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Urban Flash Floods: Global Strategies for Effective Mitigation

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Abstract

Flash flooding poses substantial risks to urban environments, incurring significant financial, social, and environmental costs. Flash floods are challenging to manage and, therefore, require a comprehensive understanding of the underlying factors contributing to their occurrence, as well as effective mitigation strategies. This research aims to develop a framework of requirements to efficiently mitigate urban flash floods by considering various aspects involved in a multi-disciplinary approach. This paper summarises previous research on flash floods, urban planning, and flood mitigation based on intensive studies. Moreover, to collect empirical data, a case study review has been conducted involving big cities within Malaysia and neighbouring countries. This research approach employs qualitative analysis to provide a deeper understanding of the complex relationship between flash floods and their mitigation options. The findings of this research highlight the critical factors influencing the effectiveness of flood mitigation efforts in urban areas during flash flood events. This involves modifying urban infrastructure design, land-use planning, early warning systems, community preparedness, and policy frameworks. This study can have significant implications for urban planners, disaster management authorities, and the local communities involved in reducing susceptibility to flash floods. The outcomes of this study provide a generic understanding for stakeholders involved in identifying and developing proactive measures that limit the impact of flash floods on urban environments. Ultimately, this research contributes significantly to the body of knowledge on urban flash flood mitigation and provides an integrated view across technology, policy, community engagement, and practice in influencing resilient communities for sustainable development in flood-prone areas.

1. Introduction

Flash flooding has been a significant threat to urban areas, resulting in extensive damage to infrastructure, disruption of daily activities, and adverse impacts on human lives. One of the missions is to develop effective management plans against the phenomenally increasing floods driven by climate change and rapid urbanisation in terms of their frequency and severity [1]. Urban areas are more vulnerable to flash flooding due to their high population and widespread impervious surfaces [2]. These present additional complexities to managing stormwater runoff and reducing the risk of flooding.

As urbanisation continues to expand, the risk of flooding in urban areas becomes a major concern. Implementing effective flood mitigation strategies is crucial to minimising the impact of flooding on cities and their inhabitants [3]. One potential flood mitigation strategy in urban areas is the implementation of green infrastructure. Green infrastructure utilises natural features and systems such as parks, wetlands, green roofs, and permeable pavement to manage stormwater runoff and mitigate or reduce floods [4]. These green infrastructure features can absorb and retain rainwater, allowing it to gradually infiltrate the ground or be released at a slower rate into nearby water bodies, thereby reducing the burden on urban drainage systems and preventing flooding. Another flood mitigation strategy in urban areas is the improvement and expansion of drainage systems [5]. Constructing larger and more efficient stormwater drainage networks, retrofitting existing infrastructure to expand capacity, and regular maintenance/clearing of drains and channels to ensure the uninterrupted passage of water [6]. Additionally, urban planning and land use management have also been influential in overcoming the flooding problem [7].

Effective implementation of flash flood mitigation systems requires a comprehensive understanding of urban hydrology, advanced forecasting technologies, and strategic infrastructure planning [8]. This study aims to explore the multifaceted approach needed to develop resilient urban environments capable of withstanding flash flood events. By integrating innovative engineering solutions, community engagement, and policy frameworks, urban planners and engineers can devise robust systems that not only mitigate the impact of flash floods but also enhance overall urban resilience. This comprehensive analysis examines the key components of flash flood mitigation strategies in urban areas, highlighting the primary themes and trends in current research, as well as the methods and technologies most commonly employed. Furthermore, it will examine case studies of successful implementations and the lessons learned from these experiences. The goal is to provide a detailed roadmap for urban areas aiming to implement effective flash flood mitigation systems, ensuring the safety and sustainability of urban environments in the face of growing environmental challenges.

1.1 Assessment of Urban Flood Risks

Flash floods can cause significant damage in urban areas, particularly in regions experiencing increased rainfall and inadequate drainage systems [9]–[12]. To address this issue, a rapid and temporary flash flood mitigation system could be implemented. This system would involve the use of mobile barriers and pumps to redirect and remove excess water during flash flood events [13]. By strategically placing these barriers and pumps in flood-prone areas, the system would be able to quickly respond to flash floods and minimise the impact on urban infrastructure and residents [5], [14], [15]. With the use of continuous simulation models like the Storm Water Management Model, volume-based and flow rate-based controls can be evaluated to determine the most effective approach for mitigating flash floods in urban areas [6], [16], [17]. This system would also take into account factors such as urban sprawl [5], structural constraints [18], socio-economic factors [19], [20], and the increasing frequency of high-intensity rainfall due to climate change [11], [21]. Additionally, river system distribution and flood source analysis will be conducted in specific case studies to further enhance the effectiveness of the flash flood mitigation system in riverside towns [22]–[24].

1.2 Design and Deployment of Mitigation Measures

Mitigation measures can be broadly classified into structural, non-structural and integrated solutions, as shown in Fig. 1. The figure outlines various flood mitigation measures divided into three main categories: Structural, Non-structural, and Integrated. Structural measures involve physical constructions like stormwater management systems, upgraded drainage, flood barriers, and river channel modifications to control floodwaters [25]. Non-structural measures focus on planning and policy, including urban planning, zoning, early warning systems, and community preparedness. Integrated measures combine both approaches, emphasising the restoration of natural floodplains, sustainable urban drainage systems, and climate adaptation strategies [26]. By combining these measures, urban areas can effectively mitigate the impact of floods, protect infrastructure, and ensure the safety and well-being of their residents [9].

In the next section, emphasis will be given to integrating these measures into a cohesive system that maximises flood mitigation while promoting sustainable urban development. Examples of successful implementations and best practices will be highlighted to provide practical insights for urban planners and engineers.

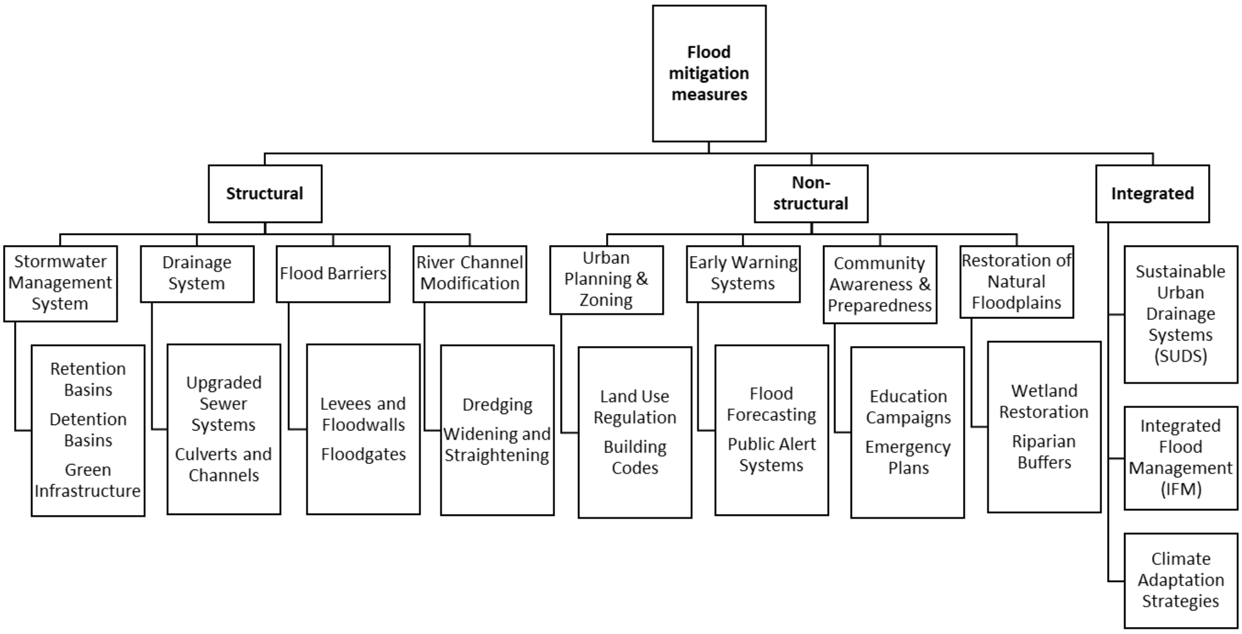

Fig. 1 *Flood mitigation measures*

2. Methodology

To achieve the objectives of this research, a two-pronged methodological approach is employed: bibliometric analysis and case study. This combined approach ensures a comprehensive understanding of existing knowledge, best practices, and real-world applications of flood mitigation strategies.

2.1 Bibliometric Analysis

Bibliometric analysis is employed to conduct a comprehensive review of the existing literature, focusing on keywords, terms, and timelines related to flash floods, urban planning, and flood mitigation strategies in urban areas. The research questions below are used to provide comprehensive insights into the topic:

- What are the key themes and trends in the research on urban flash flood mitigation?
- Which methods and technologies are most commonly implemented?

A comprehensive search of academic databases such as ScienceDirect and Google Scholar is conducted using the following search term for the range between 2020 to 2024:

"flash flood mitigation" OR "urban flood management" OR "urban flood prevention" OR "flash flood control systems" OR "flood resilience in cities"

The filtering process, as illustrated in Fig. 2, is conducted to identify all relevant articles related to the research questions. It begins with a search strategy, followed by defining relevant keywords. An initial screening is conducted using inclusion criteria that focus on urban areas, peer-reviewed articles, and publications within the last five years. Detailed screening and data extraction involve reading abstracts and titles, followed by a review of the full text. The process then branches into bibliometric analysis, where tools like CiteSpace and BibExcel are used to analyse various aspects such as publication trends, keyword analysis, and geographic distribution.

The results of the bibliometric analysis provide a quantitative overview of the research landscape, highlighting critical knowledge gaps, predominant methodologies, and innovative solutions. Insights gained from this analysis inform the selection of case studies and guide the development of recommendations for effective flood mitigation strategies.

2.2 Case Study

The case study approach provides an in-depth examination of specific urban areas that have successfully implemented flash flood mitigation systems. This subsection describes the criteria for selecting case studies, the data collection process, and the analytical framework used:

2.2.1 Selection of Case Studies

Urban areas with a history of flash flooding and documented mitigation efforts are identified. The criteria for selection include geographic diversity, the range of mitigation measures employed, and the availability of detailed implementation data. Representative examples from various continents and diverse urban settings (e.g., high-density cities, coastal areas, and inland cities) are selected to provide a broad perspective.

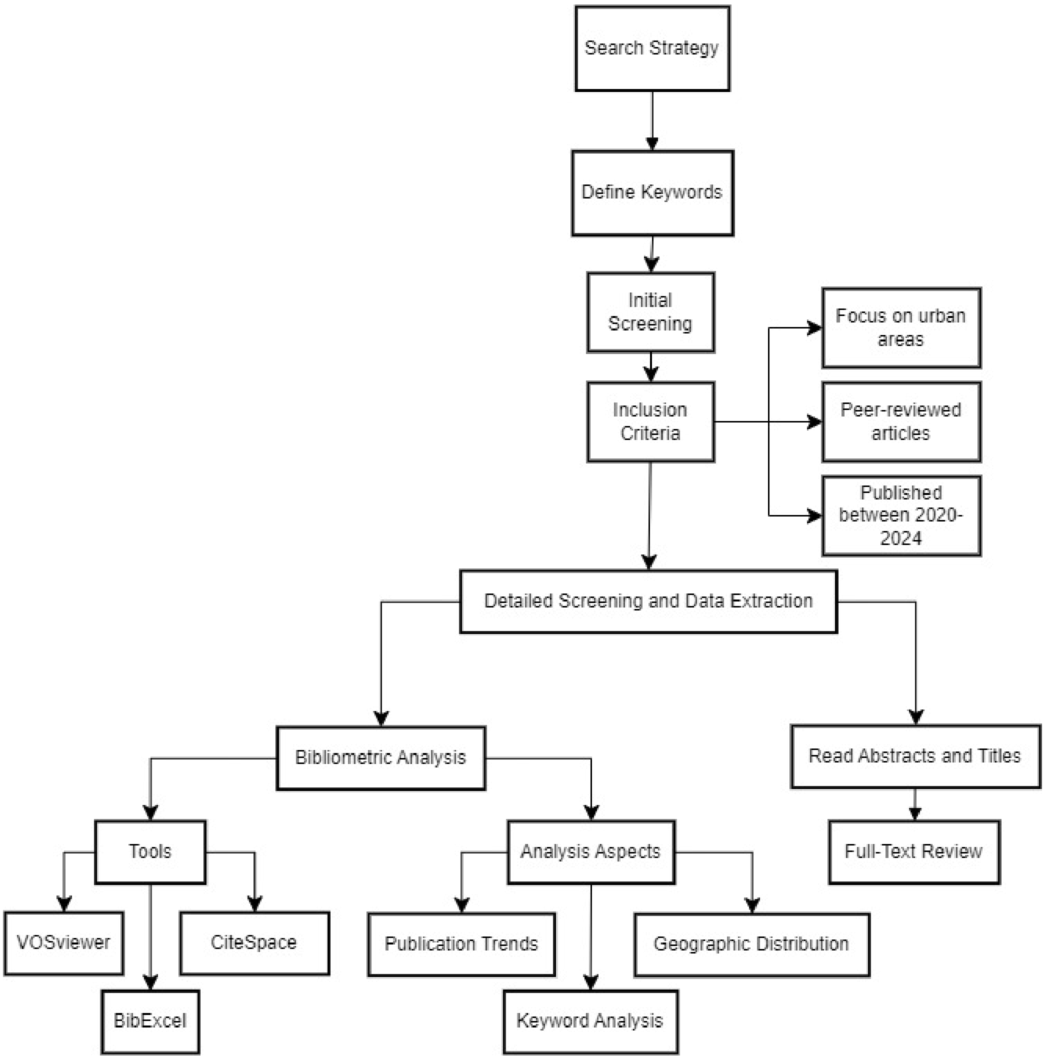

Fig. 2. *Filtering the literature process*

2.2.2 Data Collection

Primary and secondary data sources are utilised, including municipal reports, planning documents, interviews with local authorities and stakeholders, and site visits where feasible. Quantitative data on flood events, infrastructure performance, and economic impacts are collected alongside qualitative insights into the planning and community engagement processes.

2.2.3 Analysis Framework

Each case study is analysed using a standardised framework that examines the context (e.g., climatic conditions, urbanisation patterns), specific mitigation measures implemented (structural and non-structural), and the outcomes (e.g., reduction in flood frequency and severity, cost-effectiveness, community resilience). Lessons learned and best practices are identified, focusing on factors that contributed to the success or challenges of the mitigation efforts.

By integrating bibliometric analysis with detailed case studies, this methodology provides a robust foundation for understanding the complexities of urban flash flood mitigation. The findings from this research will contribute to the development of effective strategies and policies to enhance flood resilience in urban environments.

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3. Results

The results of this research, derived from the combination of bibliometric analysis and detailed case studies, provide a comprehensive understanding of effective flash flood mitigation strategies in urban areas. The findings are presented in four subsections corresponding to the methodologies used.

3.1 Research Trends and Publication Volume

There has been a significant increase in publications on urban flash flood mitigation over the past two decades, reflecting growing global concern and research interest in this area. The most prolific years were identified as the last five years, indicating a recent surge in focus due to the rising frequency and impact of flash floods. Fig. 3 illustrates the trend in the volume of publications related to flash flood mitigation strategies in urban areas from 2019 to 2023 based on Google Scholar and ScienceDirect databases. The data shows a consistent increase in the number of publications each year, starting with 430 publications in 2019, followed by 456 in 2020, 636 in 2021, and a significant jump to 726 in 2022. The trend is projected to continue rising, reaching 913 publications in 2023. This upward trajectory indicates a growing interest and emphasis on researching and implementing effective strategies for mitigating flash floods in urban settings, reflecting the increasing recognition of the importance of this area of study in the context of urban resilience and climate change adaptation.

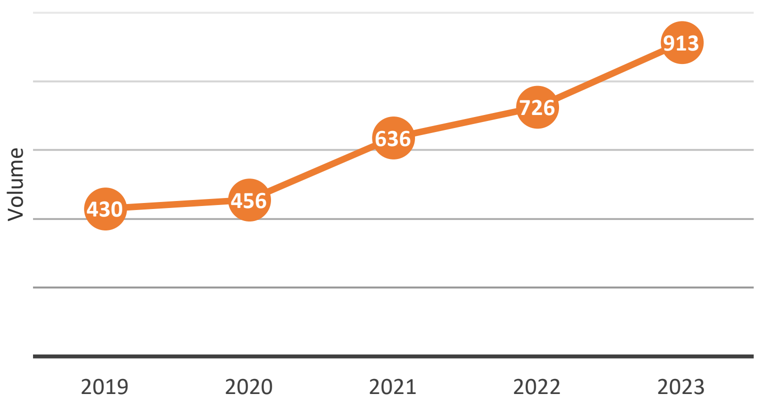

Fig. 3 *Annual volume of publications on flash flood mitigation strategies in urban areas (2019 to 2023)*

3.2 Key Research Areas and Themes

The integration of technology, policy development, and community engagement has been pivotal in advancing the field. There is a notable geographical variation in research focus, with a substantial amount of work originating from regions frequently affected by urban flooding. Fig. 4 provides a comprehensive overview of flash flood mitigation strategies, organised around three main aspects: Key Research Themes, Geographic Focus, and Types of Mitigation Strategies Studied. Key Research Themes include Technology and Innovation (e.g., IoT sensors, AI for flood prediction, GIS mapping), Infrastructure (e.g., flood barriers, improved drainage systems), Policy and Governance (e.g., regulatory frameworks, urban planning), Climate Change Impact (e.g., changing flood patterns), and Community Engagement (e.g., public awareness, education programs). The Geographic Focus highlights research and implementation efforts across Asia (China, India, Japan), North America (United States, Canada), Europe (UK, Germany, Netherlands), and Africa and South America. Types of Mitigation Strategies Studied are categorised into Structural Measures (e.g., flood barriers, levees), Non-structural Measures (e.g., zoning laws, flood forecasting systems), and Nature-based Solutions (e.g., wetland restoration, urban green spaces). This structured presentation and overview effectively encapsulate the diverse and global nature of research efforts aimed at mitigating urban flash floods.

3.3 Case Study

The case studies of selected urban areas provided practical insights into the implementation and outcomes of flash flood mitigation efforts. Special attention is given to the case studies in the cities around Malaysia and neighbouring countries due to their unique challenges and strategies.

The results as shown in Table 1 demonstrate that effective flash flood mitigation in urban areas is achievable through a comprehensive, multi-faceted approach that integrates scientific research, innovative engineering, community engagement, and adaptive policy frameworks.

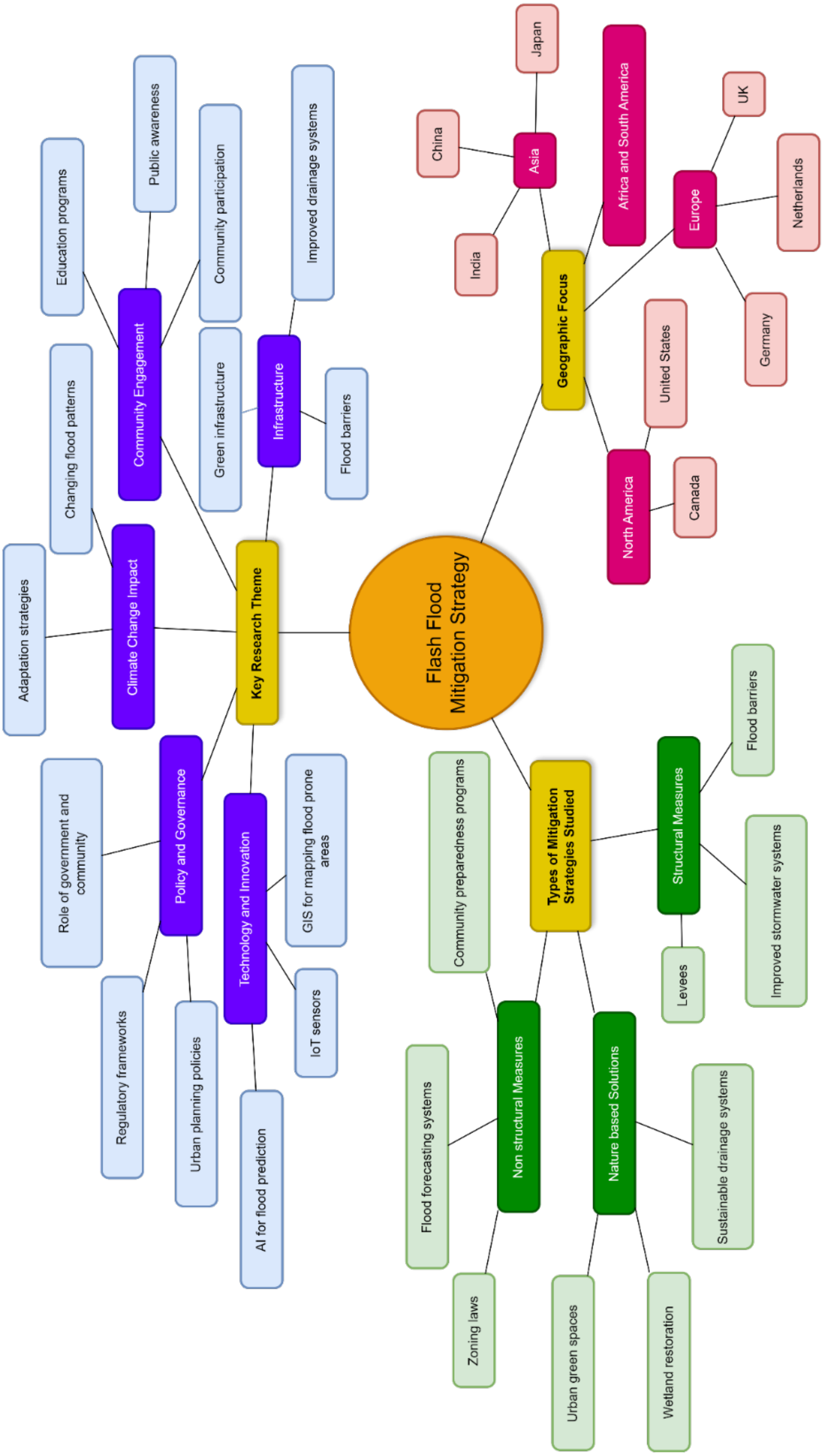

Fig. 4 *Overview of research trends in urban flash flood mitigation related to flash flood mitigation strategy in urban areas (2020-2024)*

Table 1 *Case studies of selected urban areas related to the implementation and outcomes of flash flood mitigation efforts*

City, Country	Context	Mitigation Measures	Outcomes
Kuala Lumpur, Malaysia [15], [27], [10]	Rapid urbanisation, high rainfall intensity, and a history of flash flooding.	SMART (Stormwater Management and Road Tunnel) project, a dual-purpose tunnel designed to divert floodwaters during heavy rains and serve as a traffic tunnel during dry periods.	Significant reduction in flood incidents in the city centre, improved traffic flow, and reduced economic losses from flooding.
Jakarta, Indonesia [8], [26], [28]	Dense population, frequent flooding due to heavy rainfall and inadequate drainage systems are compounded by land subsidence.	Sea walls, river dredging, and the development of retention basins and water parks to manage excess water. Revitalisation of natural waterways and the implementation of a flood early warning system.	Improved flood management and reduction in the severity and frequency of floods. Community relocation and resettlement programs have helped in reducing vulnerability and subsidence issues.
Bangkok, Thailand [29], [12]	Low-lying topography, high rainfall, and rapid urbanisation have reduced natural drainage areas.	Large underground water retention tunnels, improvement of drainage canals, installation of water pumps, and the creation of urban green spaces to absorb rainfall.	A combination of advanced infrastructure, proactive maintenance and integration of sustainable urban drainage systems into public spaces.
Singapore City [3], [29], [30]	Intense rainfall events, particularly in low-lying and highly urbanised districts.	Stamford Detention Tank is a massive underground reservoir designed to store excess rainwater during heavy storms. A network of canals, drains, and flood barriers to manage water flow effectively.	The combination of advanced infrastructure, real-time monitoring systems, and proactive maintenance has significantly reduced the incidence of flash floods.
Ho Chi Minh City, Vietnam [6], [31], [32]	Low elevation, rapid urbanisation, and inadequate drainage systems. Monsoon rains and tidal surges.	Large-scale tidal gates, improvement of drainage infrastructure, and the establishment of flood control reservoirs. Enhance the urban green space to absorb rainfall.	Noticeable reduction in the frequency and severity of floods in key areas.
Bandar Seri Begawan, Brunei [29]	Heavy rainfall, inadequate drainage systems, and low-lying areas are prone to waterlogging.	Improving the drainage network, constructing flood retention ponds, and implementing riverbank protection projects. Promote sustainable urban development practices that reduce surface runoff.	Effective management of stormwater helps mitigate the impact of flash floods. Enhanced the city's overall resilience.
Manila, Philippines [18], [21], [33]	Dense population, poor drainage systems, and exposure to typhoons and heavy monsoon rains.	Construction of pumping stations, rehabilitation of river systems, and the development of flood forecasting and early warning systems.	Reduction in flood incidents and improved preparedness among residents.

3.4 Key Requirements for Effective Flood Mitigation During Flash Floods in Urban Areas

Efficient flood mitigation during flash floods in urban areas requires a comprehensive strategy that incorporates multiple key requirements. As shown in Fig. 5, the effectiveness of flood mitigation efforts in urban areas during flash flood events is influenced by several critical factors. By addressing these critical factors, cities can better manage and mitigate the impacts of flash flood events.

Fig. 5 *Essential factors for effective flood mitigation in urban areas*

3.5 Lessons Learned and Best Practices

The research emphasises the importance of tailored solutions that take into account the unique geographic, climatic, and socio-economic conditions of each urban area. The findings from various cities offer valuable lessons for other cities facing similar challenges, contributing to the global knowledge base on effective flash flood mitigation in urban environments. As shown in Fig. 6, there are three aspects of flood mitigation strategies that can be considered: infrastructure and technology, community engagement and awareness, and sustainable urban planning. In terms of infrastructure and technology, effective flood mitigation requires a combination of robust infrastructure, advanced technology, and continuous maintenance. Projects like tidal gates, pumping stations, and drainage improvements have proven effective in reducing flood risks. For community engagement and awareness, public awareness and community involvement are crucial to the success of flood mitigation efforts. Educational campaigns and community-based programs help ensure that residents understand the risks and participate in preparedness activities. Finally, for sustainable urban planning, integrating flood risk management into urban planning is essential for creating resilient cities. Sustainable development practices that reduce surface runoff and preserve natural drainage areas are essential for effective flood mitigation.

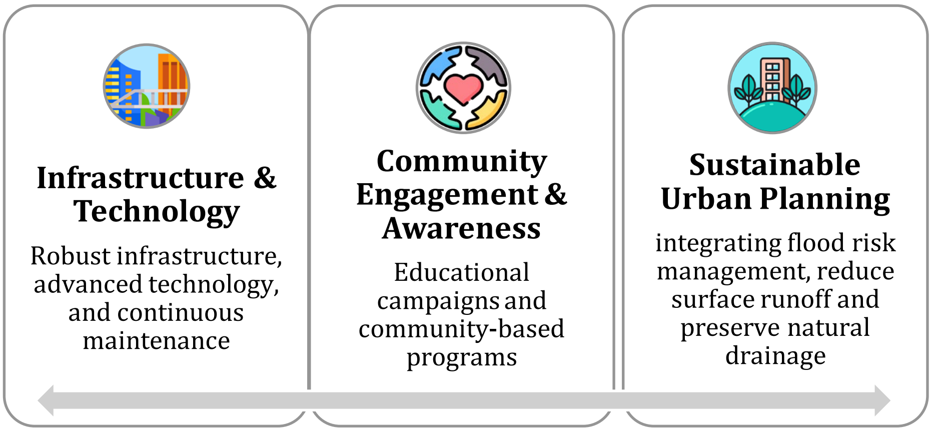

Fig. 6 *Aspects of flood mitigation strategy*

4. Conclusions

Successful mitigation requires a combination of structural and non-structural measures tailored to the specific urban context. Community involvement and public awareness are crucial for the acceptance and effectiveness of mitigation strategies. Continuous monitoring, maintenance, and adaptation of mitigation measures are crucial for addressing evolving flood risks and changing climatic conditions. These findings align with the research objectives by providing a detailed understanding of both the theoretical and practical aspects of flood mitigation, ultimately contributing to the development of more resilient urban environments.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm their contributions to the paper as follows: ***Study conception and design****: Rosmawati Mat Jihin and Azmarini Ahmad Nazri; data collection, Zanidah Ithnin and Supa'at Hj. Zakaria@Jawahir;* ***Analysis and interpretation of results:*** *Rosmawati Mat Jihin, Khairul Nizad Panior, Azmarini Ahmad Nazri;* ***Draft manuscript preparation:*** *Supa'at Hj. Zakaria@Jawahir, Zanidah Ithnin, Mohd. Zulhairi Zulkipli. All authors reviewed the results and approved the final version of the manuscript.*

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