

From barriers to bioswales: An engineering-centric review of materials and design for urban flood resilience

Salihu Yabagi Yahaya Kolo ^{1*} , Musa Danlami Salihu ² 

¹Department of Master of Science in Construction Management, Faculty of Engineering and Quantity Surveying, Inti International University, Persiaran Perdana BBN Putra Nilai, 71800 Negeri Sembilan, MALAYSIA

²Department of Chemical and Petroleum Engineering, Bayero University, PMB 3011, Kano, Kano state, NIGERIA

*Corresponding Author: syabagiyahaya98@gmail.com

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ABSTRACT

The synergistic risks posed by urbanisation and climate change have made flooding a paramount threat to global urban infrastructure. Although the combination of structural, nature-based, and policy-based solutions is widely encouraged, the specific engineering principles and material technologies that enable successful resilience have not been extensively studied in interdisciplinary discussions. This review conducts a critical, engineering-centric analysis of flood-resilient design, synthesising current knowledge through the lenses of structural integrity and materials engineering. Conventional grey infrastructure, nature-based solutions (NBS), and building-level adaptations are evaluated by performance under hydrostatic and hydrodynamic loads, failure modes, and durability. The analysis extends to the integrating role of smart digital tools, such as Digital Twins and the Internet of Things (IoT), in creating adaptive systems. The synthesis identifies formidable technical, organisational, and socio-economic barriers, including data scarcity, institutional fragmentation, and chronic underfunding, that hinder implementation. Overcoming these challenges requires an Integrated Life-Cycle Resilience Framework, which inextricably links predictive analytics with robust physical design, supported by policy and financing models that prioritise durable, adaptable, and equitable engineering solutions.

Keywords: flood resilience, urbanisation, climate change, nature-based solutions, digital twins, infrastructure systems

INTRODUCTION

The Escalating Urban Flood Challenge

Natural disasters, particularly floods, pose a significant threat to global urban centres. This trend is amplified by concurrent pressures from rapid urbanisation, increasing population density, and concentrated economic activity (Gao et al., 2022; Rentschler et al., 2022). As cities expand, their very development (through the proliferation of impervious surfaces, drainage reallocation, and construction in high-risk zones) makes them even more vulnerable to flood hazards (Adeyeye et al., 2017; Zhu et al., 2022). The impact of flooding can be severe; infrastructure systems such as transportation networks, power grids, and housing come under significant pressure, leading to failures that endanger lives, destroy property, and affect economies (Chaudhary & Piracha, 2021; Khodadad et al., 2023).

Floods are among the most common and devastating natural disasters globally. According to a UN report (Centre for Research on the Epidemiology of Disasters, 2020) or (CRED,

2020), between 2000 and 2019, the number of strong floods increased from 1389 to 3254, accounting for 44% of climate-related disasters. Between 2000 and 2019, floods affected about 1.6 billion people and resulted in the deaths of 104,614 people (Grigorieva et al., 2022). Bangladesh is widely recognised as one of the most flood-prone countries in the world. Thousands of people lose their lives and properties to floods every year in the country (Hossain, 2020)

Climate change, driving increased rainfall intensity and sea-level rise, creates a dangerous feedback loop, making cities more prone to both pluvial and fluvial flooding (IPCC, 2022; Wang et al., 2021; Wei et al., 2022). The "7.20" extreme rainstorm event in Zhengzhou (2021) serves as a tragic case study, in which rapid urban development drastically altered local water systems, underlying surface permeability, and topography, culminating in a catastrophic urban flood that underscored the systemic vulnerabilities of modern infrastructure (Li et al., 2023).

Traditionally, managing flood risk is more about controlling the flood; this approach relies on hard-engineered, structural measures designed to keep water out. While these

approaches remain relevant, their limitations are becoming increasingly evident, creating a false sense of security. (Aerts, 2018). This has prompted a fundamental shift towards flood resilience, which is the capacity of urban systems to anticipate, absorb, adapt to, and recover from flooding. This concept is now central to global policy agendas, including the Sendai Framework for Disaster Risk Reduction and the United Nations Sustainable Development Goals (SDGs) (Li et al., 2023), particularly SDG 9 (resilient infrastructure) and SDG 11 (sustainable cities), which emphasizes the need to integrate climate adaptation into all stages of urban development and planning (Allan et al., 2024; Belenguer-Plomer et al., 2025; Monaco, 2024; Vannucci et al., 2021).

Engineering Resilience can be defined as a system's capacity to predict, absorb, adapt to, and swiftly recover from a disastrous event such as a flood (Wang et al., 2022). This therefore, requires that urban infrastructure design must take strength and adaptability into consideration, The UK's, Engineering and Physical Sciences Research Council (EPSRC) defines the concept of urban flood resilience as the capacity to handle future flood risk to acceptable amounts through averting casualties, minimizing both direct and indirect harm, and ensuring prompt recovery of key services (Gao et al., 2022).

Despite growing recognition of these strategies, a significant implementation gap persists, particularly in translating policy ambitions into long-lasting, on-the-ground engineering solutions (White et al., 2018). Many reviews approach flood resilience from hydrological, planning, or policy perspectives, lacking the technical, materials-focused analysis required to inform physical design and construction. There is a need to examine flood resilience with a focus on the performance, longevity, and failure of the physical elements that make up urban infrastructure.

This review aims to bridge that gap by providing an engineering-centric synthesis. Its specific objectives are:

1. To analyse and compare flood-resilient design approaches through the specialised lenses of structural and materials engineering,
2. To evaluate the role and integration of smart digital tools in enhancing system adaptability,
3. To identify the technical, organisational, and socio-economic barriers that impede the implementation of integrated solutions,
4. To propose a novel Integrated Life-Cycle Resilience Framework and outline a priority research agenda to advance the field.

The Spectrum of Flood Resilience Strategies

Flood resilience strategies are broadly categorised into structural, non-structural, and nature-based solutions, though the most effective approaches integrate all three.

Structural measures

These are physical interventions designed to resist or manage floodwaters (Mannucci, 2022). Traditional examples include levees, flood walls, dams, and large-scale stormwater drainage tunnels (Manandhar et al., 2023). Advanced systems, such as the Modulo Sperimentale Elettromeccanico (MOSE) mobile barriers in Venice, represent the cutting edge of

structural defence. However, they pose complex challenges, including costs, maintenance, and environmental impact (Giupponi et al., 2024).

Non-structural measures

These measures focus on reducing vulnerability and exposure to floods through policy, planning, and communication. They include the development and enforcement of flood-resilient building codes, land-use planning and zoning regulations, flood forecasting and early warning systems, public awareness campaigns, and flood insurance programs (Hegger et al., 2014; Mehryar & Surminski, 2021).

Nature-Based Solutions (NBS)

NBS seek to make use of natural processes to enhance resilience. Approaches such as wetland restoration, the creation of bioswales, rain gardens, and the implementation of permeable pavements aim to manage water at its source by increasing infiltration, storage, and evapotranspiration (Chiu et al., 2021; Ferreira et al., 2023). These solutions often provide co-benefits, such as improved biodiversity, enhanced water quality, and mitigation of urban heat islands (Markus-Michalczyk et al., 2023).

The most robust approaches integrate all three categories.

METHODOLOGY

This study employs a Scoping Review methodology based on the framework of Arksey and O'Malley, complemented by refinements from the Joanna Briggs Institute (JBI). This approach is appropriate for the multidisciplinary nature of urban flood resilience research, where evidence spans structural engineering, nature-based solutions, building-level adaptations, materials science, hydrology and digital technologies. The method enables broad mapping of technical concepts, performance characteristics, and implementation considerations without restricting the review to comparable experimental designs.

A structured search strategy was implemented across major scholarly databases, including Scopus, ScienceDirect, ASCE Library, IEEE Xplore, and Google Scholar for supplementary coverage. To improve methodological transparency, Boolean logic was applied to refine the search strategy. The search incorporated combinations of engineering and flood-related terms such as ("flood resilience" OR "urban flooding" OR "flood mitigation") AND ("structural defence" OR "nature-based solutions" OR "permeable pavement" OR "bioswales" OR "digital twin" OR "IoT sensors") AND ("urban infrastructure" OR "built environment"). The search was limited to peer-reviewed publications and technical publications published between 1999 and 2024 to ensure both foundational and contemporary developments were captured. This process yielded over 80 core references, which were analysed thematically to construct the critical evaluation and synthesis presented herein.

Studies were selected through a two-stage screening process. Titles and abstracts were first reviewed to confirm relevance to urban flood resilience and engineering-based interventions. Full texts were then assessed using predefined eligibility criteria. Included studies were required to address structural systems, green infrastructure, building-level flood-proofing, or digital technologies with engineering relevance. Studies focusing exclusively on rural watersheds, socio-economic analysis without technical content, or non-scholarly sources were excluded. Studies were excluded if they lacked engineering relevance, focused solely on rural watershed management, or examined socio-economic issues without technical, hydrological, or material-performance components. Publications were also omitted if they did not address urban flood resilience, were non-scholarly (e.g., news articles or opinion pieces), or were unavailable in full text. Duplicate records were removed during the initial screening stage to ensure unique, technically relevant sources were included in the review.

Data extraction followed a structured charting procedure. Key information captured from each study included the type of intervention, engineering mechanisms, material characteristics, hydraulic performance metrics, failure modes, digital system functions, and any associated policy or implementation context. This process was iterative, allowing refinement of extracted categories as new themes emerged. A light-touch quality appraisal, consistent with JBI guidelines, was applied to ensure the technical reliability of the included studies. However, no studies were excluded solely based on methodological quality.

The extracted data were synthesised narratively and organised into four primary thematic domains: structural defence systems, nature-based and hybrid solutions, building-level adaptations, and smart/digital flood resilience technologies. Cross-domain analysis was conducted to identify convergent engineering principles, performance patterns, implementation barriers, and gaps in current practice. This synthesis underpins the development of the integrated resilience framework presented in the subsequent section.

CRITICAL ENGINEERING ANALYSIS OF FLOOD RESILIENT DESIGN APPROACHES

A flood-resilient city is not just one with installed bioswales, levees, or smart sensors. It is one whose bioswales, levees, and sensors have been designed, specified, and maintained with an integrated understanding of how each component performs, degrades, and fails. A holistic flood resilience strategy integrates multiple interventions, ranging from large-scale structural defences to building-level adaptations and smart digital tools. Structural measures resist hydrostatic and hydrodynamic loads. (Raikes et al., 2019; Van Berchum et al., 2019). Hence, their design is governed by geotechnical and structural mechanics, with distinct failure modes dictating safety factors and material selection. This section organises the evidence around four challenges that cut across all intervention types. The challenges identified are:

load capacity, longevity, physical-digital synergy, and scale compatibility.

Load Withstanding Capabilities

Flood waters exert conceptually simple forces, such as hydrostatic pressure, hydrodynamic drag, buoyancy, and debris impact, but are deceptively complex in their interaction with structures. An engineer designing a floodwall would normally calculate overturning moments and sliding resistance. However, when the flood arrives, it does so almost certainly without obeying the calculation sheet. Rather, it arrives with scour, demonstrating differential pressures that shift as water seeps through joints and cracks.

Levees and dikes are earth embankments whose stability depends on unsaturated conditions. At saturation, effective stress decreases, pore water pressure rises, and slope failures become probable (Raikes et al., 2019; USACE, 2019). One common failure mode is overtopping, which erodes the landward face, reducing confining pressure, which leads to piping that, in turn, undermines structural integrity and results in mass sliding along a curved failure surface. (Serra-Llobet et al., 2022). Modern construction incorporates geosynthetic clay liners and articulated concrete block armouring to increase impermeability and erosion resistance. However, these additions introduce their own failure modes. Geosynthetic clay liners are susceptible to puncture during installation, and articulated blocks require interlock integrity that degrades under repeated wave attack.

Floodwalls, typically of reinforced concrete or steel sheet piles, address different loading regimes. Their vulnerability lies not in slope stability but in foundation scour, which removes supporting soil and transforms a fixed-base cantilever into a propped cantilever with an uncertain prop location (Mabrouk et al., 2024). Post-event forensic investigations consistently identify inadequate foundation depth as a primary cause of failure (USACE, 2019). Joints between wall segments are another weak point. Water tightness depends on sealant durability, which is rarely verified beyond the contractor's warranty period.

The MOSE system in Venice is a prime example of the complexity of large-scale structural flood defence. It is a system featuring 78 mobile steel gates installed at three inlets to the Venice Lagoon (Alberti et al., 2023; Vergano et al., 2010). From an engineering standpoint, MOSE faces three distinct challenges.

The first challenge is material durability. The gates operate in a saline marine environment with aggressive chloride exposure. Cathodic protection and high-performance coatings provide corrosion resistance, but both require monitoring and periodic renewal. The hinge mechanisms, continuously submerged, face biofouling and crevice corrosion risks that laboratory testing cannot fully replicate.

The second challenge is mechanical reliability. Each gate is articulated by hydraulic actuators that must operate under significant dynamic loads during storm conditions. The system has demonstrated operational success since its 2020 activation, but the long-term reliability of such complex mechanical systems under infrequent but extreme loading remains an open question (Giupponi et al., 2024).

Table 1. Comparative analysis of structural flood defence systems

Structural Measure	Primary Materials	Key Design Loads	Dominant Failure Modes
Levee / Dike	Compacted earth, clay, geotextiles, riprap	Hydrostatic pressure, seepage forces, wave run-up	Overtopping & erosion, internal erosion (piping), slope failure
Reinforced Concrete Floodwall	Reinforced concrete, steel rebar	Hydrostatic pressure, overturning moment, debris impact	Toe scour, structural flexural/shear failure, joint leakage
Sheet Pile Wall	Steel sheet piles, tie-back anchors	Hydrostatic pressure, active earth pressure	Interlock failure, anchor failure, excessive deflection
Storm Surge Barrier	Steel, concrete, composites	Hydrostatic & hydrodynamic pressure, wave forces	Gate mechanism failure, foundation scour, corrosion

Foundation engineering is the third challenge. The concrete caissons housing the gates required deep foundations to resist settlement and lateral loads. This is not innovative geotechnics; it is a conventional foundation design executed on an enormous scale. The innovation lies in system integration and the associated cost, which exceeds €6 billion (Tagliapietra et al., 2024)

Synthesis of findings on structural systems

Table 1 summarises the materials, design loads, and dominant failure modes of common structural flood defence systems. What is striking is not the diversity of failure mechanisms but their predictability: every failure mode listed is well understood in the geotechnical and structural engineering literature. The fact that these failures continue to occur points not to a knowledge deficit but to an application deficit, a gap between what is known and what is built, maintained, and inspected.

The significance of these findings for resilience engineering is clear. Structural defence systems, whether earth embankments or mobile gates, are designed against specified loads. When loads exceed design assumptions, a more frequent occurrence under climate change, failure is not a malfunction. It is the system behaving as designed. Resilience engineering therefore requires not only strengthening primary defences but also designing for graceful failure. This includes incorporating controlled overtopping zones, scour-resistant toe protection, and redundant load paths that maintain structural integrity even after localised damage.

Outlasting the Maintenance Cycle

Engineering literature is replete with technologies that perform admirably in theory but fail predictably in the field. The discrepancy does not lie in flawed science, but in the assumption, rarely stated or justified, that maintenance will occur as specified.

Permeable pavements, unfortunately, illustrate this gap with clarity. A properly designed permeable pavement system comprises a pervious surface course of porous asphalt or pervious concrete, a bedding layer, an open-graded stone base that provides both structural support and temporary water storage, and a geotextile separating the base from the subgrade (Mullaney & Lucke, 2014). **Figure 1** shows a typical cross-section. The hydraulic function is straightforward. Rainfall infiltrates the surface, percolates through the base, and either exfiltrates to the subgrade or discharges via underdrains.

The failure mode is clogging, where sediment accumulates in surface pores, reducing infiltration capacity. Without

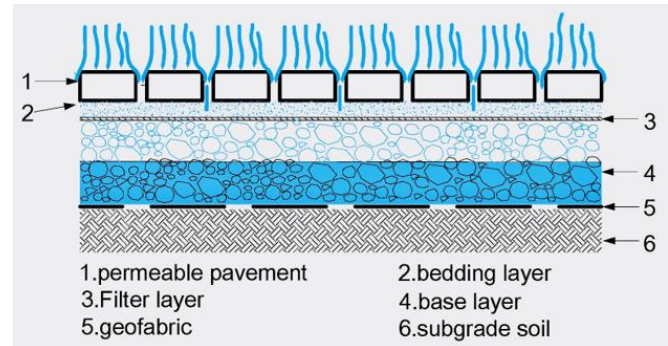


Figure 1. Permeable pavement cross-section. Rainfall infiltrates the porous surface into a subsurface reservoir base, which temporarily stores water before it gradually infiltrates into the surrounding soil, reducing runoff (Qin, 2020)

regular vacuum sweeping, typically specified at two to four times annually, depending on sediment loading, hydraulic performance degrades rapidly (Santhanam & Majumdar, 2020). Field studies consistently show that permeable pavements in residential streets, where maintenance budgets are constrained, and sediment loads from landscaped areas are high, lose 70 to 90 per cent of their designed infiltration capacity within three to five years (Mullaney & Lucke, 2014). Therefore, the technology works, but the institutional commitment to maintaining it does not.

Bioswales and rain gardens face analogous challenges. Their engineered soil media are designed for specific infiltration rates, typically 25-150 millimetres per hour, depending on the context (Mohamed et al., 2025). Vegetation plays a structural role. Root networks stabilise soil and create macropore pathways that enhance infiltration (Osheen & Singh, 2019). However, vegetation also requires maintenance such as invasive species removal, sediment accumulation management, and replacement of dead plants. Post-installation monitoring studies are rare, but those that exist document a consistent pattern. Initial hydraulic performance meets specifications, followed by progressive decline as maintenance lapses (Ferreira et al., 2023). **Figure 2** illustrates how bioswales, raingardens, and permeable pavements can be combined in a hybrid flood-resilient street. While conceptually elegant, these designs remain critically dependent upon uninterrupted maintenance regimes to ensure their long-term functional integrity.

Wetland restoration operates at a larger scale than bioswales and rain gardens but follows the same principle. One acre of wetland can store 1 to 1.5 million gallons of floodwater (Pricope & Shivers, 2022). This storage capacity, however, depends on hydraulic connectivity, sediment accumulation

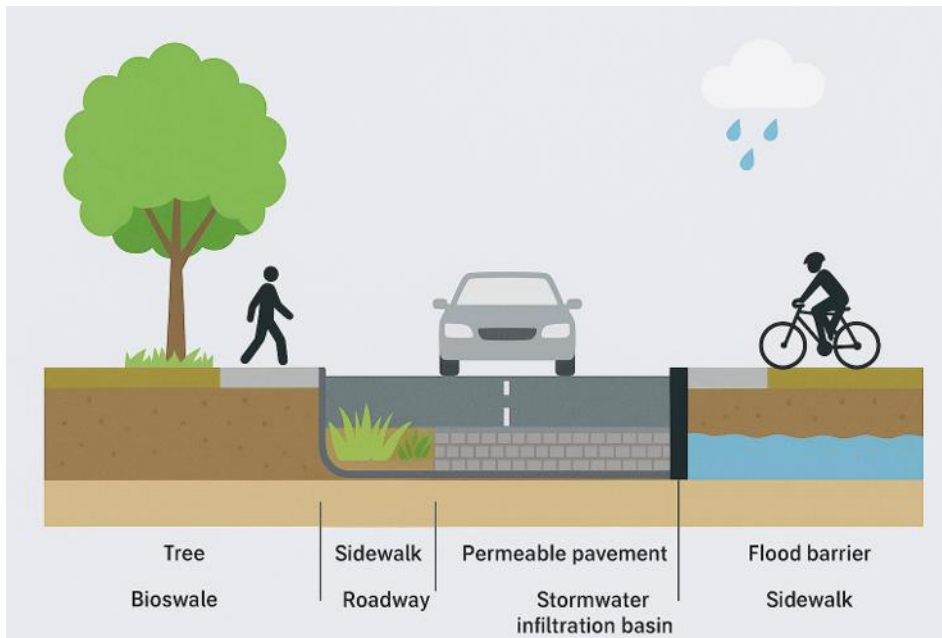


Figure 2. Conceptual cross-section of a hybrid flood-resilient street. The system works in concert to delay, filter, store, and slowly release stormwater, reducing flood risk while providing ecological co-benefits (Source: Authors' own elaboration).

rates, and vegetation community composition, all of which change over time. Wetlands are not static infrastructure. They are dynamic ecosystems. Managing them as flood defence assets requires ecological monitoring and adaptive management capacity that few municipal public works departments possess.

Self-healing concrete offers a partial answer to the maintenance challenge. Bacteria-based systems using organisms such as *Bacillus sphaericus* or microcapsules embedded in the concrete matrix precipitate calcium carbonate when moisture enters cracks, sealing the crack and reducing permeability (De Belie et al., 2018). Laboratory studies demonstrate crack-sealing efficiencies of 70 to 90 per cent under controlled conditions (Zhang et al., 2022). Field trials show promising but more variable results (Osibodu et al., 2025). The technology does not eliminate the need for maintenance, but it extends inspection intervals and addresses the microcracks that precede structural deterioration.

Synthesis of findings on maintenance problem

The maintenance trap represents not a technical deficiency per se, but rather an institutional failure that manifests in technical terms. The specification of permeable pavements unaccompanied by dedicated maintenance funding constitutes not sound engineering but an exercise in greenwashing.

The scope of resilience engineering must accordingly be extended to incorporate maintenance-centred design. This requires, first, the selection of materials and systems whose performance degrades gracefully under conditions of reduced maintenance; second, the integration of monitoring systems capable of detecting incipient performance decline prior to hydraulic failure; and third, the explicit accounting for life-cycle maintenance requirements within project budgets.

Integration Between Physical and Digital Systems

Digital technologies promise to transform flood management from static defence to adaptive response. The rhetoric is seductive: Internet of Things sensors providing real-time hydrological data, artificial intelligence models forecasting inundation with granular precision, Digital Twins simulating infrastructure performance under hypothetical storm scenarios. The reality is more mundane and more difficult.

IoT sensing networks comprise wireless sensors, including piezometers, rain gauges, flow sensors, and water level loggers, that transmit data to central platforms (Shah et al., 2019). Cities such as Copenhagen have deployed extensive sensor networks to monitor drainage performance and support early warning (Saddiqi et al., 2023). The engineering challenge is not sensor availability. It is, rather, data quality and continuity. Monitoring systems are subject to progressive degradation due to sensor drift, battery depletion, and telemetry link failures, while calibration requires trained technical personnel and recurring budget allocations. A 2022 review of urban IoT deployments found that fewer than 30 per cent of installed sensors remained operational and within calibration specifications three years after installation (Saddiqi et al., 2023). The Digital Twin is only as reliable as its data inputs. A twin fed by drifting sensors does not simulate the infrastructure. It simulates the sensors' errors.

AI and machine learning flood forecasting models have advanced substantially. Convolutional neural networks, long short-term memory architectures, and gradient boosting machines can now predict inundation depths and velocities at high spatial resolution (Al-Rawas et al., 2024; Guo et al., 2024). These models often outperform traditional hydrological models in computational speed and, in some contexts, accuracy. However, they share a fundamental vulnerability: they learn from historical data. When climate change alters rainfall frequency-magnitude relationships, when urban

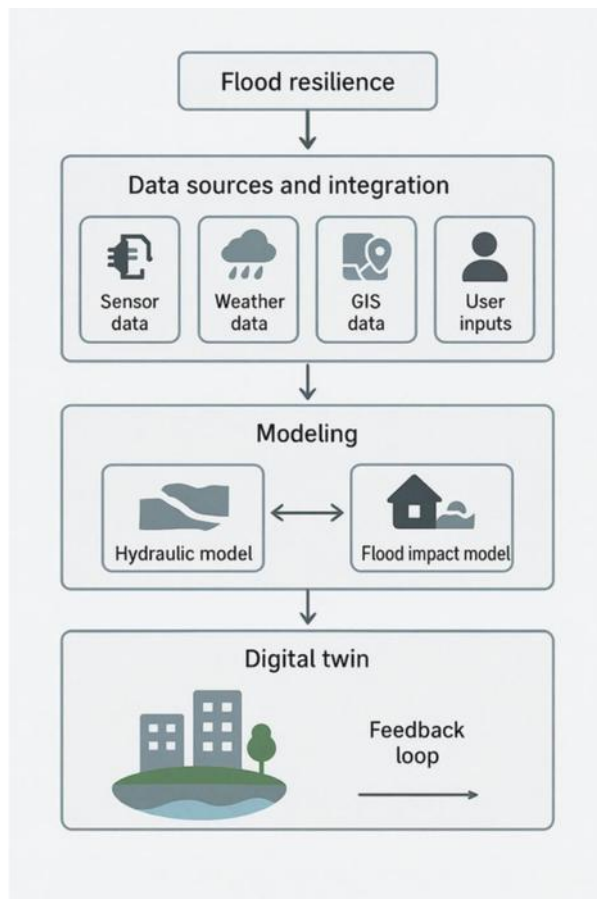


Figure 3. Architecture of a Digital Twin for flood resilience (Source: Authors' own elaboration)

development modifies drainage patterns, when a levee is raised or a culvert upgraded, the model's training data no longer represent the system it purports to predict. AI models do not generalise beyond their training distribution. They are exquisitely precise interpolators and dangerously unreliable extrapolators.

Digital Twins represent the most ambitious integration of physical and digital systems. A Digital Twin is not merely a three-dimensional model. It is a dynamic virtual replica continuously synchronised with its physical counterpart via real-time sensor data, coupled with simulation engines that predict future states (Riaz et al., 2023; Stankovic et al., 2022). Rotterdam and Singapore have deployed Digital Twin platforms for flood scenario simulation and infrastructure performance assessment (Riaz et al., 2023). **Figure 3** presents a typical architecture of the Digital Twin system. This framework illustrates the continuous data exchange between a physical urban environment with sensors and a dynamic virtual model, enabling real-time monitoring, flood simulation, and predictive analysis for informed decision-making.

Architectural diagrams and proof-of-concept implementations dominate the engineering literature on Digital Twins. What is conspicuously absent is a critical examination of failure modes. How does a Digital Twin degrade when sensor data quality deteriorates? What is the latency between a physical event and a virtual representation? How are model uncertainties communicated to human

decision-makers? These are not implementation details. They are fundamental to the twins' utility. A decision support system that does not make its uncertainty explicit cannot support decision-making. It is concealing risk.

Synthesis of findings on digital integration

Digital and physical infrastructure systems are not separate domains to be integrated after the fact. They are coupled systems whose performance and failure modes interact. Sensor drift increases the uncertainty in flood forecasts, potentially leading operators to defer gate closures or delay evacuations. An AI model trained on pre-development hydrology will systematically underestimate flood risk in rapidly urbanising catchments.

Resilience engineering must therefore treat the physical-digital interface as a first-order design consideration, with explicit requirements for data quality, model uncertainty quantification, and graceful degradation when digital components fail.

Scaling From the Building to the Basin

Flood resilience interventions operate at dramatically different scales: a sump pump in a basement, a rain garden in a street, a floodwall protecting a district, a wetland restoration project encompassing thousands of hectares. These scales are not alternatives. They are complementary. However, the engineering community lacks coherent frameworks for reasoning across them.

Building-level adaptations

Building-level adaptations are the last line of defence. Elevating structures above the Base Flood Elevation is the most reliable approach. The engineering challenge lies in foundation design that resists not only gravity loads but also lateral loads from flowing water and debris impact (Xian et al., 2017; Piątek & Wojnowska-Heciak, 2020). Scour protection for elevated foundations is frequently under-designed.

Dry flood-proofing renders the building envelope watertight below the Design Flood Level. Walls must be structurally designed to withstand hydrostatic pressure. FEMA P-55 (2021) explicitly warns that failure to account for these loads can result in catastrophic structural collapse. Removable barriers at doors and window openings require storage space and deployment protocols, organisational requirements that are rarely stress-tested outside of flood events.

Wet flood-proofing accepts water entry but manages it through flood-damage-resistant materials such as concrete, pressure-treated wood, ceramic tile, and closed-cell insulation, together with pressure equalisation openings (Aerts et al., 2013). **Figure 4** contrasts dry and wet flood-proofing techniques. This approach trades structural integrity for post-flood recovery time. It is rational at the building scale but problematic at the neighbourhood scale. If every building in a flood-prone area adopts wet-proofing, the aggregate reduction in runoff storage, water that would have ponded on streets, now enters buildings, may increase downstream flood peaks.

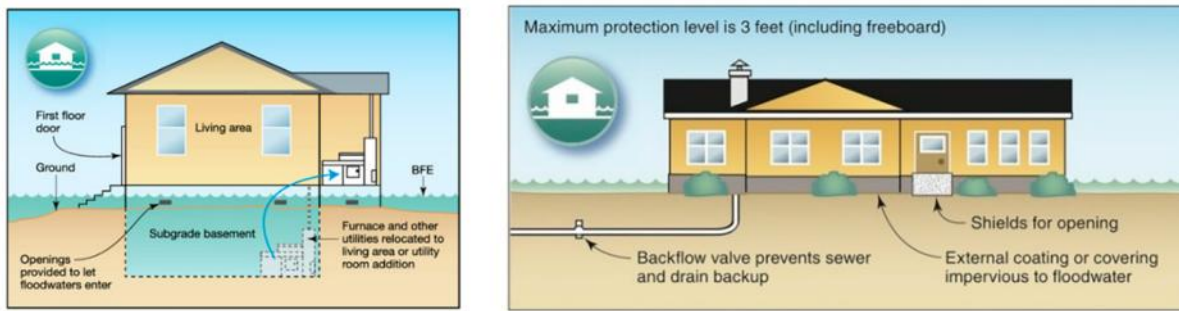


Figure 4. Comparison of dry and wet flood-proofing techniques for buildings. Dry flood-proofing on the right uses seals and barriers to prevent water entry. In contrast, wet flood-proofing on the left allows water to enter in a controlled manner, using submersible materials and vents to equalise hydrostatic pressure (Adapted from Aerts, 2018)

Nature-based solutions at neighbourhood scale

Nature-based solutions operate at intermediate scales. A bioswale treats runoff from its immediate contributing area. A network of bioswales, rain gardens, and permeable pavements can meaningfully reduce total runoff volume from a neighbourhood (Mohamed et al., 2025). However, their performance is constrained by the hydraulic conductivity of the underlying soils and the available storage volume in the aggregate layers. In dense urban cores where the impervious fraction exceeds 80 per cent, the scale of intervention required to achieve meaningful peak flow reduction is often politically or financially infeasible.

Synthesis of findings

Scale compatibility is a neglected dimension of resilience engineering. A portfolio of interventions that performs well at the building or street scale may be ineffective or counterproductive at the catchment scale. Conversely, large-scale structural defences can create perverse incentives for intensified development in protected areas, increasing residual risk when defences are ultimately exceeded (Serra-Llobet et al., 2022). Resilience engineering must therefore adopt multi-scale analysis frameworks that explicitly account for these interactions and tradeoffs.

GOVERNANCE POLICIES AND IMPLEMENTATION AS ENABLERS AND CONSTRAINTS

The most innovative engineering solutions are still theoretical without well-developed governance policies and implementation frameworks to enforce, direct, and finance them. This section critically analyses how policy frameworks directly enable or constrain technical implementation.

Institutional Frameworks as Design Drivers

Regulatory frameworks and governmental institutions provide the basic guidelines and resources for flood resilience. They translate risk awareness into actionable standards, thereby providing the technical foundation for design.

National agencies and directives

National agencies set the technical baseline. The United States Federal Emergency Management Agency Flood Insurance Rate Maps determine construction standards and insurance requirements in special flood hazard areas, directly influencing building codes and compulsory insurance (Shrestha et al., 2025). The European Union Floods Directive, formally Directive 2007/60/EC, mandates a three-stage process of risk assessment, mapping, and management planning, driving a proactive, plan-based approach across member states (Rauter et al., 2019).

These frameworks function not merely as planning instruments but as design drivers. Because the EU Floods Directive requires member states to assess and manage risks from rare but severe flood events, engineers in countries such as the Netherlands and Germany increasingly design infrastructure to withstand larger floods, add freeboard above expected flood levels, and combine traditional flood walls with nature-based measures such as wetland restoration (European Commission, 2007). Similarly, FEMA's floodplain management standards influence how buildings and infrastructure are designed in at-risk areas. Structures must be elevated above the Base Flood Elevation, and freeboard is encouraged. Because compliance is necessary for flood insurance eligibility and disaster recovery assistance, engineers must consider elevation, foundation type, and material durability during design (FEMA, 2023).

However, the effectiveness of these frameworks remains contingent on local enforcement capacity and the extent to which engineering guidance is translated into enforceable design codes. In many jurisdictions, building codes are adopted, but inspection capacity is inadequate. Variances are routinely granted. Political pressure to develop valuable land overrides zoning restrictions (Kapovic Solomun et al., 2022).

The relationship between national agencies and urban flood resilience is therefore one of necessary but insufficient conditions. Frameworks such as the EU Floods Directive and FEMA's Flood Insurance Rate Maps establish the technical baseline without which coherent design would be impossible. Yet their effectiveness relies on local enforcement capacity, the translation of guidance into enforceable codes, and the political will to resist development pressures that would compromise floodplain integrity. Where these enabling conditions are absent, national directives become merely

Table 2. Critical evaluation of flood resilience policy instruments

Policy Instrument	Primary Objective	Key Engineering/Planning Implications	Common Implementation Challenges
Building Codes	Ensure structural safety & durability in floods.	Mandates specific design loads, materials, and construction techniques (e.g., elevation, dry-proofing).	Lack of enforcement, failure to update codes with climate change data, and high perceived cost of compliance.
Floodplain Zoning	Reduce the exposure of people and assets.	Restricts or prohibits development in high-risk areas; may require compensatory storage.	Political pressure to develop valuable land, inaccurate or outdated flood maps, and existing non-conforming uses.
Stormwater Fees/Credits	Finance & incentivise decentralised management	Creates economic incentive for green infrastructure (e.g., permeable pavement, rain gardens) to reduce runoff volume.	Difficulties in quantifying runoff reduction, administrative complexity, and resistance to new fees.
Environmental Regulations	Protect natural buffer systems.	Requires preservation or restoration of wetlands, riparian zones, and coastal mangroves.	Conflicting land-use priorities and fragmented jurisdiction over environmental resources.

aspirational documents, and resilience remains an unrealised ambition.

Building codes and standards

The adoption of flood-resistant requirements in both national and local building codes may be the most direct policy impact on engineering design. Standards such as ASCE 24, Flood Resistant Design and Construction, offer minimum requirements for siting, designing, and constructing buildings in flood hazard areas, including details of foundation type, freeboard, and the use of materials resistant to flood damage (American Society of Civil Engineers, 2014).

Building codes and standards thus occupy a paradoxical position in the flood resilience landscape. They are at once the most direct and the most fragile mechanism through which policy influences design. Direct, because standards such as ASCE 24 translate abstract hazard information into concrete technical requirements for foundation elevation, material selection, and structural detailing. Fragile, because their effectiveness remains reliant upon adoption into local codes, rigorous enforcement, and resistance to the development pressures that routinely generate variances and exemptions. Where these enabling conditions are present, codes drive consistent, verifiable resilience outcomes. Where they are absent, even the most sophisticated technical standards remain aspirational documents, and the gap between policy intent and built reality persists.

Land Use Planning and its Implementation Challenges

As the primary non-structural defence, zoning restricts development in high-risk areas. It determines what is constructed and where. Properly enforced, it is preventive and future-oriented. Zoning regulations can prohibit the siting of critical infrastructure, including hospitals, power substations, and emergency response facilities, in high-probability flood zones (Der Sarkissian et al., 2022). They can also mandate on-site stormwater retention or the integration of green infrastructure in new developments.

Political and economic pressures, however, routinely compromise land-use planning. In many developing cities, the imperative to accommodate urban growth prompts the relaxation of zoning laws or the routine granting of variances, enabling construction within known hazard zones. This transfers long-term risk from developers to residents and subsequent occupants, a regressive redistribution that is rarely

accounted for in project cost-benefit analyses (Kapovic Solomun et al., 2022).

Table 2 critically evaluates common flood resilience policy instruments, and from this evaluation, a consistent pattern emerges. Each instrument, whether zoning, building codes, insurance, or structural measures, possesses a clear engineering or planning rationale. Each is theoretically capable of reducing flood risk. Yet each faces characteristic implementation barriers that are less technical than they are political and institutional. Zoning is compromised by development pressure; building codes by uneven enforcement; insurance by moral hazard and affordability constraints; structural measures by the illusion of absolute protection they create. The pattern is clear: the most significant constraints on flood resilience are not limitations of engineering knowledge but failures of governance, political will, and institutional capacity.

Community-Based Action as an Enduring Model

Top-down policy often fails at the last mile. In Bangladesh, technical warnings issued by the national Flood Forecasting and Warning Centre were frequently too general to be actionable at the village level. In response, community-based organisations, often supported by non-governmental organisations, emerged to translate technical forecasts into locally relevant, timely advice (Faruk & Maharjian, 2022; Li & Lin, 2023b).

Community-Based Flood Early Warning Systems are people-centred, low-cost systems operated by local communities. A typical system consists of simple river-level gauges read by trained volunteers, who send alerts via sirens, flags, or mobile phone messages when pre-established thresholds are exceeded. **Figure 5** illustrates the four key elements of such systems. This framework highlights the integration of local monitoring, data interpretation, and community-operated dissemination channels to generate timely alerts and trigger pre-planned evacuation procedures (Bajracharya et al., 2021). If any element, such as the gauge reading, the communication channel, or the community's evacuation rehearsal, fails, the entire system fails.

The success of these systems in countries such as Nepal, Cambodia, India, Afghanistan, and Niger demonstrates that reliability and local ownership can be more critical than technological sophistication (Cools et al., 2016; Pradhan et al., 2021; Tarchiani et al., 2020). These systems endure not because they are cheap, although they are, but because they

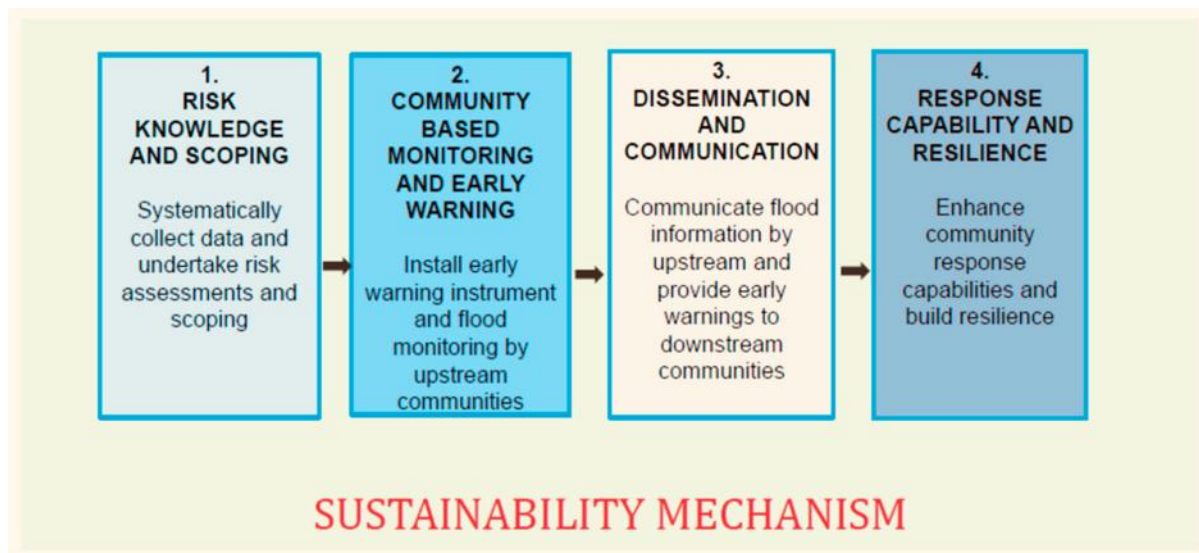


Figure 5. Key elements of a Community-Based Flood Early Warning System (CBFEWS) (Adapted from Bajracharya et al., 2021)

are embedded in existing social structures, maintained by people with direct stakes in their performance, and adaptable to local conditions.

The main governance problem is not a lack of policies but a governance gap: the disjunction between sound policies and their practical application. This gap is driven by several interconnected factors.

First, institutional fragmentation. Multiple agencies, including water resources, urban planning, emergency management, and transportation, operate with overlapping mandates and insufficient coordination, leading to conflicting actions and wasted resources (Almoradie et al., 2020; Hoang et al., 2018; Horn & Elagib, 2018).

Second, insufficient enforcement. Regulations are no better than their enforcement. Zoning and building codes are ineffective when inspection capacity is inadequate, violators are not tracked, and penalties are not imposed (Der Sarkissian et al., 2022; Hudson & Botzen, 2019).

Third, risk underestimation. Long droughts in arid and semi-arid regions can induce collective amnesia regarding flood risk, leading the public and authorities to deprioritise resilience investments (Nabinejad & Schüttrumpf, 2023; Perera et al., 2020).

Bridging this gap requires integrated governance models that enhance cross-departmental cooperation, strengthen regulatory implementation, and engage communities throughout the risk management cycle, from planning through recovery. Only within such a favourable and feasible governance framework can the technical solutions discussed in previous sections reach their potential.

SYNTHESIS OF BARRIERS AND PATHWAYS

The preceding analysis has exposed a series of technical, organisational, and socio-economic barriers that are often treated in isolation but are in fact tightly coupled. This section

synthesises those barriers and outlines integrated pathways forward.

Technical Barriers

The lack of high-resolution hydrological data and predictive ability constitutes one of the primary technical limitations. In much of the developing world, and in arid regions of the developed world, field data are scarce and hydrometeorological records are sparse (Mahmood et al., 2016; Nabinejad & Schüttrumpf, 2023). This scarcity compromises model calibration, early warning lead times, and the specification of appropriate design loads. Engineers in data-poor contexts are forced to rely on low-resolution global models that systematically underestimate localised convective storms (Borga et al., 2011; Moreno et al., 2013).

Three interlocking strategies are needed to address this barrier. First, modernise data acquisition through investment in diversified monitoring infrastructure, including Internet of Things sensors, remote sensing, and community-operated gauges (Al-Rawas et al., 2024; Munawar et al., 2022). Second, develop centralised open-data platforms that enable data sharing between national and local agencies, support model calibration, and provide training datasets for machine learning. Third, advance predictive modelling with artificial intelligence while explicitly addressing the extrapolation problem through uncertainty quantification, ensemble methods, and rigorous validation against out-of-sample events (Guo et al., 2024).

Organisational Barriers

Institutional fragmentation and weak enforcement cripple integrated planning. Responsibilities are dispersed across agencies that do not coordinate, resulting in conflicting policies and resource waste (Almoradie et al., 2020). Zoning laws and building standards are routinely evaded, often because of political pressure, corruption, or simple lack of inspection capacity (Der Sarkissian et al., 2022). In arid regions, low risk perception during extended dry periods compounds these problems (Nabinejad & Schüttrumpf, 2023).

Table 3. Synthesised roadmap for overcoming flood resilience barriers

Challenge Category	Core Problem	Future Directions & Integrated Solutions
Technical	Data scarcity & inaccurate forecasting	Investment in IoT/Remote Sensing + AI-Driven Modelling + Digital Twins. Creates a closed-loop system from data collection to predictive physical impact analysis.
Organizational	Institutional fragmentation & weak enforcement	Integrated Governance Models + Strengthened Regulatory Compliance + Targeted Risk Communication. Aligns policies, ensures they are followed, and builds public support.
Socio-Economic	High costs & lack of technical capacity	Innovative Financing (e.g., Green Bonds) + Life-Cycle Costing + Local Capacity Building. Makes projects affordable, demonstrates their value, and ensures local ownership and maintenance.

Three complementary strategies are required. First, foster integrated governance models by establishing formal coordination mechanisms that align responsibilities across urban planning, water resource management, and disaster management. The European Union Floods Directive provides a template, but its effectiveness depends on national transposition and local implementation capacity (Kapovic Solomun et al., 2022). Second, strengthen enforcement and compliance through investment in inspector training, geospatial technologies for compliance monitoring, and credible sanctions for violators. Third, implement targeted risk communication strategies that make flood risk tangible for specific communities, using local historical data, visualisations, and participatory mapping to overcome underestimation biases.

Socio-Economic Barriers

The upfront cost of flood-resilient infrastructure impedes implementation, especially in low- and middle-income countries (Fay et al., 2010). Governments face competing priorities, including health, education, and poverty alleviation, and often favour short-term infrastructure projects over long-term integrated plans (Lasage et al., 2014). Technical capacity is also unevenly distributed; many communities lack the trained personnel to maintain flood-resilient infrastructure, conduct research, monitor flood forecasts, or prepare effectively (Rosmadi et al., 2023).

Three strategies are essential. First, diversify and innovate in financing by accessing climate adaptation funds such as the Green Climate Fund, issuing resilience bonds, and supporting micro-insurance programs for vulnerable households (Cui & Huang, 2018; Surminski & Oramas-Dorta, 2014). Second, prioritise life-cycle cost analysis so that decisions are guided by the lowest long-term cost rather than the lowest initial capital cost. Demonstrating that investments in nature-based solutions and durable materials reduce maintenance and reconstruction expenses over the asset lifespan is critical for shifting procurement practices. Third, invest in human capital by partnering with universities and technical institutes to develop local expertise and create training programs for engineers, technicians, and community leaders on the design, implementation, and maintenance of resilience measures. **Table 3** synthesises these barriers and pathways into a consolidated roadmap.

AN INTEGRATED LIFE-CYCLE RESILIENCE FRAMEWORK

The analysis presented thus far leads to a conclusion that is simultaneously sobering and hopeful: the barriers to flood resilience are not primarily technical. Engineers know how to build floodwalls that resist scour. They know how to formulate pervious concrete that balances permeability and strength. They know how to train machine learning models on sparse data and quantify their uncertainty. The impediments lie elsewhere, in maintenance budgets that never materialise, in fragmented agencies that cannot coordinate, in procurement rules that penalise higher initial costs even when life-cycle savings are demonstrable, and in resilience investments that flow to wealthier districts while informal settlements rely on volunteer-read river gauges.

An integrated life-cycle resilience framework must therefore address the entire system: physical infrastructure, digital infrastructure, institutional arrangements, financing mechanisms, and social equity. Such a framework has five interconnected pillars.

The first pillar is maintenance-centred physical design. This requires specifying materials and systems whose performance degrades gracefully under realistic maintenance regimes. It requires requiring that every resilience project include a legally binding maintenance plan and dedicated funding stream before construction approval. It requires integrating passive monitoring systems that alert operators to performance decline before hydraulic failure occurs.

The second pillar is uncertainty-aware digital integration. This requires treating digital twins and artificial intelligence forecasts as components whose failure modes are as important as those of levees and pumps. It requires mandating explicit uncertainty quantification in all predictive models. It requires designing human-machine interfaces that communicate uncertainty honestly rather than concealing it behind deterministic outputs.

The third pillar is multi-scale analysis and planning. This requires requiring that resilience interventions be evaluated not only at their own scale but also for their effects on upstream and downstream flood behaviour. It requires developing planning tools that enable trade-off analysis across scales, from building to street to neighbourhood to catchment.

The fourth pillar is institutional integration and enforcement. This requires establishing formal coordination mechanisms among the agencies responsible for water, land use, transportation, and emergency management. It requires

investing in inspection capacity and credible enforcement. It requires embedding resilience requirements in procurement rules, building codes, and land use regulations and ensuring they are applied consistently.

The fifth pillar is equity-targeted investment. This requires explicitly allocating resilience investments to protect the most vulnerable populations, not only the most economically valuable assets. It requires supporting community-based monitoring and early warning systems as first-class components of urban resilience architecture, not as stopgaps until real technology arrives. It requires equity impact assessments for all major resilience infrastructure projects.

RECOMMENDATION FOR FUTURE STUDIES

If the integrated life-cycle resilience framework is to move from concept to practice, several priority research areas demand attention.

First, performance validation of nature-based solutions under real-world conditions. Standardised, replicable protocols are needed for measuring the hydraulic and structural performance of bioswales, permeable pavements, and rain gardens over decade-long timescales (Andersen et al., 1999). Current evidence is heavily skewed toward laboratory studies and short-term field trials. Without long-term performance data, engineers cannot specify these systems with confidence, and procurement officials cannot justify their higher initial costs.

Second, artificial intelligence enhanced structural design codes. Research is needed on how probabilistic flood forecasts can be embedded directly into structural design standards such as ASCE 7. This would enable dynamic load requirements that evolve as climate projections improve. The legal, insurance, and professional liability implications of such dynamic standards require investigation.

Third, equity in resilience planning. Empirical research is urgently needed on the distributional effects of flood resilience investments. Who benefits from a new floodwall? Who is displaced by it? How can community-based monitoring systems be sustained over decades, and how can their data be integrated with official early warning systems? These questions have received far less attention than the technical performance of sensors and models.

Fourth, advanced materials for durability. Self-healing concrete, corrosion-resistant alloys, and bio-based composites offer genuine promise for extending the service life of flood-exposed infrastructure (Liu et al., 2013). Yet field validation remains limited, and cost-effectiveness analyses rarely account for avoided maintenance expenditures over multi-decade lifespans. Research translation, moving from laboratory demonstration to commercially available, code-compliant products, is a critical gap.

Fifth, failure modes of digital twins. The literature on digital twins for flood resilience is dominated by success stories. Systematic research on failure modes, including sensor drift, model degradation, and human-computer interaction breakdowns, is almost entirely absent. Without such research,

there is risk of deploying brittle digital systems that create the illusion of control while masking accumulating risk.

CONCLUSION

This review has argued that achieving genuine urban flood resilience requires a fundamental reorientation away from a fragmented, technology-centric view and toward an integrated perspective that treats physical infrastructure, digital systems, institutional arrangements, and social equity as inseparable components of a single problem.

The analysis addressed the first objective by examining flood-resilient design approaches through the lenses of structural and materials engineering. The evidence shows that levees, floodwalls, and surge barriers fail in predictable ways, and that these failures continue to occur not from lack of knowledge but from gaps in application and maintenance. Permeable pavements and bioswales perform as designed under ideal conditions but degrade rapidly without sustained institutional commitment. Self-healing concrete and fibre-reinforced polymers offer promise but require further field validation (Teng et al., 2012).

The second objective was addressed by evaluating the integration of smart digital tools. The Internet of Things, artificial intelligence, and digital twins provide unprecedented capabilities for real-time monitoring and prediction, yet their performance is bounded by data quality, model extrapolation limits, and the institutional capacity to act on their outputs. Sensor drift, calibration lapses, and the brittleness of machine learning models under changing conditions represent vulnerabilities that are rarely acknowledged in the literature.

The third objective was addressed by identifying technical, organisational, and socio-economic barriers. Data scarcity, institutional fragmentation, weak enforcement, high upfront costs, and uneven technical capacity interact to impede implementation. These barriers are not independent but mutually reinforcing, creating systemic lock-in that cannot be broken by technical fixes alone.

The fourth objective was addressed by proposing an integrated life-cycle resilience framework and outlining a priority research agenda. The framework has five pillars: maintenance-centred physical design, uncertainty-aware digital integration, multi-scale analysis and planning, institutional integration and enforcement, and equity-targeted investment. The research agenda prioritises long-term performance validation of nature-based solutions, artificial intelligence enhanced design codes, equity analysis, advanced materials development, and critical examination of digital twin failure modes.

The path forward is not to abandon technical ingenuity but to embed it within a broader systems perspective. Advanced materials and sensors provide the durable physical substrate and the data streams. Artificial intelligence and digital twins convert data into predictive intelligence for system optimisation. Robust, integrated governance ensures this intelligence is translated into enforced standards and coordinated action. Innovative finance and capacity building make solutions investable and locally sustainable.

Ultimately, flood resilience must be embedded as an ongoing process within urban development, not a discrete project with a ribbon-cutting and a handover. By uniting rigorous engineering with enlightened policy and inclusive community engagement, urban infrastructures can be forged that are not only resistant to shocks but capable of adapting and thriving in the face of an uncertain climate future.

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AI statement: The authors stated that, during the preparation of this manuscript, the authors used generative artificial intelligence tools (such as Grammarly) solely for language editing and grammar refinement. Specifically, AI assistance was employed to rephrase sentences and improve readability. AI was also used to enhance Figures 2 & 3, which were adopted from previous work and the authors were appropriately cited. No AI tools were used for data extraction, analysis, synthesis, interpretation, or the generation of novel scientific insights. All intellectual content, including the critical evaluation, synthesis of literature, development of the integrated framework, and conclusions, is the original work of the authors. The authors stated that they take full responsibility for the accuracy, integrity, and originality of the manuscript.

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