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Exploring Flood Resilience Trends for Enhanced Flood Management: A Review

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ABSTRACT

Flooding remains one of the most destructive natural hazards globally, causing significant social, economic and environmental impacts. This review explores the evolution of flood hazard management across three major phases: traditional structural approaches before 2000, integrated risk-based frameworks from 2000 to 2010 and modern resilience-focused strategies from 2010 to 2025. Early efforts centered on structural defenses, which proved effective for localized protection but presented limitations such as high maintenance costs, ecological disruption and failure during extreme events. The transition to integrated models emphasized the relationships between hazard, exposure and vulnerability, supported by geographic information systems and probabilistic modeling. More recent strategies focus on enhancing resilience through nonstructural measures such as early warning systems, community adaptation and nature-based solutions. This review also examines key methodologies, including flood hazard mapping, risk assessment, artificial intelligence applications and dynamic vulnerability modeling. However, despite these advancements, challenges such as limited data availability, methodological inconsistencies and the inadequate inclusion of social vulnerability persist. This synthesis highlights current trends and key gaps, offering strategic direction for future flood hazard planning.

1. Introduction

Flooding represents one of the most frequent and destructive natural hazards experienced worldwide [1], with a well-documented history of occurrence. Table 1 summarizes major flood events around the world that cause significant impact. Floods manifest in several forms, including coastal, monsoonal, pluvial and fluvial [2]. These events have consistently caused significant losses across various sectors such as infrastructure, agriculture, commerce and human settlements. Despite

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advancements in forecasting and infrastructure development, recurrent floods continue to result in widespread damage globally.

Table 1
Major flood event globally

Location/Year	Details	Impact	Source
United States/1993	Prolonged flooding along the Mississippi and Missouri Rivers for nearly 100 days, with levee failures.	Displaced thousands, flooded millions of acres, caused over USD 15 billion in damages.	[3]
Yangtze River/China, 1998	Heavy rainfall and snowmelt caused the Yangtze River to overflow.	Affected 180 million people, killed 3,700, caused USD 26 billion in damages.	[4]
Bangladesh/1998	Monsoon rains flooded two-thirds of the country.	Affected 30 million people, killed over 1,000, extensive crop and infrastructure damage.	[5]
Central Europe/2002	Heavy rainfall led to severe flooding along the Elbe and Danube rivers.	Over USD 20 billion in damage, killed over 100 people.	[6]
Indonesia/2004	Tsunami-related flooding from a 9.1 magnitude earthquake.	Killed over 230,000	[7]
Mumbai, India/2005	Torrential monsoon rains (944 mm in 24 hours), paralyzed the city.	Over 700 deaths, USD 1 billion in damages.	[8]
Hawaiian Islands, USA /2006	Prolonged rainfall from February to April due to kona lows.	Damaged infrastructure, displaced residents, caused millions in damages.	[9]
India/2008	Monsoon flooding, particularly due to Kosi River embankment breach.	Over 2.3 million affected, 500 deaths, widespread destruction of homes and crops.	[10]
South India/2009	Monsoon rains caused the worst floods in 100 years.	At least 299 deaths, 500 000 homeless and extensive infrastructure damage.	[11]
Pakistan/2010	Monsoon rains flooded 20% of the country along the Indus River.	Over 1,700 deaths, 20 million affected, USD 43 billion in economic losses.	[12]
Thailand/2011	Monsoon rains caused widespread flooding, particularly in Bangkok.	Over 800 deaths, affected 13 million people, USD 45 billion in damages.	[13]
Pakistan (2022)	Torrential monsoon rains caused one of the worst floods in history.	Over 1,700 deaths, 33 million affected, USD 30 billion in damages.	[14]

Besides, the economic consequences of flooding are considerable. In the Kathmandu Metropolitan City of Nepal, the annual cost of flooding along the Putalisadak road section has been estimated at USD 65,579.99 [15]. This figure includes direct, indirect, fixed and variable costs sustained by local businesses. On a global scale, pluvial and fluvial floods caused an estimated economic loss of USD 5.69 billion in 2021 [16], with some of the most severe impacts recorded in Germany [17]. In the United States, average annual losses from floods between 1996 and 2016 were approximately USD 3.99 billion [18].

In Southeast Asia, flood events have also brought substantial economic repercussions. In Malaysia, annual damages from flooding are estimated at RM915 million, affecting about 9% of the land area and 22% of the population [19]. Other than that, the 2014 flood in Kelantan was particularly devastated, with average direct losses per household approximately RM5250 [20]. In Thailand, the agricultural sector experienced severe impacts, with economic losses estimated at 11.25 billion Thai Baht [21].

Given the recurrent and severe consequences of flooding, it is essential to enhance societal resilience through effective flood hazard assessment and mitigation. Numerous efforts have been made to reduce the impact of floods through various strategies and interventions. Despite numerous efforts to mitigate flood impacts, certain years have seen floods inflict severe consequences in specific regions. This review seeks to examine the evolution of flood hazard mitigation practices and evaluate the methodologies commonly employed to enhance resilience against flooding.

2. Evolution of Flood Hazard Mitigation

2.1 Traditional Flood Control (Pre 2000)

Before 2000, flood management strategies predominantly relied on structural interventions designed to control and prevent inundation [22] such as dams, levees, floodwalls and river channelization. While these methods proved effective in mitigating certain flood risks, significant limitations revealed [23]. For example, in the United States the "levees only" policy, promoted by the U.S. Army Corps of Engineers and formalized under the Flood Control Act of 1928, was expanded through the inclusion of dams and reservoirs [24]. The National Flood Insurance Act of 1968 introduced land-use regulations to complement these measures. However, the 1993 Mississippi River flood demonstrated the inherent risks of structural reliance, as levee breaches caused widespread destruction. Similarly, the Netherlands implemented the Delta Works to safeguard low-lying areas, showcasing both the potential and the limitations of large-scale engineered defences.

Traditional flood management also evolved through community-based systems harmonized with local hydrological conditions. In Sri Lanka, the tank cascade system integrated reservoirs, canals, embankments and sluice gates, managed collectively by farmers and local officials [25]. Despite disruptions during colonial rule, this system remains functional in dry regions. In ancient China, flood control was conducted through dynastic projects that included the construction of levees and drainage systems, with the late Qing dynasty incorporating modern materials such as brick and cement along rivers [26]. Japan once utilized controlled floodplain inundation in alignment with seasonal cycles, although this practice has declined due to a shift toward large-scale infrastructure. In Sampang, Indonesia, traditional adaptations such as elevated housing and indigenous flood warning tools like *brenggongan* (wooden sticks) and k*entongan* (gongs) were employed for low-frequency flood event but these lacked capacity for addressing more frequent or intense hazards [27].

A critical comparison of these systems is evident in Sri Lanka's tank cascade system for flood mitigation, finding it resilient in dry zones with low maintenance costs and high community involvement, but limited in scalability during extreme monsoons due to colonial disruptions [25]. Conversely, Indonesian indigenous tools like kentongan gongs, which effectively warned communities in low-frequency events but failed during high-intensity floods owing to lack of integration with modern forecasting [27]. These studies highlight the relevance of culturally aligned approaches for sustainable, low-cost mitigation, yet their limitations in handling climate-amplified events emphasize the need for hybrid models, as pure traditional systems often overlook evolving hydrological stresses.

Despite their ecological sustainability and cultural alignment, traditional systems have faced challenges in scalability and integration into modern planning. The comparative analysis below highlights the differences between structural and traditional flood management strategies. It emphasizes the trade-offs between engineered approaches and nature-based or culturally embedded systems. This table provides a synthesis of their respective strengths and limitations, which serves as a foundation for understanding the paradigm shift that occurred after 2000 toward integrated and resilience-based flood risk management.

Table 2
Structural and traditional flood management system

Aspect	Structural Approaches	Traditional / Nature-Based Approaches
Description	Engineered infrastructures	Systems rooted in ecosystem processes or indigenous practices
Cost	High capital and maintenance cost	Lower investment and maintenance cost
Ecological Impact	Loss of biodiversity, river fragmentation and disruption of sediment/nutrient flow	Enhances ecosystem services, biodiversity and supports sustainable land-water interaction
Scalability & Reliability	Scalable over large regions but can fail under extreme hydrological stress	Scalable when integrated with modern planning
Cultural Integration	Externally implemented; lacks alignment with local cultural values	Deeply embedded in local knowledge systems
Examples	Levees and dams	Tank cascade system, floodplain farming, elevated homes

As flood disasters intensified in the early 2000s, the limitations of both structural and traditional system became increasingly apparent.

2.2 Flood Risk Management (2000-2010)

Globally, the number of flood disasters nearly doubled in the 2000s compared to the 1990s [28]. In China, high and very high-risk flood zones grew from 1.362% to 4.936% between 2000 and 2010 [29]. These developments proved methodological limitations in risk assessments. Plus, the absence of standardized methodologies introduced uncertainty.

Between 2000 and 2010, flood risk management experienced a significant shift from a prevention-based model to an integrated risk-based framework. This era emphasized the interrelated dimensions of hazard, exposure and vulnerability. Technological advancements, particularly in probabilistic modelling and geographic information systems (GIS), facilitated spatial analysis of flood risk [30]. Non-structural measures gained prominence, although these initiatives often prioritized physical and economic aspects over social vulnerabilities. In addition, by 2013, such approaches were deemed unsustainable due to their inability to ensure long-term safety and resilience.

For example, Lu *et al.*, [30] integrated Bayesian networks with GIS for flood risk in Yinchuan, China, achieving high spatial accuracy in identifying vulnerable zones, but the model's relevance is tempered by its dependence on high-resolution data, which may not transfer to data-poor regions. In contrast, Zhang *et al.*, [36] used a multi-index GIS model in the Yangtze Basin, classifying 40% of areas as high-risk based on topography and population, yet criticized for subjective indicator weighting that introduced uncertainty. This comparison reveals the strength of GIS-integrated approaches in supporting policy decisions during this era, while exposing limitations like methodological subjectivity which contributed to the shift toward more adaptive resilience strategies post-2010.

2.3 Flood Resilience Management (2010-2025)

Non-structural measures have become increasingly central, including early warning systems, community-based adaptation and nature-based solutions such as urban wetlands. Singapore's Active, Beautiful, Clean (ABC) Waters Programme exemplifies the integration of sustainable drainage into urban planning to enhance resilience. This evolution is shaped by growing awareness of climate change and social equity. It shifts flood management from static, engineering-based damage control toward transformative, learning-oriented processes.

Technological innovation plays a growing role. In Tehran, the Climate Disaster Resilience Index (CDRI), enhanced with machine learning, improves temporal adaptability of flood resilience assessments but faces limitations due to the inherent static nature of many traditional evaluation tools [31]. Similarly, in Pakistan, post-2010 flood evaluations revealed effective local organizational capacity and infrastructure adaptation, but identified critical gaps in early warning systems and deficiencies in key resilience dimensions [32]. Government response delays further hampered effective adaptation.

Building on this, Pour *et al*., [31] applied machine learning to enhance CDRI in Tehran, improving temporal flood predictions by 15-20%, but noted limitations in handling static input data that fail to capture real-time social dynamics. Comparatively, Kangana *et al*., [32] reviewed community engagement in Pakistan's post-2010 floods, emphasizing technological innovation like early warning apps for resilience, yet highlighting gaps in accessibility for rural populations and political delays [32]. These studies demonstrate the relevance of hybrid AI-community approaches for modern resilience, but their limitations such as data biases in ML models and unequal implementation underscore the need for inclusive, equitable frameworks to address persistent vulnerabilities in developing nations.

3. Methodologies in Flood Hazard Studies

3.1 Flood Hazard Mapping

Flood hazard mapping (FHM) is an important component of flood risk management. It provides spatially explicit information on areas vulnerable to inundation [33]. It serves as a decision-support tool for land-use planning, emergency preparedness, infrastructure design and climate change adaptation. FHM methodologies generally fall into three categories: numerical, empirical and physical modelling [34].

These methodologies, enhanced by modern technologies, provide critical tools for flood risk management. Table 3 compares numerical, empirical, and physical modelling approaches, highlighting their integration with remote sensing and GIS for improved flood hazard mapping.

Table 3
Flood hazard mapping methodologies

Attribute	Numerical Models	Empirical Models	Physical Models
Description	Simulate hydrological and hydraulic processes using mathematical equations (e.g., HEC-RAS, HEC-HMS, MIKE FLOOD).	Rely on historical flood records and observed stream discharges to estimate flood patterns.	Use scaled physical representations in laboratory settings to simulate flood dynamics.
Key Inputs	Rainfall intensity, river flow, topography, digital elevation models (DEMs).	Historical flood data, stream discharge records, recurrence intervals.	Physical parameters (e.g., channel geometry, flow conditions) in controlled settings.

Attribute	Numerical Models	Empirical Models	Physical Models
Outputs	Detailed flood inundation maps, flood depth, and velocity predictions.	Flood discharge peaks, recurrence interval estimates, basic flood extent maps.	Experimental flood behaviour data, flow patterns.
Strengths	High accuracy in data-rich environments; suitable for complex flood scenarios; supports precipitation loss and flood routing.	Less data-intensive; effective for areas with robust historical records; simpler to implement.	Provides detailed insights into complex flood dynamics; useful for model validation.
Limitations	Requires extensive data and computational resources; less effective in data-scarce regions.	Lacks robustness under non-stationary climate conditions; limited predictive power.	High cost; limited scalability; constrained to laboratory settings.
Integration with Remote Sensing/GIS	Uses high-resolution satellite imagery (e.g., Sentinel-1) and GIS-based DEMs for precise inundation mapping.	Incorporates GIS for spatial analysis of historical data; limited use of real-time remote sensing.	Minimal integration; GIS used for post-experiment spatial visualization.

A deeper examination reveals that numerical models like HEC-RAS, as applied in Antony et al. [33], provide detailed inundation maps for Kerala, India, with high accuracy in complex terrains, but are computationally intensive and less viable in real-time scenarios. In comparison, Rezvani *et al.*, [34] advocated empirical models using historical data for urban resilience in Europe, offering simpler implementation but limited by climate which reduces predictive power for future events. This contrast highlights the relevance of numerical models for scenario planning, while empirical ones suit data-scarce areas; however, both face limitations in integrating GIS fully, often resulting in overlooked socio-economic layers.

3.2 Flood Risk Assessment

This method integrates multiple analytical approaches to evaluate the likelihood and consequences of flooding. The goal is to provide a comprehensive understanding of flood risk, enabling the development of targeted mitigation strategies and informed decision-making [35].

A variety of methods have been developed to conduct flood risk assessments, including historical disaster statistics, index-based systems [36], simulation models and multi-criteria decision analysis (MCDA) embedded within Geographic Information Systems (GIS). The historical disaster statistics method relies on past flood events to identify patterns and recurrence intervals. It offers insight into the frequency and severity of potential future events. Other than that, the index system method, on the other hand, quantifies hazard and vulnerability through weighted indicators and provides spatially explicit risk evaluations. For example, in a high-resolution grid-based assessment conducted in Hubei Province, China, a combination of historical data and index-based approaches revealed that 55.6% of the region was classified as medium to high flood risk. The eastern and southern parts of the province were identified as particularly vulnerable.

Advanced techniques such as MCDA (2022) within GIS frameworks have further enhanced flood risk assessments by incorporating participatory weighting of risk factors [37]. This allows for the prioritization of flood-prone areas based on various vulnerability parameters. Similarly, simulation-based models provide dynamic analysis of flood behaviour under various scenarios, though require substantial data and computational resources, and are often used in conjunction with empirical methods for validation.

These diverse methodologies enable tailored flood risk assessments to inform mitigation strategies across varied contexts. Table 4 compares the key flood risk assessment approaches, limitations to guide application in flood management.

Table 4
Flood risk assessment methodologies

Attribute	Historical Disaster Statistics	Index-Based Systems	Simulation Models	Multi-Criteria Decision Analysis (MCDA)
Description	Analyses past flood events to identify patterns and recurrence intervals.	Quantifies hazard and vulnerability using weighted indicators.	Simulates flood behaviour under various scenarios using computational models.	Integrates participatory weighting of risk factors within GIS frameworks to prioritize flood-prone areas.
Key Inputs	Historical flood records, event frequency, and severity data.	Weighted indicators (e.g., topography, population density, infrastructure vulnerability).	Hydrological data, topography, rainfall scenarios, and computational models.	Risk factors (e.g., exposure, vulnerability, hazard), stakeholder inputs, GIS data.
Outputs	Flood recurrence intervals, historical risk patterns, severity estimates.	Spatially explicit risk maps and vulnerability classifications (e.g., low, medium, high).	Dynamic flood behaviour maps, scenario-based risk projections.	Prioritized flood risk zones, weighted risk factor maps.
Strengths	Provides insights based on real events; simple to implement with historical data.	Offers spatially explicit results; adaptable to diverse indicators; supports decision-making.	Enables scenario analysis; high accuracy in data-rich environments; dynamic modelling.	Incorporates stakeholder input; flexible for multiple criteria; enhances prioritization.
Limitations	Limited by availability and quality of historical data; less effective for future climate scenarios.	Subjective weighting of indicators; requires robust data for accuracy.	High data and computational demands; complex to implement in data-scarce regions.	Relies on stakeholder consensus; complex integration of diverse criteria.

Critically, Efraimidou and Spiliotis [37] employed MCDA-GIS in Greece to prioritize flood zones with stakeholder input, achieving robust risk maps, but the method's reliance on consensus introduces subjectivity and scalability issues in diverse regions. Conversely, Maskrey et al. [35] critiqued simulation models in the UK for their dynamic scenario capabilities, yet noted high computational demands that exclude participatory elements. Comparing these, MCDA enhances decision-making relevance through inclusivity, while simulations offer predictive depth; limitations like data intensity and bias, however, persist, calling for hybrid integrations to improve flood management efficacy.

3.3 Deep Learning and Artificial Intelligent

The application of artificial intelligence (AI), particularly machine learning (ML) and deep learning (DL) techniques, has gained significant attention in the field of flood hazard mapping and forecasting [38]. Since 2010, the number of studies utilizing AI approaches for flood risk management has risen sharply [39]. This trend reflects the capacity of AI models to efficiently process large volumes of complex and heterogeneous data. Deep learning models such as convolutional neural networks (CNN) and long short-term memory (LSTM) networks are among the most widely applied in flood-related studies [40]. CNNs are particularly effective in image classification tasks and have been successfully employed to extract flood-affected areas from satellite images. LSTM networks are capable of capturing temporal dependencies in hydrological data, making them suitable for modelling rainfall-runoff processes and stream-flow forecasting [41]. These models provide rapid and accurate predictions and are increasingly integrated into flood early warning systems.

AI-based approaches demonstrate superior performance compared to traditional statistical or physical hydrological models. It can incorporate a wider range of flood-related variables [42]. A study conducted in Vietnam, applied a hybrid approach combining a decision tree algorithm with the Analytic Hierarchy Process (AHP) to identify flood-prone zones [43]. The resulting model demonstrated high predictive accuracy and produced reliable flood risk maps even in data-scarce environments. Similarly, Wahba *et al.*, [44] employed Least Absolute Shrinkage and Selection Operator (LASSO) regression to evaluate compound risks of flooding and landslides in Japan. Their model achieved high accuracy and was effective in identifying critical influencing factors. These examples highlight the potential of AI methodologies, particularly when integrated with geographic information systems (GIS), to generate high-resolution and robust flood hazard assessments.

Despite these advancements, several challenges limit the broader application of AI in flood modelling. One primary constraint is the requirement for large, high-quality datasets, which are often unavailable or incomplete in many developing regions.

3.4 Vulnerability Assessment

Flood vulnerability assessments frequently rely on static assumptions, treating exposure and susceptibility to floods as fixed over time [45]. Such approaches often overlook temporal variations in social, economic, environmental and physical factors. In contrast, dynamic vulnerability assessment provides a more realistic framework by incorporating changes over time and space, such as urban expansion, population mobility, and climate-driven migration [46].

There is significance of integrating real-time population data into flood vulnerability evaluations. A dynamic model applied in Zhengzhou City revealed that high-vulnerability areas shifted throughout the day due to variations in population distribution [47]. It emphasizes the necessity of capturing temporal dynamics to enhance the accuracy of urban flood risk management. Dynamic assessments have also incorporated information diffusion theory to examine how flood-related information is communicated within communities. This approach facilitates the development of vulnerability curves that link hazard intensity with population exposure, even in the absence of comprehensive historical data. However, the reliability of such methods is hindered by incomplete datasets and challenges related to validation.

Physical vulnerability assessments for buildings under dynamic flood conditions have utilized various tools, including vulnerability matrices, indices and curves [48]. Among these, vulnerability curves are particularly prominent due to their capacity to estimate damage based on flood intensity. However, the applicability of these models is often constrained by the scarcity of detailed empirical data and the uncertainties associated with future climatic and socio-economic scenarios.

Lv *et al.*, [47] demonstrated dynamic modeling in Zhengzhou, showing vulnerability shifts with population mobility, improving urban planning but limited by real-time data privacy concerns. Comparatively, Papathoma-Köhle et al. [48] developed vulnerability curves for buildings in alpine regions, estimating damage accurately under varying intensities, yet constrained by empirical data scarcity for validation. These approaches highlight dynamic models' relevance for adaptive management, contrasting static ones' simplicity; limitations like data incompleteness, however, emphasize the need for integrated socio-economic datasets to enhance reliability.

4. Flood Hazard Drivers

4.1 Climate Change

Climate change is one of the factors in the intensification of flood hazards through increased extreme precipitation, sea level rise, and altered hydrological regimes. According Intergovernmental Panel on Climate Change (IPCC), the frequency of heavy rainfall events is expected to increase by 10 to 20% by the year 2050 [49], thereby elevating the risk of both riverine and surface flooding. Additionally, the progressive rise in sea levels has heightened the vulnerability of coastal cities, such as Jakarta [50], to tidal and storm surge inundation. In China, climate change has been identified as a more influential driver of flood hazards than urban expansion [51]. Empirical assessments indicate that approximately 70% of major Chinese cities have experienced a significant increase in flood hazard intensity, with the contribution of climate change surpassing that of urbanization. This observation underlines the predominant role of climatic variables in altering flood dynamics in rapidly developing areas.

The hydro-climatic drivers of flooding affected by climate change include variations in extreme precipitation, moisture conditions and snowmelt patterns [52]. These variables interact in complex ways and produce regionally distinct flood responses. Global flood patterns are characterized by heterogeneous changes that reflect the influence of local topography, catchment characteristics and climatic regimes.

In coastal regions, sea level rise and intensified tropical cyclones increase the probability of extreme storm surges. Modelling approaches that integrate global climate data and physics-based storm surge simulations project that 100 year flood probabilities could increase by factors of up to 7 in densely populated areas. Although the future frequency of tropical cyclones remains uncertain [53], increased storm intensity and sea level elevation necessitate more comprehensive assessments of coastal flood hazards.

Panagos *et al.*, [49] projected 10-20% increases in erosive rainfall by 2050 using global models, relevant for policy but limited by regional downscaling uncertainties. In comparison, Bennett et al. [50] modelled compound flooding in Jakarta, attributing 50% risk rise to sea levels, yet overlooked socio-economic adaptations in simulations. This reveals climate projections' strength in long-term planning, while empirical studies ground local risks; both face limitations in uncertainty quantification, advocating for ensemble modelling.

Overall, climate change is a dominant and evolving driver of flood hazard and risk, influencing both environmental and socio-economic systems. The interaction of climate-induced changes with regional factors creates diverse flood risk profiles.

4.2 Urbanization

Urbanization significantly contributes to the escalation of flood hazards through extensive land-use changes and the proliferation of impervious surfaces. The expansion of urban settlements often results in the replacement of natural landscapes with impermeable structures such as roads, pavements and buildings, which impede water infiltration into the soil. This transformation increases surface runoff volumes and peak discharges, thereby intensifying the frequency and magnitude of urban flooding.

Numerous studies have documented the impact of urbanization on flood dynamics. In Poland indicates that urban catchments exhibit higher flood frequencies and magnitudes than non-urban counterparts due to reduced infiltration capacity and altered hydrological response [54]. Globally, urban expansion within floodplains has nearly doubled since 1985, with an accelerated rate of growth observed post-2000, increases population exposure to flood hazards [55].

In rapidly developing regions, the conversion of agricultural land and wetlands into urban areas has further compromised the natural water retention capacity. In Chiang Mai, Thailand, the transformation of rice paddies into urban infrastructure has considerably heightened flood risks, highlighting the need for sustainable urban development [56]. Similarly, land use and land cover changes in Surat, India, have been linked to increased flood risk and economic losses, underscoring the economic implications of unchecked urban growth [57].

Urban growth also alters the spatial distribution of flood risk. In Nakhon Ratchasima, Thailand, urban expansion has shifted flood vulnerability from central zones toward peri-urban areas, necessitating regulatory interventions in land use planning to mitigate emerging risks [58]. Moreover, in coastal cities, the interaction between urbanization and rising sea levels amplifies flood impacts, demanding integrated urban and environmental planning.

Gu *et al*., [56] linked urbanization in Chiang Mai to 30% runoff increase via GIS, highlighting mitigation needs but limited by static land-cover assumptions. Conversely, Huang et al. [55] analyzed Phnom Penh's floodplain growth, noting doubled exposure since 1985, yet underemphasized green infrastructure solutions. Comparing these, urbanization studies underscore hydrological alterations' relevance, but limitations in dynamic modeling hinder comprehensive risk forecasts.

4.3 Human Intervention

Human interventions are a major factor in shaping flood risks, with both beneficial and adverse effects [59]. While intended to reduce flooding, many interventions have unintentionally increased exposure and vulnerability, particularly when natural systems are heavily altered or poorly managed.

One key example is the construction of levees and embankments. These structures are designed to prevent flooding but can lead to the "levee effect", where people and infrastructure concentrate in protected areas, increasing potential damage if the levees fail. The flooding of during Hurricane Katrina in 2005 illustrates how structural protection can result in greater losses when protection breaks down [60].

River modification projects, such as channelization and sediment extraction, have also changed natural flood dynamics. In India river system, embankments and human-induced sediment changes have reduced natural floodplain function, increases localized flood risks [61]. Similar impacts are found across Europe, where improved flood defences have reduced some risks but may not be sufficient under future climate conditions [62].

Community actions and individual behaviours play a critical role in flood outcomes. Studies using simulation models show that community-level mitigation efforts, such as household flood-proofing or participation in early warning systems, can reduce flood damage.

Aerts *et al*., [59] integrated behavioral dynamics into risk assessments, showing community actions reduce damages by 20-30%, but models overlook cultural variances. In contrast, Ward *et al*., [62] evaluated global river protections, projecting cost-benefit ratios up to 4:1, yet ignored levee failure risks under climate extremes. This comparison emphasizes human interventions' dual role in mitigation and amplification, with limitations in behavioral integration calling for socio-technical frameworks.

5. Conclusion

In conclusion, flood hazard management has undergone a significant transformation from structural control measures to resilience-based strategies driven by climate change, urbanization, and socio-economic pressures. Advances in flood hazard mapping, risk assessment, and the application of AI and deep learning have enhanced our ability to predict and mitigate flood risks. However, substantial gaps remain. Data limitations, uncertainty in extreme event modeling, and the under-representation of social vulnerability continue to hinder effective management, particularly in developing countries. Future research should focus on integrated, equitable, and sustainable approaches to strengthen global flood resilience. Equitable strategies are essential to address disparities in vulnerability and to ensure inclusive, community-centered resilience-building efforts. This review offers a comprehensive synthesis of current knowledge, serving as a roadmap for researchers and policymakers tackling one of the most urgent challenges of the 21st century.

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The authors declare that there is no conflict of interest regarding the publication of this paper.

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