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Research Article

Flood-proof Architectural Solutions for Urban Environments: A Review

Daad Fatehelrahman Yassin Mustafa[1, *]

[1] Architecture Urban design Department, Faculty of Engineering and Architecture, Sudan international University, Khartoum, Sudan

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ABSTRACT

Uban flooding is an ongoing problem due to climate change and increased urbanization. This paper aims to research solutions on flood-proof architecture, and flood-proofing techniques that can lessen the impact of urban flooding. Based on an intensive literature review and case-based analysis, solutions were proposed. This includes design principles, elevated structures, water-resistant construction materials, and green design plans. Modern solutions that focus on technology were also discussed, such as amphibious structures and hydraulic barriers. These architectural solutions not only contribute to flood-proofing but also increase resilience and ensures functionality in our urban spaces with aesthetic value. Ultimately, architectural practices must address environmental issues in mind to promote healthy urbanization.

1. INTRODUCTION

The Natural disasters, such as flooding, have grave consequences for urban spaces, including high casualties, severe property damage, and the destruction of public buildings and private businesses. Flooding is a recurring problem for many cities globally due to their geography, low elevation, and proximity to large water bodies. Flooding can result from extreme and sustained rainfall or rapid melting snow. The arrangements of urban infrastructures, such as highways, railways, and buildings, often impede the drainage of water. Urban flooding is a gradual process that ultimately transforms into a flash flood, resulting in localized water accumulation [1].

Urban flooding can be classified into meteorological flooding, drainage flooding, and tidal flooding. Meteorological flooding occurs due to high-intensity rainfall, which can overwhelm drainage mechanisms. Parts of cities initially designed to deal with water from a predetermined return period become flooded. Drainage flooding occurs from the malfunctioning of drainage systems due to high sedimentation rates, inadequate maintenance, or damage to pumping systems. Tidal flooding is associated with storm surges generated in deep waters, which lead to higher water levels near river mouths and threaten urban communities [2]. The devastation caused by flooding is further exacerbated by urban heat islands. Building materials and surface textures that absorb heat trap warmth in cities, leading to increased temperature and resulting in high-pressure zones over cities. When accompanied by intense rainfall, such high-pressure zones aggravate the development of thunderstorms over cities. In addressing urban flooding, it is crucial to understand the complex interaction between built spaces, hydrology, and topography.

1.1 Background and Rationale

Water is a defining part of city life. Waterfront locations are preferred for settlement and development, as they bring amenities and economic opportunities. Yet urban-water interaction is inherently vulnerable, made worse by climate change. Cities around the globe are threatened by coastal and river flooding, with significant economic risks to critical infrastructures like transportation, energy, health, and education. Storm surges, high river discharges, and heavy rainfall overwhelm drainage systems. Rising sea levels amplify these risks, making flood resilience essential for sustainable city development. Flood resilience helps water-adapted urban development by mitigating flooding's likelihood, impact, and recovery time [3].

Designers and policymakers must balance water safety, urbanization, and natural habitats. This requires innovative flood-proof architectural solutions, integrating flood resilience into urban planning and building design from the early stages. Solutions should suit local contexts and be supplemented by drainage systems, dikes, rivers, and wetlands. A watershed-based, holistic approach ensures effective integration of blue-green infrastructure in urban planning. A systematic review

*Corresponding author email: daadyassinyassin@gmail.com
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examines existing flood-proof architectural solutions for urban environments impacted by river and coastal flooding, identifying their design principles and effectiveness. This aids future solution development [4].

1.2 Scope and Objectives

The review focuses specifically on architectural responses to flooding, highlighting relevant strategies implemented in urban environments worldwide. It seeks to analyze flood-proof architectural solutions by examining a series of case studies through the lens of typologies. Ultimately, the review aims to identify key elements and considerations in the development of flood-proof architectural solutions. Recent extreme weather events have raised awareness of the importance of flood resilience in urban planning. With climate change leading to higher sea levels and increased flooding, cities must adapt. Although cities like Amsterdam and Venice have successfully dealt with water for generations, many others are at risk. Various scales of flood-proofing solutions exist, from urban planning to building design. This review focuses on building-scale flood-proof solutions in urban environments. There is a growing interest in and need for flood-proof architectural proposals, prompting a desire to better understand existing solutions. Critical buildings in cities are of particular interest, as their functionality during flood events is essential for public safety and recovery [5]. Designing flood-proof buildings poses challenges, as it is difficult for architects to find reference projects. This review aims to provide an overview of recent flood-proof architectural solutions for buildings in urban environments.

2. UNDERSTANDING FLOODS IN URBAN ENVIRONMENTS

Flooding is often considered a natural disaster, but it is a consequence of poor planning and environmental degradation in most cities. Floods caused by natural causes like excessive rainfall can be viewed as a manageable risk in cities with good planning . They turn into a disaster due to human negligence. Urban flood disasters are characterized by a high influx of floodwater and its prolonged retention. Urban flood plains have a high retention possibility due to the large number of buildings, roads, and other urban structures. Surface runoff drains the floodwater into the drainage system, and if the drainage system has the possibility of flooding, it leads to the retention of floodwater on the surface. In urban flood disasters, the floodwater first inundates the low-lying areas and then spreads to the higher areas and finally comes to a halt. Flood disasters are problematic because they affect the urban society's economy, security, and health. The loss is higher in a dense urban society because of the interdependent infrastructure systems. Flood-induced building failure also causes human casualties, which is a significant risk in urban flood disasters. With each urban flood disaster, a city can learn from its mistakes and become more flood resilient, but in reality, the opposite is true. Almost every flood-prone city has become more vulnerable to flood disasters. Hence, it becomes necessary to adopt flood-proof architectural solutions along with the urban planning solutions [6].

2.1 Types of Urban Flooding

In developed countries, urban flooding has gained recognition as a critical issue affecting both the environment and public safety in metropolitan areas. Casualties and damage from floods are projected to rise due to the anticipated increase in severity and frequency of torrential rains and urban runoff. Flooding events are characterized as catastrophic disasters, involving basin-wide flooding, mass evacuation, and significant property losses. In contrast, urban flooding is often non-catastrophic, localized, and gradual. While an entire watershed may flood during a basin-wide event, urban flooding typically occurs in selected areas, often in its center, given that upstream runoff converges to the low-lying and flat sections of the urban landscape. Urban flood hazards result from a complex interplay of natural and anthropogenic influences within densely built-up areas. Natural factors influencing flood hazards include topography, soil permeability, rainfall amount and patterns, and watershed size. some researchers presented a case studies like Park et al., 2021 [7], The study analyzes flood risks for buildings in Ulsan City, South Korea as shown in Figure 1, using vulnerability and exposure factors like building materials and environmental conditions. High-risk areas near the Taehwa River show dense urbanization and high property values, emphasizing the need for sustainable urban planning. The findings highlight the importance of combining structural and non-structural measures for effective flood mitigation.

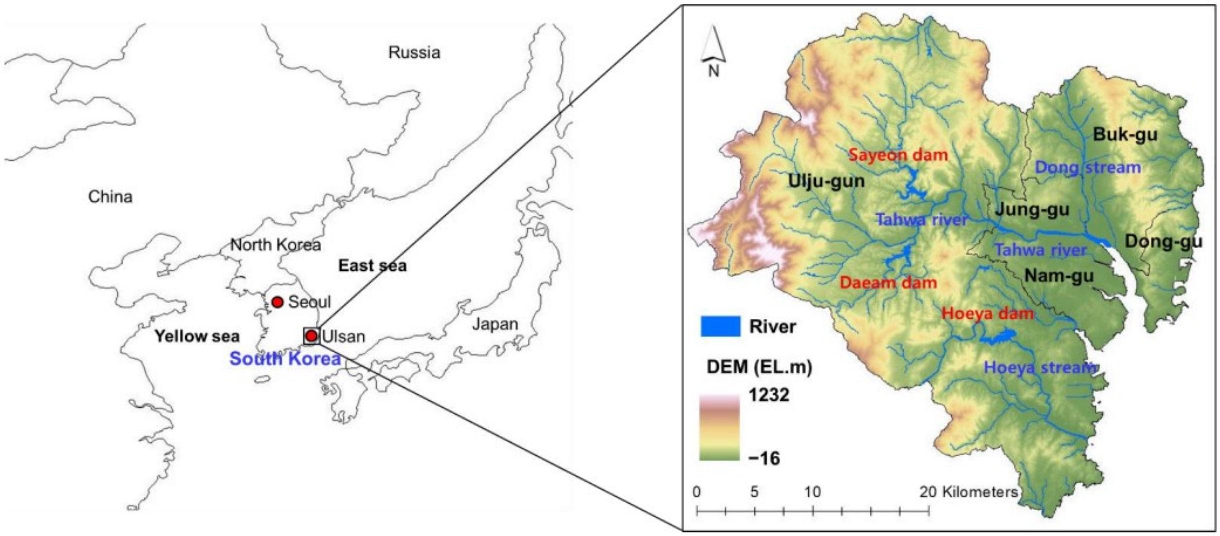

Fig 1. Region study of floods effect [7]

Aside from natural factors, anthropogenic factors significantly impact flood hazards. Widespread urbanization of flood-prone areas and the growing impermeability of the landscape increase flood hazards. As urban areas expand, the size of their watersheds often grows, resulting in longer time lags between rainfall onset and runoff arrival at the watershed outlet. Nonetheless, as pavement areas increase within the watershed, routing times decrease for runoff reaching the outlet, which can cause flooding at the watershed outlet. Such localized flooding, particularly in headwater settings, was observed across the Boston metropolitan area in the early 1990s and continues to afflict the city. For older neighborhoods, the convergence of several factors makes them particularly vulnerable to increasingly frequent and severe flooding events [8].

2.2 Causes of Urban Flooding

Flooding is one of the most common natural disasters that strongly interacts with the urban environment. A large proportion of the world's population lives in cities. Urbanization significantly alters the landscape, transforming vegetation and soil into artificial surfaces. This landscape change dramatically affects the water cycle and causes various water-related problems in urban environments. Urban flooding is one such problem; it occurs when urban drainage systems fail to remove excess rainwater runoff from the built environment to receiving water bodies [6]. Although urban drainage systems are designed to prevent flooding, flooding still occurs, particularly in developing countries. The existing drainage systems cannot cope with rapid urbanization, and problems such as encroachment, blocked drains, and poor maintenance increase flood risks. As a result, urban flooding is a major concern that poses public health and safety, infrastructure damage, and economic loss risks [9].

Urban flooding is caused by complex interactions between the urban environment and drainage systems. With urbanization, the land surface changes from pervious to impervious. This significantly increases surface runoff, generating excess inflow to the drainage system. On the other hand, the drainage system also interacts with the built environment. Drains are often constructed underground to facilitate land use. The complex and hidden nature of the drainage infrastructure makes it difficult to see how design modifications affect flooding risk. Moreover, in the urban environment, human activities have significantly altered natural drainage processes, increasing flood risk. A good understanding of urban drainage processes is thus required to appropriately model urban flood hazards and risks. Challenges in the urban environment complicate modeling drainage processes [10].

3. ARCHITECTURAL DESIGN CONSIDERATIONS FOR FLOOD-PROOFING

There is a clear correlation between design considerations for flooding and include considerations taking on board environmental and other considerations that could affect the public realm. In this respect, flood-proof architectural solutions especially urban flood-proof solutions–should have design considerations that involve non-flooding design considerations too [11].

Considering flooding design measures like enough elevation so as to prevent flooding ingress in an interior space might create a kind of dead-space, the space might not bring benefits if flooding should increase and the flood-proof design should not work. Such design-considerations can be viewed as local and only-flood focused. Urban flood measures at the architectural-scale should also have urban-phase design-considerations taken onto account. For example, urban flood-proof measures at the architectural-scale can have flood-realm design-considerations like creating a place for water-nature based recreation/service beings during dry-phases. So, flood-proof architectural solutions for urban environments would have design considerations involving floodplain but also taking on board non-flood design-considerations like enhancing the urban space outside flooding events [12].

3.1 Building Elevation and Foundation Design

Floor elevation is by far the most common response to flooding and is often required by state law. The most common approach is to raise a building's first floor above a computed flood elevation . Proposed elevations above modeled flood levels account for allowable changes in flood levels, freeboard, and anticipated effects of climate change. Elevation by fill is not permitted where it would block drainage. A foundation is a structural system that transfers loads from a building to underlying soil or rock. Foundations can be classified as shallow or deep depending on their depth relative to the ground surface. A shallow foundation typically derives its bearing capacity from soil with adequate load-bearing strength located just beneath the building. A deep foundation transfers building loads to deeper soil strata with adequate load-bearing strength. Deep foundations can be classified as driven or drilled. Driven foundations are installed using pile drivers that impact or vibrate the pile into the ground. Piles can be made of timber, steel, or concrete. Driven foundations commonly use precast concrete piles or H-piles. Drilled foundations are constructed using augers to excavate shafts, which are then filled with concrete and reinforcing steel. Drilled foundations are generally larger than driven foundations and construct continuous footing walls below ground similar to residential basements. The choice of foundation type depends on soil properties, construction conditions, building size, and other factors. Foundations may be designed to resist uplift forces due to natural hazards such as floods or hurricanes [13].

Flood resistant construction techniques can be used to mitigate damage to buildings during floods. Flood-resistant techniques include elevated construction, the use of flood proofing, and the use of floodwalls. Floodproofing can be subdivided into wet floodproofing and dry floodproofing. Wet floodproofing allows floodwaters to enter and exit a building and uses materials that are resistant to flooding. Wet floodproofing is commonly used in basements. Dry floodproofing involves constructing barriers to prohibit floodwaters from entering a building. Flood walls are barriers against floods with more stringent design conditions than floodproofing used in building construction. Flood walls are typically made of concrete and are designed to withstand soil pressure and hydrostatic forces from floods. Floodproofing is more commonly applied than flood walls because buildings often need to be elevated above base flood elevation. Floodplain management regulations describe floodplain development requirements to protect natural and beneficial floodplain functions [14].

3.2 Water-resistant Materials and Finishes

Flooding presents significant challenges for urban environments, necessitating the development of flood-proof architectural solutions. An effective approach in this context is the utilization of water-resistant materials and finishes in the construction of new buildings or during renovation. These special materials or protective layers create a barrier that restricts water penetration into the building's structure, components, and systems.

Water-resistant materials and finishes can be classified as either naturally water-resistant or artificially water-resistant. Naturally water-resistant materials contain inherent properties that make them resistant to water absorption, such as ceramic materials, polymers, metals, glass, and some wood species. On the other hand, artificially water-resistant materials initially absorb water but have been chemically treated to hinder the capillary rise of water precipitation [15].

4. INNOVATIVE TECHNOLOGIES FOR FLOOD-PROOFING

The water's edge is often a favored location for housing, conviviality, and work. Cities across the globe have historically settled alongside rivers and lakes, drawn in by the prospects of resource provision, food sustainability, agricultural trade routes, and accessibility. However, environmental shifts over time have turned these assets into liabilities. The consequences of climate change, such as soil sealing, urban heat islands, and increased extreme weather occurrences like rainstorms and rapid snowmelt, have led to flooding becoming a regular urban challenge that cities must address [16]. Can water be transformed from a destructive force into a city asset? This question has prompted research into innovative flood-proof architectural solutions for urban areas. Due to rising sea levels, the Netherlands is projected to face significant flood-related challenges. As a low-lying delta city, Rotterdam has implemented various flood-proof architectural measures, including the "water plaza" and "floating neighborhood." These flood-proof architectural solutions utilize innovative technologies, old and new. This study analyzes and discusses selected flood-proof architectural solutions adopted globally. A summary of this discussion is offered, along with suggestions for potential future flood-proof architectural solutions.

The devastation caused by floods is expected to intensify due to climate change, resulting in increased precipitation and rising sea levels. Cities are increasingly susceptible to flooding as a result of the sealing of soil, which restricts its capacity to absorb water [1]. Rivers can overflow and inundate the surrounding area if heavy rainfall occurs concurrently with high water levels in the river. In this case, the river can no longer hold the excess water. Storm overflows, when rivers overflow their banks and inundate the surrounding land, can occur in water courses with or without flood defence structures. Urban Flooding Cities are often subject to flooding as a result of the overloading of drainage systems and waterways. Flooding of this kind generally occurs during and shortly after heavy rainfall. Water is unable to run off because drainage systems are full and are therefore unable to take in any more water. The waterways are often also too full, which prevents water from being discharged from the drainage system to the waterway [17].

4.1 Flood Barriers and Gates

Flood Barriers and Gates, such as walls and gates, are the most common flood control structures currently being implemented globally. Existing flood walls can be refashioned to accommodate public programs and urban circulation. Dry flood walls can be shaped into hills that accommodate elevated public programs. Wet flood walls can be fully submerged and shaped into an island in a river. This strategy allows public programs to use these flood walls in the dry season and function as flood passageways between dikes.

Flood gates are usually combined with flood walls and riverfront planning. Existing flood gates, embedded within flood walls, can be designed as folding bridges to accommodate urban circulation during floods. They can also be designed as retractable gates, locally uplifting flood walls between two dikes, opening flood passageways to rivers while establishing bridge operations on the dry land between two dikes. This type of design maintains a continuous dry urban territory during standard flood protection, which can prevent non-river-connected flooding but is not accessible to rivers [18].

4.2 Green Infrastructure Solutions

Urban flood management strategies can comprise a range of engineering solutions from hard engineered flood defenses, such as flood walls or levees, to softer, more nature-based solutions like restoring wetlands and riverine buffers. These nature-based solutions also form a part of ‘green infrastructure’ that incorporate trees, soils, and green spaces to deliver complementary flood risk management benefits alongside their ecological, social, and aesthetic advantages. Green infrastructure solutions can take a number of forms such as raingardens, green roofs, green walls, permeable pavements, trees and bio-retention swales. A large body of monitored case study evidence demonstrates the capacity of these systems to reduce run-off and attenuate flood risk. Green infrastructure systems can help to mitigate flooding by promoting the natural infiltration and interception of rainfall, thereby reducing surface water run-off and peak flows reaching drainage systems. In particular, green roofs and raingardens have been shown to dramatically reduce runoff in some circumstances, achieving up to 100% runoff control for smaller rain events. However, the ability of green infrastructure as a flood mitigation approach is ultimately dependent on the local context including rainfall, existing drainage systems, the type and scale of urbanization, and the type and distribution of green infrastructure systems. The drainage systems and green infrastructure need to be designed to ensure that peak rainfall events are redirected away from the heavily impervious, high runoff urban areas into the adjacent pervious area. On the other hand, with a consideration of global change, extreme flooding could occur more frequently even with global efforts to limit temperature increase. Therefore, in addition to improving green infrastructure, it is critical to reduce the urban vulnerability to flooding by adopting appropriate architectural solutions [19].

5. CASE STUDIES OF FLOOD-PROOF ARCHITECTURAL PROJECTS

The following overview indicates the diversity of architectural solutions currently being embraced within urban environments facing flood risks. Such solutions can range from the simple yet effective theft of a house on stilts to do-it-yourself sandbag installations, through to long-term approaches, such as the construction of dikes, the redesign of river banks, and the planning of reservoir systems. In the first category, there is no lack of interesting viewpoints. It does seem contradictory, however, that an extreme, bioclimatic context such as Venice leads to such a passively elegant building: essentially, a hyper-inflated pavilion with rain-water collecting domes, shaped like “a hat gone wrong.” An equally challenging climate, that of Bangladesh, inspires a totally opposite approach. [20]

5.1 Project A: City Resilience Center

Project A: City Resilience Center. The design focuses on creating a community's central infrastructure to prepare and recover from flood events, keeping urban space functional and safe. It's located in the Jersey City & Hoboken area, adjacent to a flood-prone waterfront. Envisioned as a gathering point for the community and first responders, it provides resources like flood insurance and emergency supplies. It features an elevated amphitheater for public events, a multi-function auditorium, outdoor classrooms, a greenhouse, and active ground-level parking with robust emergency exits. Future design delves into activations in the adjacent flood zone park, enhancing water integration while preserving ecological habitats [21].

The site is in Hudson County, NJ, characterized by waterfront parks and historic districts. With 15 km of coastline facing the Hudson River, it attracts growth but poses flood risk, especially with climate change predictions. Extreme weather events are increasingly threatening coastal cities' safety and infrastructure. After hurricane sandy in 2012, Hoboken was declared a disaster area, revealing vulnerabilities in current flood management systems. Need for resilient urban environments to mitigate flooding, heat, and other climate effects. Embraces existing rivers and waterfronts as resilient ecosystem enhancement channels [22].

5.2 Project B: Waterfront Redevelopment

The historic heart of Amsterdam is confined by a canal ring built in the 17th century, recognized as a UNESCO World Heritage site. These canals are crucial in managing the city's water levels and flood risks. However, climate change challenges this delicate balance. In 2016, the City of Amsterdam developed the "Amsterdam Flood Resilience Strategy," focusing on improving flood resilience beyond expected extremes. Project B is part of this strategy, exploring contemporary architectural interventions for the city's waterfront. The proposal involves redeveloping an existing industrial harbor site into public space, with a docking location for a flood-proof emergency center. The waterfront's edge and flood-proof architecture are designed to accommodate different water levels while providing alternative access points [23].

Amsterdam's historic heart and UNESCO World Heritage Site are confined within a canal ring created in the 17th century. The canals now form a significant part of the city's infrastructure, as they contain and manage the water that flows through the city, thereby controlling its levels. The canals also provide protection against floods, as they keep excess water away from the city's lower lying areas. However, this delicate balance is challenged by climate change. In 2016, the City of Amsterdam developed the "Amsterdam Flood Resilience Strategy," focusing on improving flood resilience beyond what is expected from events with extreme probabilities. Project B is part of this strategy, exploring contemporary architectural interventions for the waterfronts of Amsterdam. Specifically, the proposal redevelops an existing industrial harbor site into public space for the city, with a docking location for a flood-proof emergency center. The design emphasizes the waterfront edge and the flood-proof architecture beside it, focusing on their responses to different water levels. At the same time, alternative access points are provided for normal conditions, as well as for flood situations [24].

6. ASSESSMENT AND EVALUATION OF FLOOD-PROOF ARCHITECTURAL SOLUTIONS

Flood-proof architectural solutions are proposed and assessed starting from the scale of the city and ending with the building, so that the solutions can mitigate the risk of a flood for one of the most vulnerable areas of the city of Ljubljana. Current flood-proof architectural solutions are collected and categorized in detail. The pros and cons of each solution are assessed and the measures, which are the most beneficial at avoiding or mitigating the risk of a flood, are highlighted [25]. These assessment criteria are used to assess flood-proof architectural solutions for the area of the potential investment in flood-proof architectural solutions in the Cankarjevo nabrežje waterfront in the city of Ljubljana. Currently, this waterfront with publicly accessible space by the river is most at risk from a flood, because the flood-proof architectural solution runs along the edge of the water. Therefore, flood-proof architectural solutions are first proposed to protect the Cankarjevo nabrežje waterfront and the buildings along it from a flood at the scale of the city. These solutions prevent flooding, while also retaining public space by the river. However, the waterfront would still be flooded in the case of a five-centimeter higher flood. Therefore, flood-proof architectural solutions are proposed primarily for the buildings at the Cankarjevo nabrežje waterfront, starting with an overview of the buildings and their assessment in terms of flood vulnerability [1]. In addition, the proposed flood-proof architectural solutions, which are raised floors, flood-proof walls, and passive flood-proof doors, allow building entrances and exits to remain at the same level.

6.1 Performance Metrics and Criteria

A review of performance metrics and assessment criteria for flood-proof architectural design solutions is presented. Performance metrics focused on urban built environments were included as the basis for the review. A discussion on the design solutions is provided, highlighting the importance of performance metrics and assessment criteria to ensure the viability of flood-proof design solutions. Flooding poses challenges to urban areas worldwide. Climate adaptation is crucial for the sustainability of cities, particularly the protection of urban built environments. Flood-proof architectural design solutions have been developed to protect urban built environments from flooding. Design solutions, such as elevation and waterproofing, consideration of access and safety during flooding, use of natural systems, and hybrid approaches were reviewed. Performance metrics and assessment criteria were often overlooked in the review of flood-proof design solutions [26]. Without an evaluation framework, there is a risk of adopting design solutions that may perform poorly under unforeseen risk scenarios.

6.2 Cost-benefit Analysis

Flood proofing is used to refer an action taken to prevent flood from damaging a certain property. Flood proofing can be an alternative for flood control. Flood control measures are water-based measures which require a huge investment in construction of dams, levees and flood channels, and on-going maintenance. On the other hand, flood proofing measures require minimal maintenance and can save damage and loss from flooding [27]. In architecture, flood proofing can be considered as designing the structure in such a way that it can resist flood or elevating the structure so that the flood cannot reach or affect it. The architectural flood proofing techniques vary with the type of flood. Generally, the flood proofing techniques can be passive flood proofing techniques or active flood proofing techniques. Passive flood proofing techniques do not require any intervention from the owner during the flood. These techniques usually include elevating the buildings by building berms or raising the plinth. The most extreme passive flood proofing technique is building the structure underground. Meanwhile, active flood proofing techniques require intervention of the owner or management during the flood [28].

7. REGULATORY AND POLICY FRAMEWORKS FOR FLOOD-PROOF ARCHITECTURE

A more integrated approach to flood risks and security by linking land-use planning, regulation and urban flood forecasting and warning is presented. The need to develop proactive strategies for flood prevention and mitigation in mega cities under global change scenarios with increased probability and intensity of extreme weather events, and urban expansion and densification is identified. A necessity concern for the improvement of current flood risk mitigation strategies, recent flood events in European cities including the city of Prague and the Roztoky conurbation is analyzed. A range of flood risk mitigation approaches, from infrastructural adjustments to regulatory measures, early warning systems and flood proof design are critically reviewed.

The current regulatory and policy framework, related to flood risk assessment and management as well as flood dealing architecture concepts and solutions, developed at different stages is elaborated and some new possibilities suggested. The necessity of flood proof design solutions and their integration in the urban environment is illustrated on the example of flood proof building design concept in Prague dealing with the flood plain of the river Vltava. The challenges of dealing with flood protection and prevention in an urban environment are discussed together with the needs for the design of flood proof architecture integrated with the urban landscape [29].

7.1 Building Codes and Standards

Globally, the problem of flood risks and climate change effects has significant attention from researchers, urban planners, and policymakers. As the number of urban flooding events rises, various flood-proof architectural solutions are discussed. Many cities require consistency with national and local building codes that can limit the choice of flood-proof architectural solutions. The review is focused on flood-proof architectural solutions applied in permanent constructions. A classification of flood-proof architectural solutions is proposed and discussed. The planning and design process of flood-proof architectural solutions is determined on the basis of cases applied in urban environments in various countries considering local building codes and standards.

Global attention is paid to the problem of urban flooding and flood risks exacerbated by climate change effects. In cities with a high level of imperviousness, even small rainfalls can cause flooding. As a result, there is a need for extensive approaches to urban flooding mitigation, such as Green Infrastructure, Low Impact Development, Sustainable Urban Drainage Systems, etc. Despite the measures for the prevention of urban flooding, the most vulnerable areas must be protected from the consequences of flooding. Permanent constructions are the most significant buildings in urban environments, and their protection from flooding is crucial. In many cities, flood-proof architectural solutions are applied to permanent constructions. Approaches how to make buildings flood-proof are widely discussed. However, most of the solutions are unique and designed according to local requirements and building codes. The focus is on flood-proof architectural solutions applied to permanent constructions in urban environments [30].

7.2 Government Incentives and Support

Government authorities play a vital role in the decision to implement flood-proof solutions. Especially in developing countries, these solutions must be supported by the government. Governments in ASEAN countries must make efforts to improve urban planning to be more resilient to floods by the year 2025. The implementation of this regulation can be a big step for ASEAN countries. National policies can be translated to local policies through respective government regulations. In Indonesia, Law No. 26/2007 on Spatial Planning regulates that the resilience of settlement from flood must be considered in spatial planning. To support this regulation, the government has issued several policies regarding flood control in Jakarta and other cities in Indonesia. Jakarta has been designated as a pilot city for a flood resilience city program initiated by Indonesia and ADB.

Building flood resilience in cities requires long-term investment. Financial support from the government is necessary to increase the motivation of property developers to build flood-proof developments. In Indonesia, the government offers incentives for developers that build affordable housing, such as subsidized housing loans. This type of incentive can also be implemented to encourage developers to build flood-proof developments. Special incentives such as a transferable or tradable development rights scheme could be considered for developments in flood-prone areas that convert a portion of the land use to flood-proof developments [31]. This would entail allowing one developer to build a larger development in another location in exchange for developing a flood-proof development.

8. CHALLENGES AND FUTURE DIRECTIONS

Flooding in urban environments can be caused by heavy rainfall, storm surges, or snowmelt. Flooding may be exacerbated by natural or human-induced changes to the landscape, such as urbanization, deforestation, wetland drainage, and dam construction. Over 20% of the world's urban population currently lives in flood-prone areas, with that number expected to grow drastically in the years to come. Floods posing a risk to anthropogenic systems have serious societal implications, including loss of human life, destruction of buildings and infrastructure, and high economic costs. Action is required at the building level in order to avoid disaster [32].

Flood-proofing strategies for buildings are examined. Firstly, an overview of relevant flood-proofing strategies is presented. Attention is then turned to the potential role of architectural solutions in accommodating flood-proofing strategies. The implementation of flood-proofing strategies cannot be considered solely from the perspective of flood-proofing. Decisions about flood-proofing will shape buildings and environments for a long time. This will be especially true in the case of passive flood-proofing strategies, which typically involve significant alteration or adaptation of a building's waterproof envelope. Therefore, it is crucial that flood-proofing strategies are implemented in a way that does not compromise design quality. Lastly, the limitations of current knowledge and potential avenues for further research into flood-proofing strategies are highlighted.

8.1 Technological Advancements

The approach taken in the review is that of a retrospective analysis of new flood-proof architectural solutions with the aim of grouping them according to their architectural and technological characteristics. The new flood-proof architectural solutions have been grouped into four main types based on their flood-proof technological systems: hydraulic barriers, floating constructions, amphibious constructions, and concessions. Each type has been further categorized into sub-types based on different technological approaches and solutions within each main type. The review also provides the latest examples of each sub-type. The up-to-date situations with each type and sub-type of flood-proof architectural solutions are shown together with their main advantages and drawbacks. Some general conclusions and thoughts about prospective developments in this research area are also provided. Flooding poses a danger to urban environments all around the globe, particularly given the prevalence of climate change impacts. Effective design approaches must be developed in order to lessen the consequences of flooding. A number of significant inundations that affected cities across the world in the last several decades provided the impetus for research into new flood-proof architectural solutions. An overview of the newest flood-proof architectural solutions created for urban settings from 1990 until the present is provided in this review article. Recent studies and developments of flood-proof architectural solutions are examined and linked to other approaches and technologies. Regarding generally used technological systems, the reviewed flood-proof architectural solutions are categorized into four main types with several sub-types: (1) hydraulic barriers, (1.1) movable hardened barriers, and (1.2) inflatable barriers; (2) floating constructions, (2.1) rigid floating structures and (2.2) flexible floating structures; (3) amphibious constructions, (3.1) buoyant foundations and (3.2) elevating structures; and (4) concessions [33].

8.2 Community Engagement and Education

Participatory Design Workshop Analyses and Discussions by Professionals The workshop was held on May 4th at KTH. Four professionals were invited to discuss the student group proposals and the state of flood-proof architectural solutions. Participants included an architect and urban planner, an architect and researcher, an architect and artist, and an architect and researcher. The group discussions provided insight into implementation possibilities and the advantages and challenges of the proposed solutions. The points raised in the discussions were summarized in comments on each proposal and general insights about the state of flood-proof architectural solutions.

These insights include the acknowledgement of the transformative quality of spaces designed to accommodate floods. The flood-proof solutions were seen as a shift of the design attitude, understanding that flooding cannot be avoided and designing built environments with an ability to adapt to flooding. This transformative quality of the spaces should be made visible to the public during their normal functions to improve flood awareness. Most proposals primarily focused on how spaces transform during flooding at the expense of their normal function. To maximize the efficiency of the spaces, the transformation could be dual, serving both a flood-proof purpose and other functions to improve flood awareness. For example, dikes were designed as a recreational space but didn't consider how people would understand the flood-proof purpose of the space [34].

9. CONCLUSION AND RECOMMENDATIONS

Floods have emerged as one of the most destructive disasters globally, severely affecting urban environments and their inhabitants' quality of life. Urban environments, constructed with concrete, geotechnical materials, and impermeable surfaces, do not harmonize with natural water systems. Despite ongoing efforts to control and utilize floods as a resource, many cities remain susceptible to inundation due to urbanization and climate change [35].

This study examines flood-proof architectural solutions in urban settings, exploring how water/river frontage areas or zones can be transformed into flood-proof zones through architectural and urban design interventions. It aims to review several significant architectural solutions or interventions, categorize them, and assess their existing or potential application in current and future urban flood-proof developments, thereby contributing to forming flood-proof architectural solutions in urban city zones. The findings show that diverse flood-proof architectural interventions are being implemented or explored in various river/sea cities worldwide. These architectural flood-proof solutions can be categorized into four main typologies based on their primary flood-proof design strategies or approaches: raise and protect, hybrid, explore, and accommodate. The first two typologies transform flood-prone areas into flood-proof zones, while the last two consider floods a resource/asset, enhancing the area's livability and resilience .

9.1 Key Findings

A literature review is performed on architectural solutions against flooding based on previous research. A selection of designs is evaluated based on their flood-proofing techniques, structure, and energy consumption assessment. Although the building standards for flood-proof architecture are well set for the structural protection against floods, there are indications that not all possible strategies are currently used on newly constructed flood-proof buildings [1]. The aim of this review is to look for relevant examples of flood-proof architecture in urban environments and map their approaches. Designed flood-proof buildings are collected from different countries that experienced damage due to flooding in the past or have critical flood risks for the future. The local flood risk and subsequent building standards are explained for each case study. A selection of buildings is then presented and categorized according to their flood-proofing techniques. Several buildings featuring innovative designs are explained in more depth. Finally, an evaluation of the selected designs is performed based on their flood-proofing technique, structural approach, and energy consumption assessment [2].

9.2 Practical Recommendations for Implementation

Flood resilience through architecture is of vital importance to long-term sustainability of urban environments. As flooding risk changes intensively across the world, a multitude of architectural solutions have been produced and implemented. A range of such architectural solutions is reviewed here, from levees and flood walls to amphibious buildings. The focus is on urban environments architecturally either already flood-vulnerable or about to be exposed to increasing flood risk due to climate change and related sea level rise. The aim is to provide a stepping stone for further research on flood-proof architectural solutions addressing specific flood risks.

In order to mitigate flooding vulnerable sites in cities today innovative architectural solutions are critical. By essentially building flood resilience into the architecture itself, negative side effects of conventional flood mitigation such as blight or dead zones can be reduced. An abundance of flood-proof architectural solutions have been designed and implemented across the globe. The majority of solutions are representative case studies addressing a range of specific flood risk scenarios. Organised by their core principles, flood-proof architectural solutions are here critically reviewed and illustrated with examples from around the world [2]. The review is intended to provide a foundation for further research and development of flood-proof architectural solutions. With the right design sensitivity, vulnerable sites can be transformed from liability into opportunity, erasing boundaries between land and water. All solutions reviewed here as well as the case studies presented within share this potential and envision alternative futures for flood-vulnerable urban environments [1].

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