominence as a focal point of investigation. Therefore, the scope of the search for relevant articles was kept broad, aiming to encompass various perspectives related to coastal flood preparedness. Figure 2 provides a visual summary of the systematic review methodology applied, following the PRISMA framework. It outlines the key stages, starting from the identification of 874 articles in the Web of Science database, through the screening process using tools like *LitReview* and *ASReview*, to the final inclusion of 49 articles for full-text analysis.

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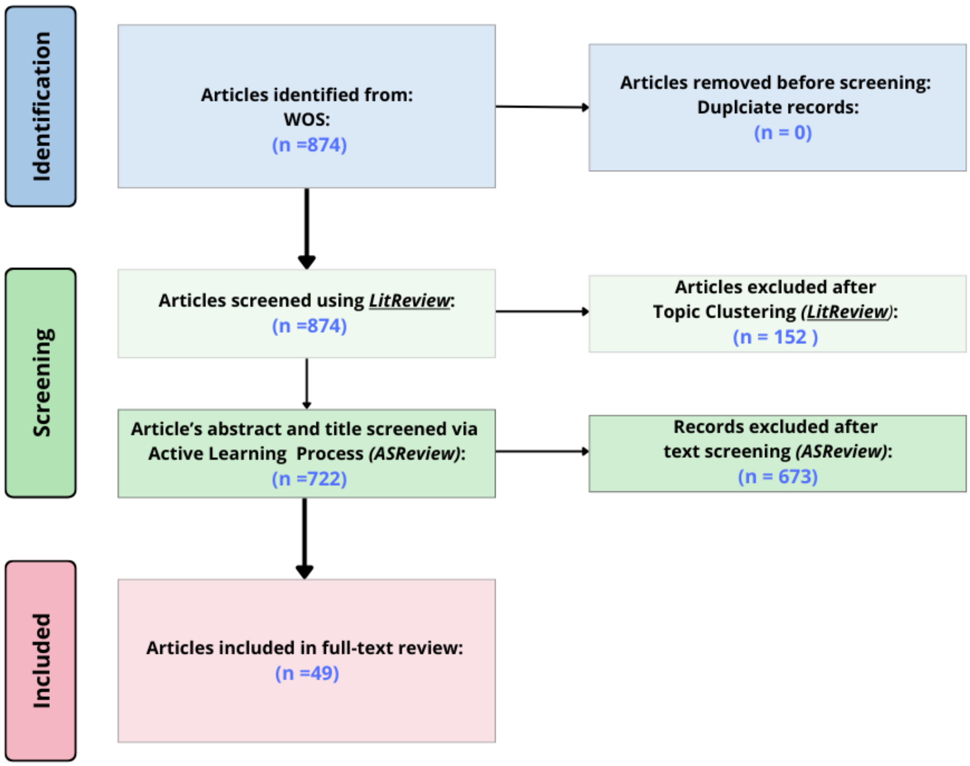

Figure 2. Flowchart of the Review Process Following the PRISMA Framework. From 874 articles identified in WOS, 152 were excluded through topic clustering (*LitReview*), and 673 more were removed after title and abstract screening (*ASReview*). This resulted in 49 articles included for full-text review, forming the final dataset.

4 Results

4.1 Preparedness research: Emerging trends

An examination of the research areas associated with the initial dataset reveals a predominant focus on Environmental Sciences, Ecology, and Meteorology and Atmospheric Sciences (see Figure 3). These fields are strongly represented, reflecting the emphasis on the physical and environmental dimensions of flood preparedness. However, a significant gap becomes evident in the limited presence of social sciences.

Although research on risk modeling, water management, and ecological resilience is well-represented, there is comparatively less prominence given to socio-economic resilience, governance, and community engagement. This imbalance may stem from the historical focus on technical and environmental solutions in flood preparedness, particularly in coastal regions, where infrastructural approaches have often been prioritized. The broad scope of the search, intended to capture various aspects of flooding, may have further contributed to the underrepresentation of studies addressing social vulnerability, participatory

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governance, and policy innovation. Closing this gap is crucial for fostering a more comprehensive understanding of resilience, integrating both technical and socio-economic dimensions.

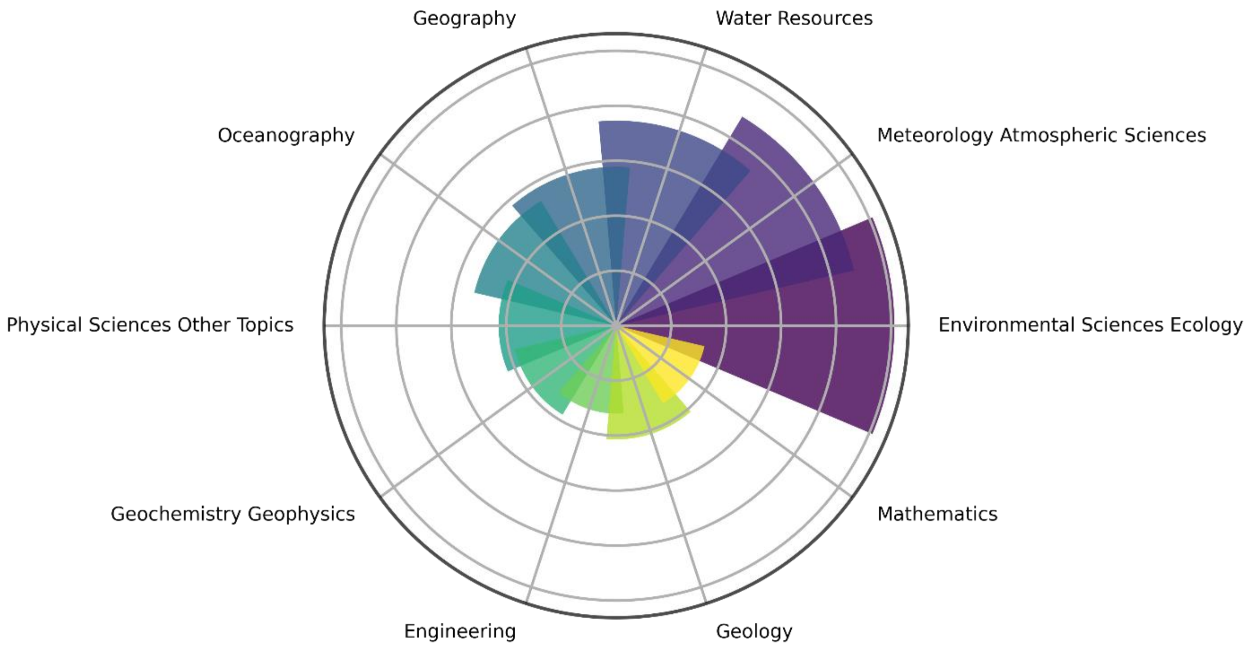

Figure 3. Disciplinary Coverage of Reviewed Articles: Contributions from Various Fields. This visualization depicts the strong representation of Environmental Sciences, Ecology, and Meteorology, alongside the limited inclusion of Social Sciences in the dataset.

A closer analysis reveals a marked increase in publications addressing these challenges starting around 2012 (see Figure 4). In parallel, it is important to acknowledge that this increase also reflects a general exponential growth of scientific production in the past decade. This is marked by an increase in the average individual outputs, the number of authors per paper, and the total number of people pursuing academic careers (Ioannidis et al., 2018). As recently highlighted by (Priem et al., 2022), more than 60% of all the world scientific publications have been produced after the year 2000. The general global expansion of academic publishing is surely affecting also the trends emerged in this research.

However, as shown in Fig. 4, the year 2012 has marked a shift in the scientific production about the topics at the core of our research. Prior to this, research in the area was relatively limited, with a gradual rise in published papers. This notable growth in scientific attention after 2012 aligns with a broader shift in natural hazard research paradigms, particularly following significant developments in climate risk frameworks. The surge in publications, particularly after 2015, coincides with the growing recognition of the need for integrated approaches that address the complexities of compound flooding and other interconnected hazards. The evolution of research in this area reflects a deeper commitment to understanding and managing the multifaceted risks posed by these events.

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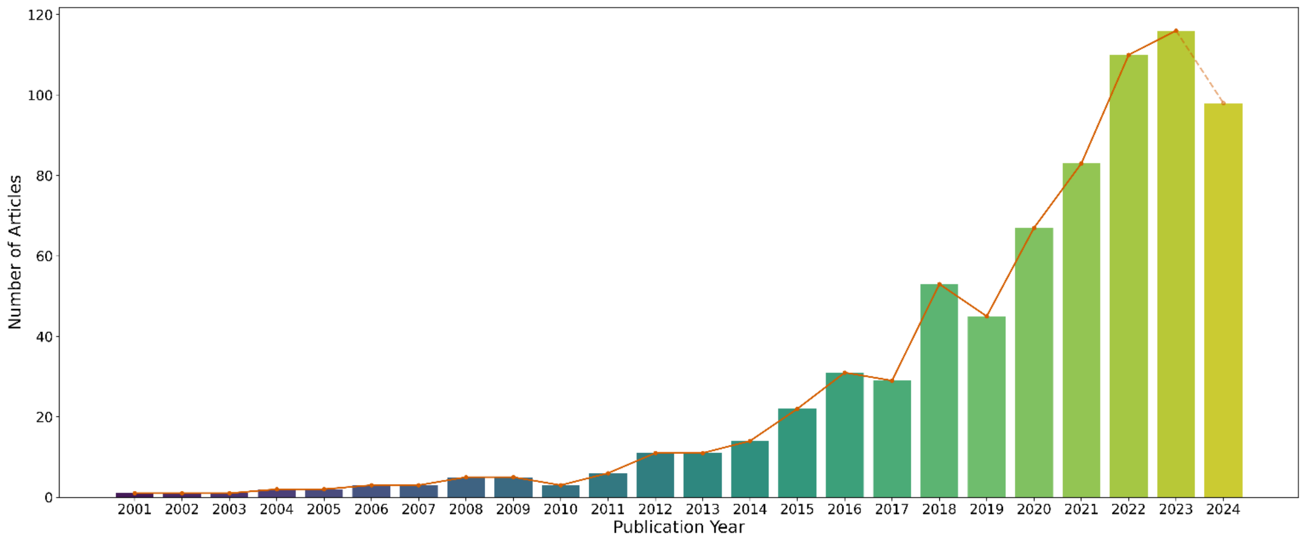

Figure 4. Yearly Distribution of Published Articles: A Trend Analysis. The data for 2024 includes publications available up to September, as the search was conducted prior to the end of the year, thereby excluding any studies published subsequently.

The analysis of preparedness-related terms in the dataset (see Figure 5) suggests a compelling narrative of thematic evolution, shedding light on the shifting priorities and emerging challenges in this domain. Early research efforts, particularly before 2010, were fragmented and focused predominantly on isolated hazards such as riverine flooding, storm surges, or sea-level rise. These studies largely neglected the interdependencies between multiple drivers, resulting in a siloed understanding of flooding phenomena and limited integration of systemic risk perspectives. The years following 2010 marked a pivotal transformation in the field, as the limitations of hazard-specific approaches became increasingly apparent. Terms such as "compound," "multi-hazard," and "risk management" gained prominence, reflecting a growing recognition of the interconnected nature of natural hazards and the need for integrated frameworks. Global initiatives, such as the Sendai Framework introduced in 2015, reinforced this paradigm shift by advocating for multi-hazard, multisectoral approaches to disaster preparedness, emphasizing the importance of addressing cascading risks and systemic vulnerabilities in a coordinated manner.

To fully understand the evolution of preparedness strategies, it is crucial to consider how research approaches changed during this transition. Early studies, conducted prior to 2010, primarily treated riverine and coastal flooding as distinct phenomena, focusing on variables such as storm surges, sea-level rise, and tides (Burch et al., 2010; Slinger et al., 2007; Zaalberg et al., 2009). These studies did not explicitly address preparedness for compound flooding, reflecting a fragmented approach to risk management. The conceptual breakthrough came with the introduction of "compound events" in the IPCC's Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) in 2012, which defined these events as the combination of multiple physical processes.

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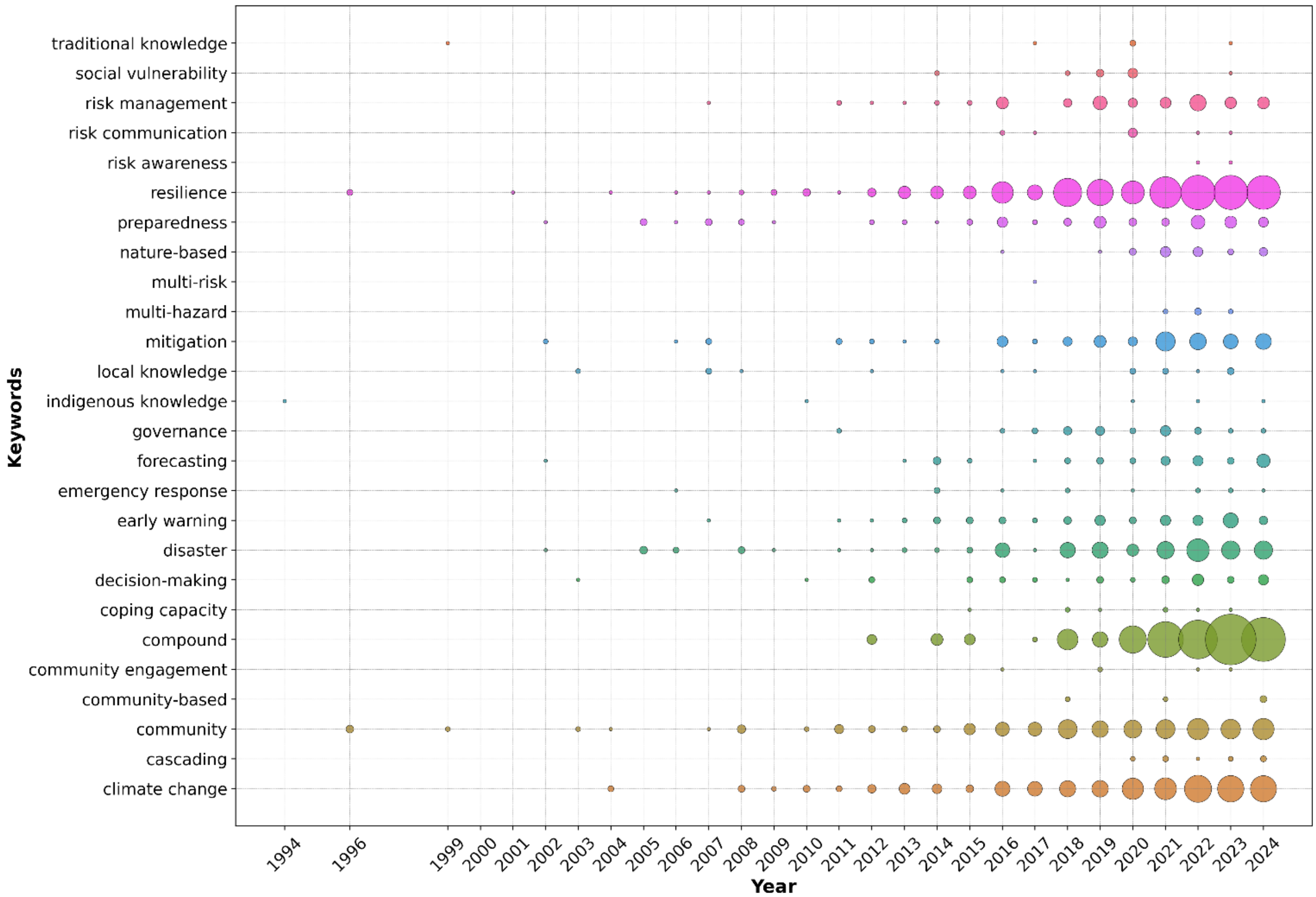

Figure 5. Temporal Distribution of Absolute Frequencies of Key Terms extracted from the Abstracts of Reviewed Articles. This bubble plot illustrates the occurrence of key terms over time, suggesting shifts in research focus and the introduction of new topics within the reviewed articles. The size of each bubble represents the frequency of a specific term during a particular year.

The term "compound event" gained further prominence with Leonard and colleagues (Leonard et al., 2014), who refined this definition, emphasizing the multivariate nature of compound flooding. (Freire et al., 2016) subsequently underscored the importance of preparedness in transitional systems, particularly estuarine regions where tides, river flows, wind, and waves converge. Their work highlighted the socio-economic complexities of these systems and emphasized the need for integrated, multi-hazard preparedness strategies capable of addressing the cascading impacts of CF.

The trends post-2020 illustrate a period of thematic diversification, with increasing emphasis on community-centered and ecosystem-based approaches. Terms such as "community," "local knowledge," and "nature-based" solutions reflect a growing understanding of the need to balance technical solutions with social and environmental considerations. Simultaneously, terms like "resilience" and "mitigation" remain central, emphasizing the dual focus on reducing vulnerability and enhancing adaptive

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capacity. However, the relatively modest visibility of "governance" and "cascading" highlights persistent gaps in addressing the interconnected and feedback-driven risks associated with compound flooding. Similarly, the underrepresentation of localized and traditional knowledge systems suggests an ongoing need to integrate diverse perspectives into preparedness frameworks.

The upward trajectory in the frequency and diversity of key terms signals a maturing research landscape, transitioning from fragmented hazard-specific studies to interdisciplinary, systems-based frameworks. However, this evolution remains incomplete. The limited attention to social vulnerability, participatory governance, and localized knowledge indicates that technical and infrastructural solutions continue to dominate preparedness efforts. Moving forward, the research community must embrace the inherent complexity of compound flooding by developing adaptive, community-driven strategies that integrate governance, equity, and cascading impacts into preparedness frameworks. Such an approach will not only strengthen resilience but also ensure that preparedness strategies are robust, inclusive, and sustainable, effectively addressing the increasing challenges posed by climate change.

From the detailed review of the 49 articles identified through systematic screening, 45 were identified as directly relevant to the study's focus on preparedness for compound flooding in coastal regions. These studies offer critical insights into the integration of technical, environmental, and social dimensions in managing compound flood risks, as well as the role of governance and multi-stakeholder collaboration. The remaining four articles, while insightful, focused on non-coastal contexts or broader themes of disaster preparedness, making them less central to the objectives of this research. Table 2 categorizes the selected articles by country and organizes them into four thematic clusters: Perceptions and Behavioural Responses, Compound Events Forecasting, Governance and Policy, and Participatory and Innovative Methods for Risk Management. These clusters represent an approximation to the primary thematic focus of each study, aligned with the objectives of this analysis.

Figure 6 synthesizes key findings from the selected articles. Panel a) illustrates the geographic distribution of studies, distinguishing those specifically addressing compound flooding preparedness from those focused on broader coastal flooding contexts. This distribution highlights the global research landscape, reflecting varying regional priorities and challenges in flood preparedness. Panel b) identifies the principal flood drivers considered in compound flooding studies, shedding light on the technical aspects prioritized in current preparedness frameworks, such as storm surges, river discharge, and rainfall. Lastly, panel c) aggregates the total number of studies by country, revealing geographic trends and disparities in research efforts. Together, these panels form a cohesive snapshot of the academic landscape, laying the groundwork for a deeper exploration of how preparedness strategies are evolving and the role of governance in enhancing resilience against complex flood risks.

By analysing key studies, this review sheds light on the challenges and limitations of existing approaches, offering insights that can inform more adaptive, inclusive, and actionable strategies to enhance resilience and preparedness in coastal regions increasingly affected by complex flood risks.

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Table 2. Overview of Selected Studies Grouped by Key Topics and Geographic Context.

Key Topic	Geographic focus	Year and References
Perceptions and Behavioural Responses	Spain	2008 (Raaijmakers et al., 2008)
	Botswana	2011 (Motsholapheko et al., 2011); 2018 (King et al., 2018)
	Vietnam	2015 (Casse et al., 2015); 2016 (McElwee et al., 2017); 2020 (Ngo et al., 2020)
	Netherland	2016 (De Boer et al., 2016); 2020 (Mol et al., 2020)
	Fiji	2016 (Nolet, 2016)
	France	2016 (Rambonilaza et al., 2016); 2019 (Lemée et al., 2019); 2022(Lemée et al., 2022)
	Indonesia	2018 (Maryati et al., 2019)
	USA	2019 (De Koning et al., 2019); 2020 (Johns et al., 2020); 2024(Richmond and Kunkel, 2024)
	Myanmar	2020 (Lwin et al., 2020)
	Brazil	2022(Pereira Santos et al., 2022)
	Italy	2023 (Sacchi et al., 2023)
	Bangladesh	2023 (Faruk and Maharjan, 2023)
	Nigeria	2024 (Michael, 2024)
Compound events forecasting	China	2020 (Du et al., 2020); 2023 (Guo et al., 2023; Yu et al., 2023); 2024 (Chan et al., 2024; Sun et al., 2024; Xu et al., 2024)
	Mozambique	2023 (Matos et al., 2023)
Governance and Policy	Netherland	2005 (Gerritsen, 2005); 2022 (Oukes et al., 2022)
	Botswana	2017 (Shinn, 2018)
	China	2017 (Liang et al., 2017); 2023 (Xie et al., 2023)
	Canada	2019 (Chang et al., 2020)
	UK	2024 (Coletta et al., 2024)
Participatory and Innovative Methods for Risk management	Netherland	2007 (Slinger et al., 2007)
	Botswana	2015 (Motsholapheko et al., 2015)
	UK, Netherland, USA, Indonesia	2015 (Jeuken et al., 2015)
	USA	2015 (Cheung et al., 2016)
	Portugal	2016 (Freire et al., 2016)
	Ghana	2017 (Yankson et al., 2017)
	Italy, Portugal	2018 (Martinez et al., 2018)
	China	2022 2023 (Chan et al., 2023)
	Vietnam	2020 (Binh et al., 2020)
	Bangladesh	2022 (Azad et al., 2022)

The topics serve as a preliminary and illustrative framework for organizing the studies, without implying a definitive categorization.

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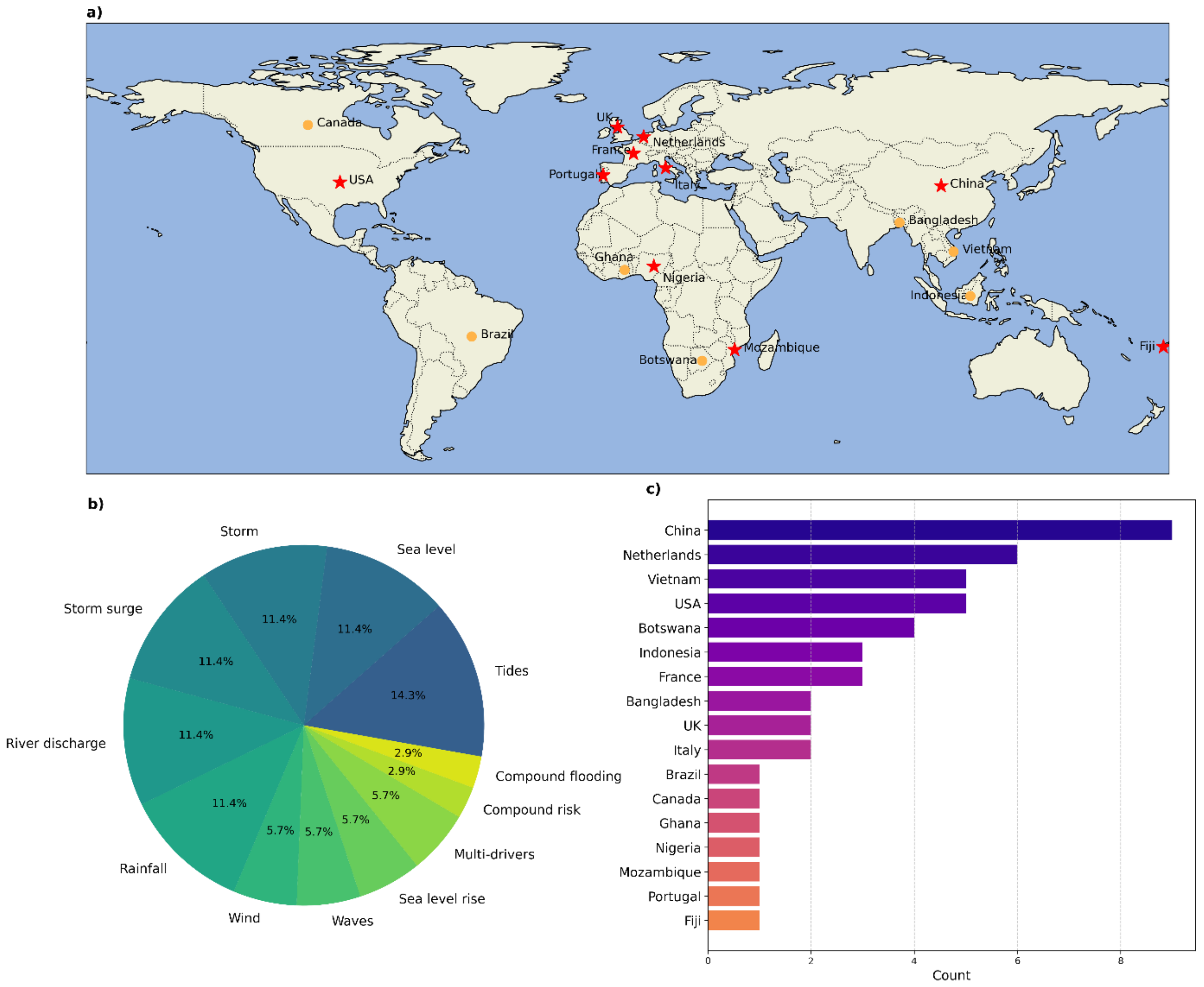

Figure 6. Global Perspectives on Flood Preparedness Studies: (a) Geographic distribution of studies, with red stars highlighting research focused on compound flooding and orange circles indicating those centred on coastal flooding preparedness. (b) Primary flood drivers in CF studies, represented in a pie chart to emphasize the most frequently addressed factors. (c) Total number of studies by country, visualized in a bar chart to showcase regional trends and disparities in research efforts.

4.2 Evolution of preparedness strategies and integration of different dimensions

A marked transition from isolated, hazard-focused measures to integrated approaches that simultaneously address technical, environmental, and social dimensions has been identified. This shift reflects an evolving recognition that CF risks—emerging from the interplay of multiple drivers such as storm surges, rainfall, and sea-level rise—cannot be effectively mitigated through

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traditional, siloed interventions. The following analysis delineates this temporal evolution and provides evidence from the literature to explicitly address the research question.

- *Pre-2010: Technical Dominance*

Preparedness efforts before 2010 were dominated by hazard-specific, infrastructure-based solutions aimed at mitigating singular risks. These measures, while technically robust, often excluded environmental and social dimensions, limiting their capacity to address the systemic nature of CF. For instance, the Netherlands' Delta Plan (Gerritsen, 2005) epitomized this approach with its focus on advanced dyke systems, storm surge barriers, and hydraulic modelling. Though effective in managing storm surges and sea-level rise, these interventions lacked adaptability to cascading effects or simultaneous hazards. Environmental considerations were peripheral, limited to augmenting engineered defenses with natural dunes, while social engagement was minimal, typically confined to rudimentary awareness campaigns. This singular focus created blind spots, particularly in anticipating the compounded impacts of multiple drivers, such as storm surges coinciding with heavy rainfall.

- *2010–2020: Transitioning Toward Integration*

The period between 2010 and 2020 marked a pivotal transition, driven by the recognition of limitations in traditional methods. Emerging hybrid approaches sought to integrate technical, environmental, and social strategies, although still in its early stages. For example, Portugal (Freire et al., 2016) adopted WebGIS-based hazard mapping to enhance flood preparedness, while Fiji (Nolet, 2016) emphasized the preservation of wetlands and mangroves as natural buffers against flooding. Social dimensions gained prominence, with efforts in China (Liang et al., 2017) leveraging informal networks and community-based initiatives to enhance urban preparedness. However, these advancements were often fragmented, and frameworks for addressing the interaction of multiple flood drivers—such as urban runoff, tidal forces, and extreme rainfall—remained underdeveloped. Despite these challenges, this period laid the groundwork for a broader understanding of CF as a complex, multi-dimensional risk requiring collaborative solutions.

- *Post-2020: Toward Holistic and Adaptive Approaches*

Post-2020, preparedness strategies have embraced the complexity of CF, integrating advanced technical tools with adaptive, community-focused approaches. Coupled hazard models and bivariate statistical analyses now enable planners to simulate interactions between multiple drivers. For instance, China (Sun et al., 2024) employs hydrodynamic models to predict cascading impacts, while the UK (Coletta et al., 2024) combines socio-hydrological frameworks with blue-green infrastructure to mitigate long-term flood risks.

Nature-based solutions (NbS) have emerged as central to these strategies. Programs like China's Sponge City initiative (Chan et al., 2024) integrate wetlands and mangroves into urban hydrology restoration, while Nigeria (Michael, 2024) incorporates

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indigenous practices and gender-focused adaptations to address systemic vulnerabilities. These examples highlight the increasing importance of aligning environmental restoration with technical and social measures. Social inclusion now defines modern preparedness, with participatory governance and equitable decision-making shaping interventions. Mozambique (Matos et al., 2023) integrates community surveys into planning, amplifying local knowledge, while Italy (Sacchi et al., 2023) applies behavioural psychology to address biases in risk perception. Such initiatives reflect a shift from reactive measures to anticipatory frameworks that prioritize resilience.

Figure 7 further reinforces the narrative of this temporal evolution, emphasizing the increasing complexity and interconnectedness of technical, environmental, and social dimensions. Historically, flood preparedness has focused on technical solutions such as risk assessments, forecasting models, and early warning systems that consider multiple flood drivers. Techniques like hydrodynamic modeling and statistical frameworks have greatly enhanced the prediction of flood zones and inundation scenarios, which are pivotal for mitigation planning (Xu et al., 2024).

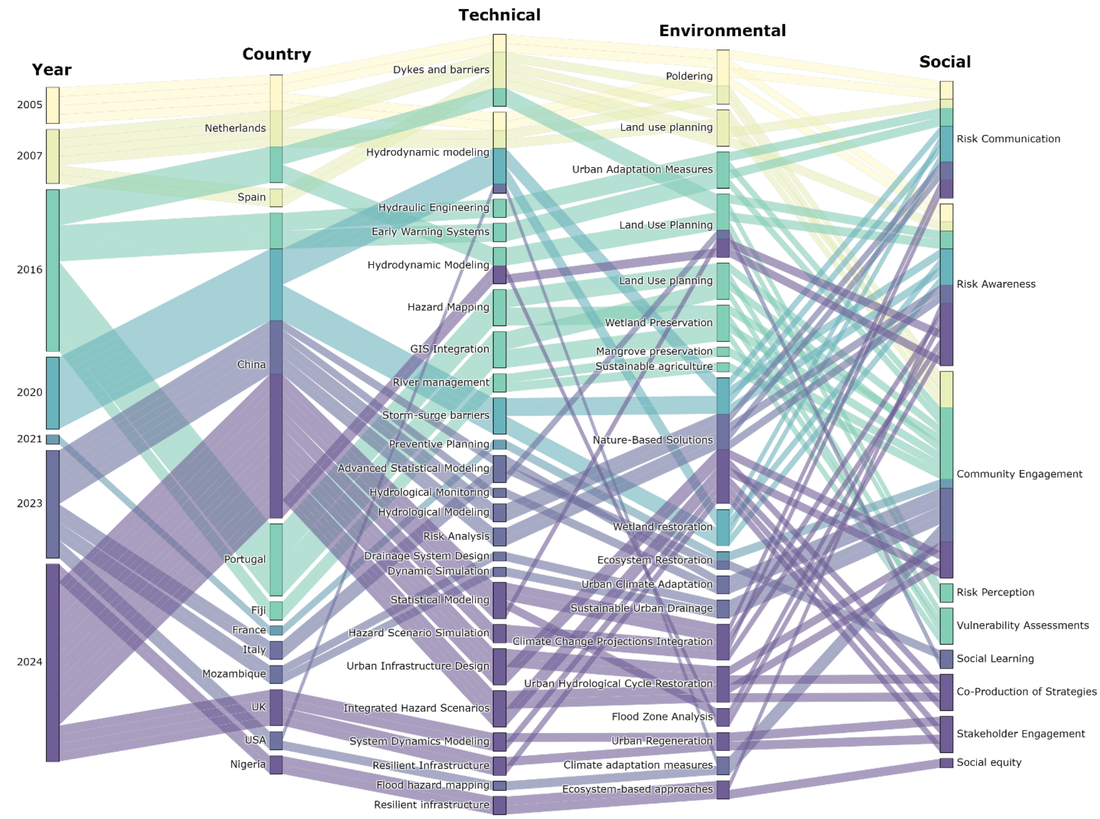

Figure 7. Temporal Evolution of Technical, Environmental, and Social Dimensions in Preparedness Strategies for CF. This visualization presents the evolution of preparedness strategies for compound flooding, comprising technical, environmental, and social dimensions. It illustrates connections between countries, methodologies, and thematic areas, showing trends, shifts in focus, and the increasing integration of interdisciplinary approaches.

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However, this review identifies a crucial gap: while technical advancements have flourished, their integration into local risk reduction efforts remains insufficient. Coastal and estuarine communities often lack awareness of the compounded risks they face, and technical insights frequently fail to translate into actionable community plans. Moreover, as Sacchi and colleagues (Sacchi et al., 2023) notes, individuals tend to oversimplify their risk assessments in the face of compound climate-related hazards, focusing on a single dominant factor instead of considering the complexity of multiple interacting drivers. This cognitive simplification often leads to incomplete evaluations, weakening mitigation and preparedness efforts. Without fully harmonizing these dimensions, compound flooding risks may still exceed the capacity of even the most advanced preparedness efforts. Furthermore, these strategies suggest distinct regional trends influenced by economic contexts, institutional capacities, and socio-environmental priorities. High-, middle-, and low-income countries demonstrate varying approaches to integrating these dimensions into flood risk management. Trends not only reflect the availability of resources but also highlight contextual challenges and opportunities for enhancing preparedness across income levels.

- *.High-Income Countries: Technological Innovation and Policy Integration*

High-income countries often leverage advanced technological capabilities and well-established institutional frameworks to manage compound flood risks. For example, the Netherlands (Gerritsen, 2005) employs state-of-the-art hydraulic modelling, dyke systems, and storm surge barriers under its Delta Plan. These approaches prioritize technical resilience, integrating engineered solutions with environmental strategies such as the use of natural dunes and inland lakes. Social strategies in these contexts tend to focus on public awareness campaigns and targeted communication to enhance risk perception. The UK (Coletta et al., 2024) exemplifies a shift toward holistic preparedness, combining blue-green infrastructure with socio-hydrological models to address long-term impacts.
Participatory approaches engage stakeholders in scenario building, fostering community awareness and improving flood perception. However, while high-income countries demonstrate strong technical and environmental integration, gaps in addressing equity and marginalized populations persist, particularly in tailoring solutions to diverse community needs.

- Middle-Income Countries: Bridging Infrastructure and Nature-Based Solutions

Middle-income countries exhibit a growing emphasis on hybrid approaches that combine technical measures with emerging nature-based solutions (NbS). For instance, China's Sponge City Program (Chan et al., 2024) integrates wetlands, mangroves, and green infrastructure into urban planning to restore hydrological cycles and mitigate flood risks. Advanced statistical models and coupled hazard scenarios (Sun et al., 2024) also enable precise planning for cascading impacts. Similarly, Portugal (Freire et al., 2016) demonstrates progress in integrating hazard mapping, early warning systems, and sustainable land-use practices to enhance preparedness. However, social strategies in middle-income countries often remain fragmented. In China (Liang et al., 2017), informal networks and social capital play a role in urban preparedness, yet systematic integration of these efforts

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into broader frameworks is limited. Middle-income countries face the dual challenge of balancing rapid urbanization with the need for equitable and sustainable preparedness measures.

- Low-Income Countries: Community-Based Adaptations and Indigenous Knowledge

In low-income countries, resource constraints often necessitate community-driven, localized strategies that prioritize social dimensions and leverage indigenous knowledge. For example, Mozambique (Matos et al., 2023) employs community surveys to inform planning, amplifying local voices and fostering participatory decision-making. Nigeria (Michael, 2024) highlights gender-focused strategies, incorporating women as key agents in preparedness through flood-resistant marketplaces and makeshift ferry systems. These efforts underscore the critical role of community solidarity and informal networks in mitigating systemic vulnerabilities.

Environmental strategies in low-income countries are often rooted in ecosystem-based approaches. For instance, Nigeria integrates NbS with indigenous practices to improve resilience, such as using elevated market stalls to reduce flood impacts (Michael, 2024). However, technical measures remain limited, with reliance on rudimentary interventions like sandbags and moisture barriers. Institutional capacity and funding constraints present significant barriers to scaling integrated approaches in these regions.

4.3 Governance and multi-stakeholder collaboration in enhancing preparedness

Governance and multi-stakeholder collaboration emerge as central themes in flood preparedness literature, reflecting the interplay between policy frameworks, community engagement, and technical advancements. These elements collectively define the capacity of communities to respond to CF events by aligning resilience strategies with localized realities.

- Governance: Centralization and inclusivity

Governance frameworks significantly influence the success of preparedness strategies, but their effectiveness often depends on reconciling centralized efficiency with inclusive decision-making. In China, for example, centralized flood management policies, such as large-scale relocation initiatives, have shown technical efficiency but often lack the community engagement needed for widespread acceptance (Yu et al., 2023). This gap underscores the importance of participatory governance models that bridge top-down planning with local needs. Moreover, fostering collaboration and information sharing across sectors is essential to enhance disaster prevention and relief efforts (Guo et al., 2023).

By contrast, projects like the Thamesmead urban regeneration initiative in the UK demonstrate the benefits of stakeholder-driven governance. By actively integrating technical expertise with local knowledge, these models foster trust, enhance public acceptance, and ensure that resilience measures align with community priorities (Coletta et al., 2024). Such approaches

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highlight how participatory governance can address the challenges of implementing adaptive strategies while maintaining social legitimacy.

- Multi-Stakeholder Collaboration: Strengthening collective capacity

Collaboration among diverse actors—government agencies, NGOs, private sectors, and local communities—is critical for managing the complex risks of compound flooding. In China, the Sponge City Program exemplifies the integration of nature-based solutions (NbS), such as wetlands and green infrastructure, with urban planning to mitigate flood risks while restoring hydrological cycles (Chan et al., 2024). Similarly, in Fiji, traditional leadership structures, including chiefs and religious leaders, play a vital role in disseminating preparedness messages, strengthening local resilience through cultural trust (Nolet, 2016).However, challenges persist in ensuring equitable collaboration. While participatory mapping in Portugal successfully integrates technical and local knowledge for risk management (Freire et al., 2016), many regions still rely heavily on top-down approaches that limit community involvement. This is particularly evident in urban projects, where technical solutions often overshadow the inclusion of marginalized voices, reducing the overall effectiveness of resilience strategies. For instance, while China's application of hydrodynamic models emphasizes technical precision, it often overlooks meaningful opportunities for community participation, which limits the integration of local perspectives into flood resilience strategies (Xu et al., 2024).

- Governance and Technology: Effective preparedness

Addressing compound flooding risks requires a seamless integration of governance and technological advancements. Advances in hydrodynamic modelling and predictive tools, such as those used in China (Du et al., 2020; Xu et al., 2024), have significantly enhanced predictive accuracy, enabling more efficient resource allocation during flood events. However, as demonstrated by the Sponge City Program, the full potential of these technologies is realized only when combined with governance frameworks that prioritize inclusivity and community engagement (Chan et al., 2024).Furthermore, the success of early warning systems depends not only on technical accuracy but also on the accessibility of information conveyed to at-risk populations. Studies from the USA highlight that clear, actionable communication is crucial for ensuring timely community responses to compound hazards (Richmond and Kunkel, 2024). Without such transparency, even the most advanced predictive models' risk being underutilized, leaving vulnerable communities exposed to preventable losses. Similarly, as observed in Italy, these tools often fail to translate into actionable governance frameworks, thereby limiting their effectiveness at the community level (Sacchi et al., 2023).

The integration of participatory governance with cutting-edge technology not only enhances predictive capabilities but also fosters trust among stakeholders, ensuring resilience measures are both scientifically robust and socially relevant. This highlights the importance of hybrid approaches that balance technological precision with the lived realities of vulnerable populations, bridging the gap between technical expertise and local needs.

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- Governance Challenges: Addressing fragmentation and enhancing coordination

As CF risks grow increasingly complex, fragmented governance frameworks exacerbate vulnerabilities and undermine resilience. Figure 8 illustrates the interconnected roles of key actors identified in the literature—local governments, NGOs, research institutions, and traditional leaders—in shaping governance strategies for preparedness. However, the lack of cohesive coordination among these entities highlights a critical barrier: sectors often operate in isolation, focusing on single hazards rather than addressing the interconnected nature of compound risks (Sakic Trogrlic and Hochrainer-Stigler, 2024)

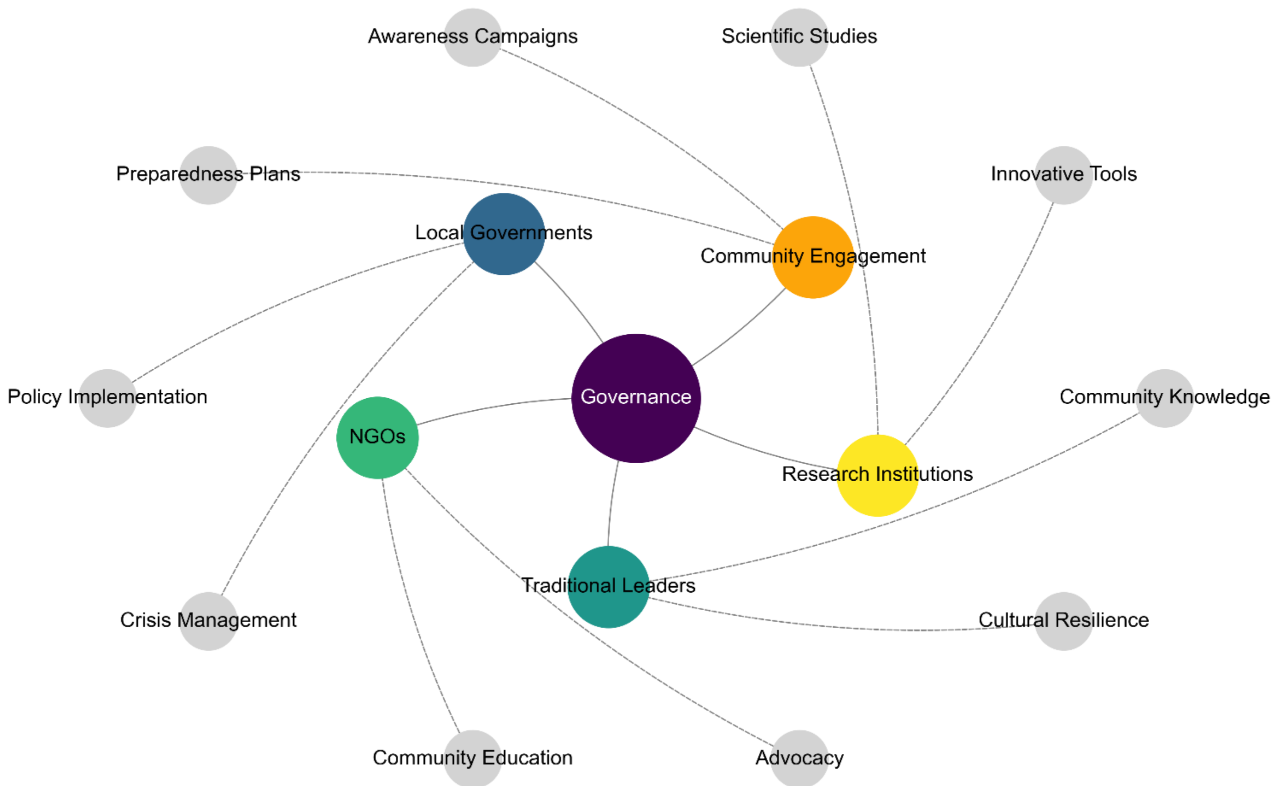

Figure 8. Governance Dimensions and Actor Interactions in Preparedness Strategies for CF. This diagram illustrates the fragmented roles of key actors—local governments, NGOs, traditional leaders, research institutions, and communities—in shaping governance strategies for preparedness. Approaches are often siloed, focusing on individual hazards and sectors, with limited interaction across different areas and levels of governance, resulting in unclear responsibilities for compound events.

While scientific advancements, such as hydrodynamic modelling and flood forecasting, have significantly improved the understanding of compound hazards, their application in actionable governance remains limited. For example, in China, despite progress in predictive tools, these advancements are rarely integrated into community-specific strategies (Xu et al., 2024). Similarly, Mozambique's urban resilience initiatives, though infrastructure-focused, fail to achieve their full potential due to

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the exclusion of community participation (Matos et al., 2023). These examples underscore how fragmented governance not only limits inter-agency collaboration but also hinders the equitable allocation of resources, leaving vulnerable populations inadequately supported.

A recurring challenge lies in the failure to institutionalize cross-sectoral coordination. As represented in Figure 8, research institutions play a pivotal role in generating valuable data on compound hazards. However, without clear mechanisms to translate these insights into policy, their potential impact is diminished. This disconnect is especially evident in early warning systems, where technical precision often does not align with accessible, community-focused communication (Richmond and Kunkel, 2024). The resulting mismatch between technical capabilities and the needs of at-risk communities perpetuates preventable vulnerabilities.

To address these gaps, governance must evolve beyond siloed approaches and embrace systemic frameworks that incorporate multi-hazard or compound thinking into policy and practice. Collaborative models, such as China's Sponge City Program, exemplify the benefits of aligning technical solutions with participatory governance to address interconnected and cascading risks (Chan et al., 2024). However, these remain exceptions rather than norms. Bridging the gap between science and policy requires harmonized frameworks that integrate cross-sectoral coordination and prioritize inclusive, locally grounded solutions. Such approaches must emphasize the co-production of knowledge, equitable resource distribution, and communication strategies tailored to community needs.

5 Conclusions

This review explored how preparedness strategies are evolving to integrate technical, environmental, and social dimensions, alongside the role of governance and multi-stakeholder collaboration in enhancing preparedness for compound flooding (CF). The findings reveal a clear shift toward integrative approaches, incorporating resilient infrastructure, predictive models, early warning systems, and nature-based solutions (NbS) with community engagement and risk perception aspects. However, significant gaps remain in operationalizing these advancements into frameworks that are actionable, inclusive, and adaptable to local contexts.

Governance emerged as a decisive factor, with fragmented coordination and top-down approaches frequently undermining the effectiveness of CF preparedness efforts. While initiatives like China’s Sponge City Program and the Thamesmead regeneration project in the UK demonstrate the potential of participatory governance, such examples are rare. The lack of cohesive frameworks limits cross-sectoral collaboration and equitable resource allocation, leaving many vulnerable populations inadequately supported. Addressing these gaps requires governance models that not only integrate multi-hazard concepts but also actively empower local stakeholders through shared decision-making processes.

Behavioural insights, such as cognitive biases and missing links between knowledge, attitudes and behaviours further complicate efforts to increase preparedness. Many strategies fail to account for how individuals and communities interpret complex risks, leading to oversimplified or reactive responses that weaken resilience. Effective preparedness must bridge these gaps by improving risk communication and integrating behavioural dynamics into strategy design, ensuring that actions are both scientifically grounded and socially relevant.

Advancing CF preparedness also requires translating research and predictive models into practical, community-driven solutions. Cascading impacts, non-linear climate feedback, and systemic vulnerabilities demand adaptive frameworks capable of anticipating complex interactions. Co-production of knowledge between scientists, policymakers, and communities is essential for aligning technical innovation with local priorities and ensuring the implementation of sustainable, context-sensitive strategies.

Overall, preparedness for compound flooding must evolve into a holistic, adaptive process that unites technical precision, participatory governance, and behavioural insights. By fostering collaboration across disciplines and empowering communities, preparedness strategies can more effectively address the multifaceted risks of CF, building both immediate and long-term resilience in an era of growing climate uncertainty.

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