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Advocating integration of human responses in the flood resilience framework for inland cities of northern China

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ABSTRACT

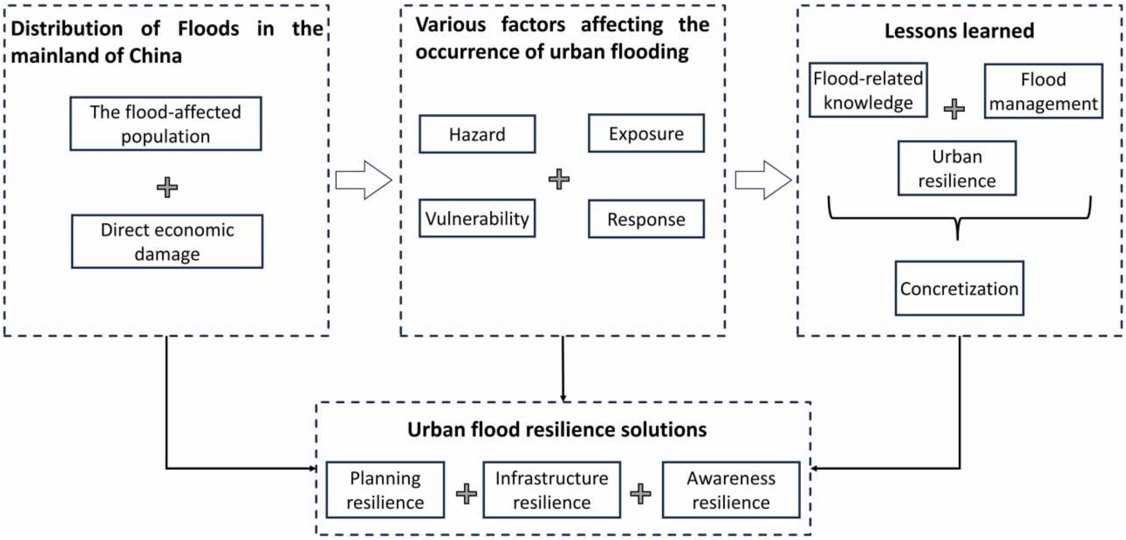
Frequent urban flooding poses a predominant challenge to resilience managers and the public in inland cities. Nevertheless, various facets of the formation, development, and response to inland flooding in developing countries are still less understood. Using the statistics data of typical flood events in China, this paper examines the causes of devastation in inland areas of the north combined with a comprehensive risk assessment methodology and explores a nuanced understanding of resilience. The conclusions reveal that the inland cities of northern China are facing an imminent threat from escalating flood hazards. 11% of the flood-influenced population and 17% of the disaster-caused economic losses are concentrated in the region. Increased extreme precipitation, heightened exposure and vulnerability, and a sluggish human response to crises are main factors contributing to these complex disasters. The study also proposes a transformative flood resilience framework for inland flooding from three dimensions, emphasizing the integration of human responses. The three aspects of the framework are summarized based on the driving factors mentioned earlier and a simplified multidimensional perspective of resilient cities, reflecting the adaptive and evolutionary features of resilience. Hence, incorporating the resilience strategies to urban flood risk management is a relatively practical approach to urban flood risk management in inland regions.

Key words: Flood risk, Inland cities of northern China, Policy recommendation, Practical strategy, Urban flood resilience

HIGHLIGHTS

- A resilience framework is presented here to mitigate inland flooding.
- Flood resilience is preferably viewed as a flexible symbol.
- Inland cities are facing an increasing challenge of flooding.
- Human response is one of the leading causes of flooding in inland cities.
- The devastating inland floods also provide an opportunity for policymakers.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Flooding is one of the most damaging natural disasters in urban areas. Also, floods cause severe financial harm, supply disruptions, and danger to human life, which can adversely influence economic activities and development. According to the statistics from AON Corporation, direct economic losses related to flooding disasters in 2021 were estimated at $112 billion globally (AON, 2022). With a growing population in flood-prone areas, global warming, and rising sea levels, the number of people vulnerable to flood disasters is expected to reach 2 billion by 2050 (UNESCO World Water Assessment Programme, 2012). A large-scale flood in Western Europe that resulted from heavy precipitation in July 2021 affected millions of people in the inundated region (He *et al.*, 2022). Such statistics and studies illustrate that floods are among the most significant weather-related disasters threatening human life and asset security. A review of typical flood events will yield valuable lessons that significantly contribute to preparing for future floods (Guo *et al.*, 2023).

Attribution analysis of extreme precipitation events contributes to the understanding of these occurrences for governments and societies. Rapid anthropogenic changes in the urban surface pose a fundamental issue that contributes to the occurrence of urban flooding in addition to climate change. Urbanization has replaced natural vegetation with impermeable structures, reducing rainfall infiltration and retaining vegetation (Whitford *et al.*, 2001). The evident transformation of urban landscapes has played a pivotal role in the hydrological cycle, particularly in terms of the increased frequency of flooding. Urban catchment processes are significantly smaller than basin hydrological processes on a spatial-temporal scale, which have short response times (typically to less than 1 h) and small catchment areas (typically no more than a few hundred km^2) (Fletcher *et al.*, 2013). Furthermore, by exploring the development of events, scientists are also able to identify the mechanisms behind hazards, providing a better understanding of the likelihood of similar events. For instance, Europe, especially Germany, witnessed many strong convections in 2013 and 2016. Both hydrological and statistical analyses identify these events as some of the most severe inland floods in Germany. A considerable body of literature on these extreme floods in Germany has emerged in the academic community since then (Thieken *et al.*, 2016, 2022; Laudan *et al.*, 2017). The effect has significantly deepened the local comprehension of extreme hazards.

Urban flooding management experiences more valuable insights in the inland areas of developing countries than in those of developed countries. Urban flooding, which has recently emerged as an essential challenge, is still often disregarded in the planning of inland cities (Hossain & Meng, 2020). Developing countries differ from developed countries, both in terms of the scale of extreme floods and the responses to them. Western countries like the United States predominantly adopted a bottom-up approach. At the same time, the Chinese government, as the largest developing country, primarily follows the nationwide catastrophe response mode (i.e., the top-down approach) (Ge *et al.*, 2021). The approach may make the Chinese respond to flood danger in a different way than people in other countries. In addition, urban flooding in inland areas of developing countries offers insights into flood management. The devastating floods of 2022 in Pakistan impacted a large area of the inland (IFRC, 2023). Similarly, intense rainfall frequently occurred in inland cities of northern China in 2023, like the Haihe and Songliao River Basins. These devastations demonstrated that cities, especially megacities in the inland region, could not withstand a 1-in-100 or 1,000-year storm event when it occurs (Guo *et al.*, 2021). Several factors contribute to the heightened vulnerability of inland areas. Firstly, more and more extreme precipitation occurs inland, far from the coast. Secondly, the accuracy of real-time flood predictions in China is 70% for northern rivers, which is 20% lower than their southern counterparts (Liu, 2019). Other developing countries may have even lower accuracy rates. Thirdly, it is challenging for individuals to respond rationally to risks beyond their experience (Shepherd *et al.*, 2018). These areas do not have the adequate experience to prioritize and respond to flooding, potentially leading to substantial losses during disaster events. Such incidents are representative and typical not only in China but also in other developing countries. These catastrophic events are gradually sounding a wake-up call for possible future events. Presently, there is an urgent need to understand flood management in inland cities of developing countries to avoid relatively enormous losses.

Urban resilience is being discussed as a new approach in the academic literature and policy management. The idea of resilient cities originated from research on ecosystems' stability and ability (Dianat *et al.*, 2021). Urban resilience is a multidimensional and evolutionary idea. As the impact of global warming intensifies, the current paradigm of disaster management in cities has gradually moved from crisis management after a disaster to comprehensive governance. Many policymakers and planners have begun to focus on flood resilience and have attempted to implement various measures in urban planning. Examples of such initiatives include the 'London City Resilience Strategy 2020' in the UK and 'Future Tokyo: Tokyo's Long-Term Strategy' in Japan (Mayor of London, 2020; Office of the Governor for Policy Planning, 2021). Insights from the UN Sustainable Development Goals (SDGs) explicitly mention achieving resilient cities in many goals, particularly for SDG 1 (No poverty), SDG 9 (Industry, innovation and infrastructure), and SDG 11 (Sustainable cities and communities) (UN, 2015). Urban flood resilience comprises three interconnected capacities: prevention capacity in the prior stages, coping capacity in the middle stages, and recovery and adaptation capacity in the later stages (Zhu *et al.*, 2021; Liu *et al.*, 2024). Prevention capacity refers to mitigating flood impacts before their occurrence. Coping capacity refers to promoting collaborative response to flooding across all city sectors. Recovery and adaptation capacity refers to increasing the resilience of cities after a flood event by learning from past experiences and upgrading policies. Improving resilience is an integrated effort encompassing various aspects of new technology, spatial planning, social organization, and decision-making. A city is generally a massive synthesis of openness and complexity. However, these aspects have made resilience a vague concept without particular connotation, i.e., where it may come from, how it gets there, how it changes, and why it is beneficial (Adekola, 2018; Disse *et al.*, 2020).

To date, limited research has focused on resilience frameworks based on typical flood scenarios within developing countries, especially those in inland regions. Recent research on urban flood resilience has primarily concentrated on developed countries (Rushforth & Ruddell, 2016; Rosenzweig *et al.*, 2019). Inland cities in developing countries often confront unrecognized heightened flood risks, significantly impacting management policies. Moreover, while the fuzziness of resilience is consistently recognized, the term's meaning has been sparsely analyzed, and large lacunae have been created. Lack of clarity has confused practitioners on implementing resilience in practice. This paper aims to address these gaps by discussing specific strategies for implementing resilience in inland cities of northern China. An analytical flowchart is shown in Figure 1. The objectives of this study are to (1) discover the specific triggers of flooding in inland cities of northern China, (2) seek the implementation approaches for the policymakers and the public during the transition period from structural flood protection to an integrated resilience framework, and (3) draw the attention of people and policymakers to the critical aspects of resilience management.

2. METHODS

2.1. Data sources

The data in section 3.1.1 are mainly flood hazard statistics and precipitation data. The flood-related information is cited from the Bulletin of Flood and Drought Disasters in China published by the Ministry of Water Resources of the People's Republic of China in recent years (MWR 2020). The data mainly include the economic losses and population caused by floods in each province in the mainland of China, excluding Hong Kong SAR, Macau

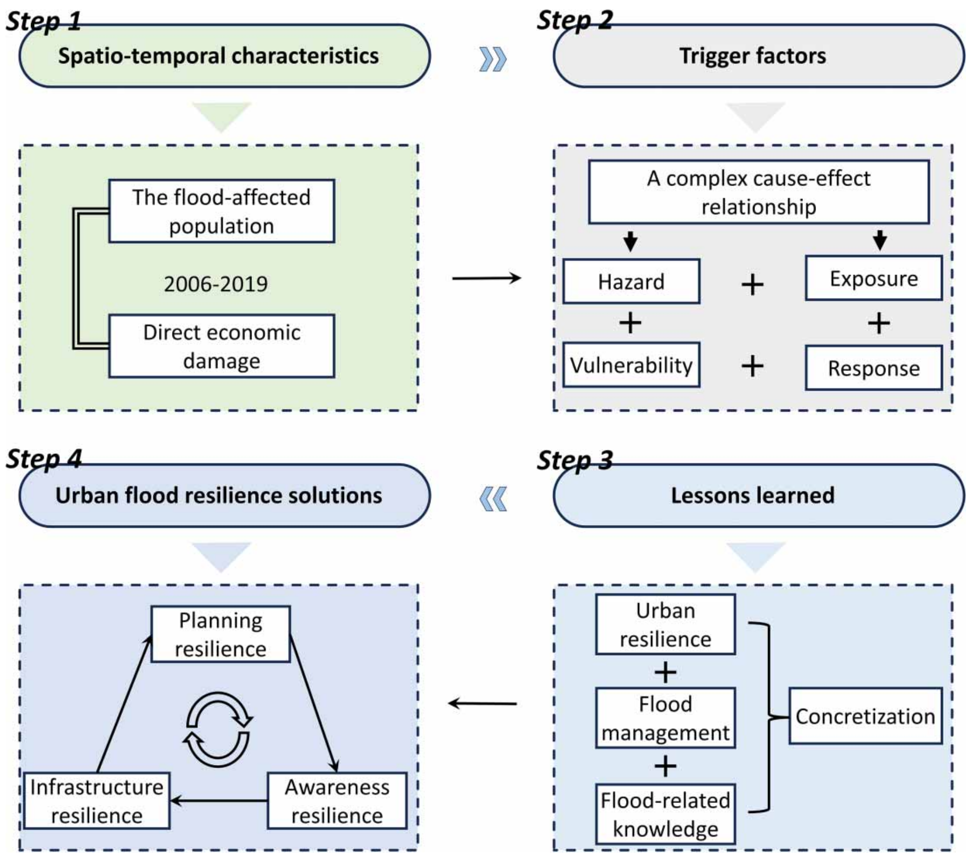


Fig. 1 | Analytical flowchart of the study.

SAR, and Taiwan Province. Precipitation data in Beijing are derived from the Beijing Water Authority (https://nsbd.swj.beijing.gov.cn/csyq1.html). The quality of this data was firmly controlled before its release. Subsequently, the paper employs a geographical classification that divides the southern, northern, and inland provinces of China based on the Qinling-Huaihe line and the actual geographic location. The demarcation line, recognized around the world, is an important geographic and ecological boundary for China. The final delineation of northern inland provinces includes Heilongjiang, Jilin, Inner Mongolia, Beijing, Shanxi, Shaanxi, Henan, Gansu, Ningxia, Qinghai, Xinjiang and Tibet. Using descriptive statistical methods and visual bubble maps, the evolutionary trends of annual average economic losses and population caused by floods are analyzed in each province. The work reflects the spatial and temporal patterns of flood occurrences, both nationwide and specifically in the northern inland provinces.

2.2. Comprehensive risk assessment

An extended assessment methodology is applied to analyze the characteristics of typical flooding events in inland cities of northern China. The assessment framework includes the terms specific to describing risk in the IPCC (hazard, exposure, and vulnerability) and considers the response as an additional impact factor. Among these, the IPCC risk framework is widely utilized for the driving mechanisms and impact assessment of floods. Human response is intricately reflected in the impact of numerous factors, such as population density, social resources, and land use functions. Thus, the paper searches for both the natural and anthropogenic causes of flooding in the inland cities of northern China through four perspectives: hazard, exposure, vulnerability, and response. A hazard is primarily a threatening natural event, including the probability of the event occurring. The term here refers to flooding produced by extreme rainfall or typhoon remnant precipitation. Exposure refers to the impact of population density, socio-economic environment, and land cover in cities. Vulnerability is the adverse impact or tendency of carriers such as populations, infrastructures, and houses. Response refers to the potential effects and reactions of stakeholders to external disturbances. The term here mainly focuses on their ability to forecast, understand, and make decisions about hazardous situations. In addition, the article then combines these four areas of insight and provides methods for relevant stakeholders. Many policy discussion articles evaluate flood mitigation measures in cities or communities using less quantitative data, which could suggest that such a qualitative approach to interpretation is also a good idea (Chan *et al.*, 2021; Sayers *et al.*, 2021; Ma *et al.*, 2022). A mixed research method of scientific papers and policy files thus identified critical goal orientations for urban flood resilience, expanding the interpretation of resilience management.

3. RESULTS

3.1. Discoursing urban flood disaster in China

3.1.1. Current status

China is vulnerable to the high frequency of flood hazards and rainstorms because it is surrounded by strong and deep East Asian summer monsoon circulation. Over the last half-century, especially since the 1990s, heavy precipitation and flooding have tended to become relatively intense and prolonged. Official statistics indicate that 62% of 351 cities had severe flooding during 2008–2010. More seriously, 137 cities were hit more than three times, including 57 cities with a maximum inundation duration of more than 12 h (China Meteorological Administration, 2012). Severe flood disasters in the mainland of China were distributed mainly in the southern and central-eastern regions, especially in the middle-lower Yangtze River (Figure 2(a)) (MWR, 2020). Direct economic damage was positively correlated with the flood-influenced population ($R^2 = 0.71$, p value $= 0.84$). It indicates that rapid urbanization and socio-economic development were essential reasons for the increased frequency and losses associated with urban flooding in China.

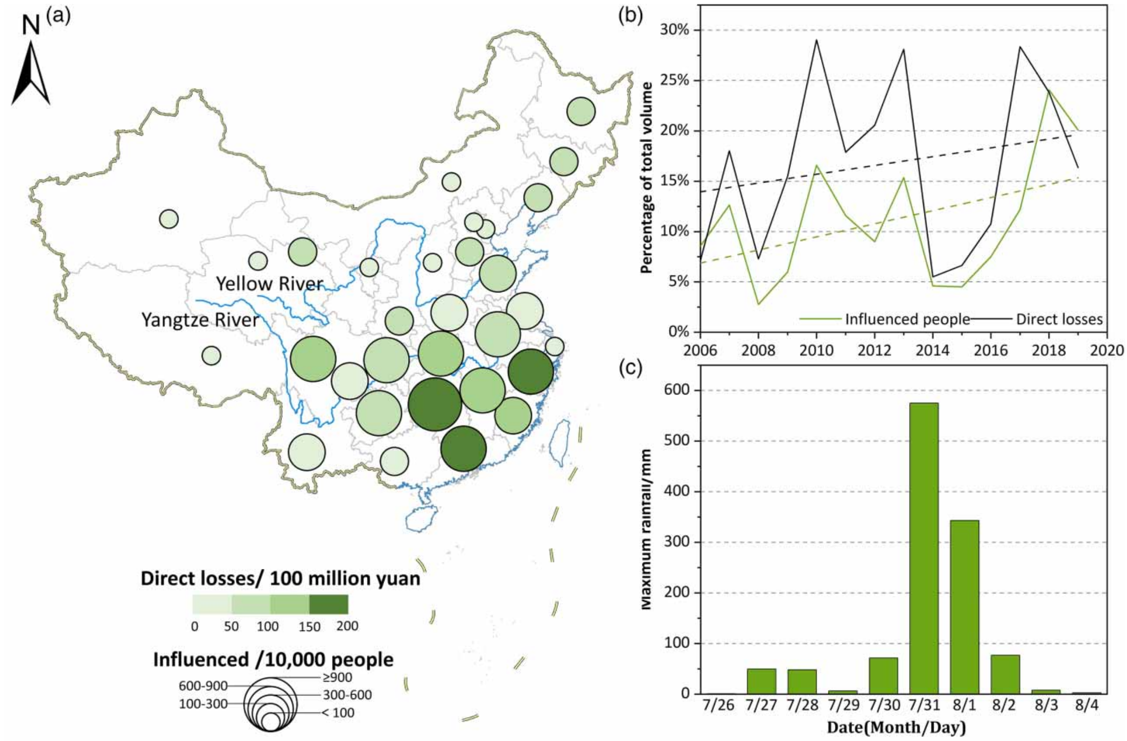


Fig. 2 | Spatial and temporal distribution of flood impacts in China over the past decade. (a) Flood-influenced population and disaster-caused economic losses in the mainland of China; (b) the impact of affected floods in the inland province of northern China; (c) extreme precipitation in Beijing from July 26 to August 4, 2023.

The inland cities of northern China are facing an increasing challenge of flooding. The flood-influenced population and direct economic damage by floods in inland cities of northern China accounted for 11 and 17% of the total, respectively (Figure 2(b)). These figures also demonstrated a gradual upward trajectory over the years, indicating an escalating severity of floods in the region. Notably, a significant increase with up to 12, 24 and 20% of the population was affected by flooding in 2017–2019. The percentage of direct economic losses surpassed 25% in 2010, 2013, 2017, and 2018. The investigation organizes typical urban floods in inland cities of northern China in recent years, drawing upon statistical yearbooks or news reports (Table 1). The horrible impact was further exacerbated by the urban flooding during the summer of 2023 in inland cities of northern China. The Haihe River Basin was affected by the residual circulation of Typhoon Doksuri. The Central Weather Bureau issued seven red warnings for heavy rain within 70 h. The average rainfall in Beijing matched the level of July 21, 2012, which is representative of one severe rainfall event in Beijing in recent years (Figure 2(c)). Some districts, such as Fangshan and Mentougou, recorded rainfall exceeding 500 mm, far above the maximum point rainfall of 541 mm in 2012 (Xinhua News Agency, 2023). As of the 9th, the catastrophe in Beijing had claimed 33 lives and affected 1.29 million people. The typhoon then extended to the Songliao River Basin and brought heavy rainfall to southeastern Heilongjiang and northern Jilin. Among them, Shulan City in Jilin province recorded an average precipitation of 106.7 mm. By August 6, the heavy rains resulted in 14 casualties and affected over 130,000 individuals (BJnews, 2023). Those serious incidents have revealed numerous problems and difficulties in urban development, risk prevention, hazard perception, and emergency rescue. The co-existence of natural catastrophes

Table 1 | Recent flooding events in inland cities of northern China.

Date	Places	Precipitation	Casualties
July 21, 2012	Beijing	The maximum rainfall of 541 mm in the Fangshan District	79 deaths
July 13, 2017	Yongji in Jinlin Province	The average precipitation of 172 mm over the entire city	25 deaths
July 26, 2017	Yulin in Shanxi Province	The cumulative maximum point rainfall of 272 mm at Lijiawa Station	12 deaths
July 31, 2018	Hami in Xinjiang Province	The maximum 24 h rainfall is 116 mm in Yizhou	28 deaths
July 20, 2021	Zhengzhou in Henan Province	The average annual rainfall of 534 mm over the entire city	380 deaths
July 31, 2023	Beijing	The maximum rainfall of 500 mm in Fangshan and Mentougou	33 deaths
August 1, 2023	Shulan in Jinlin Province	The average precipitation of 106.7 mm over the entire city	14 deaths

and man-made accidents was a microcosm of the extraordinary rainstorm disaster (Cheng *et al.*, 2022). From another perspective, those floods also allowed policymakers to transition toward flood resilience in the face of global warming. In order to better cope with the problem, it is crucial to gain a deeper understanding of the causes and characteristics of flooding events in inland cities of northern China.

3.1.2. Various factors affecting the occurrence of urban flooding in inland cities

Combining typical flood events and complex risk assessment approaches (Simpson *et al.* 2021), the section explains the formation of devastating floods in inland cities of northern China in terms of hazard, exposure, vulnerability, and response (Figure 3). First, the frequency of successive typhoon extremes in the interior has increased significantly (Chen *et al.*, 2021a). There is a growing likelihood of typhoons affecting northern China in the future, especially in north China (Chen *et al.*, 2021b). The typhoon may also interact with the western Pacific subtropical high-pressure systems to transport water vapor over long distances, creating inland typhoon remnant precipitation (Zhao *et al.*, 2022). Notable instances of the phenomenon are observed in events like the Zhengzhou flood in 2021 and the Haihe and Songliao River Basin flood in 2023. In addition, most urban drainage systems can only handle rainfall events in China at a 1-in-1 to 1-in-5 years return period (Chan *et al.*, 2021). Climate change is expected to increase moisture input into meteorological systems (IPCC, 2021). Hence, extreme rainstorms, which far exceed the existing drainage capacity, are becoming increasingly frequent and problematic.

Inland cities of northern China are experiencing increased exposure due to growing population and socio-economic development. Compared to the frequent floods in the south, the population affected and direct economic damage by urban flooding have witnessed an annual escalation in inland cities of northern China. The gentler topography coupled with more concentrated precipitation accentuates short-duration flooding in the area (Lu *et al.*, 2019). Along with a rapidly growing population, many urban developers are building in inappropriate places, especially in many urban rivers and low-lying floodplains, further increasing exposure and vulnerability in northern cities. In addition, many urban lifeline systems are laid in underground spaces, such as subways, power components, and underground pipelines, which potentially pose a greater hazard to life and property in the event of flood intrusion (Li *et al.*, 2024).

Inland cities in northern China have a very high concentration of various infrastructures, leading to a greater vulnerability to risks. Regional supply chains and trade networks have been disrupted due to the destruction of railways and roads by rainstorms. The phenomenon reflects the possibility that the lack of comprehensiveness in

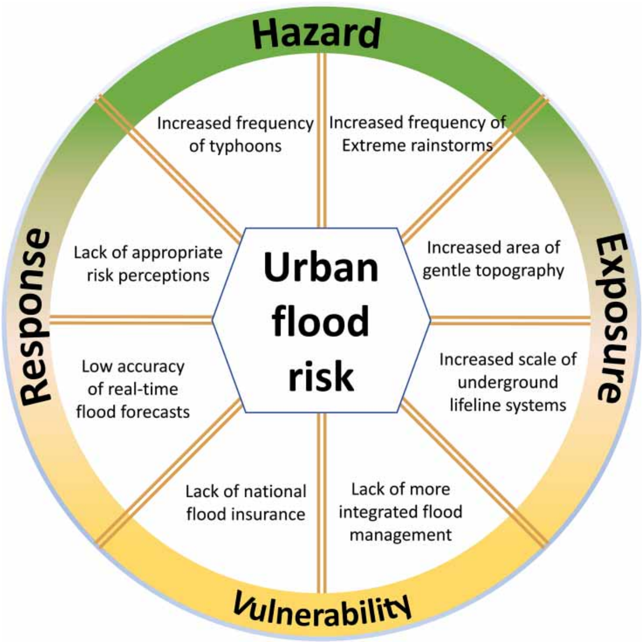


Fig. 3 | Various factors affecting the occurrence of urban flooding. Hazard, exposure, vulnerability, and response factors occupy different sides in affecting complex urban flooding.

priorities and macro policies results in intangible effects and spillover reactions occurring outside the actual area (Willner *et al.*, 2018). In addition, the global insurance coverage for flood risks was just 21% in 2021, compared to only 8% in the Asia-Pacific region (AON, 2022). What's even more concerning is that these flood-prone areas, especially in China, are more exposed to risk due to the lack of national flood insurance than before. Government subsidies and social donations after a disaster are only restricted to ensure the essential restoration of people's livelihoods, making compensating for their losses difficult.

In inland cities of northern China, slow flood response and weak risk awareness are common problems. The limited availability of rainfall data is still a weak point in the urban hydrology model, which now requires more motivation for government investment and individual participation than before (Fletcher *et al.*, 2013). Torrent flows during urban floods could easily contribute to hydraulic anomalies, making their related effects challenging to predict. Furthermore, decision-makers and citizens in northern cities have little experience with flood disasters. The warning and reaction times for urban flooding are transient compared to river flooding (Li *et al.*, 2021a, 2021b). Most decision-makers and citizens may lack appropriate risk perceptions and are at risk of losing valuable time when precautionary emergency measures are taken (Netzel *et al.*, 2021). In summary, these issues above accentuate the complexity of urban inundation in inland cities of northern China and stimulate discussion among developers and scholars.

3.2. Enhancing urban flood resilience in inland cities of northern China

3.2.1. Evolution of the terminology

In recent years, resilience has received much attention and popularity as a new concept of urban development in urban planning and governance. Originally rooted in engineering, resilience denoted the system's ability to restore itself to its original state. In the 1990s, the concept of resilience was introduced to urban development and sparked a surge in related research (Figure 4). For example, in 2009, the United Nations defined the concept of disaster resilience in one sentence: 'The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including the preservation and restoration of its essential basic structures and functions' (UNISDR, 2009). Research on urban resilience is often closely associated with the escalating threat of disasters. Generally, the contention is that disaster resilience in communities has five dimensions: social, economic, institutional, physical, and natural domains (Ostadtaghizadeh *et al.*, 2015). The quantification of the resilience level and identification of influencing factors involve a careful calculation of contributions from each dimension. Urban resilience research reflects on multiple dimensions and the mechanisms of their interactions at a relatively macro level. Urban flood risk management concentrates on reducing vulnerability and impacts, utilizing mainly structural and non-structural measures (Wang *et al.*, 2022). With urbanization and climate warming, urban flood risk has emerged as a critical

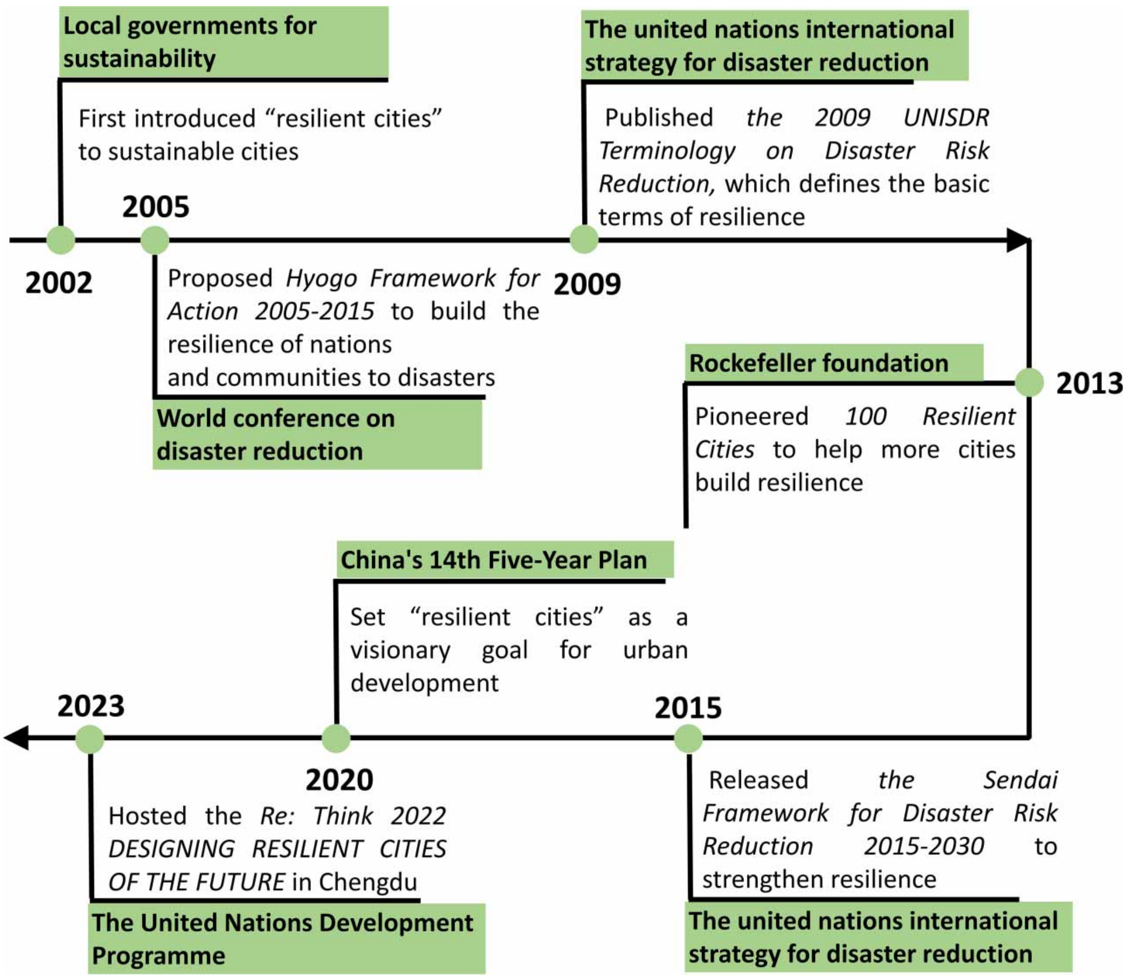


Fig. 4 | Key events in the development of the resilience concept.

constraint to sustainable urban development. Traditional approaches to urban flood risk management are no longer able to cope with evolving flood risks. Consequently, practitioners and scholars are increasingly shifting their focus toward urban flood resilience. Regarding the essence of urban flood resilience, it goes beyond highlighting the significance of the city's physical infrastructure. It also places a central emphasis on the establishment of an effective management system, underlining the capacity of preparation, coping, recovery, and adaptation.

A broad abstraction exists in the conclusive definition of the term resilience. More than 70 concepts of resilience have been studied in academic research (Fisher, 2015). As its coverage and utilization, resilience is bound to contain relatively internal connections and contradictions. It may seem complicated and fuzzy that managers are expected to consider the simultaneous achievement of stability and adaptability components (Hegger *et al.*, 2016). Resilience emphasizes 'preparation and recovery' to the original status, which promotes the concept of system stability in the city. Also, resilience includes continuous adaptation, which may appear as a conflict between stability and adaptation and lead to the emergence of ambiguity. When complex but essential goals arise from an ill-defined concept, the emerging terminology may become no more than another buzzword, eventually leading to a lack of specific meaning in practice (Davoudi *et al.*, 2012). Thus, concretizing the abstraction of resilience will be necessary.

3.2.2. Urban flood resilience in China

The progress of urban flood resilience in China is still in the nascent stage. The term only rose to the level of a national strategy in 2020 (The State Council, the People's Republic of China, 2020). Due to the inherent ambiguity and malleability of resilience, it can be combined with diverse practices to serve different political purposes. The meaning of resilience only emerges when it is clear where it may come from, how it gets there, how it changes, and why it is beneficial. The idea penetrates the abstraction of resilience and forces solutions to concrete problems. Authorities in China do not rush to replicate the shaped solutions of other countries, which is not feasible in most cases. Instead, it is crucial to tailor solutions and services that take into account local conditions. Many indigenous cases in China have been successful because there has been sufficient time to consider and respond to the real needs of cities. For example, in 1991, an inland lake was preserved in Xiamen, China, serving as a landscape feature and a rainwater storage area. Regulating and storing water in the lake follows the half-day cycle of the Xiamen tides, which ingeniously utilizes the tidal cycle to discharge the captured rainwater into the sea at low tide (Liu, 2005). The design cleverly optimizes the construction and operation costs of low-probability disaster event prevention. Typhoon Meranti hit Xiamen unexpectedly in 2016, making the area one of the few cases in mitigating the damages in China. However, from a national perspective, cities like Zhengzhou are not the exception since water security is not reasonably solved according to local conditions. In conclusion, flood resilience is preferably seen as a flexible symbol that combines the various practices of flood control, which we believe may be a universal way of politicizing and pragmatizing the concept.

Under the current infrastructure and management level of Chinese cities, most cities cannot resist the force of such persistent or intense rains whenever they occur. A major discrepancy between urban floods and other disasters (e.g., earthquakes and typhoons) is that the former has a certain degree of adaptability but a limited scope for flood control standards (Kreibich *et al.*, 2022). Modern design standards and operations for flood control infrastructures are based on historical precipitation and flooding in their countries rather than being targeted at adapting to urban flood hazards caused by climate change (Rubinato *et al.*, 2019). The reality is that incomplete infrastructures would only partially cope with future expanding urbanization and pose a potential technical risk to urban safety. Flood resilience is understood as individuals or communities having the capacity to respond to the basis of warnings received and thus effectively mitigate the underlying threat of harm. Despite China's steady growth in socio-economic development over the last 40 years, the issue of urban flood resilience deserves far greater attention than it has received over the years. Hence, in the most recent phase, cities are comprehensively well advised to understand the objects, scopes, and methods of resilience management to tailor solutions. An urgent need exists to curb the growth of flood risk more holistically and thoughtfully than before. Notably, the strategy can also serve as a tactic to provide adaptive and robust resilience capability.

3.2.3. Call for tailored resilient solutions

Resilient strategies, informed by flood-related knowledge, could exert a differential influence on adopting urban flood hazards. Numerous inland disasters also represent a window of opportunity. Specifically, these events have the potential to prompt stakeholders to use resilience theory for informed decision-making before, during, and after a disaster. Defining the main elements is the key to a resilient urban flood-proof system. Based on the four characteristics of hazard, exposure, vulnerability, and response summarized above, a framework for urban flood resilience strategies with simplified dimensions is proposed here. The following discussion revolves around three dimensions to move forward in flood resilient management for inland cities of northern China: planning resilience, infrastructure resilience, and awareness resilience (Figure 5). The dimensions are relatively appropriate for the important characteristics of resilient cities: adaptation and evolution. This study endeavors to build resilience at the strategic level of government through these three-pronged efforts to understand the meaning of flood resilience.

Planning resilience constitutes a fundamental cornerstone to mitigate the menace of urban flooding. Government departments, through appropriate resilience measures, would take an integral role in addressing complex urban flooding (Ribeiro & Gonçalves, 2019). In the face of relatively frequent and intense weather extremes in northern cities, the top department is crucial for updating current flood protection standards to withstand an effective range of major urban infrastructures (Guo *et al.*, 2023). Local management does its best to adapt to local conditions to enhance the capacity of runoff control. The approach will not only increase the capture and reuse of urban rainwater at sources but also benefit community welfare for residents (Kim *et al.*, 2020). Communities would also embrace the conservation and revitalization of wetlands as an opportunity to promote well-functioning hydrologic cycles and capture a substantial opportunity to promote well-functioning hydrologic cycles and capture a substantial portion of flooding. The vulnerability and distribution of high flood disaster bearers within each risk category could be quantified and mapped by the local government. Furthermore, the critical element of lifeline systems is desired to be located outside the flood risk area or above the maximum inundation level to ensure proper working operation as far as possible (Qiang, 2019). To alleviate social and environmental inequalities, it's desirable for the central and local governments to actively consider emergency programs, socially vulnerable populations, flood insurance systems, and post-disaster recovery plans. These non-structural resilient strategies in the future will be an imperative practice to reduce response times and ultimately achieve a financial risk reduction associated with possession. In addition, the challenges and opportunities for policymakers require that they do their best to focus on actions targeted at multidimensional collaboration. Inter-city and inter-disciplinary collaboration for inland cities is required to design at the watershed-wide or megacity cluster levels to establish a holistic flood-proof program.

Infrastructure resilience is pivotal in fortifying against the impacts of flooding. Most cities, rooted in traditional Chinese ideologies like Confucianism and Feng Shui, grew from villages built along rivers (Liao *et al.*, 2021). Beyond the function of urban landscapes and cultural identities, urban river systems connect man-made water bodies, green parks, and wetlands and are prime examples of urban blue-green infrastructure (Kati & Jari, 2016). Consequently, existing rivers flowing through the city form the backbone of flood control systems in northern cities. The harmonious collaboration between urban drainage networks and rainwater harvesting

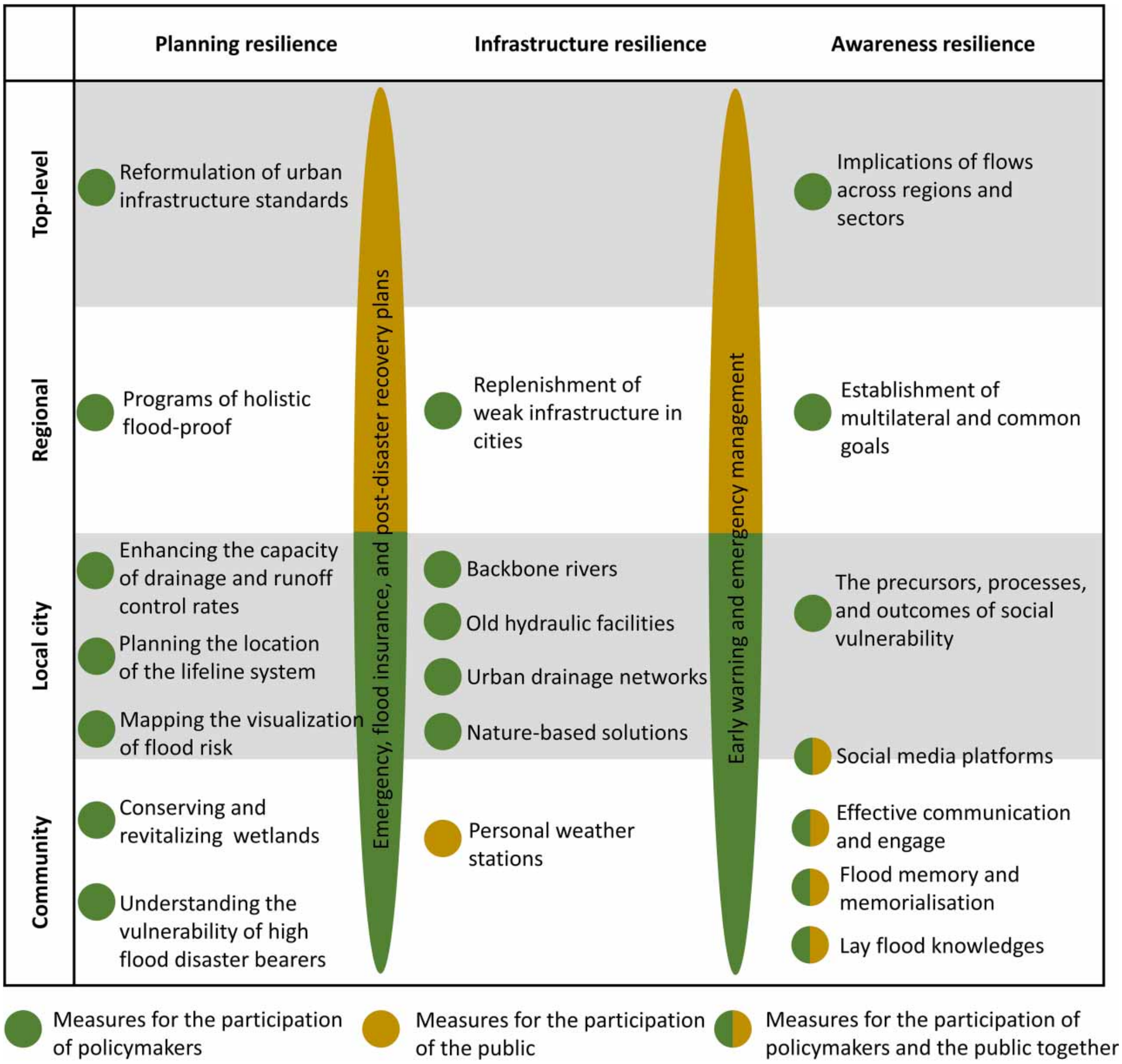


Fig. 5 | Resilient framework to control urban flooding. The schematic illustration of a resilient framework encompasses planning resilience, infrastructure resilience, and awareness resilience.

mechanisms efficiently manages internal urban drainage, which acts as an intricate capillary branch of the system. In this way, flooding and runoff from urban areas are safely discharged farther downstream through the system. By the planning requirements, the management urgently revitalizes the backbone rivers and maintains the old hydraulic facilities to mitigate inherent vulnerabilities. For different levels of urban drainage networks, urban planners design various programs of storm and sewerage pipes in as much detail as possible. Nature-based solutions may be a new method of helping to control local flooding in urban areas. For example, artificial wetlands, rain gardens, and green roofs mainly infiltrate rainwater through vegetation and soil. The practice has the potential to become the linchpin of a sustainable system of natural and semi-natural spaces in the city to make it possible for its absorption and release. Depending on the design requirements, a well-designed nature-based solution possesses the capacity to effectively capture between 70 and 80% of the target control rate of total annual runoff (Chan *et al.*, 2018). The drainage network adeptly accommodates stormwater flows that exceed the capacity of nature-based solutions when moderate-intensity rainfall occurs, while simultaneously ensuring minimal disruptions to the daily lives of residents. The backbone rivers, on the other hand, securely convey the majority of stormwater runoff that exceeds the cumulative capacity of the drainage network and rainwater harvesting (Table 2). When the design criteria are exceeded, the river becomes a major floodway but may potentially impact the contiguous floodplain regions along the river (Nelson *et al.*, 2024). In that case, it is necessary for the relevant authorities to precisely identify the location and consequences of overtopping occurrences and develop evacuation plans and early warning systems as early as possible. In addition, future work will not only remedy flood control infrastructure locally but also focus on appropriate investments in weak transportation infrastructure between cities. The work can strengthen regional supply chain resilience and guarantee the stability of regional commodity prices.

It is essential to ensure awareness resilience within the scope of urban flood resilience strategies with simplified dimensions. The aspect of resilience is likely to be understood as an evolutionary trait, specifically referring to the ability to adapt and learn from flooding disturbances. The phase shows up as a sudden upturn at some point or a spiral over time and is also the time when a crisis becomes an opportunity again. All relevant local departments and lifeline systems are responsible for educating about the precursors, processes, and outcomes of floods in advance (Liu *et al.*, 2024). It is also necessary to clarify and distinguish the emergency response measures for each level of risk. City managers also actively invite local citizens to participate in community modeling to facilitate communication between flood-affected residents and engineers. The significance of lay knowledge with traditional and indigenous practices is also recognized in community management, which could be fed into government scientific systems. Furthermore, social media platforms like TikTok and Weibo can be utilized to augment community and public hazard awareness (Guo *et al.*, 2023). By leveraging community flood memories and memorabilia, executives could enrich the flood narrative by linking it to individual experiences, places, and people. Meanwhile, the public also uses social media platforms to quickly record floods, which tremendously assists the government and warning systems in determining the location and intensity of floods. From a technical viewpoint, flood estimation with a high spatial and temporal resolution still appears to be a gauntlet. Notably,

Table 2 | Brief description of the urban flood control system.

Portion		Recurrence interval (years)	Representative measures
Capillary branches	Sources: nature-based solutions	1–2	• Green walls • Rain gardens • Green roofs
	Midway: drainage networks	3–5	• Drainage pipes • Detention ponds • Stormwater drains
Backbone projects	Extremities: backbone rivers	20–100	• Rivers • Lakes • Floodplain • Pumping station • Water locks

communities and citizens, such as those in Houston, have installed personal weather stations. The monitored data could be conveniently exchanged through online websites, which fills the deficiencies of primary data collection to better understand the flood risk in certain locations (Chen *et al.*, 2022). Such rainfall data are ultimately used by local government departments to build high-resolution flood models in flood-prone areas. The system is crucial for integrating early warning and emergency management focused on flood disasters, with timely warning and rescue information effectively transmitted through multiple channels to reduce flood exposure. It is also critical to establish the presence of multilateral agreements and effective partnerships in a region. Top government departments draw much attention to the impact of flows across regions and sectors in developing water resource management. The critical components of effective partnerships include overall stable stakeholder involvement, trusted information sharing, and clear and valid agreements.

4. DISCUSSIONS

4.1. Flood risk in inland cities

At present, the risk of inland flooding continues to increase worldwide. The phenomenon confirms recent research in the IPCC (2021) report that extreme rainfall is becoming relatively intense in many areas, particularly increasing the impact of inland flooding. Residents in inland areas of northern China have gradually acquired experience in dealing with drought through drought cycles. However, people in inland cities are relatively unfamiliar with preparing for floods compared to coastal areas, which increases the risk of flooding from rainfall (Mongold *et al.*, 2021). A flash flood occurred in Zhengzhou in 2021 when a rare and record-breaking rainstorm poured down (National Scientific Meteorological Data Center 2021). The disaster killed over 100 people in Zhengzhou and caused many tragic incidents, such as the inundation of Metro Line 5 (Xinhua News Agency, 2021). Similarly, the remnants of Hurricane Ida reached New York in 2021, breaking records for hourly rainfall (City of New York 2021). Local drainage networks were overwhelmed, particularly impacting inland cities outside the floodplain (City of New York 2021). These facts validate existing research that inland flooding disproportionately affects those lacking resources for mitigation, adaptation, or recovery from flooding events (Messager *et al.*, 2021). Hence, the importance of inland flooding reveals this potential inequity and establishes a foundation for addressing these critical issues.

4.2. Relationship between flood risk and flood resilience

The development of urban flood resilience is an important step in the future management of water sectors. Recent flood events underscore that traditional flooding patterns no longer follow previous occurrences under the influence of climate warming and extreme weather. The risks posed by disasters are escalating, necessitating the prompt development of flood management strategies in the new context. It has been argued that the relationship between risk and resilience falls into three main categories: resilience as the goal of risk management, comprehensive risk-resilience management, and resilience as an alternative to risk management (Suter, 2011). In the framework mentioned above, resilience acts as a complement and refinement of risk management, which is used to deal with some unexpected risks that exceed expectations. As illustrated in Figure 5, our study combines numerous risk management tools, such as forecasting systems and risk maps with the actual national conditions in China. Ultimately, the corresponding recommendations are proposed, striving to achieve a certain degree of feasibility and superiority.

Rodina considers the twofold difference between flood resilience and flood risk management (Rodina, 2019). Firstly, resilience is technologically oriented and requires a focus on systems and infrastructures along with many social factors. Secondly, flood resilience, in addition to the ability to bounce back, includes the notion of adapting to change in response to disturbances. It involves learning from the past, active planning, and anticipating failures. In the face of flooding, managers and individuals in inland cities often grapple with limited awareness and inadequate self-help capabilities. Hence, the resilience framework proposed in the paper urgently incorporates the relevant components of awareness resilience. Resilient cities require the comprehensive participation of various stakeholders, including governments, social organizations, and individuals. Each stakeholder is required to clarify their respective roles while upholding the principle of safeguarding equal status among pluralistic subjects.

4.3. Rationality of the resilience framework

The urban flood resilience strategy with a simplified dimension is served as an enhanced and complementary approach to risk management that is applicable to flood management practices in inland cities. Numerous studies have employed a dimensional approach to characterize and evaluate urban resilience capacities. Scientists have described multiple dimensions of resilience by encompassing the natural, economic, social, physical, and institutional factors, while others have characterized different urban networks by considering governance, socioeconomics, infrastructure, and materials and energy (Ribeiro & Gonçalves, 2019; Li *et al.*, 2021b). The same rationale extends to the consideration of urban flood resilience in three dimensions: prevention capacity in the prior stages, coping capacity in the middle stages, and recovery and adaptation capacity in the later stages (Liu *et al.*, 2024). Therefore, the research framework summarizes the relevant literature and proposes three dimensions for flood resilience in inland cities of developing countries: planning, infrastructure, and awareness, focusing more on the multidimensional and evolutionary aspects of urban resilience than others. Planning is the foundational element for flood mitigation, representing the cornerstone of resilience. Current risk management planning, predominantly adopting a risk-focused approach, often overlooks the resilience perspective. Although some existing regulations indicate an attempt at policy change, structural protections have continued to predominate in flood management (Moore, 2017). Resilience emphasizes the ability to handle unknown crises. The part of our study enables stakeholders to recognize and address existing weaknesses in planning measures. Infrastructure is identified as the primary tool against flooding, emphasizing the necessity for well-designed and strategically implemented solutions. Urban flooding in the present context is frequently attributed to the inadequacies of development in stormwater management infrastructure (Jiang *et al.*, 2018). These include limited capacity for reducing emissions at source, insufficient conveyance capacity of the drainage network, weak capacity of river flood discharges, and interdependencies of infrastructure. The part of our study emphasizes the critical role of a hydraulic infrastructure and further describes specific measures. Human awareness, determining the enhancement or mitigation of flood losses, forms the third dimension of the proposed framework. When confronting flood incidents, the government and individuals in inland areas often have limited awareness and inadequate self-rescue skills. The fact that people underestimate flood risk is a primary issue and a significant challenge in flood mitigation (Lechowska, 2018). These insights serve as a critical dimension in understanding the evolutionary nature of resilience, providing a valuable complement to existing studies. Ultimately, the article utilizes these three dimensions to present resilience guidelines for the specific problem of inland flooding in the previous section.

5. CONCLUSIONS

Overall, urban inundation due to extreme weather creates challenges in China's urbanization process. Several recent devastating floods in inland cities of northern China have been attributed to the inexperience of managers and citizens in coping with rainstorms and floods. The expectation of solving urban flooding cannot entirely depend on constructing urban flood control and drainage projects. It is also necessary to enhance the construction ideology of urban resilience. Especially, the ideology is expected to be bolstered by top-down and bottom-up actions that require a move toward a multi-level management direction, including urban planning, urban flood control systems, and risk prevention awareness. The success of the resilient strategies proposed hinges on the willingness and competence of relevant partners. Achieving urban resilience involves a continuous development process that includes operating authorities, flood capital, and stakeholders. To offer a relatively comprehensive and integrated solution, the study establishes a framework to facilitate the combination of specific measures. The framework is intended to rationalize flood management across the entire city and optimize the allocation of social resources as much as possible. In doing so, all participants in the system will be imperative to break free of their silos and actively pursue multi-disciplinary and multi-level cooperation among all parties. In this way, flood resilience strategies will mitigate the impact of disasters and protect the people and resources that are vital to our communities. In addition, urban floods have been at the forefront of climate change and sustainability dialogues. Solutions are not amenable to normalization. The ambiguity of flood resilience makes its practical application complex and dynamic. As its coverage and utilization, flood resilience is bound to contain relatively internal connections and contradictions. For the most part nonetheless, we believe that resilient strategies can usually create novel opportunities for inland cities in China and other regions during flood crises, at least in the short term.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: Bulletin of Flood and Drought Disasters in China (http://www.mwr.gov.cn/sj/tjgb/zgshzhgb) and the precipitation data in Beijing (https://nsbd.swj.beijing.gov.cn/csyq1.html).

CONFLICT OF INTEREST

The authors declare there is no conflict.

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