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Integrated catchment and coastal management for resilient urban flood mitigation under climate change

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Urban areas at river mouths are exceptionally vulnerable to flooding due to their dual exposure to coastal and riverine flood risks. These risks are exacerbated by the lack of coordination between coastal zone and river basin management, compounded by climate change impacts, particularly sea-level rise, which increases riverine flooding intensity by raising drainage bases. This review underscores the urgent need for integrated management to address these intertwined challenges. It advocates for an Integrated Catchment Management (ICM) approach, which bridges the management of river basins, coastal zones, and urban areas, to mitigate flood risks. The article examines case studies from Hamburg, Kolkata, and the Haifa Bay area to highlight the necessity and challenges of implementing ICM. Hamburg serves as a model of successful integration, combining robust governance, extensive coastal defenses, and upstream river basin management. Kolkata, by contrast, struggles with frequent flooding and lacks integrated policy frameworks, underlining the critical need for coordinated strategies. The Haifa Bay area, although historically less flood-prone, faces growing risks from climate change, offering a timely opportunity for proactive ICM adoption. Governance systems, institutional structures, and legal frameworks in these contexts are analyzed to extract lessons for global applicability. Despite differences in flood histories and socio-environmental settings, commonalities in successful strategies emphasize the importance of holistic and inclusive management approaches. The study highlights the potential of ICM to mitigate escalating flood risks in coastal urban areas while addressing the limitations posed by governance gaps and resource constraints. By fostering coordination across scales and sectors, ICM offers a pathway to sustainable and resilient flood management in the era of climate change.

KEYWORDS
integrated catchment management, coastal urban flooding, climate change resilience, flood mitigation, urban adaptation

1 Introduction

Coastal regions worldwide frequently face natural disasters such as storm surges, tidal waves, and tsunamis, with vulnerabilities heightened by human activities and population pressures. Over half of the global population lives within 200 km of the coast, and rising sea levels—projected to increase by 20–86 cm by 2,100—further exacerbate these risks (Creel, 2003; Thuc et al., 2016). Coastal urban areas worldwide thus face escalating threats from flooding (Barbaro et al., 2022; Dawson, 2017). Many coastal cities are located at the mouths of rivers, making them particularly vulnerable to rising sea levels and increased storm surges, as well as flooding from inland rivers due to higher drainage bases (De Sherbinin et al., 2012; Burkett and Davidson, 2012; Del-Rosal-Salido et al., 2021; Garcia and Loaiciga, 2014; Lin et al., 2010). This vulnerability is further heightened by extreme precipitation events (Kuenzer and Renaud, 2012; Siegel, 2019), which may become more frequent due to the seemingly unavoidable multiple climate hazards expected over the next two decades even with global warming of 1.5°C (Masson-Delmotte and Zhai, 2022a,b). Surpassing this warming threshold will exacerbate effects, some of which will be irreversible.

The effects of climate change on coastal urban areas include sea-level rise, more frequent and severe storms, and changing precipitation patterns, all contributing to the destruction of critical infrastructure (Crossland et al., 2005; Clark, 2018; Nazarnia et al., 2020; Clarke et al., 2022). Concurrently, urban populations in coastal areas are increasing rapidly, exacerbating the risk of flooding (Zhou et al., 2019; Pour et al., 2020; Vamvakeridou-Lyroudia et al., 2020). Expanding impervious surfaces further increase flood risks (Du et al., 2015; Yu et al., 2018; Prokic et al., 2019; Abass et al., 2020), straining existing infrastructure and governance capacities, and leading to greater insecurity for life, livelihoods, and ecosystems (Vivekananda and Bhatiya, 2017). Therefore, Coastal cities are identified as hotspots of climate impacts and seen as crucial in addressing climate stressors (Hennessy et al., 2022a,b; González et al., 2021; Glavovic et al., 2022; Cao, 2023; Scialabba, 1998).

However, cities alone cannot manage these issues effectively. Integrated, interdisciplinary, and inclusive planning at the basin level is essential for reducing risks and enhancing resilience in coastal areas (Coccossis, 2004; UNESCO - Programme Hydrologique International, 2009; Verwey et al., 2017). This requires careful siting of monitoring stations upstream (Singhal et al., 2024). While terms such as integrated basin management, urban drainage management, and coastal management are frequently used, they often fail to achieve true integration across these domains. These management frameworks typically operate in silos, with little coordination among them, leading to fragmented and inefficient approaches to addressing flood risks. Aligning these three critical systems remains a significant challenge, as their spatial, temporal, and institutional scales often differ.

This article explores the potential of integrated catchment management (ICM) strategies for addressing coastal urban flooding amidst climate change. This review critically examines the limitations of Integrated Coastal Zone Management (ICZM) in effectively addressing the multifaceted risks associated with coastal urban flooding. It subsequently evaluates the potential of Integrated Catchment Management (ICM) as a more comprehensive and holistic approach to mitigating these challenges. It, thus, attempts to understand the concept and framework of ICM, analyze the necessity for integrated approaches in urban flood mitigation, and exemplify these strategies through case studies. By examining Hamburg, Germany; Kolkata, India; and Haifa, Israel, the study provides varied perspectives on flood management practices. Scrutinizing governance systems, institutional structures, and legal frameworks across these regions reveals commonalities in successful approaches despite differing flood experiences and socio-environmental contexts, emphasizing the significance of integrated strategies for sustainable flood mitigation. This review article introduces an integrated catchment management (ICM) approach aimed at bolstering flood resilience in coastal urban areas. While ICM shares some commonalities with Integrated Water Resources Management (IWRM) as noted by Michels-Brito et al. (2023), this paper distinguishes ICM as a unique framework that explicitly tackles the scale disparity often overlooked in traditional IWRM strategies. Beyond merely summarizing existing literature, this study adopts a qualitative analytical stance to critically evaluate how ICM can comprehensively enhance flood resilience. It considers hydrological, infrastructural, and governance aspects, emphasizing the incorporation of sea level rise impacts on drainage systems—a dimension typically absent in conventional IWRM. Furthermore, the scope of ICM extends to encompass entire coastal basins, where urban centers reside at their mouths, thus broadening the perspective of Integrated Coastal Zone Management (ICZM).

1.1 The research questions

How can Integrated Catchment Management (ICM) address the systemic gaps in current flood management frameworks by integrating river basins, urban drainage systems, and coastal zone management, and what transferable strategies can be derived to enhance flood resilience in diverse socio-environmental contexts?

1.2 The structure of the article

In the next section the review approach for selection and information extraction from the relevant literature is presented; Then we briefly review the risk of urban coastal flooding in the context of climate change, highlighting the need for adaptive strategies. Integrated Coastal Zone Management (ICZM) has been proposed to address coastal flooding. In section four we critically review this proposal showing that ICZM is insufficient. This leads us to the presentation of Integrated Catchment Management (ICM) in section five. Three case studies of Hamburg, Kolkata, and Haifa, illustrating varied flood histories and existing policies are reviewed in section six to identify the challenges facing ICM in the context of seashore cities which are prone also to inland flooding. The Conclusions section synthesizes key insights, addresses challenges, and suggests future research directions, emphasizing the significance of ICM in building resilient coastal urban communities.

2 Review approach

The literature review is primarily conducted through Meta-narrative review approach to achieve an overarching, combine framework (Hampton, 2011; Galanti et al., 2021) which seeks to address the broad contextual aspect of urban flood mitigation strategies, particularly focusing on catchment and coastal management for three distinct geo-climatic regions. By doing so other narratives also unfold, contributing to the identification of the policy gaps in Integrating ICZM with coastal urban flood mitigation.

2.1 Overview of the review approach

This article seeks to provide comprehensive insights into the potential of integrated catchment management policies in reducing the impact of natural and climate change-related coastal and riverine flooding in coastal urban areas. To this end the literature pertaining to flooding of coastal cities that are prone also to riverine flooding is reviewed, as well as the integrated management approaches to addressing these risks under climate change. To ground the review in real cases, we then review the policies used in three regions: Hamburg, located at the mouth of the Elbe River in Germany; Kolkata, situated in the estuarine region of the Hooghly River in close vicinity to the coast in India; and Haifa Bay area in Israel, situated at the lower Kishon River Basin (Figure 1). By juxtaposing these distinct locales, the study aims to glean valuable lessons regarding the effectiveness of integrated flood management strategies, considering factors such as infrastructure, governance frameworks, and socio-economic dynamics, thus enriching our understanding of adaptive responses to coastal flooding risks.

The selection of three coastal/estuarine cities—Hamburg, Haifa, and Kolkata—is based on their diverse hydrological, socio-political, and infrastructural characteristics. These cities represent varying degrees of exposure to coastal and inland flooding, making them suitable for comparative analysis.

- *Hamburg*: A European example where sophisticated flood protection infrastructure coexists with estuarine dynamics, offering insights into hybrid infrastructure strategies.
- *Haifa (Bay area)*: A Mediterranean case demonstrating how coastal flood management must integrate with limited freshwater resources and geopolitical constraints.
- *Kolkata*: A South Asian metropolis facing extreme precipitation and rising sea levels, illustrating the governance and infrastructural challenges in rapidly urbanizing deltaic regions.

While no single set of case studies can comprehensively represent all global coastal cities, the selected examples provide insights applicable to a broad range of urban coastal environments, particularly those with complex water governance structures and hybrid infrastructure challenges. The selection also ensures geographic diversity, enhancing the study's applicability across different climate and governance contexts.

2.2 Literature search and selection

The approach employed in the literature review aimed at identifying and selecting relevant articles for a comprehensive review (Figure 2). A total of 632 publications (peer-reviewed journal articles were majority) were initially identified through the database search. The search was conducted using databases such as PubMed, Google Scholar, and academic search engines, focusing on peer-reviewed English-language articles. The keywords used included "integrated catchment management," "coastal zone management," "coastal urban flooding," "river basin management," and "flood risk mitigation." To capture the most recent findings, the search prioritized publications published since 2010, while also including older seminal works dating back to the late 1950s for their foundational insights.

The search strategy aimed to encompass a wide range of studies pertinent to the research topic. Initial selection was based on the relevance of articles to the specified keywords. Following the screening of titles and abstracts, 415 studies were deemed potentially relevant. The inclusion criteria required articles to be peer-reviewed and to provide comprehensive analyses of integrated policies and practices for managing flood risks in coastal urban areas. Special emphasis was placed on case studies from Hamburg, Kolkata, and the Haifa Bay area. Additionally, the articles needed to focus on governance systems, institutional structures, and legal frameworks. Government documents and white papers pertaining to the three case studies were also reviewed to extract crucial information, despite being outside the primary peer-reviewed criterion. Exclusion criteria eliminated non-peer-reviewed articles and non-English articles, except for essential government documents and white papers regarding the three case studies. Articles were not excluded based on the date of publication, allowing the inclusion of seminal works that provided valuable historical context.

Titles and abstracts of identified studies (415) were screened for relevance, and full texts of potentially relevant studies were retrieved for detailed assessment against the inclusion criteria. This full-text assessment resulted in the inclusion of more than 200 articles for the review. Key information extracted from each selected study included authors, year of publication, study aims, review approach, key findings, and theoretical frameworks. Primary narratives within each study were identified and grouped into thematic clusters, representing distinct research traditions or perspectives within the field of coastal urban flood risk management. These narratives were subsequently organized into several thematic clusters, including:

- Floods and Flood Risk Management
- Coastal Issues and Management
- Urban Water Management
- Water Scarcity and Management
- Climate Change and its Impacts
- River Basin Management
- Disaster Management and Resilience
- Case Studies and Regional Focus
- Environmental Policy and Law
- Other

A comparative analysis was conducted within each narrative cluster to discern similarities and differences among the studies and to track the evolution of each narrative over time. This involved identifying key turning points and seminal works that significantly influenced the development of these narratives. Findings were synthesized across different narrative clusters to highlight the interplay between narratives, areas of convergence and divergence, and gaps in the existing literature. The quality of the included studies was assessed based on criteria such as methodological rigor, theoretical contribution, and relevance to the research topic. Potential biases in the selected studies and in the narrative synthesis process were critically examined. Strategies to mitigate bias included triangulation of findings from multiple sources and reflexive discussions among the research team. This structured approach ensured a comprehensive and critical review, incorporating both contemporary and historical perspectives, to provide in-depth insights into the effectiveness of integrated catchment management policies in mitigating flooding impacts in coastal urban areas. The findings are presented through detailed discussions in the following sections.

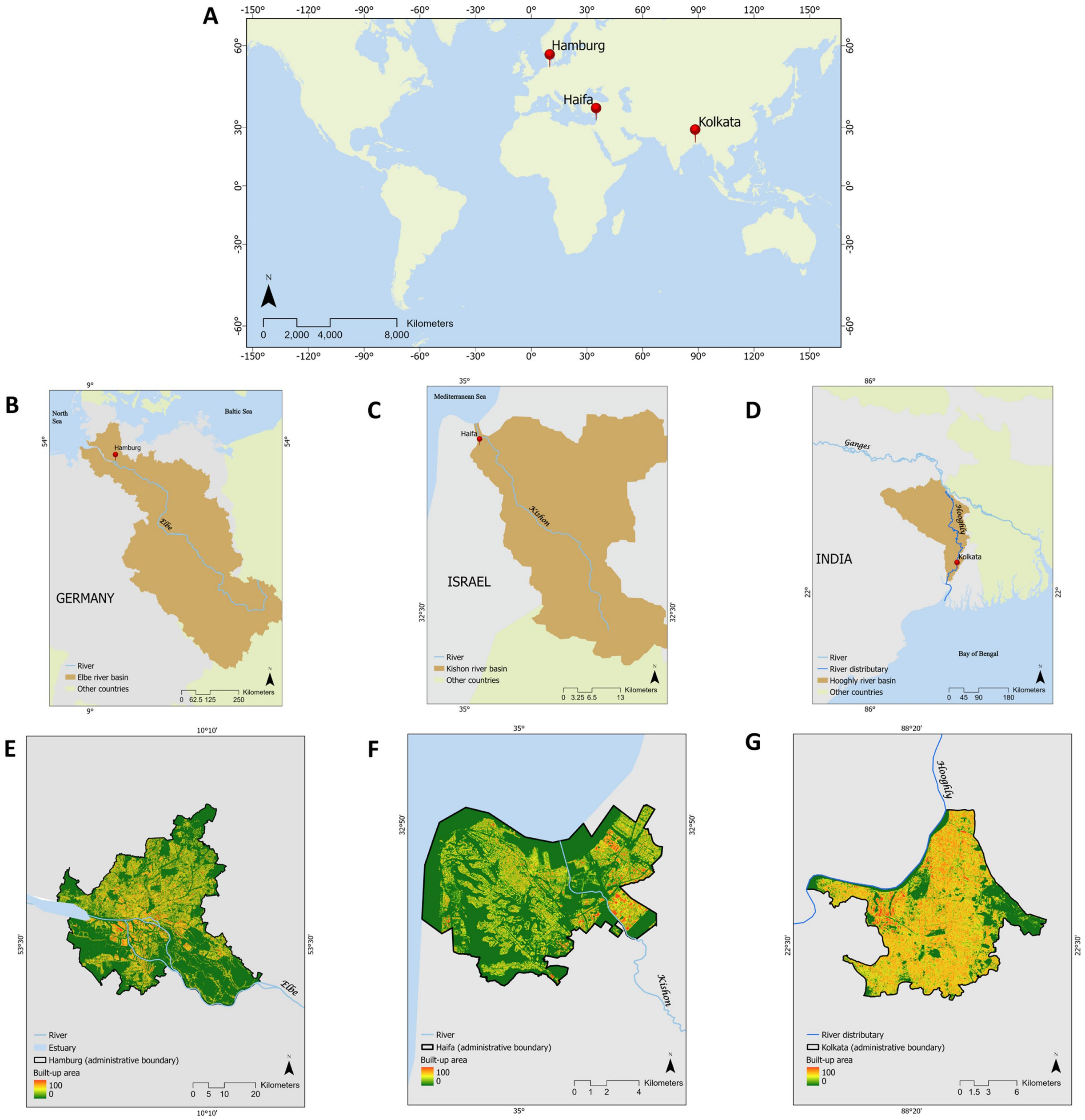

FIGURE 1
Geographical context and urban development of case study areas. **(A)** Global locations of Hamburg, Haifa, and Kolkata. **(B–D)** Respective river basins (Elbe, Kishon, Hooghly) and coastal proximity. **(E–G)** Spatial distribution of built-up areas in each metropolitan region, highlighting their respective hydrological and geographical contexts (Haifa Bay area is marked by green rectangle).

2.3 Key information extractions: the initial findings

The systematic examination of 213 publications spanning from 1959 to 2024 (*partial only*) offers a comprehensive analysis of the evolution of Integrated Catchment Management (ICM) and its application in mitigating coastal urban flooding under the pressures of climate change. While not all earlier publications from this period were directly accessible, their relevance was preserved through references cited in later works. By incorporating these references as individual entities, the analysis effectively captures the distribution of articles, reports, and other relevant materials, uncovering significant trends and patterns across temporal, geographical, and thematic dimensions. This approach highlights the intricate dynamics that have shaped research and practice in this field.

2.3.1 Temporal trends and scholarly engagement

The temporal distribution of the reviewed literature (Figure 3) illustrates a clear trajectory of increasing scholarly engagement with ICM and coastal urban flooding. Notably, there has been a rise in research output since 2000, with an overall growth of 9% within the timeframe of the publications cited in this article. This surge in academic publications reflects a growing

FIGURE 2
Flow chart of the review approach.

global awareness of the urgent need to address the intertwined challenges posed by climate change, urbanization, and water management. The proliferation of studies in this period suggests a significant shift in research priorities, driven by the escalating impacts of climate-induced flooding in coastal regions and the corresponding demand for resilient, adaptive management strategies.

Earlier decades (until 2000) witnessed relatively sparse research, focused on foundational hydrological and water management principles. However, the post-millennium era marks a transition toward more integrated approaches, such as integrated basin management for addressing the complexities of water resource management in the context of urban and climatic pressures and of integrated coastal zone management to address coastal flooding. This temporal analysis underscores the evolution of ICM from a niche topic to a central theme in environmental and urban studies, driven by both academic interest and the pressing real-world challenges faced by coastal cities.

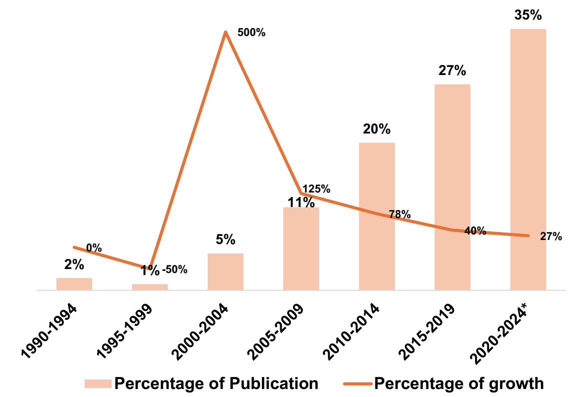

FIGURE 3
The distribution of publications used in the study per year pertaining to Integrated Catchment Management (ICM) and the mitigation of coastal urban flooding within a changing climatic context utilized in this study.

2.3.2 Thematic distribution and emerging discourses

The thematic scope of the literature (Figure 4) is diverse, reflecting the multifaceted nature of ICM and its application across different contexts. Thematically, the cluster of "Floods and Flood Risk Management" emerges as a dominant focus, constituting 21% (of the publications used in this study, i.e., 213) of the reviewed publications. This emphasis highlights the critical need to understand and manage the impacts of flooding in urban areas, where population density and infrastructure vulnerabilities can significantly amplify the risks posed by extreme weather events.

The cluster of "Coastal Issues and Management" is closely related, appearing in 18% of the studies. These studies often explore the specific challenges and management approaches relevant to coastal zones, underscoring the importance of integrated strategies in these vulnerable areas. The strong thematic linkage between coastal issues and flood risk management reflects the particular susceptibility of coastal urban areas to flooding.

Another significant theme is the cluster focusing on "Urban Water Management," which is addressed in 12% of the publications. This theme reflects the growing recognition of the importance of managing water resources effectively within urban environments, particularly in the context of increasing urbanization and its impact on water systems.

The literature also frequently explores the cluster concerning "Water Scarcity and Management," which constitutes 12% of the publications. While seemingly distinct from flooding, this theme highlights the broader context of water resource management challenges that often intersect with flood risk management, particularly in terms of integrated and sustainable approaches.

Furthermore, the cluster of "Climate Change and its Impacts" appears in 11% of the studies. These studies often explore the influence of climate change on water-related risks, including flooding, and the need for adaptation strategies. The strong thematic linkage between climate change and the other themes underscores the overarching influence of a changing climate on water management.

The cluster of "River Basin Management" is addressed in 7% of the publications. This theme emphasizes the importance of managing water resources at the river basin scale, recognizing the interconnectedness of upstream and downstream areas in influencing flood risks and water availability.

The cluster of "Disaster Management and Resilience" constitutes 6% of the publications. This theme focuses on broader strategies for preparing for, responding to, and recovering from disasters, including floods, and building resilience in urban areas.

The cluster of "Case Studies and Regional Focus" appears in 5% of the studies. These publications offer in-depth analyses of specific geographic locations, providing valuable context and lessons learned for managing flood risks in diverse settings.

Finally, the cluster of "Environmental Policy and Law" and "Other" each constitute 4% of the publications. The former highlights the role of regulatory frameworks and policy instruments in shaping flood risk management practices, while the latter encompasses diverse topics that are relevant but do not fit neatly into the other defined clusters.

3 Coastal urban flooding in the context of climate change

Coastal urban areas are facing heightened exposure to climate change impacts, with flooding being one of the most pressing threats. Rising sea levels, along with the increasing frequency and intensity of extreme weather events, are significantly increasing the risks of coastal flooding, which is now affecting millions of people worldwide and leading to extensive economic and environmental harm (Hanson et al., 2011; Nicholls et al., 2021a,b). These changes are driven by a complex interplay of factors, including rising sea levels, changes in precipitation patterns, accelerated urbanization, and inadequate management practices. This section briefly reviews the principal contributors to coastal urban flooding in the context of climate change, highlighting the influence of rising sea levels, rapid urbanization, and the role of Integrated Coastal Zone Management (ICZM) in mitigating these threats.

3.1 Rising sea levels

Rising sea levels represent one of the most observable effects of climate change, predominantly caused by the thermal expansion of seawater and the accelerated melting of polar ice caps and glaciers (Church and White, 2011; Hennessy et al., 2022a,b). Even with global efforts to cap warming at 1.5°C, sea levels are projected to rise significantly over the next two decades, leading to increased flooding risks in coastal regions (Oppenheimer et al., 2019; Masson-Delmotte and Zhai, 2022a,b). Sea-level rise elevates the baseline for storm surges and high tides, making even minor storm events capable of causing substantial flooding, disrupting daily life, and damaging critical infrastructure (Dahl et al., 2017; Mallick et al., 2011; Ridha et al., 2022). These conditions are worsening due to the continued emissions of greenhouse gases, which accelerate ice melt and further contribute to rising sea levels (Bamber et al., 2019).

Moreover, rising sea levels raise the drainage base of rivers flowing into the sea, thereby raising downstream boundary conditions. Higher downstream drainage bases cause upstream flood stages to be higher, thereby raising flood risk in the urban areas and widening the floodplains (Garcia and Loaiciga, 2014; Wang et al., 2021). Higher sea

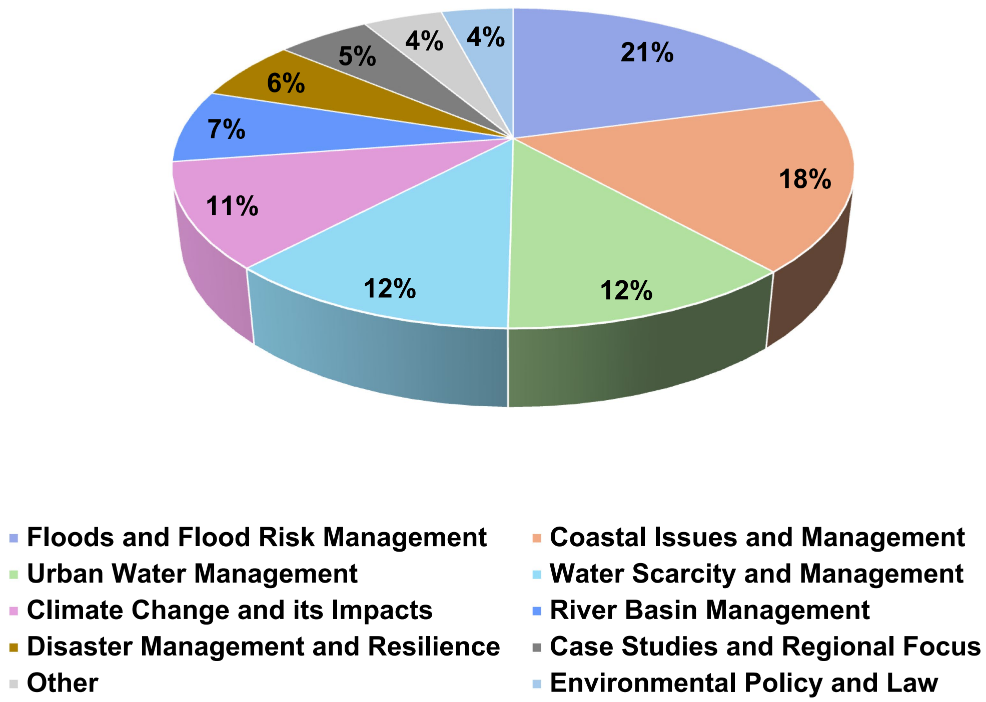

FIGURE 4
Diagram showing detailed categorization (in %) of subject areas depicted in the publications analyzed in this study (*n* = 213).

levels also raise the base of urban drainage systems, thereby increasing the probability of over-topping of such systems (Griffiths et al., 2019; Grip et al., 2021).

3.2 Rapid urbanization

The rapid growth of urban populations in coastal areas significantly increases flood risks (Gandhi et al., 2022). As urbanization accelerates, the expansion of impervious surfaces leads to higher runoff coefficients and overwhelms existing drainage systems, exacerbating the severity of flooding (Guneralp et al., 2017; Sahavacharin A. et al., 2022a; Sahavacharin M. et al., 2022b; Le et al., 2024). Urban growth not only heightens the immediate risk of flooding but also magnifies the long-term economic and health impacts on these populations (Duvat et al., 2021). Current projections indicate that by the end of this century, the risk of coastal flooding could increase fivefold globally, with more than 70 million people likely to be affected (Hanson et al., 2011; Clarke et al., 2022). Coastal cities such as Santos, Brazil, Cotonou, Benin, and Kolkata, India, are especially vulnerable, with long-term impacts expected to double by 2,100 if greenhouse gas emissions continue unabated (Palinkas, 2020; Dodman et al., 2022; Khan, 2022).

3.3 Vulnerable populations

Urban areas near rivers host some of the largest concentrations of population on Earth, making them critical zones for exposure to environmental risks (Qin, 2020; Cea and Costabile, 2022; Peiris, 2024). In cities like Kolkata or Lagos, where dense populations, especially the urban poor, are concentrated, vulnerabilities are exacerbated by frequent flooding and limited capacity to mitigate such risks (Dasgupta et al., 2012; Ndimele et al., 2024). Similarly, low-lying Small Island Developing States (SIDS), such as the Bahamas, Maldives, and Tuvalu, face some of the most severe consequences of climate change, particularly rising sea levels, which threaten to submerge significant portions of their land (Martyr-Koller et al., 2021; Vousdoukas et al., 2023a,b). Coastal flooding in these regions not only disrupts local economies and infrastructure but also imposes considerable strain on healthcare systems, exacerbating financial and health challenges for affected populations (Bell and Masys, 2020; Ejeta et al., 2015). These islands are particularly vulnerable due to their limited capacity to adapt to rapidly changing environmental conditions (Nurse et al., 2014). Together, these regions highlight the urgent need for comprehensive strategies to address the socio-environmental and infrastructural challenges posed by climate-induced risks.

3.4 Lack of integrated catchment management

The vulnerability of coastal cities to flooding is not only a function of the extent to which they are exposed to sea surges and riverine flooding. Rather it is also a function of the measures that are taken to mitigate such risks. Integrated Coastal Zone Management (ICZM) has been advanced as a critical strategy for addressing flood risks in coastal urban areas, particularly under the growing threat of climate change (Brown et al., 2013; Sandhu et al., 2019). ICZM adopts a multidisciplinary approach that incorporates environmental, social, and economic considerations to sustainably manage coastal regions (Krishnamurthy, 2008). By facilitating cooperation among government agencies, local communities, and scientific experts, ICZM strives to balance the competing demands of coastal development with the need to protect natural ecosystems and reduce flood risks (Nicholls et al., 2021a,b; UNEP, 2020).

4 Gaps in integrating integrated coastal zone management for coastal urban flood mitigation

It has been suggested that ICZM has been effective in reducing the vulnerabilities of coastal zones to flooding (Olsson et al., 2015). Yet, the effectiveness of resilience-building efforts for coastal urban areas hinge on overcoming significant hurdles. These include spatial and temporal scale mismatches between urban flood management and ICZM, limited data integration for comprehensive risk assessment, fragmented governance structures hindering policy alignment, underutilization of ecosystem-based approaches, and insufficient community engagement.

One of the fundamental challenges in integrating coastal management with urban flood mitigation lies in the disconnection between river basin management policies, coastal zone management policies, and urban flood management policies (Coccossis, 2004; UNESCO - Programme Hydrologique International, 2009). These "disconnects" stem from the mismatch in spatial and temporal scales inherent to each approach. Urban flood management traditionally focuses on localized, immediate responses within urban areas, emphasizing infrastructure like drainage systems and flood barriers to mitigate flood impacts swiftly, or in retention and detention of flood water thereby potentially reducing flooding and increasing groundwater recharge (Carmon and Shamir, 2010). In contrast, ICZM operates at broader scales, encompassing entire coastal ecosystems and aiming for sustainable management that considers long-term environmental health and resilience (Coccossis, 2004; UNESCO - Programme Hydrologique International, 2009). In this context, the primary policy gap lies in the exclusive focus on river basin management at the basin scale, which overlooks the critical influence of sea-based flooding and downstream coastal dynamics.

The scale mismatches lead to fragmented efforts and inadequate coordination between urban, basin and coastal management strategies (Almoradie et al., 2015; UNESCO - Programme Hydrologique International, 2009). Urban flood management's localized focus often overlooks the broader coastal dynamics and ecological interdependencies that affect flood risks, or the basin-wide sources of flood water and the ability to mitigate floods upstream. Conversely, ICZM's ecosystem-level approach may not sufficiently address the immediate flood protection needs of densely populated urban areas (Ashley et al., 2005), and the complexity of modeling riverine processes and protecting riparian areas (Sarker et al., 2023). This disjointed approach results in a lack of cohesive strategies that can effectively manage both urban flood risks and coastal ecosystem health simultaneously.

Furthermore, the temporal differences between these management approaches exacerbate the disconnect (Crossland et al., 2005). Urban flood management necessitates rapid responses to flooding events, focusing on short-term mitigation measures to protect lives and property. In contrast, ICZM requires a long-term horizon and resilience-building efforts to enhance coastal ecosystem functions and adapt to climate change impacts like sea-level rise and storm surges. The challenge lies in developing adaptive management frameworks that can bridge these temporal scales effectively, ensuring that short-term flood responses align with long-term ecosystem resilience planning (Coccossis, 2004; UNESCO - Programme Hydrologique International, 2009; Ouillon, 2018).

Similarly, there is a spatial mismatch between ICZM and basin management. In most cases the scale and scope of coastal management schemes is limited, and does not include river basins (Ariel et al., 2021). Yet, the basin scale is often referred to as the scale at which flood mitigation plans should be prepared and implemented, as is stipulated also in the European Water Framework Directive (Giakoumis and Voulvoulis, 2018). Thus, while ICZM may be useful to mitigate sea surges it is limited in its capacity to mitigate riverine flooding.

The main fallacy of existing policies arises from these spatial discrepancies. By treating river basin management, coastal zone management, and urban flood management as distinct entities with separate institutional structures, mandates and strategies, policymakers risk overlooking critical interactions and interdependencies (Lejano et al., 2013; Verwey et al., 2017). Coastal urban areas, which are increasingly vulnerable to flooding due to urbanization and climate change, require integrated approaches that holistically address flood risks while safeguarding coastal ecosystems. Overcoming this disconnect requires overcoming institutional barriers, enhancing data-sharing mechanisms, and fostering collaborative governance frameworks that promote cross-sectoral coordination and integrated decision-making (Seebauer et al., 2019; UNESCO - Programme Hydrologique International, 2009). Only then, can we develop resilient strategies that effectively manage urban flood risks while ensuring the sustainability and health of coastal ecosystems in the face of evolving environmental challenges.

Effective urban flood management relies heavily on detailed urban data such as drainage networks, land use patterns, and hydraulic modeling. In contrast, ICZM lacks comprehensive spatial data integration that incorporates urban-specific parameters critical for flood risk assessment and management (Crossland et al., 2005; Clarke et al., 2022), or the parameters needed to site upstream flood mitigating measures such as dams (Gao et al., 2022). Additionally, the integration of climate change predictions, which impact precipitation patterns, upstream runoff coefficients, urban flood risks and coastal dynamics (e.g., sea-level rise, storm surges), remains limited. Bridging these gaps requires enhanced data-sharing mechanisms and the development of predictive models that encompass both urban and coastal dynamics under varying climate change scenarios.

The fragmented governance structures across urban, river basin and coastal authorities pose significant challenges to integrating ICZM with urban flood mitigation (Almoradie et al., 2015; UNESCO - Programme Hydrologique International, 2009). River basin authorities, urban drainage bodies and coastal management bodies often operate under different mandates, priorities, and administrative procedures, complicating efforts for cohesive policy alignment and coordinated decision-making. This fragmentation can lead to inconsistencies in flood management strategies and hinder the implementation of integrated approaches that consider both urban and coastal resilience objectives (De Kok et al., 2009; Förstner et al., 2016).

Ecosystem-based approaches, which leverage natural coastal defenses such as mangroves and salt marshes, hold promise for enhancing urban flood resilience. However, integrating these approaches into urban flood mitigation strategies remains underexplored and underutilized (Ashley et al., 2005; Verwey et al., 2017). Challenges include quantifying and incorporating the ecosystem services provided by coastal habitats into flood risk assessments, as well as promoting hybrid solutions that combine engineered infrastructure with natural defenses to maximize resilience benefits. Concurrently, nature-based measures are called for in river basin management schemes, yet they require that the scale and scope of basin management be enlarged, thereby requiring engagement with a wider array of interests (Gurnell et al., 2015).

Community engagement and social resilience are also critical gaps in integrating ICZM with urban flood mitigation (Seebauer et al., 2019; UNESCO - Programme Hydrologique International, 2009). Vulnerable communities often endure the most of urban flooding, yet their voices and needs are frequently marginalized in decision-making processes (Moulds et al., 2021). Effective integration requires inclusive approaches that prioritize community resilience, address social vulnerabilities, and engage diverse stakeholders in planning and implementation phases. Such engagement has to be well prepared to be effective (Salame-Rubin et al., 2024).

Financial resources for implementing integrated urban-coastal management strategies are often limited, posing a barrier to scaling up resilient infrastructure and ecosystem restoration projects (Nicholls et al., 2021a,b; UNEP, 2020). Demonstrating the cost-effectiveness and economic benefits of integrated approaches over traditional sectoral investments is crucial for garnering support from policymakers and investors. Moreover, the lack of established knowledge networks and learning platforms hinders interdisciplinary collaboration and innovation needed to address complex urban-coastal challenges under uncertain climate futures (Lejano et al., 2013).

5 Integrated catchment management: concept and framework

The limitations of Integrated Coastal Zone Management (ICZM), which often isolates coastal concerns from upstream activities, highlight the need for Integrated Catchment Management (ICM). ICM is a holistic approach that bridges river basin and coastal zone management, recognizing the hydrological, ecological, and socio-economic interconnections between these areas (Crossland et al., 2005; Ouillon, 2018; Laignel et al., 2023). Unlike Integrated River Basin Management (IRBM), which primarily focuses on managing river systems within their terrestrial confines, ICM extends its scope to include coastal considerations such as sea-level rise, sediment transport, and changes in runoff coefficients (Hooper, 2005). By adopting a watershed-based perspective, ICM ensures that upstream actions are evaluated for their downstream impacts, promoting sustainable resource management and effective flood risk reduction (Laignel et al., 2023; Hooper, 2005; Molle, 2009). This approach also enhances urban water management through practices like water-sensitive urban planning (Carmon and Shamir, 2010).

Although IWRM theoretically claims to integrate water management across scales, its practical implementation often remains fragmented due to sectoral and jurisdictional barriers (Benson et al., 2015) and rarely addresses coastal flooding if at all. ICM, in contrast, explicitly prioritizes system-wide connectivity by integrating inland and coastal water processes within a unified management structure. The disjointed nature of IWRM often stems from its broad and flexible definitions, which allow for varying interpretations across different governance scales. This study argues that while a modified IWRM could, in principle, address some scale challenges, it lacks a structured framework that explicitly accounts for the dynamic interactions between precipitation-driven flooding, riverine flows, storm surges and sea level rise.

The three case studies examined in this study illustrate the necessity of an ICM approach by demonstrating how scale-specific governance, hybrid infrastructure, and cross-sectoral coordination play decisive roles in achieving flood resilience. By integrating inland hydrological processes with coastal dynamics, ICM provides a more comprehensive perspective on mitigating flood risks in urban environments vulnerable to climate change.

5.1 Watershed-based perspective

ICM emphasizes managing entire river basins as functional units. This perspective ensures that actions taken upstream have significant downstream consequences, promoting a systematic and effective approach to flood risk reduction (Crossland et al., 2005). It addresses the root causes of coastal flooding by considering the entire catchment area, from headwaters to the coast.

Traditional flood management relied heavily on engineering solutions like levees and channelization, which often had unintended downstream consequences. ICM encourages a more comprehensive approach, prioritizing natural processes and enhancing the basin's natural capacity to regulate water flow (Ashley et al., 2005). By viewing the entire basin holistically, ICM identifies and addresses the root causes of coastal urban flooding, taking upstream actions to reduce downstream risks (Verwey et al., 2017), as well as the implications of sea level rise and sea surges.

ICM thus offers numerous potential benefits, including more effective and sustainable flood mitigation and a holistic understanding of the interconnectedness between river basins and coastal zones (Coccossis, 2004). It promotes measures that mimic natural processes, such as creating retention basins and implementing nature-based solutions like afforestation and green buffers (Ashley et al., 2005). These methods help regulate water flow, improve water quality, and create habitats. In the case of coastal cities, it also incorporates water-sensitive urban planning measures intended to reduce the runoff within the urbanized area (Carmon and Shamir, 2010).

ICM fosters interdisciplinary collaboration among experts from various sectors and disciplines. This approach brings together water resource managers, urban planners, environmental scientists, and governance experts to develop comprehensive strategies for coastal urban flooding (Ouillon, 2018). Such collaboration enables a holistic understanding of flood risks and the development of more effective solutions, taking into account also sea level rise and sea surges, as well as the changes in runoff coefficients due to urbanization.

5.2 Inclusivity and stakeholder engagement

Overcoming institutional and governance barriers is crucial for implementing ICM. Fostering collaboration among diverse stakeholders and building interdisciplinary expertise are essential but resource-intensive aspects of ICM (Coccossis, 2004). To this end stakeholders should be engaged throughout the planning and implementation process.

Inclusivity is thus integral to ICM, involving local communities, governments, non-governmental organizations, and industry stakeholders within the basin, the urban milieu and along the coast. By engaging a diverse range of voices in the planning and decision-making processes, ICM strives to advance policies are that technically sound and socially and politically acceptable (UNESCO - Programme Hydrologique International, 2009). Yet, in order to engage such a diverse set of stakeholders in a meaningful manner it is essential that the core issues that need to be discussed are identified and that the meetings address those issues (Salame-rubin et al., 2024). If such core issues are identified and addressed then this inclusivity may indeed promote community ownership and enhance the effectiveness of flood mitigation strategies.

5.3 Implementation of ICM: addressing institutional and governance barriers

ICM fosters a comprehensive understanding of the interconnectedness between river basins and coastal zones, allowing for proactive management strategies that address the root causes of coastal flooding. For instance, addressing issues like deforestation and excessive development upstream can reduce flood risks downstream, including coastal areas (Chou et al., 2021).

In practice, successful implementation of ICM requires robust policy frameworks and institutional capacity-building at local, national, and regional levels (Cutter et al., 2010). By integrating scientific knowledge, traditional wisdom, and community perspectives, ICM can facilitate informed decision-making and foster adaptive responses to coastal flooding (UNEP, 2020). Case studies from diverse coastal regions demonstrate the effectiveness of ICM in mitigating flood risks and enhancing resilience (Stone et al., 2021). For instance, in the Netherlands, the Room for the River program employs a combination of dyke reinforcement, floodplain restoration, and spatial planning measures to reduce flood exposure while enhancing ecological values (Van Alphen et al., 2020). Similarly, in Bangladesh, community-based adaptation initiatives, such as raised homesteads and embankments, have proven effective in protecting coastal communities from recurrent flooding events (Haque et al., 2018). These examples underscore the importance of context-specific approaches and stakeholder engagement in implementing ICM interventions tailored to local needs and vulnerabilities.

Looking ahead, advancing ICM in coastal urban areas requires sustained political commitment, financial investment, and international cooperation (Nicholls et al., 2021a,b). By mainstreaming ICM principles into urban planning policies and development strategies, decision-makers can foster resilient and sustainable coastal cities that are better equipped to withstand the impacts of climate change (Nicholls et al., 2021a,b). Moreover, fostering knowledge-sharing networks and capacity-building initiatives can empower coastal communities to actively participate in the co-management of their local environments, thereby enhancing social cohesion and adaptive capacity (Lejano et al., 2013). By embracing the principles of ICM, coastal urban areas can navigate the challenges of climate-induced flooding while promoting long-term sustainability and well-being for present and future generations.

While the research presented thus far provides valuable insights into coastal flood management, a critical knowledge gap remains regarding its generalizability across diverse climatic regions. Much of the existing literature focuses on humid environments. This raises a crucial question: can the concept of Integrated Catchment Management (ICM) be effectively adapted and implemented in areas with different climatic characteristics?

The following section addresses this knowledge gap in the generalizability of ICM across diverse climatic regions by presenting a comparative analysis of flood management practices in Hamburg, Germany (at the mouth of the Elbe River), Kolkata, India (at the mouth of the Hooghly River), and the Haifa Bay area, Israel (at the mouth of the Kishon River Basin). These case studies, representing highly varied climatic zones—temperate in Hamburg, tropical in Kolkata, and Mediterranean in Haifa—allow us to explore the transferability of ICM principles and best practices. By examining the effectiveness of existing flood policies in both locations, alongside their commonalities and limitations, we can gain crucial insights for developing a more comprehensive approach to coastal flood mitigation applicable across a wider range of settings.

Quantifying the impact of ICM presents methodological challenges, particularly in attributing resilience outcomes to specific policy interventions. However, integrating modeling techniques such as hydrodynamic simulations, risk-based assessments, and spatially explicit scenario modeling can provide preliminary insights into how ICM strategies mitigate flood risks.

While this study does not include in-depth modeling, it recognizes the necessity of employing data-driven approaches to enhance decision-making. Future research should incorporate flood inundation models, agent-based simulations, and economic cost–benefit analyses to systematically assess ICM's effectiveness under varying climate scenarios. Establishing performance indicators for ICM interventions will also be crucial for evaluating long-term resilience impacts.

6 Example cases

6.1 Example 1: Hamburg, Germany: flood history and existing policies

Hamburg's vulnerability to flooding is intricately tied to its coastal location and physiographic features. Positioned at the mouth of the Elbe River on Germany's northern coast, it faces the North Sea directly, rendering it susceptible to storm surges and escalating sea levels, both exacerbated by the effects of climate change (De Guttry and Ratter, 2022; Pörtner et al., 2019). With much of the city lying just meters above sea level, its low-lying terrain magnifies the risk of inundation, particularly during heavy precipitation or minor sea level increases (Magnan et al., 2022; Kron et al., 2019). The confluence of the Elbe River with the North Sea adds another layer of complexity, as heavy rainfall upstream combined with rising sea levels can culminate in a convergence of floodwaters from both river and sea (Serra-Llobet et al., 2022; Strehz et al., 2019). Moreover, Hamburg's history is marked by devastating flood events like the catastrophic North Sea flood of 1962, which serves as a stark reminder of the city's vulnerability and the urgency for robust flood risk management strategies (De Guttry and Ratter, 2022; Özer et al., 2019).

In the face of a changing climate and rapid urbanization, Hamburg grapples with escalating flood risks (Rose and Wilke, 2015). Climate change exacerbates these threats, due to sea-level rise and altering precipitation patterns, consequently heightening the potential for both coastal and riverine flooding (Sterr, 2008). Furthermore, the city's status as a major economic hub has spurred extensive urbanization and critical infrastructure development, resulting in impervious surfaces that impede natural drainage and exacerbate runoff during heavy rainfall events (Kurzbach et al., 2013). Thus, while urban growth has brought economic prosperity, it has also intensified the challenges posed by flooding, necessitating comprehensive and adaptive flood risk management strategies to safeguard the city's inhabitants and infrastructure in the face of an uncertain climate future. In response to historical flooding events and recognizing the need for a more comprehensive approach, Hamburg has adopted integrated catchment management strategies that combine river basin and coastal zone management (De Kok et al., 2009; Nielsen et al., 2013). Central to this approach is the acknowledgment of the interconnectedness of the Elbe River basin and the city's coastal areas (Förstner et al., 2016). Hamburg's flood management strategies extend beyond the city's limits, considering the entire Elbe River basin as a functional unit. The key strategies and initiatives, their benefits and limitations are summarized in Table 1.

Hamburg's integrated catchment management approach has yielded significant successes in mitigating the threats of coastal urban flooding. The combination of structural measures, such as dykes, with nature-based solutions has enhanced the city's resilience to flooding (Davis and Naumann, 2017). Hamburg has implemented a range of policies and measures to mitigate coastal urban flooding, with an emphasis on integrated approaches that include coastal zones within river basin management policies. The policies and measures detailed in Table 1 reflect the city's recognition of the interconnectedness of its river basins and coastal areas in addressing flood risks. A detailed overview of Germany's national flood protection programs and legal frameworks relevant to Hamburg is provided in Supplementayh Appendix A—Table A1.

Hamburg's policies and measures for mitigating coastal urban flooding demonstrate a high degree of integration, where coastal zones are included within river basin management policies as well as coastal areas outside the Elbe basin (Evers, 2016). This integrated approach recognizes the interconnectedness of river basins and coastal areas and seeks to address flood risks comprehensively. By incorporating watershed-based planning, Hamburg has addressed sea level rise in conjunction with flood planning (Heinzlef et al., 2020). This approach considers the entire river basin, acknowledging that rising sea levels will impact the discharge capacity of the Elbe River and potentially exacerbate flooding risks upstream. Additionally, interdisciplinary collaboration ensures that flood planning integrates expertise in coastal engineering, hydrology, and urban planning, leading to more comprehensive solutions. Hamburg's embrace of nature-based solutions, such as wetland restoration, can further mitigate the impact of rising sea levels by providing natural buffers and improving water retention.

Coastal storms have been addressed through a combination of infrastructure development and early warning systems. Hamburg's Storm Surge Warning System, a collaborative effort between meteorological and water authorities, provides advanced warnings of storm surges, allowing for proactive measures like evacuation and temporary flood defenses. Additionally, investments in dikes and levees serve as the first line of defense against coastal storm surges. These combined approaches offer Hamburg a multi-layered strategy for addressing the threats posed by coastal storms.

Hamburg's approach to coastal flooding management, outlined in Table 1, integrates multiple strategies that address the interconnectedness of river basins and coastal zones. A network of dykes provides primary defense against storm surges, complemented by green infrastructure like parks and rain gardens that reduce runoff and offer environmental benefits. Early warning systems deliver real-time data, enabling proactive measures during flood events. Watershed-based planning leverages designated areas within the Elbe River basin as natural buffers to attenuate flood peaks downstream. However, assessing the effectiveness of this integrated approach is challenging due to the complex interplay of factors influencing flood events and the reliance on long-term, comprehensive data. Incomplete data on flood occurrences, such as heights, affected areas, and economic damages, complicates evaluations. Additionally, counterfactual scenarios, imagining outcomes without the measures, are inherently hypothetical and difficult to model accurately.

Despite these limitations, Hamburg's approach offers valuable insights. The perceived decrease in flood risk and the city's enhanced preparedness suggests positive progress. Continuous monitoring and evaluation are crucial for further refinement. This includes continued data collection, advancements in flood modeling techniques to isolate the contributions of different strategies, and collaboration with other coastal cities to share best practices in building resilience for a changing climate. By continuously adapting and improving its integrated approach, Hamburg remains a leader in coastal urban flood management. By recognizing the interconnectedness of these systems and implementing a range of strategies, including structural defenses, green infrastructure, and early warning systems, Hamburg has reduced its vulnerability to flooding and enhanced the safety and resilience of its coastal urban areas.

6.2 Example 2: Kolkata, India: flood history but lack of effective policies

Coastal cities are particularly at risk due to factors like sea level rise, storm surges, and tropical cyclones, especially in the Global South, where rapid population growth and economic expansion often lead to infrastructure development that neglects environmental concerns, increasing climate vulnerability (Nagendra et al., 2018). In India, where the coastal region supports 25% of the national population, a 1 m rise in sea level could displace approximately 7 million people (Nayak, 2017; Bose, 2013; Dhiman et al., 2019). The impact of storm events on urban centers in these regions depends on the storm's intensity, the location of the urban centre, and the level of preparedness. However, these factors are complex and interconnected, as demonstrated in West Bengal, where prolonged floods and cyclones frequently impact the region, often overwhelming disaster mitigation strategies (Pattanayak et al., 2016).

TABLE 1 Hamburg's multifaceted approach to coastal flood risk management: strategies, policies, and measures.

Category	Description	Benefits	Limitations	References
Dyke systems	Hamburg has constructed and reinforced a network of dykes along the Elbe River, providing a primary barrier against storm surges and rising sea levels.	Protects urban areas and critical infrastructure. Proven effectiveness.	Expensive to construct and maintain. Disrupts ecosystems and aesthetics.	Schindler et al. (2022), Kippnich et al. (2017), and Leyer et al. (2012)
Retaining areas	Designated areas within the Elbe basin store excess water during high-water events, mimicking natural floodplains and promoting groundwater recharge.	Reduces downstream flood risk. Promotes infiltration and creates wetland habitats.	Limited effectiveness in extreme floods. Potential environmental impacts on retention areas.	Schuetze (2013), Salazar et al. (2012), Collentine and Futter (2018), and Posthumus et al. (2008)
Green urban infrastructure	Includes parks, rain gardens, bioswales, and green roofs, promoting infiltration and reducing surface runoff.	Mitigates flood risk. Provides ecological and urban benefits like reduced heat island effects.	Requires planning and maintenance. Effectiveness limited in impervious areas.	Nickel et al. (2014), Soz et al. (2016), Green et al. (2021), and Depietri (2022)
Early warning systems	Sophisticated systems monitor weather and water levels, providing real-time data and alerts to enable proactive measures like evacuations and emergency services.	Saves lives and minimizes property damage. Enhances preparedness.	Relies on accurate data and functioning communication. Public education is crucial.	Kundzewicz (2017), Doong et al. (2012) and Penning-Rowsell et al., 2014
Watershed-based planning	Considers the entire river basin as a functional unit, ensuring upstream actions reduce downstream flood risks.	Enhances systematic flood risk reduction.	Requires comprehensive coordination across regions and disciplines.	Zahmatkesh and Karamouz (2017) and UNESCO - Programme Hydrologique International (2009)
Interdisciplinary collaboration	Facilitates collaboration across sectors for a holistic understanding of flood risks and integrated strategy development.	Ensures diverse expertise informs strategies.	Coordination and consensus-building can be time-consuming.	Almoradie et al., 2015; UNESCO - Programme Hydrologique International (2009)
Stakeholder engagement	Inclusive planning ensures flood management strategies are socially equitable and technically sound.	Promotes diverse perspectives and buy-in from affected communities.	May require significant time and resources to build consensus.	Seebauer et al., 2019; UNESCO - Programme Hydrologique International (2009)
Adaptation and resilience	Adaptive strategies address climate uncertainties with solutions like runoff reduction and critical flood alerts.	Enhances urban resilience.	Effectiveness depends on accurate climate projections and stakeholder cooperation.	Dickhaut and Richter (2020) and Verwey et al. (2017)
Nature-based solutions	Initiatives like wetland restoration and retention areas mitigate flood risks while promoting biodiversity and community benefits.	Aligns flood resilience with environmental conservation and community well-being.	Effectiveness varies with ecological and climatic conditions.	Josipovic and Viergutz (2023) and Verwey et al. (2017)
Floodplain management	Regulates land use in vulnerable areas and designates retention areas for excess water, promoting sustainable practices.	Reduces flood risk in prone zones.	Implementation can face opposition from landowners and developers.	Serra-Llobet et al. (2022), Restemeyer et al. (2015), Heyden and Natho (2022), Clerici et al. (2013), and Weissteiner et al. (2016)

The Kolkata Metropolitan Area (KMA) is one of Asia's largest urban centers, with a population of 15.87 million. Within KMA, the most urbanized area is the Kolkata Municipal Corporation (KMC), which serves as the core component, covering about 10% of the area and accounting for 31% of KMA's population. Although being 145 km from the sea, KMC experiences flooding due to both infrastructural issues and its location as a maritime city along the Hooghly River, a tidal river flowing into the Bay of Bengal. The city has faced significant cyclonic storms, such as Aila in 2009 and Amphan in 2020 (Dasgupta et al., 2012). The mangrove areas of South Bengal, situated perpendicular to Kolkata, act as a natural buffer against cyclonic depressions in the Bay of Bengal (Pattanayak et al., 2016). However, increasing population density, expanding impervious surfaces, untreated sewage, decreasing vegetation, and rising built-up areas contribute to urban pluvial floods—floods caused by rainfall-induced runoff, independent of existing water bodies.

To understand the urban floods in Kolkata, we can examine two key aspects: the nature and causes of these floods. The nature and causes of floods in Kolkata are linked, with several factors leading to two distinct types of flooding: urban pluvial floods and coastal urban floods (see Table 2). Infrastructural issues often cause flooding in the city following rainfall events, particularly during the monsoon season (especially July–August), leading to waterlogging in various parts of Kolkata. Additionally, Kolkata's proximity to the Bay of Bengal exposes

TABLE 2 Nature of floods and vulnerable areas in Kolkata city.

Nature of urban flood	Cause and description of urban flood	Vulnerable areas from urban flood	References
Flood due to cyclone	The main cause of cyclone is due to the concave or trough shape of Bay that makes wind more conductive to gain force to push water up and it is due to low pressure formed due to heat absorption of oceanic water	Coastal low-lying areas and zones near estuarine regions, particularly those adjacent to the southern boroughs of the city.: such as Monikhali Basin, Hooghly Basin, Maheshtala area which are adjacent to Boroughs XIV and XV.	Mukherjee and Bardhan (2021)
Urban water logging	Apart from cyclonic storm moderate to heavy continuous rain causes water logging in a significant portion of the city. The reason behind the water logging are- Absence of drainage network in many areas Back flow of water due to tidal effect in Hooghly River Inadequate capacity of drains Unsatisfactory reconstruction of canals	Residential, commercial, and central areas prone to inadequate drainage, including streets in the northern, central, and southern sectors of the city with old infrastructure and flat topography: such as, Streets in Dum Dum, Kankurgachi, Patipukur, Haldiram, Shyambazar R. G. Kar Street Area, Chitpur area, College Street area, B. B Ganguly Street and Central Avenue crossing, Lalbazar Street near Writer's Building, Kali Krishna Tagore Road area, Park Street, Camac Street area, RajaDinendra Street area, Mirja Ghalib Street	Paul (2021) and Mukherjee et al. (2018)

it to cyclonic storms, making the city prone to the adverse effects of such events. Even cyclones with moderate intensity can cause urban pluvial floods due to heavy rainfall.

Waterlogging caused by pluvial floods is a recurring issue in Kolkata, particularly during the onset and middle of the monsoon season, though there are no official government records of these events. Several major causes of urban pluvial floods in Kolkata include:

1 *Irregular canal restoration*: During the monsoon season, many canals are not fully functional due to extensive weed growth. The absence of canal bank walkways in some areas hinders cleaning and maintenance, contributing to flooding (Paul, 2021).
2 *Encroachment of east Kolkata Wetlands*: The encroachment on these wetlands disrupts natural drainage and exacerbates flooding.
3 *Basin system and water flow direction*: The natural basin system and water flow direction in Kolkata play a role in the city's susceptibility to flooding.
4 *Cyclonic storms*: The formation of low-pressure systems in the Bay of Bengal during April–May leads to cyclonic storms. Kolkata's funnel shape and low-lying location in the Bengal Delta amplify the impact of these storms. Although the Sundarbans region experiences less severe flooding, high-intensity cyclones like *Amphan* (113 km/h) can cause significant urban flooding in Kolkata.
5 *Mangrove depletion*: The mangrove forests along the Bengal Delta's coastline serve as natural buffers against cyclonic winds. However, due to erosion, settlement, and climate change, the mangrove ecosystem has declined by 25% over the past three decades, posing a serious threat to Kolkata.
6 *Land subsidence*: Recent studies indicate that land subsidence of 0.5 meters could worsen waterlogging and flooding in the KMA by 2070. Areas like Bantala, BaghaJatin, Rajarhat, Bamanghata, and parts of Salt Lake are at high to very high risk for land subsidence (Hanson et al., 2011; Sahu and Sikdar, 2011).

Flood vulnerability in the Kolkata city region has been significantly accelerated by urban land use, with the risk of flooding unevenly distributed across communities. According to Dasgupta et al. (2012), flood vulnerability is closely linked to the socio-economic status of communities, with poorer wards being at higher risk.

To introduce Kolkata's flood mitigation strategies, it is important to understand how they align with national efforts, which include both structural and non-structural measures. Table 3 provides an overview of various Indian organizations and their respective flood mitigation efforts, highlighting their roles and responsibilities in managing flood risks across the country. Unlike the national approach, which equally emphasizes both types of measures, Kolkata's strategy places a stronger focus on early warning systems. This emphasis is evident in the activities of the Indian Meteorological Department (IMD) and the joint venture between the Kolkata Municipal Corporation (KMC) and the Asian Development Bank (ADB). These organizations play a key role in managing Kolkata's flood mitigation efforts, with a particular focus on early warning systems as the primary component of the city's strategy (see Table 4). While Kolkata has not yet implemented rigorous structural flood mitigation strategies, several significant flood management efforts are underway.

These early warning systems are managed by two major organizations:

1) The Indian Meteorological Department (IMD), Alipur, Kolkata, and,
2) A joint venture between Kolkata Municipal Corporation (KMC) and the Asian Development Bank (ADB).

The IMD in Alipur initiated the rainfall warning system in Kolkata following the devastating cyclone of 1864. Initially, the IMD focused on standardizing rain measurement through a government-endorsed common rain gauge. Today, the IMD is responsible for processing climate data, forecasting cyclones, and supporting agricultural communities by predicting monsoon patterns and rainfall intensity. A significant achievement of the IMD is the National Monsoon Mission (2012), which offers dynamic prediction systems for monsoon rainfall over different time scales—seasonal (entire monsoon season), extended range (up to 4 weeks), and short range (up to 5 days). While these forecasting efforts do not weaken cyclones or severe storms, they play a crucial role in disaster preparedness for urban communities and those living near the Bay of Bengal.

TABLE 3 Different Indian organization and their flood mitigation effort.

Organization	Organizational type and general responsibility	Statutory structure	Flood management	
			Method	Feature
Indian Meteorological Department (IMD), 1875	Government organization, which forecast weather	Ministry of Earth Science, Government of India	Mainly forecasting weather	1. Rainfall forecast and classifying region where the intensity will be higher 2. Forecasting pathway of cyclone and naming 3. SMS alert of rainfall 4. Preparing climatic data set and make it accessible for research
Central Water Commission (CWC) 1945	Technical Organization	Under the Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India	Dam safety	The large dams with the spillway crest more than 500 m are meant to construct flood. These large dams are workable when the flood discharge is more than 2000 cumecs.
			River basin management	Although the basin management plan has not paid explicit emphasis on flood management, but still the remote sensing data assessing flood inundation and for the character and extent of floodplain vegetation coupled with simple models
			Monitoring of flood	Real time flood forecast with the help of flood monitoring stations which provides the indication of (1) above normal flood, (2) severe flood and (3) extreme flood with definite symbol of color code in the web.
Damodar Valley Corporation (DVC) 1948	Multipurpose river basin management	Ministry of Power, Government of India	Structural measures to mitigate flood	Dam construction to mitigate flood Flood Forecasting System, Real Time Data Acquisition System (RTDAS) & Real Time Decision Support System (RTDSS).
Ganga Flood Control Commission (GFCC) 1972			Comprehensive flood control plan in Ganga basin	The GFCC has prepared comprehensive flood management plan of the 23 sub-basins of Ganga River basin
National Hydroelectric Power Corporation (NHPC), 1975	Sustainable power generation, i.e., hydropower, solar power and wind energy	Ministry of Power, Government of India enterprise	NHPC explicitly moderating flood vulnerability for large hydropower dam and basin	Currently NHPC focusing on dam designing in Arunachal Pradesh to prevent GLOF event
Rashtriya Barh Ayog (RBA) or National Flood Commission (NFC) 1976		Ministry of Agriculture and Irrigation	Construction based flood control measure	Especially embankment restoration to combat
The National Institute of Hydrology (Roorkey) 1978	Research and development organization	Under the Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India	Estimation of design basis flood	Hydrological design to estimation of flood and safe grade elevation, with the association of NPCIL
			Concurrent evaluation of Flood management schemes	Although this is not the direct problem-solving approach of flood incidents, but a number of projects undergoes in the parts of Uttarakhand region with the association of irrigation department
			Glacial lake flood	The study was undertaken through NHPC to identify structural measure to prevent further flood in Tawang basin at Arunachal
Brahmaputra Board 1980		Under the Ministry of Irrigation (now Ministry of Water Resources)	The jurisdiction of Brahmaputra Board includes all NE States of Brahmaputra basin including Barak Basin	1. Investigation with survey in Brahmaputra and Barak basin 2. Preparing master plan to flood control and riverbank erosion 3. Preparation of DPR for dams

(Continued)

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TABLE 3 (Continued)

Organization	Organizational type and general responsibility	Statutory structure	Flood management	
			Method	Feature
National Disaster Management Authority (NDMA) 2005	NDMA is the apex body for Disaster Management in India	Headed by the Prime Minister of India	Mobile Radiation Detection Systems (MRDS) to handle Radiological Hazards in Metros/Capital Cities/Big Cities in India	–
			Flood Risk Mitigation Scheme (FRMS)	The FRMS scheme undergoes with-(1) modeling for multi-purpose flood shelters, (2) river basin specific flood early warning system and (3) financial support for flood prone states
			Landslide Risk Mitigation Scheme (LRMS)	This scheme is under preparation, which aims to provide-(1) financial support to land slide prone areas, (2) early warning system and (3) capacity building
National Disaster Response Force (NDRF)	1. Special force dealing with rescue operation from natural and manmade disaster 2. Constituted through Disaster Management Act, 2005	NDRF constituted with total 16 battalions, with are situated in different parts of the country	Proactive availability and pre-positioning during natural calamities	The activity of NDRF structures into 3 particular phases- 1. Emergency Operation centre – which alert 247 to response emergency call from authentic source 2. Preparatory state- develop unit of force to tackle situation 3. Activation state- action being paid in by the unit members in areas where rescue operation is being carried out

Kolkata also hosts India's first city-level flood forecasting and early warning system, known as the Kolkata Environment Improvement Investment Program (KEIIP). This initiative is a collaborative effort between the ADB and KMC, aimed at transforming Kolkata into a smart and resilient city. KEIIP focuses on modernizing financial, administrative, and asset management systems, reducing urban flood risks, improving land use planning, and enhancing the city's capacity to communicate with citizens through a flood forecasting and early warning system (FFEWS). The FFEWS, developed with technical assistance from ADB's Urban Climate Change Resilience Trust Fund (UCCRTF), uses real-time sensors, including pumping station sensors, canal sensors, inundation sensors, location sensors, rain gauge sensors, mobile phone alerts, cloud-based sensors, and a real-time flood and air quality dashboard. These sensors are cost-effective, modular, widely accessible, and capable of monitoring multiple parameters, with provisions for crowd-sourcing data (Asian Development Bank, 2018). According to ADB reports, flooding has already been reduced across approximately 4,800 hectares, with further reductions expected in over 6,000 hectares under the project.

While the early warning system is a key component of Kolkata's flood mitigation strategy, it primarily alerts citizens to impending storm events without reducing the storm's intensity. These technology-driven measures may not be fully effective for marginalized communities living in informal settlements. In this context, maintaining the city's sewage and canal systems is crucial for preventing the aftereffects of flooding and waterlogging. Although a significant portion of the city has a canal system intended to enhance its sewage network, neglect of canal maintenance exacerbates waterlogging, not only during the monsoon season but after any rainfall event. Dasgupta et al. (2012) highlight that the time lag between canal restoration in dry and wet seasons is approximately 4–5 years. Additionally, the encroachment of natural wetlands and their conversion into built-up areas has further hindered the city's ability to optimize flood mitigation efforts. Kolkata's flood mitigation strategy is primarily focused on forecasting mechanisms to manage natural calamities approaching from outside the city. However, the city still needs to develop sustainable infrastructure to effectively mitigate flooding.

6.3 Example 3: Haifa Bay area, Israel: no significant flood history but potential future risks

Haifa is located at the mouth of the Kishon River (Klausner et al., 2021), offering strategic advantages but also significant risks (Lichter and Felsenstein, 2012). The Kishon River itself, flowing through the industrial north before emptying into the sea, adds to this vulnerability (Naff, 2020). The combination of Haifa's coastal location, the influence of the Kishon River estuary, and its low-lying coastal plain where most residents live, makes the city highly susceptible to flooding, especially during heavy rainfall events or storm surges (Pasternak et al., 2017; Shtienberg et al., 2022; Gideon, 2003). The gentle slope of the Kishon River further impedes drainage, exacerbating flood risks in lower-lying areas (Pasternak et al., 2017; Shoshana, 2013).

Climate change and rapid urbanization worsen these vulnerabilities. Sea-level rise increases the risk of coastal flooding (McNeill and Engelke, 2016; Negev et al., 2022). Urbanization leads to

TABLE 4 City level flood mitigation strategies in Kolkata.

Mitigation strategies and undertaking organization	Nature	References
Forecast of Indian Meteorological Department (IMD), Alipur, Kolkata	1. Five days ahead forecast about Cyclone from 2017 2. Launching of dedicated website for cyclone in 2014 3. Digital India Program with SMS service about rainfall and storm from 2014 4. Dynamic Risk Atlas for Cyclones in 2021 5. Launching "MAUSAM GRAM" program, which includes weather information at all locations at any time	Mohapatra (2014), Chug et al. (2021), and Mohapatra (2015)
1Kolkata Environmental Improvement Investment Program (KEIIP), 2014 a. Joint effort by ADB and KMC	1. It is a comprehensive city level planning, which design to forecast flood, rainfall, air temperature too. KEIIP is the 1st city level early warning flood forecast in India	Shaw and Saharan (2019)
b. State Action Plan on Climate Change, West Bengal (SAPCC, WB), 2012 c. In collaboration with NDMA (based on Disaster Management Act, 2005)	2. Strengthening and improvement of 3,121 km embankments in Sundarbans area	Dey et al. (2016)
Kolkata City Disaster Management Plan, 2014 a. In collaboration with NDMA (based on Disaster Management Act, 2005)	1. Model framework for District Disaster Management Plan by NDMA 2. Constructing Borough wise flood/cyclonic shelter 3. City level flood warning system through the introduction of *kflood* android app as well as thorough *kflood.in* website	Rumbach (2017)

the widening impervious surfaces, hindering natural drainage and increasing surface runoff during heavy rainfall events (Efrat, 2017; Babitsky et al., 2023). Historical flooding events, often exacerbated by sediment deposition in the river mouth during dry summers, underscore the city's vulnerability and the need for robust flood risk management strategies (Zituni et al., 2021; Lichter et al., 2009). The unpredictable nature of extreme weather events, as evidenced by the severe flooding in Haifa and Tel Aviv in 2020 (receiving 20% of their annual rainfall in a single day), highlights the critical importance of building resilience (Lynn et al., 2021; Felsenstein and Lichter, 2014).

Past floods in Haifa (1991), the Sharon Region (2003), and Carmel (2010) underscore this urgency for effective mitigation strategies (Laster et al., 2005; Tal, 2017).

While Israel has a well-established water management framework, a critical gap exists when it comes to integrated flood management specifically for Haifa Bay. An outline of Israel's national flood and basin management programs and policies is presented in Supplementary Appendix B—Table B1. This gap becomes especially concerning when considering the potential consequences of climate change, as sea level rise was not integrated into drainage planning until recently. The Drainage and Flood Control Law of 1957 lays the groundwork for regional drainage plans, but the question remains whether these plans consider the potential for increased flood severity due to climate change. The Kishon River Plan (2001) focuses solely on improving the Kishon River ecosystem, neglecting to explicitly address flood control. Public engagement in flood risk management is crucial, but more can be done to ensure local knowledge and concerns are integrated (Mishor et al., 2023). While these policies touch upon flood management and coastal protection, they lack the necessary integration and focus on climate change scenarios.

Although, we are focusing on the bay area within the Haifa city at the mouth of Kishon river, which is the most vulnerable part of the city, it is imperative to look at the city and basin scale for polices for flood mitigation techniques and measures. Haifa city appears to be fostering collaboration among experts from various disciplines involved in flood risk management, similar to Hamburg's successful approach. Additionally, stakeholder engagement seems to be present, and Israel has invested in flood risk mapping and early warning systems to enhance preparedness (Eini et al., 2020; Marin et al., 2017). Concurrently retention and detention schemes are increasingly being advanced in the Kishon basin, thereby helping to reduce the vulnerability of coastal urban areas to flooding. However, the large-scale residential plans that were approved in the Haifa Bay area will lead to wider impervious areas. These in combination with a higher drainage base due to sea level rise, increase the risk to the Haifa Bay area.

The city's industrial complexes, concentrated at the bay area, pose potential environmental hazards during flooding, requiring coordinated efforts between environmental authorities, local governments, and industrial stakeholders (Shmueli, 2008), which can be at risk due to prospective flooding events. Haifa has undertaken infrastructure projects to mitigate flooding, including stormwater drainage improvements, flood protection barriers, and riverbank enhancements (Goulden et al., 2018; Stavi et al., 2024; Tal and Katz, 2012). However, the integration of these measures with coastal zone management is not evident.

Furthermore, Haifa's emphasis on adaptation and resilience aligns with best practices. The city's focus on green infrastructure, floodplain management, and early warning systems demonstrates a commitment to addressing flood risks. However, more concrete evidence is needed to verify the actual implementation and effectiveness of these practices in Haifa. While Israel has recognized the importance of nature-based solutions (NbS) for flood risk reduction, the implementation of such approaches is relatively limited (Domínguez-Tejo et al., 2016). In the Haifa Bay area, integrating NbS, which can include wetland restoration and upstream afforestation into both river basin and coastal management may be essential for enhancing resilience to coastal urban flooding (Rezvani et al., 2023; Shadar and Shach-Pinsly, 2024).

7 Discussion: the imperative of integrated catchment management

This paper reviews the potential role of Integrated Catchment Management (ICM) as a crucial strategy for mitigating coastal urban flooding across different regions. By analyzing the cases of Hamburg, Haifa Bay, and Kolkata, this discussion emphasizes the universal relevance of ICM while addressing the distinct challenges in its global implementation. The review also answers key research questions regarding the contributions of ICM policies, the comparative approaches of different regions, the primary strategies, and how these insights can inform global flood mitigation efforts.

7.1 Contributions and effectiveness of ICM policies

ICM policies may play a potentially critical role in mitigating coastal urban flooding by enhancing resilience and adaptive capacity in both developed and developing urban contexts. These policies acknowledge the interconnectedness of upstream and downstream activities, facilitating coordinated responses that effectively reduce flood risks (European Commission, 2007). Hamburg's robust ICM framework, supported by the EU Floods Directive, exemplifies how centralized governance can foster collaboration among stakeholders and ensure cohesive flood management strategies (Petry and Dombrowsky, 2007). The city's integrated approach, involving extensive infrastructure investments and community engagement, has significantly reduced vulnerability to flooding, demonstrating the effectiveness of a well-implemented ICM policy.

In contrast, the Haifa Bay area illustrates the difficulties arising from fragmented governance structures, where the lack of cohesive strategies to integrate river basin and coastal management leads to coordination gaps and inefficiencies (Becker et al., 2017). Haifa's experience underscores the importance of robust governance frameworks in implementing comprehensive ICM strategies, as the absence of such integration can exacerbate flood risks and hinder effective mitigation efforts.

Expanding the discussion to include Kolkata provides a broader perspective on the application of ICM in diverse socio-economic settings. Kolkata, a city grappling with rapid urbanization and frequent monsoonal flooding, faces significant challenges due to its decentralized governance and resource constraints (Guhathakurta et al., 2011). Despite these challenges, Kolkata's partial adoption of ICM strategies highlights the potential for adaptive approaches that integrate local governance with broader flood management frameworks. The city's experience demonstrates the need for context-specific strategies that address local governance issues while aligning with comprehensive flood management goals.

7.2 Strategies and outcomes of ICM implementation

ICM strategies must operate across multiple spatial scales to be truly effective. It is essential that ICM encompasses not only the city and its immediate coastal area but also all or part of the upstream basin. This holistic spatial approach ensures that measures addressing flood risks, such as mapping vulnerable zones, implementing early warning systems, enhancing infrastructure (e.g., dikes and levees), and promoting sustainable land-use policies, account for interconnected systems. Such comprehensive management fosters preparedness and resilience while mitigating upstream activities' environmental impacts on downstream and coastal regions (World Meteorological Organization, 2018; FEMA, 2013).

Hamburg serves as a model with its advanced flood risk mapping and infrastructure investments, which have significantly strengthened the city's flood resilience. The integration of early warning systems and sustainable land-use policies in Hamburg exemplifies how ICM can effectively mitigate flood risks. Conversely, Haifa's lack of comprehensive strategies has left the region more vulnerable to flooding, underscoring the importance of holistic planning in ICM.

Kolkata's ongoing efforts to improve its drainage systems and implement early warning mechanisms highlight the potential benefits of a more fully integrated ICM approach. However, the persistent issues of inadequate infrastructure and governance challenges demonstrate the difficulties of applying ICM in rapidly urbanizing and resource-constrained environments.

7.3 Enhancing global frameworks for coastal urban flood resilience

The comparative analysis of Hamburg, Haifa, and Kolkata informs several key recommendations for enhancing global coastal urban flood resilience:

1 Adoption of watershed-based approaches: The integration of river basin and coastal zone management, as seen in Hamburg, is crucial for effective flood mitigation. This approach ensures that actions in one part of the watershed do not inadvertently increase risks in another, promoting a more sustainable and resilient flood management strategy.
2 Fostering collaborative governance models: Effective ICM implementation requires strong governance frameworks that promote collaboration among various stakeholders. Hamburg's centralized governance model serves as a successful example, while Haifa's challenges underscore the need for more cohesive and integrated approaches.
3 Integration of nature-based solutions: Incorporating nature-based solutions, such as wetland and floodplain restoration, can enhance flood resilience while providing additional environmental benefits. These strategies should be integrated into ICM policies globally to support both flood mitigation and ecosystem health.
4 Inclusive decision-making processes: The involvement of governments, communities, and non-governmental organizations is essential for the effective and sustainable implementation of ICM policies. Inclusive decision-making ensures that the needs and perspectives of all stakeholders are considered, leading to more equitable and effective flood management outcomes.

The review highlights that while ICM is essential for managing coastal urban flooding, its success depends heavily on the context in which it is implemented. The experiences of

Hamburg, Haifa, and Kolkata provide valuable lessons on the importance of governance, infrastructure, and community engagement in ICM implementation. By adopting watershed-based approaches, fostering collaborative governance, and integrating nature-based solutions, regions worldwide can enhance their resilience to coastal urban flooding. The global applicability of ICM is evident, yet its adaptability to local conditions and the capacity to address specific regional challenges are crucial for its successful implementation.

Table 5 succinctly highlights critical areas of the specific challenges and shortcomings of Integrated Catchment Management in each of the regions discussed—Hamburg, Kolkata, and Haifa Bay—while answering the research questions posed in the study. The sources of flooding, the deficiencies in current ICM strategies, the unique governance and infrastructure issues in each region, and the overall outcomes in terms of flood risk mitigation are all addressed in the table. This structured overview helps in understanding the complexities and regional specificities of implementing ICM globally.

7.4 The study and its relevance in the contemporary era of climate change

This study underscores the urgency of adopting Integrated Catchment Management (ICM) as a comprehensive strategy to strengthen flood mitigation policies in coastal urban areas, particularly in the context of escalating climate change impacts. For example, in many Southeast Asian countries, with India being a prominent example, the construction of multipurpose dams continues to be a dominant water management approach. However, such interventions are often mired in socio-political controversies and ecological trade-offs, frequently leading to community-level conflicts and policy debates (Somokanta et al., 2021).

From a hydrological standpoint, dams serve as artificial interruptions to the natural river flow, impeding the transport of sediments and nutrients downstream. When positioned in the upper course of a river, dams can disrupt the natural flood pulse—an essential process for replenishing nutrient-rich sediments on downstream floodplains and agricultural lands. This phenomenon has been empirically documented in the Mekong River Basin, where Gao et al. (2022) used river network analysis to evaluate the ecological suitability of dam placement.

Moreover, even within similar climatic zones, rivers often exhibit significant morphodynamical variability along their course. This spatial heterogeneity calls for tailored flood management strategies that account for local environmental, geomorphological, and socio-economic characteristics. As noted by Singhal et al. (2024), hydrological monitoring must go beyond topographical assessments to incorporate demographic trends, land use patterns, and existing infrastructure networks.

The increasing frequency and intensity of flood events, driven by extreme precipitation, storm surges, and sea level rise, further amplify the need for an integrated, basin-wide perspective. ICM is especially relevant in addressing the rising drainage base in coastal areas, which, when coupled with upstream changes and urban expansion, requires a unified framework that can harmonize hydrological, infrastructural, and governance dimensions.

8 Conclusion

The imperative for a holistic catchment management system integrating coastal zone management and river basin management is underscored by the interconnectedness of these systems and the challenges posed by climate change-induced flooding. Coastal zones and river basins are intricately linked through biophysical and socio-economic processes, such as water and sediment transport, which extend from the headwaters to the coast. Neglecting this holistic perspective can lead to fragmented and ineffective flood management strategies. Therefore, a comprehensive approach that considers both upstream and downstream factors, as well as water sensitive urban planning, embracing principles of collaboration, adaptability, and inclusivity, offers a promising pathway to mitigate the escalating risks of coastal urban flooding.

The review examines the cases of Hamburg, Germany; Kolkata, India; and Haifa, Israel, highlighting diverse flood histories and existing policies. Hamburg exemplifies proactive measures and integrated management practices that have yielded long-term benefits (Petry and Dombrowsky, 2007). Conversely, Kolkata's frequent flooding events and inadequate policies underscore the urgent need for comprehensive flood management strategies tailored to its socio-economic context (Guhathakurta et al., 2011). Haifa, though currently experiencing minimal flooding, stands to benefit from proactive ICM principles in anticipation of future climate-induced risks.

The literature review as well as the three cases reviewed suggest that effective flood management strategies must recognize and address the interdependencies between river basins, coastal zones, and urban environments. A holistic approach that considers upstream and downstream interactions is crucial for resilience. Moreover, successful flood management requires collaboration among diverse stakeholders at different levels of government. Clear lines of responsibility and coordinated efforts are essential for effective implementation of ICM strategies.

Comprehensive flood mitigation measures should integrate infrastructure development, flood risk mapping, early warning systems, land-use planning, and nature-based solutions (World Meteorological Organization, 2018; FEMA, 2013). Finally, cities worldwide can benefit from sharing experiences and best practices in flood management. Fostering knowledge exchange and collaboration between coastal urban centers is crucial for developing effective flood management approaches.

While ICM offers a robust framework for flood management, its implementation faces several challenges. These include institutional coordination, securing adequate funding and resources, and engaging local communities and stakeholders effectively. Successful ICM requires overcoming these barriers to foster collaboration across administrative boundaries and sectors.

The analysis acknowledges limitations due to the scarcity of English-language resources, potentially affecting the comprehensiveness of the review. Nonetheless, the insights provided aim to inform the development of robust flood mitigation frameworks for coastal urban areas worldwide. The study advocates for integrating river basin, coastal zone and urban scale management practices to enhance resilience against climate-induced flooding in the coastal urban areas.

TABLE 5 Critical Shortcomings of integrated catchment management in addressing coastal urban floods.

Area type	Sources of flooding	Existing integrated catchment policies miss	Governance challenges	Infrastructure gaps	Flood Mitigation outcomes
Areas with history of flooding and effort to mitigate (e.g., Hamburg,)	Heavy rainfall events affecting river discharge, storm surges, Sea-level rise	Lack of fully integrated approaches encompassing river basin, coastal zone, and urban area management; Insufficient adaptive strategies to address climate change impacts; Limited incorporation of nature-based solutions in flood risk management	Centralized governance under the EU Floods Directive supports effective coordination	Well-developed infrastructure, but ongoing maintenance is key	Successful in significantly reducing flood risks
Areas with history of flooding but ineffective management (e.g., Kolkata,)	Inadequate drainage infrastructure, rapid urbanization	Lack of coordinated governance structures across different levels (local, regional, national); Inadequate investment in flood infrastructure and maintenance; Limited involvement of local communities in planning and decision-making	Decentralized governance struggles with resource allocation and coordination	Outdated infrastructure fails to meet growing urban demands	Partial implementation of ICM limits overall flood risk reduction
Areas where flood risk may increase (e.g., future risk in Haifa Bay area, Israel)	Anticipated sea-level rise, changing precipitation patterns	Absence of proactive policies addressing future flood risks exacerbated by climate change; Inadequate assessment and mapping of future flood risks considering projected climate scenarios; Lack of initiatives to build institutional and community capacity for future flood resilience	Fragmented governance leads to coordination gaps and inefficiencies	Limited infrastructure investment exacerbates vulnerability	Higher flood risk due to lack of integrated strategies

To advance global coastal urban flooding mitigation efforts, future research should focus on evaluating the transferability of ICM strategies across diverse geographical and socio-economic contexts. The three highly diverse cases reviewed in this study suggest that ICM is pertinent across settings, though the measures must be tailored to the specific setting. This includes assessing the feasibility and effectiveness of ICM policies in regions with varying climate conditions, levels of urbanization, and governance structures. Research into the impacts of climate change on coastal urban flooding, including sea-level rise and changing precipitation patterns, is crucial. Additionally, exploring innovative nature-based solutions and green infrastructure integrated into flood risk management strategies is essential to enhance resilience.

To validate ICM as a cross-comparative framework for flood resilience in coastal cities, this study identifies key dimensions that are consistently relevant across urban coastal contexts:

1 *Governance Coordination Across Scales*: Examining how institutional fragmentation impacts flood resilience and the role of multi-level governance in ensuring integrated water management.
2 *Hybrid Infrastructure Deployment*: Analyzing the interplay between gray (engineered) and green (nature-based) infrastructure in mitigating flood risks.
3 *Adaptive Management Mechanisms*: Assessing how cities can incorporate flexibility into flood management strategies to respond to changing climate conditions and socio-economic pressures.

By structuring the analysis around these dimensions, the paper establishes ICM as a replicable framework for assessing flood resilience strategies in other coastal cities globally. This structured approach enhances the applicability of findings and provides a methodological basis for future comparative research on urban flood resilience. Integrated Catchment Management (ICM) offers a holistic approach to mitigating coastal urban flooding amidst a changing climate. By connecting policies across river basin, coastal, and urban scales, ICM fosters a coordinated and sustainable response to flood risks. The cases of Hamburg, Kolkata, and Haifa illustrate varying flood histories and policy contexts, highlighting the importance of proactive and integrated flood management strategies. Collaboration, innovation, and adaptive management are pivotal in building resilient coastal urban communities. This review underscores the necessity of shifting toward integrated and adaptable approaches, advocating for regional and international cooperation in flood risk management. By learning from each other and sharing best practices, coastal cities worldwide can enhance their resilience against the multifaceted challenges of climate-induced flooding.

Author contributions

SM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing – original draft, Writing – review & editing. SK: Data curation, Investigation, Methodology, Resources, Writing – original draft. TB: Visualization, Writing – original draft. EF: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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