

Flood Risk Management and Optimization of Flood Control Infrastructure in the Context of Resilient Cities

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Abstract. In the context of resilient cities, flood risk management and the optimization of flood control infrastructure are key issues for urban sustainable development. Climate change and urbanization have increased the frequency and severity of floods, prompting governments and researchers to focus on flood risk assessment and management. This paper comprehensively analyzes the research status at home and abroad in the fields of resilient cities and flood control infrastructure, points out that the concept of resilient cities provides new ideas for flood risk management, and emphasizes that urban planning and design with “resilience” as the core should be integrated into the construction of flood control facilities. At the same time, the study found that the existing flood control infrastructure is vulnerable to sudden flood events and urgently needs to improve its resilience through optimized design and scientific management. Through the assessment of flood risks, the vulnerable links of the city in the face of floods can be identified, and corresponding optimization strategies can be proposed. The paper aims to contribute to the understanding of resilient city development, promote the scientific planning and rational allocation of flood control infrastructure, thus enhancing disaster resistance and adaptability of the city, and ultimately achieving sustainable development goals.

Keywords: Resilient city, Flood risk management, Flood control infrastructure, Sustainable development, Optimal design

1. Introduction

With the intensification of global climate change and the acceleration of urbanization, the frequency and intensity of flood disasters have significantly increased, posing severe challenges to urban safety and sustainable development [1,2]. As a new urban development model to deal with natural disasters and social shocks, resilient cities have received widespread attention in recent years. Its core idea is to ensure that cities can quickly recover and maintain basic functions in the face of emergencies by enhancing their adaptability [3,4]. The construction of resilient cities is particularly important in the field of flood risk management. Existing studies have shown that resilient cities can effectively reduce potential losses caused by floods through means such as optimizing land use, improving infrastructure, and enhancing community resilience [2,5]. However, existing research falls short in applying the concept of resilient cities to the optimal design and management of flood control

infrastructure, lacking systematic risk assessment, localized implementation strategies, and a cohesive theoretical and operational framework. [6,7]. Therefore, the study examines systematic risk assessment and optimization strategies for flood control infrastructure in the context of resilient cities. By establishing a scientific risk assessment framework, it aims to identify vulnerabilities in existing systems and propose practical optimization measures to enhance urban flood resilience and support sustainable development [1,4]. In particular, a resilience-based flood risk framework is developed. Thereon, optimization strategies are extracted from relevant successful cases, adapted to local conditions, and translated into policy advice to support the planning and management of flood control infrastructure. Through a literature review and case analysis, it evaluates the vulnerability of flood control infrastructure and proposes theoretically grounded optimization strategies to inform resilient city planning and policy-making.

2. Overview of flood risk management in the context of resilient cities

2.1. Definition and development of resilient cities

The essence of a resilient city lies in its ability to respond swiftly to crises, such as natural disasters and social shocks, while maintaining essential urban functions throughout recovery. This concept highlights comprehensive, multi-dimensional governance that goes beyond post-disaster recovery to integrate infrastructure planning, social and economic resilience, and ecological sustainability. The core of a resilient city lies in its systematicness, dynamics, and adaptability, which can flexibly respond to complex risk environments [3]. For example, the Natural Infrastructure (NI) concept, proposed by the U.S. Army Engineer Research and Development Center (ERDC), emphasizes the integration of ecological engineering and traditional gray infrastructure to improve flood control and ecosystem services. This concept enhances not only urban flood resilience but also ecosystem health and stability, contributing to community well-being. By introducing natural infrastructure, cities can reduce the immediate impacts of disasters while simultaneously enhancing adaptability and sustainability via ecological restoration and green space development. While managing present flood risks and disasters, a resilient city seeks to ensure long-term sustainable development in the face of environmental and climate change. By strengthening their social, economic, and ecological foundations, resilient cities can provide a more robust support system for facing future disasters, climate change, and social challenges, ensuring that they remain healthy, vibrant, and sustainable in a complex and changing global environment.

2.2. Core technologies and strategies of flood risk management

At the heart of flood risk management lies scientific assessment, which relies on data analytics and modeling techniques. The integration of past flood data, terrain features, and land use patterns with hydrological-hydraulic models enables precise flood risk estimation and supports more effective urban flood management [6]. In recent years, the adoption of modern technologies like Geographic Information Systems (GIS) and remote sensing technology has greatly improved the efficiency and accuracy of flood risk assessment, particularly in identifying high-risk areas and predicting flood dynamics. For example, GIS technology can analyze the spatial distribution of floods in real time, predict potentially affected areas, and support for emergency response decisionmaking [2]. Besides, the construction of a flood warning system is one of the core means to improve the city's response capabilities. By combining real-time monitoring of key data, such as rainfall and water levels, with Bayesian estimation and multi-objective optimization algorithms, early warnings can be issued

before floods occur, improving the accuracy of flood forecasting. Based on these technologies, decision-makers can formulate more robust emergency response measures, effectively reducing flood-related losses [7]. The core strategies of flood management include prevention, adaptation, and recovery. Prevention strategies reduce flood risks through scientific land use planning and strict building codes, while also avoiding excessive development in unsuitable areas. To strengthen urban flexibility and responsiveness, adaptation strategies promote measures like adjustable embankments and green infrastructure, such as permeable pavements and wetland restoration, that enhance flood response and support ecosystem recovery[3]. In recovery strategies, emphasis is placed on rapid post-disaster actions, including the optimization of emergency systems, fast deployment of rescue and repair teams, and timely restoration of essential services [2].

2.3. Role and improvement space of flood control infrastructure

Flood control infrastructure is the core guarantee for cities to resist flood disasters. Through the synergistic effect of physical facilities such as reservoirs, embankments, and flood storage areas, it can effectively regulate water flow and intercept floods, thereby reducing the threat of floods to cities and their residents. However, with the frequent occurrence of climate change and extreme weather events, the limitations of traditional gray infrastructure have gradually been exposed. Most existing facilities were designed based on historical climate patterns and are ill-equipped to handle current and future extreme weather, resulting in significant shortcomings in managing extraordinary flood events [1]. In addition, such facilities often lack flexibility and fail to adapt to evolving flood risks, thereby leading to inadequate emergency responses during sudden events.. To improve the adaptability and response capabilities of flood control infrastructure, improvements should be made from multiple levels. Design standards should be updated according to future climate change trends and extreme weather predictions. This improvement will enable flood control facilities to provide more effective protection in the face of floods under different climate conditions, rather than just relying on past historical data. Second, improving the flexibility of facilities is key. For example, modular design flood walls can be adjusted according to the scale and dynamic changes of floods to provide more accurate protection. This flexibility enables facilities to cope with rapidly changing flood conditions and avoid the slow emergency response caused by fixed structures. In addition, promoting ecological transformation is also an important direction for improving flood control infrastructure. Green infrastructure, including wetland restoration, permeable pavements, and green roofs, enhances urban rainwater absorption and flood control while boosting ecosystem resilience and natural flood regulation.

3. Research progress in flood risk management and resilient cities

The flood risk management must move beyond technical fixes to integrated governance involving policy, technology, and society. Current challenges include poor interdisciplinary cooperation, weak stakeholder coordination, and underused innovations. Future efforts must integrate disciplines and align policies, technology, and community actions to address the urgent need for adaptable and sustainable flood management amid climate change and urbanization.

3.1. Flood management from a social risk perspective

The main social impact of floods is reflected in community vulnerability and resident safety. The disaster resistance of communities is influenced by many factors, including population density,

infrastructure level, and socioeconomic status. The enhancement of community resilience is key to reducing social risks, involving improved disaster awareness, optimized urban infrastructure, and efficient government-community collaboration [3].

Community-based flood management models are widely implemented worldwide. For instance, the Netherlands' "Living with Water" strategy integrates flood defenses with public spaces through community participation, transforming dikes and flood storage areas into multifunctional spaces that enhance residents' climate adaptation [2]. Fort Lauderdale in the U.S. focuses on enhancing the flood resistance of key infrastructure, such as power and transportation networks, reducing the social chain effects caused by floods by 40%. Its practices include waterproofing and reinforcing underground power facilities and optimizing the emergency evacuation routes of transportation networks to ensure the rapid recovery of urban functions during floods [2]. For policy governance, multi-department collaboration is key to effective flood management policy. Also, the Netherlands clarifies the responsibilities of water conservancy, urban construction, and environmental protection departments through the Water Management Act, and establishes a cross-departmental data-sharing platform. And this enables flood control planning to integrate information from different fields, enhancing the scientific basis and coordination of policy implementation [8,9]. China's Sponge City initiative promotes the integration of green infrastructure, such as permeable pavements and rain gardens, with traditional flood control projects, such as drainage networks and flood storage ponds, by setting mandatory rainwater permeability indicators, such as 80% of surface runoff needing to be absorbed locally, enhancing the city's ability to respond to extreme rainfall [5,10].

3.2. Flood management from a financial risk perspective

Flood disasters cause widespread social impacts and major financial risks like infrastructure damage, economic disruptions, and costly post-disaster reconstruction. Effective financial management is essential for enhancing the economic sustainability of flood control systems. Key strategies include flood insurance, public-private partnerships (PPP), and green financial instruments to mitigate these risks [3].

In terms of risk diversification, flood insurance mechanisms have been applied in many countries. For example, the United Kingdom's Flood Re insurance fund combines government subsidies with private insurance to provide affordable coverage for residents in high-risk areas, mitigating 40% of financial risks. [11]. Furthermore, the U.S. National Flood Insurance Program (NFIP) provides government-supported insurance compensation for affected residents and adjusts insurance premiums through risk assessment to incentivize residents and businesses to take more active flood control measures. In terms of infrastructure investment and resource allocation, the PPP model provides a new financing channel for flood control projects. This model introduces private capital to reduce government financial pressure and improve project construction and operation efficiency. For example, the Netherlands widely uses the PPP model in water conservancy projects, making the maintenance and upgrading of flood control facilities more flexible to adapt to the uncertainties brought by climate change [9]. The rise of green financial instruments has also provided sustainable financial support for flood management. For example, Morocco has issued climate bonds to fund the ecological restoration of the Atlas Mountains river, thereby making ecological flood control a sustainable long-term solution [9]. Similarly, preferential financing for ecologically beneficial flood control projects is encouraged by China's green credit policy, promoting the integration of green and traditional infrastructure.

3.3. Flood management from a technical risk perspective

Technical risks in flood management primarily concern forecast accuracy, timely early warnings, and the reliability of flood control infrastructure design. With the advancement of technology, flood forecasting models, early warning systems, and flood control engineering design schemes have been significantly improved, providing effective means to reduce the losses caused by flood disasters.

In recent years, flood forecasting has increasingly adopted machine learning models, particularly long short-term memory (LSTM) neural networks. Through this technology, the forecasting error has been reduced to within 15%, effectively improving the accuracy and real-time performance of forecasting [2]. Additionally, integrating Bayesian estimation with multi-objective optimization in decision-making frameworks enhances the robustness of flood control strategies under uncertainty, as demonstrated by the successful application in Iran's Taleghanrood River Basin [1]. In practice, China has implemented multi-source precipitation data fusion in flood warning systems for small and medium rivers, allowing warnings to be issued 3 to 7 days in advance. By integrating Kalman filtering with dynamic system response curve (DSRC) technology, these systems have markedly enhanced forecasting accuracy and emergency response effectiveness [7,10]. By integrating super dikes, adjustable sluices, and coordinated community evacuation plans, the Netherlands has boosted flood evacuation efficiency by 60% [5]. The integrated application of these technologies has made flood management more intelligent and refined, able to dynamically adjust flood control measures based on real-time data, and boost the city's disaster resistance. In addition, with the development of monitoring technologies, the health status of infrastructure has been monitored more accurately. For example, the combination of ground-penetrating radar (GPR) and sensor networks can real-time monitor the status of flood control facilities, promptly detect potential risks and faults, and provide data support for facility maintenance and risk early warning [7].

4. Challenges and optimization strategies in flood risk management

4.1. Challenges in implementation

Flood risk management faces key challenges, notably funding shortfalls and technical barriers. In particular, funding shortfalls remain a key barrier to flood control in developing countries. Though urban flood control projects typically require funding equivalent to 1.5%-2% of GDP, actual investment often falls significantly short of this benchmark. [9,11]. For example, an assessment of the stormwater pipeline network in the High-tech Zone of Zhengzhou City shows that the existing system can only cope with rainfall with a return period of 1-2 years, far below the design standard [10]. Fiscal pressure, imbalanced allocation, and low private sector involvement are key drivers of funding gaps. Addressing this requires innovative financing, such as PPPs, green bonds, and climate funds, to attract private capital to flood control projects. Difficulties in technical implementation also affect the effectiveness of flood management, especially data barriers and insufficient public participation. The 2021 flood in Germany showed that although a 72-hour advance warning was issued, the lack of public emergency training eventually led to heavy losses [8]. Similar problems have also occurred in Bangkok, Thailand, where the intelligent monitoring system suffered from inefficient flood responses due to poor data sharing and coordination [9].

4.2. Corresponding optimization strategies

In response, coordinated strategies across technological, policy, financial, and planning dimensions are essential. Flood control projects should prioritize adaptive design by integrating climate models (e.g., CMIP6) with probabilistic risk assessment to ensure resilience to climate change and extreme weather. For example, the Taleghanrood River Basin in Iran has effectively addressed parameter uncertainties through Bayesian estimation and multi-objective optimization algorithms, improving flood control effects [10]. For different regions, design standards and facility schemes should be flexibly adjusted based on local climate and precipitation patterns. At the policy level, strengthening legal constraints and performance evaluation is essential. The Netherlands' Water Law mandates flood impact assessments for new projects and factors flood control performance into annual local government evaluations[2]. This approach reinforces local flood control accountability. In addition, cross-departmental collaborative governance is key to ensuring policy implementation, and close cooperation between departments needs improvement [8,9]. In terms of funding, a risk-stratified financing model effectively addresses funding gaps by aligning project types with suitable funding sources. High-yield projects such as commercial embankments adopt the PPP model, public welfare projects like slum drainage rely on climate funds, and mixed projects are financed through green bonds. Morocco successfully applied this model, raising \$320 million for flood control in desert areas [9]. Besides, systematic planning and urban resilience design are crucial. The water square design in Rotterdam, the Netherlands, uses water-retainable public spaces and modular paving materials to meet flood storage needs during heavy rains while also serving as a venue for daily activities [2]. Its success lies in fully considering community needs and ensuring that the design is practical. Similarly, Zhengzhou's sponge city project renovated 200 km of permeable pavement but failed to upgrade drainage systems, resulting in continued waterlogging. In the future, Zhengzhou should use digital twin technology to model system responses and build a three-tier drainage system (micro-drainage, basic pipelines, and main channels) to enhance emergency response [5,10].

5. Conclusion

From the perspective of resilient cities, the research on systematic risk assessment and optimization strategies for flood control infrastructure is of great significance. The construction of resilient cities not only improves the city's ability to deal with floods and other disasters but also promotes urban sustainable development. The key to dealing with the complexity of natural disasters is to achieve effective risk management by integrating multidisciplinary knowledge and technologies. Future research should focus on interdisciplinary cooperation, deepen the understanding of resilient cities and their flood control strategies, and continuously improve relevant policies and measures. Public participation and community resilience building are important directions for future research. Residents should be encouraged to actively participate in flood risk management, and public disaster prevention awareness and self-rescue capabilities should be improved through community education and emergency drills. At the same time, urban planning should fully consider the unique needs of communities, integrate resilience building into urban and rural development policies, and achieve higher-quality community resilience and overall urban safety. Technological innovation is the key to the development of resilient cities. Future research should explore the application of new technologies in urban flood control infrastructure, such as the construction of intelligent monitoring and early warning systems, to improve the city's ability to respond to flood risks. By continuously improving relevant policies and optimizing management measures, we hope to build a safer and more sustainable resilient city system to cope with the increasingly severe challenges of flood risks.

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